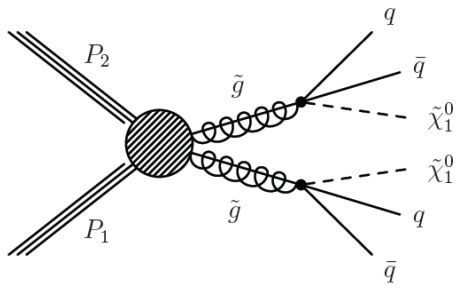
SUSY searches at the LHC

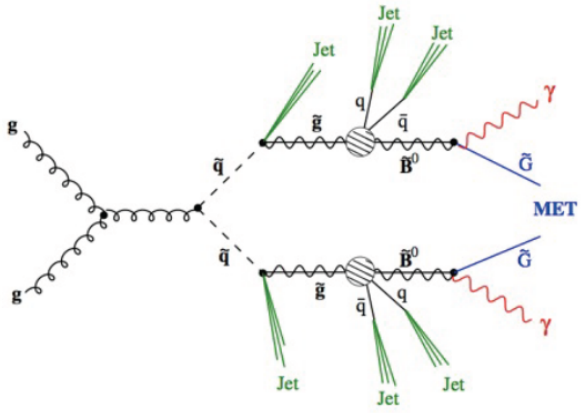
Purely hadonic:

Jets + missing energy

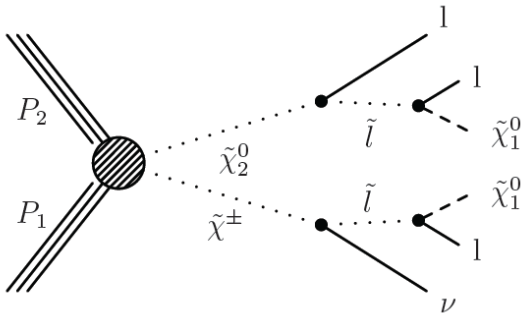


Photons:

- targets:
  - -> **gauge mediated SUSY**
  - -> **dark matter**
  - -> **large extra dimensions**



Leptonic:



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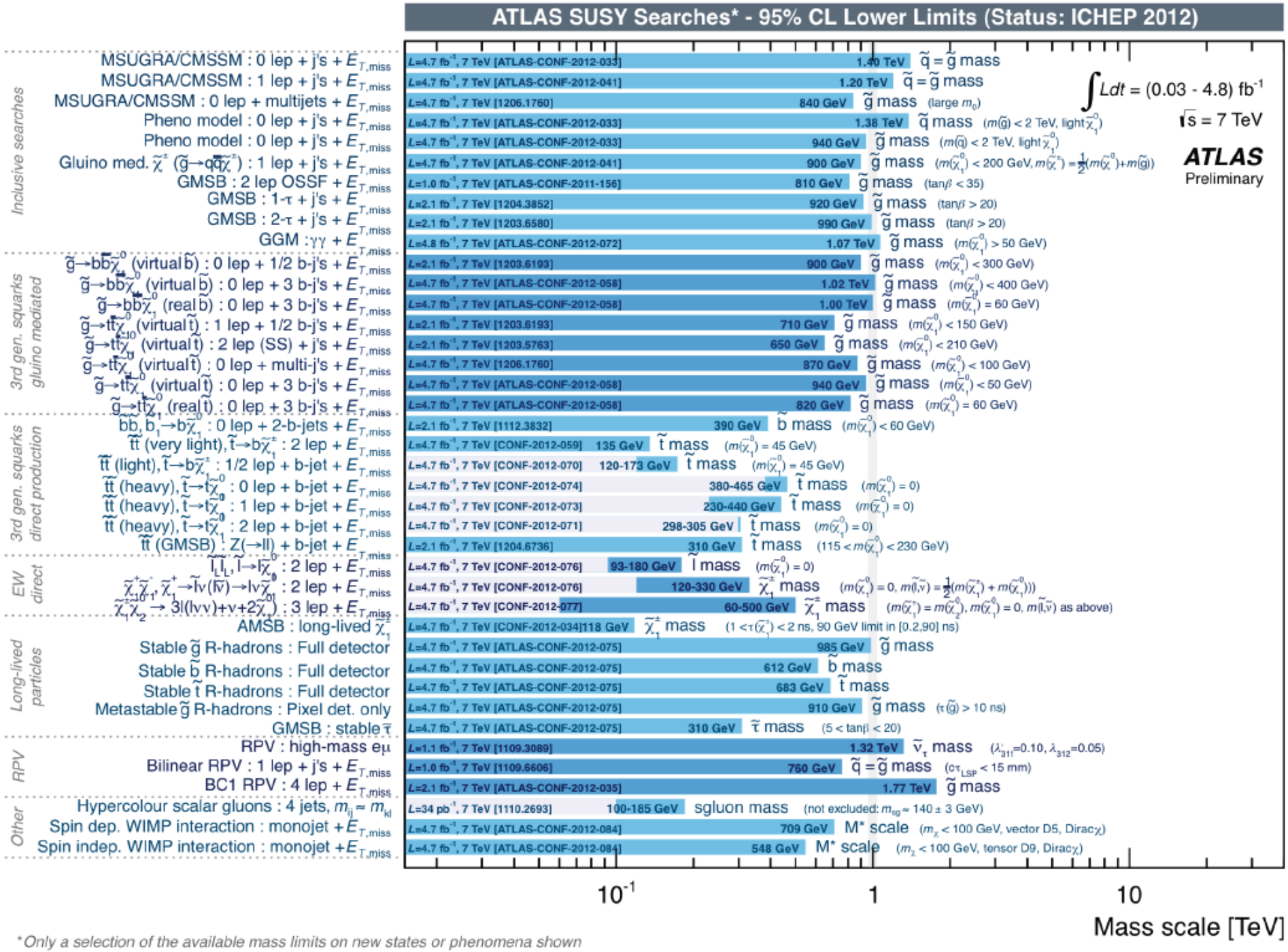
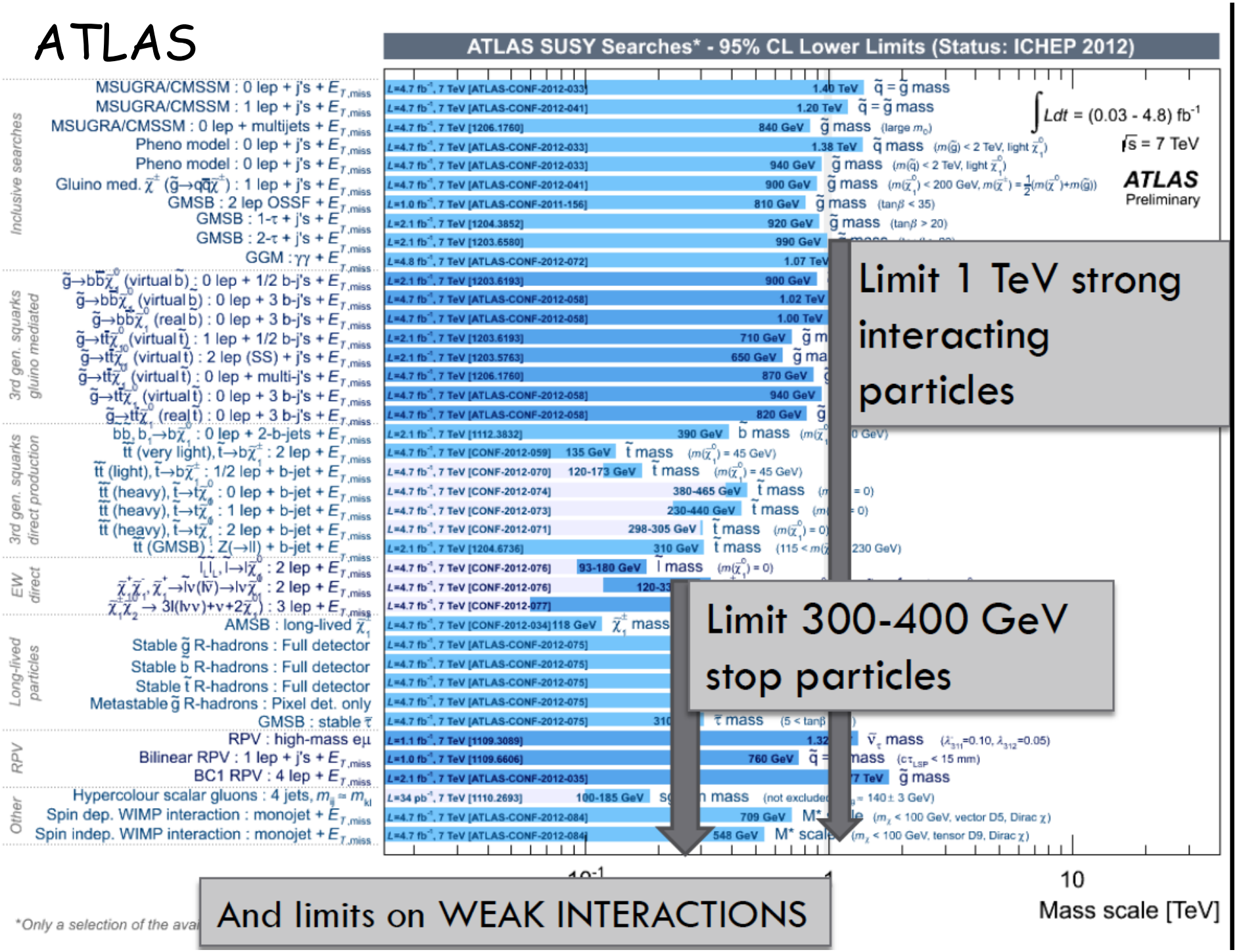


*Only a selection of the available mass limits on new states or phenomena shown

ATLAS


ATLAS SUSY Searches* - 95% CL Lower Limits (Status: ICHEP 2012)
Inclusive searches
3rd gen. squarks gluino mediated
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
Other
MSUGRA/CMSSM : 0 lep + j's + E_T,miss
MSUGRA/CMSSM : 1 lep + j's + E_T,miss
MSUGRA/CMSSM : 0 lep + multijets + E_T,miss
Pheno model : 0 lep + j's + E_T,miss
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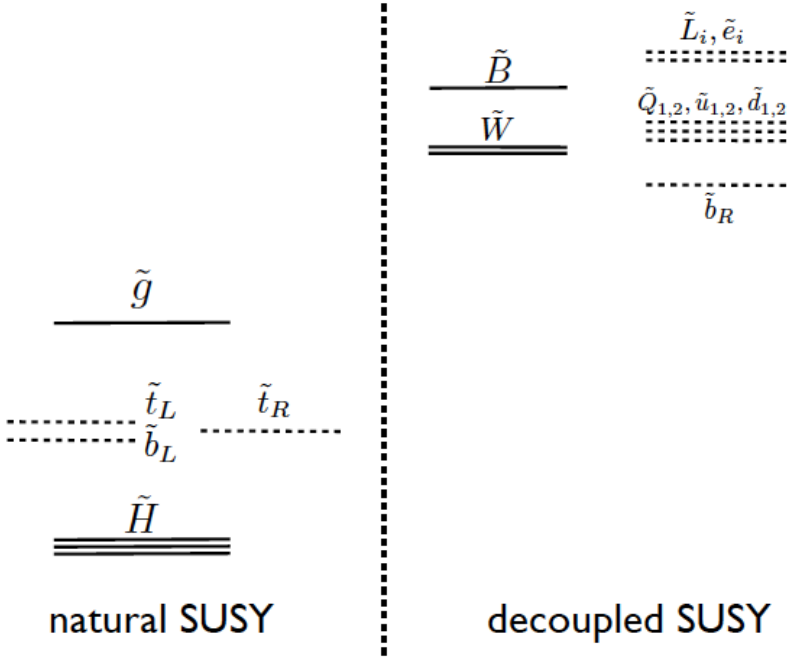
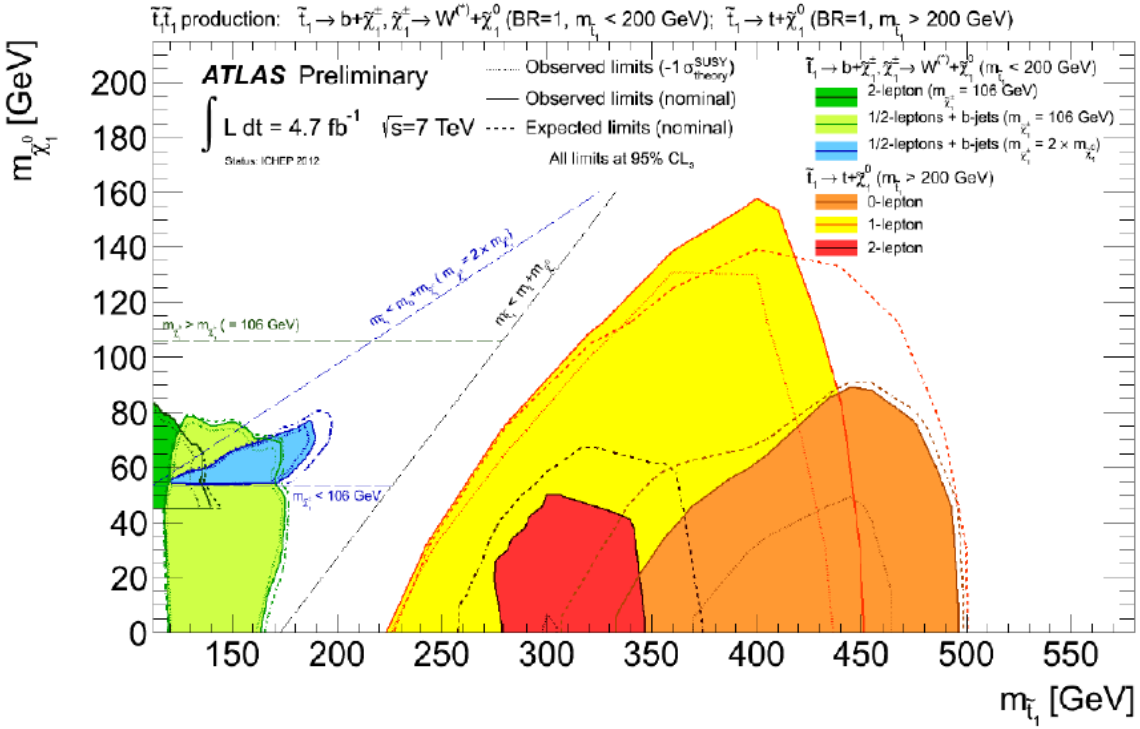
Gluino med. χ̃± (g̃→qq̄χ̃±) : 1 lep + j's + E_T,miss
GMSB : 2 lep OSSF + E_T,miss
GMSB : 1-τ + j's + E_T,miss
GMSB : 2-τ + j's + E_T,miss
GGM : γγ + E_T,miss
g̃→bb̄χ̃10 (virtual b̃) : 0 lep + 1/2 b-j's + E_T,miss
g̃→bb̄χ̃10 (virtual b̃) : 0 lep + 3 b-j's + E_T,miss
g̃→bb̄χ̃1 (real b̃) : 0 lep + 3 b-j's + E_T,miss
g̃→tt̄χ̃10 (virtual t̃) : 1 lep + 1/2 b-j's + E_T,miss
g̃→tt̄χ̃10 (virtual t̃) : 2 lep (SS) + j's + E_T,miss
g̃→tt̄χ̃0i (virtual t̃) : 0 lep + multi-j's + E_T,miss
g̃→tt̄χ̃1± (virtual t̃) : 0 lep + 3 b-j's + E_T,miss
g̃→tt̄χ̃10 (real t̃) : 0 lep + 3 b-j's + E_T,miss
bb̃, b̃1→bχ̃10 : 0 lep + 2-b-jets + E_T,miss
tt̃ (very light), t̃→bχ̃1± : 2 lep + E_T,miss
tt̃ (light), t̃→bχ̃1± : 1/2 lep + b-jet + E_T,miss
tt̃ (heavy), t̃→tχ̃10 : 0 lep + b-jet + E_T,miss
tt̃ (heavy), t̃→tχ̃0i : 1 lep + b-jet + E_T,miss
tt̃ (heavy), t̃→tχ̃1± : 2 lep + b-jet + E_T,miss
tt̃ (GMSB) : Z(→ll) + b-jet + E_T,miss
l̃Ll̃L, l̃→lχ̃10 : 2 lep + E_T,miss
χ̃1±χ̃20, χ̃1±→l̃ν(l̃ν̄)→lνχ̃10 : 2 lep + E_T,miss
χ̃1±χ̃20 → 3l(lνν)+ν+2χ̃10 : 3 lep + E_T,miss
AMSB : long-lived χ̃1±
Stable g̃ R-hadrons : Full detector
Stable b̃ R-hadrons : Full detector
Stable t̃ R-hadrons : Full detector
Metastable g̃ R-hadrons : Pixel det. only
GMSB : stable τ̃
RPV : high-mass eμ
Bilinear RPV : 1 lep + j's + E_T,miss
BC1 RPV : 4 lep + E_T,miss
Hypercolour scalar gluons : 4 jets, m_qj ≃ m_kl
Spin dep. WIMP interaction : monojet + E_T,miss
Spin indep. WIMP interaction : monojet + E_T,miss
∫Ldt = (0.03 - 4.8) fb-1
√s = 7 TeV
ATLAS
Preliminary
Limit 1 TeV strong interacting particles
Limit 300-400 GeV stop particles
And limits on WEAK INTERACTIONS
*Only a selection of the ava
10
Mass scale [TeV]

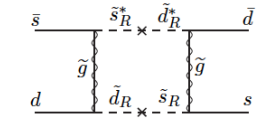
An exception: "Natural" SUSY

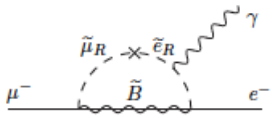
FCNC: 1,2 sgenerations heavy

Hierarchy problem: 3rd sgeneration light









Status of SUSY -little hierarchy problem

MSSM: 105 +(19) Parameters

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

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

(Unless light stop $m_{\tilde{t},LHC} > 250\ GeV$)

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

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definite SUSY structure

Fine Tuning measure:

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

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

$$\gamma_i = \{\tilde{m}_i, \tilde{M}_i, \ldots\}$$

Ellis, Enquist, Nanopoulos, Zwirner

Barbieri, Giudice

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Ellis, Enquist, Nanopoulos, Zwirner

Barbieri, Giudice

Likelihood:

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

$$\chi^2(\gamma_i) = -2\ln(L) = \chi^2_{old}(\gamma_i) + 2\ln\Delta_q$$

Ghilencea, Ross

$$\Delta_q = \left(\sum_i \Delta^2_{\gamma_i} \right)^{1/2}$$

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

$$\Delta_q = 1000, \quad \delta\chi^2 / d.o.f. \sim 1.5$$

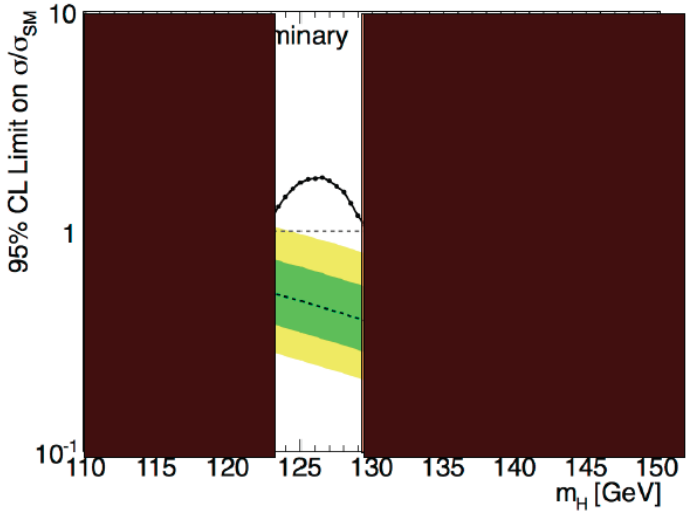
$$\chi^2 / d.o.f. = 2\,(2.5), \quad P = 3\,(0.6)\%$$

The Higgs mass in SUSY ?

$$M_S^2 = m_{q_3} m_{U_3} \geq (500 GeV)^2$$

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

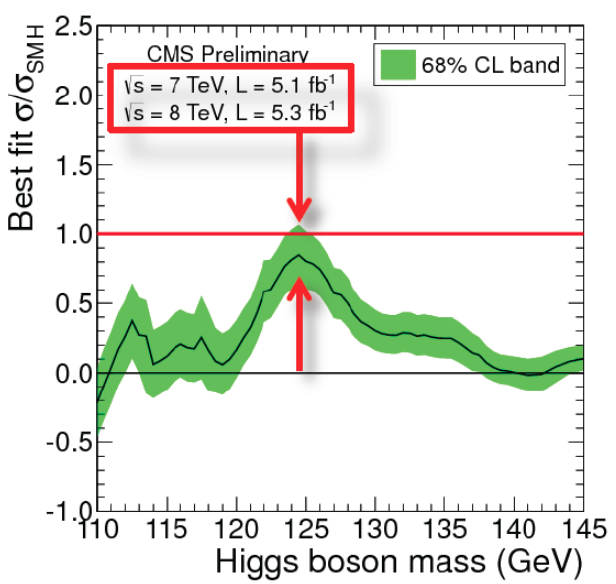
Atlas



Excluded at 95% CL

110-122.7 129-557 GeV

CMS



- The CMSSM

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

assume correlation between SUSY breaking parameters

The CMSSM

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

$$
\begin{aligned}
V &= m_1^2 |H_1|^2 + m_2^2 |H_2|^2 - (m_3^2 H_1 \cdot H_2 + h.c.) \\
&+ \frac{1}{2}\lambda_1 |H_1|^4 + \frac{1}{2}\lambda_2 |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1 \cdot H_2|^2 \\
&+ \left[\frac{1}{2}\lambda_5 (H_1 \cdot H_2)^2 + \lambda_6 |H_1|^2 (H_1 \cdot H_2) + \lambda_7 |H_2|^2 (H_1 \cdot H_2) + h.c.\right]
\end{aligned}
$$

Minimisation conditions:

$$v^2 = -m^2/\lambda, \qquad 2\lambda\frac{\partial m^2}{\partial \beta} = m^2\frac{\partial \lambda}{\partial \beta}$$

$$
\begin{aligned}
m^2 &= m_1^2 \cos^2\beta + m_2^2 \sin^2\beta - m_3^2 \sin 2\beta \\
\lambda &= \frac{\lambda_1}{2}\cos^4\beta + \frac{\lambda_2}{2}\sin^4\beta + \frac{\lambda_{345}}{4}\sin^2 2\beta + \sin 2\beta\,(\lambda_6 \cos^2\beta + \lambda_7 \sin^2\beta)
\end{aligned}
$$

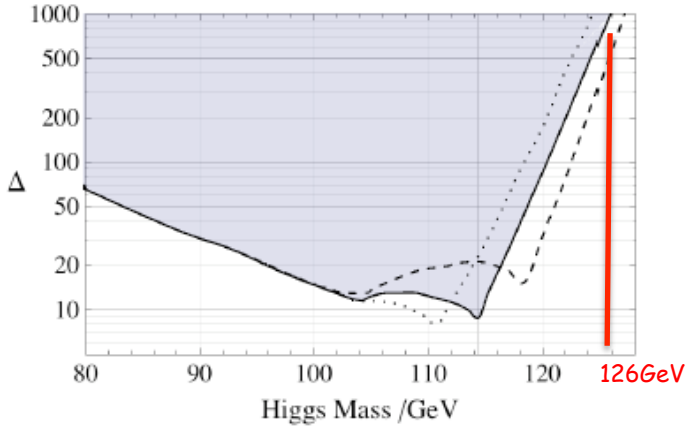
$$\Delta \equiv \max \left|\Delta_p\right|_{p=\{\mu_0^2, m_0^2, m_{1/2}^2, A_0^2, B_0^2\}}, \qquad \Delta_p \equiv \frac{\partial \ln v^2}{\partial \ln p}$$

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

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

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

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



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

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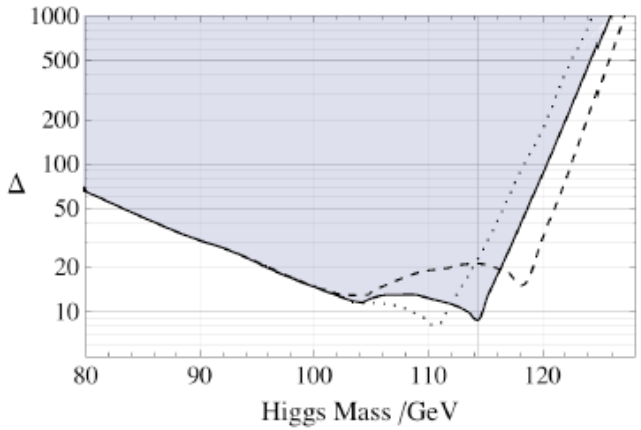
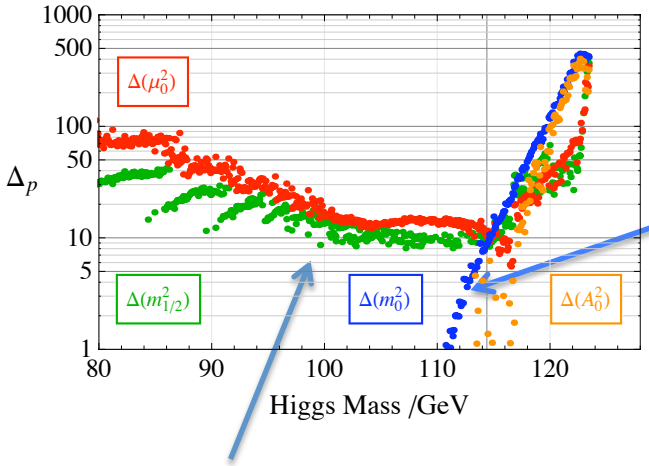
$$\Delta_{Min} = 9, \quad m_h = 114 \pm 2GeV$$

(No Higgs bound applied)

The CMSSM





Limit of focus point

λ increase with m_H

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Radiative EW breaking

Relic density unrestricted

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

S.Cassel, D.Ghilencea, GGR

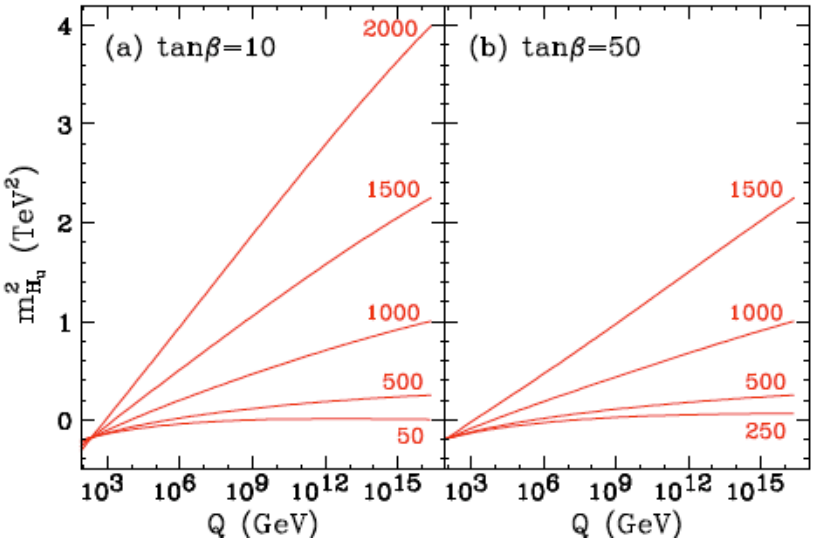
Focus Point

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

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

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

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



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

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

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

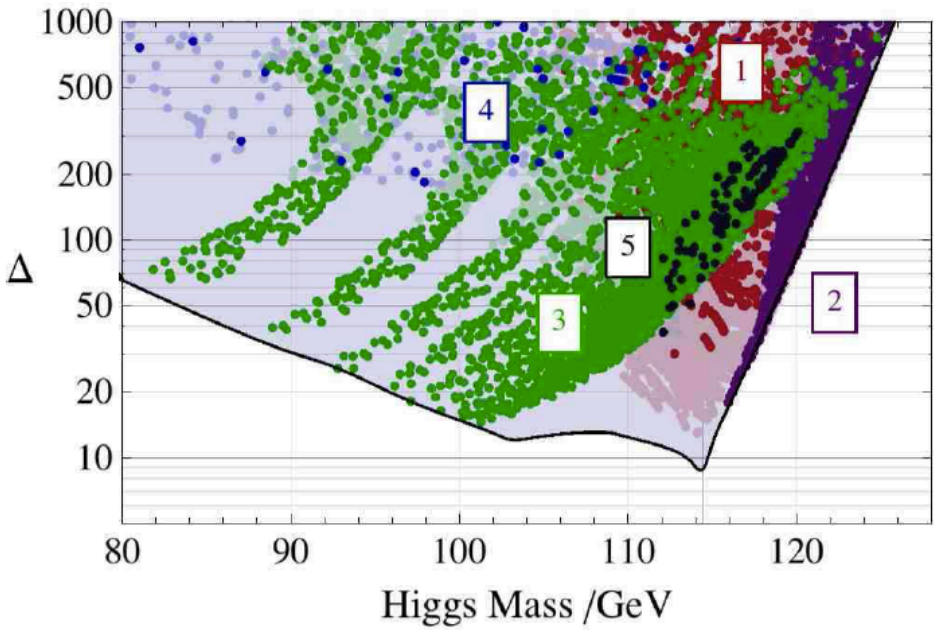
$$m^2_{H_u}\left(t_0\right)=a_0\,m^2+..,\ a_0\le 0.1$$

Natural choice

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

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

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

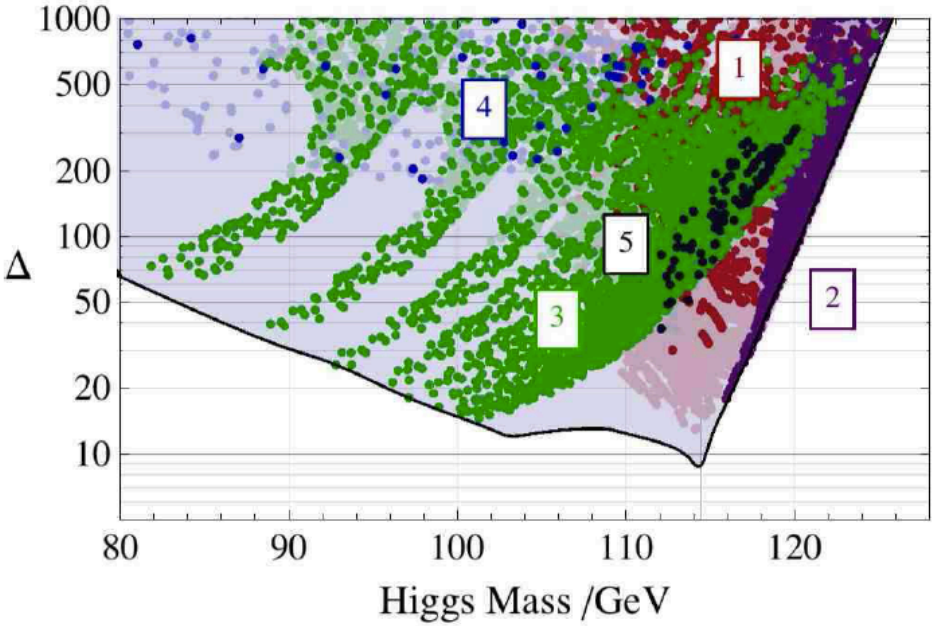
Within 3σ WMAP:

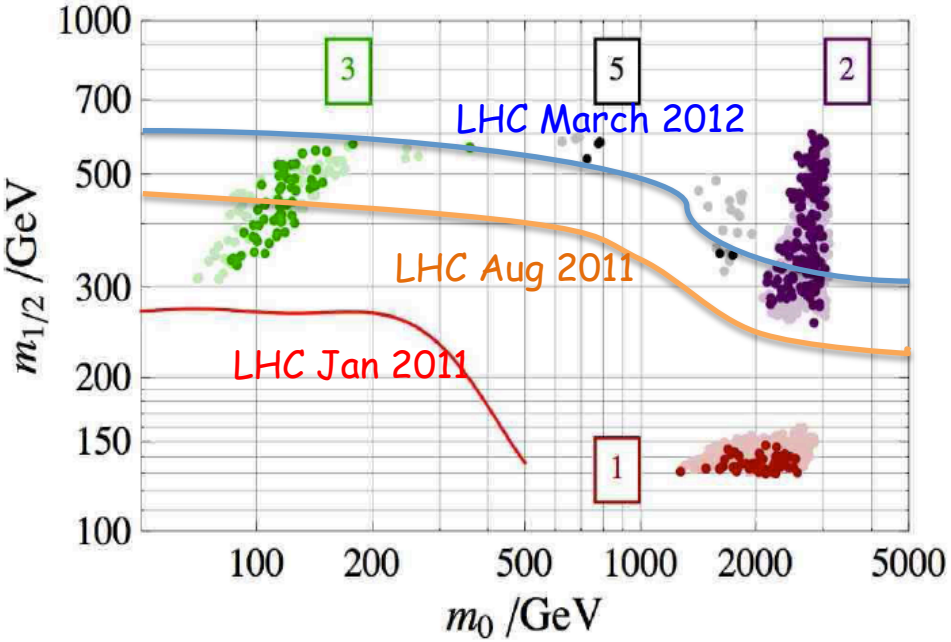
$\Delta_{Min} = 15, \quad m_h = 114.7 \pm 2GeV$

< 3σ WMAP:

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

Cassel, Ghilencea, GGR





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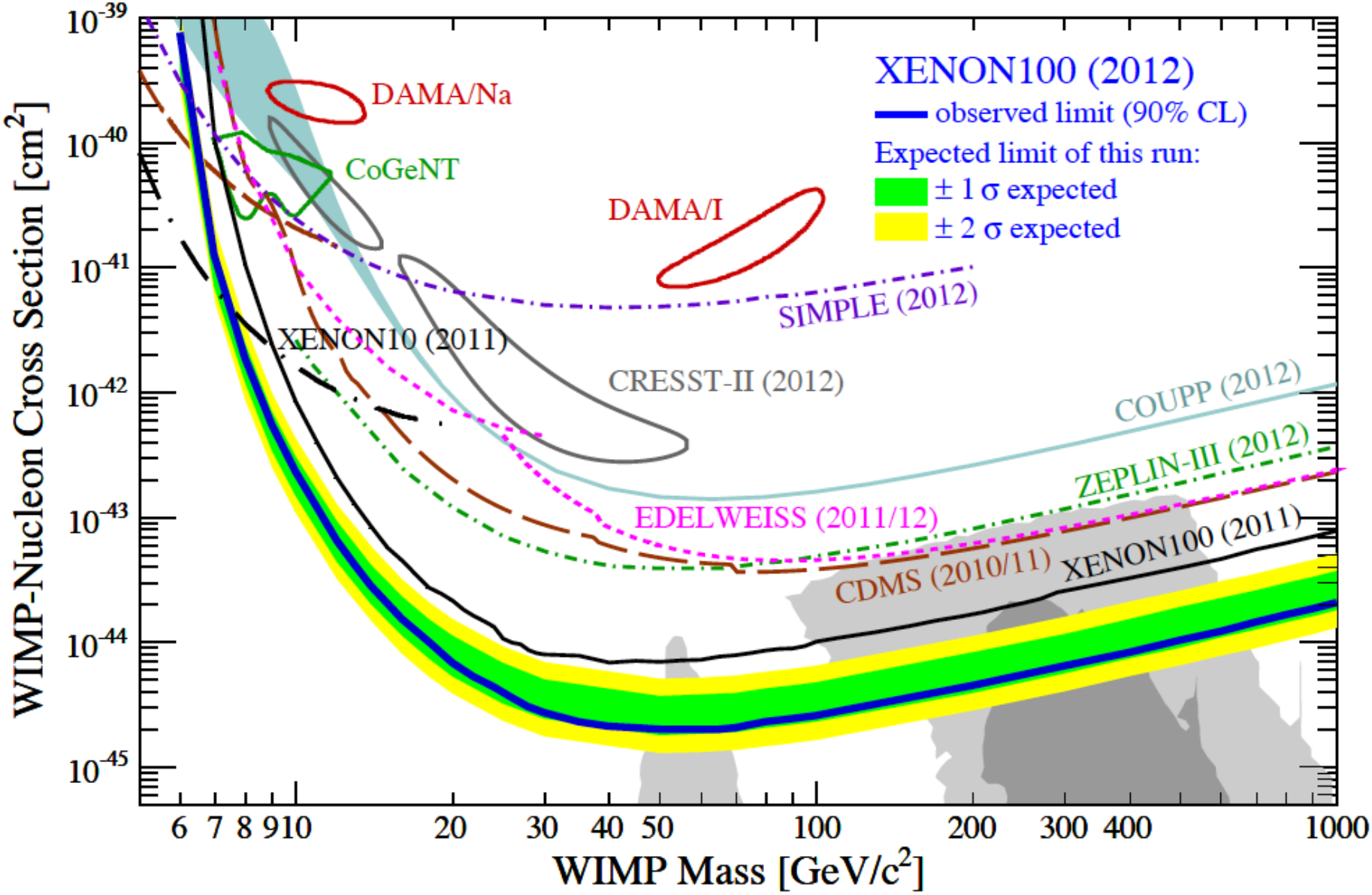
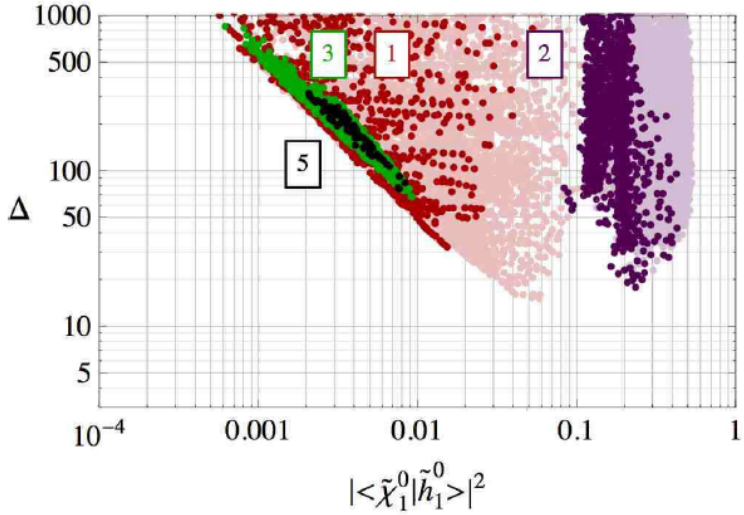
Cassel, Ghilencea, GGR

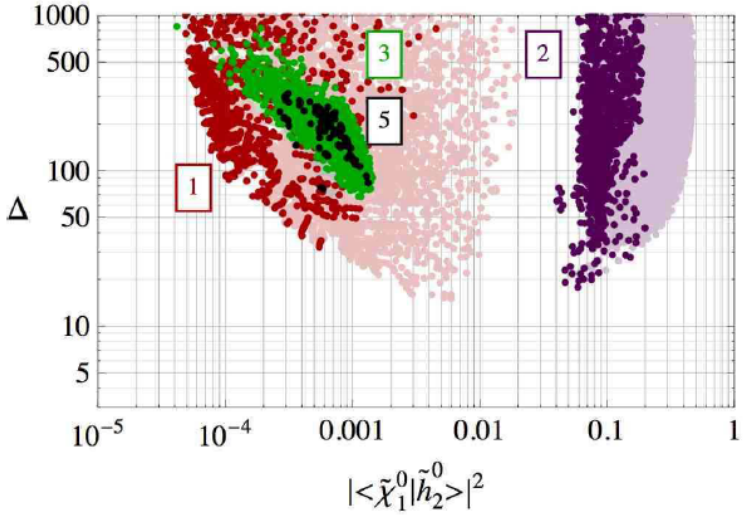
Direct dark matter searches: (spin independent)



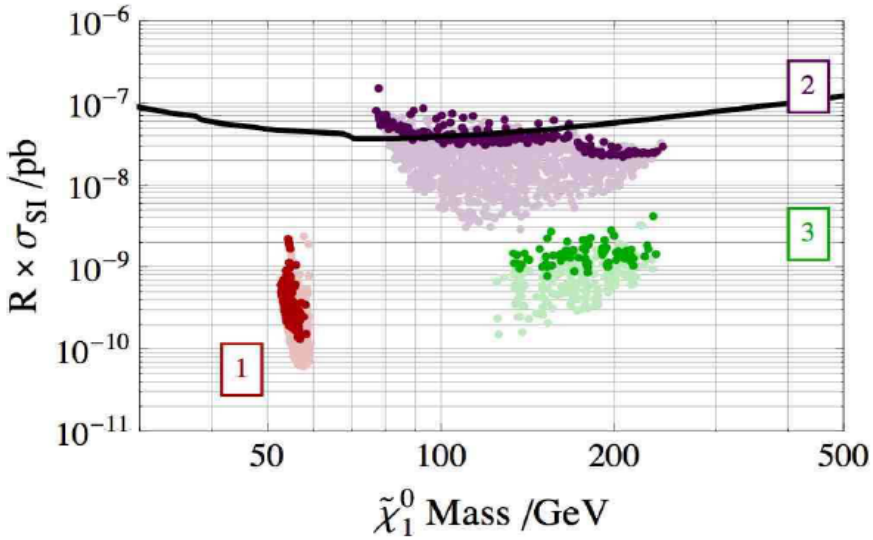
DM - Scaled spin independent cross section for LSP-proton scattering:



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

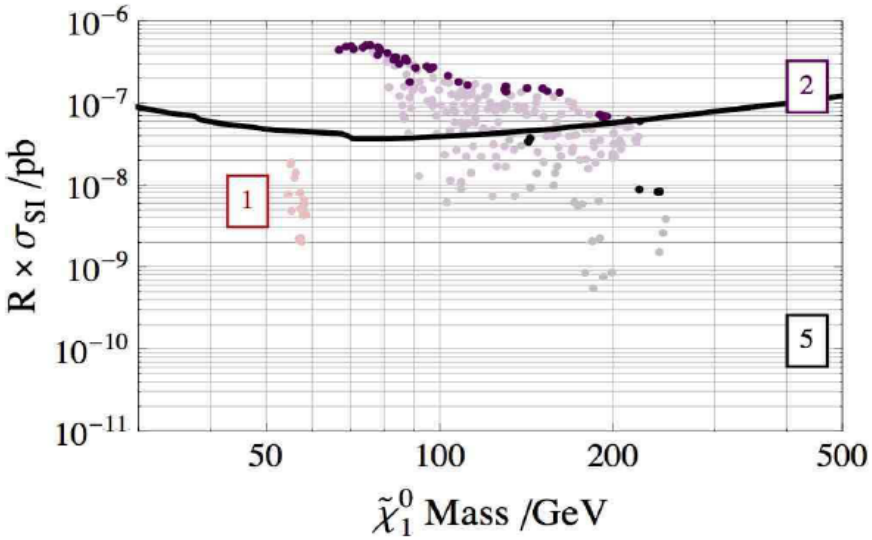


(b) LSP $\tilde{h}_2^0$ component



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

$\Delta < 100$



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

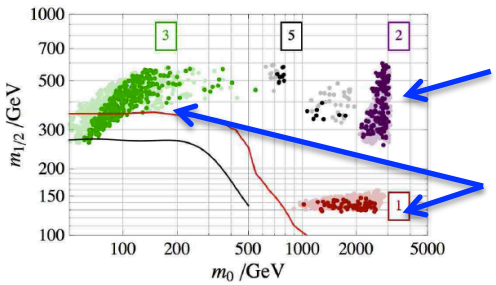
$\Delta < 100$

CMSSM summary:

- Minimises MSSM fine tuning (focus point)

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

- Complementary DM & LHC searches



(a) $m_h > 111$ GeV

DM $\quad \Delta \le 100 \quad$ Sensitivity $\times (10-100)$ $\quad$ (Now achieved!)

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

- *BUT* $\quad \Delta > 300$ for $m_H = 126GeV$

- (General) Gauge mediation in the MSSM

$$M_{\tilde{\lambda}_i}(M_{mess}) = k_i \frac{\alpha_i(M_{mess})}{4\pi} \Lambda_G$$

$$m^2_{\tilde{f}}(M_{mess}) = 2 \sum_{i=1}^{3} C_i k_i \frac{\alpha_i^2(M_{mess})}{(4\pi)^2} \Lambda_S^2$$

No focus point

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

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

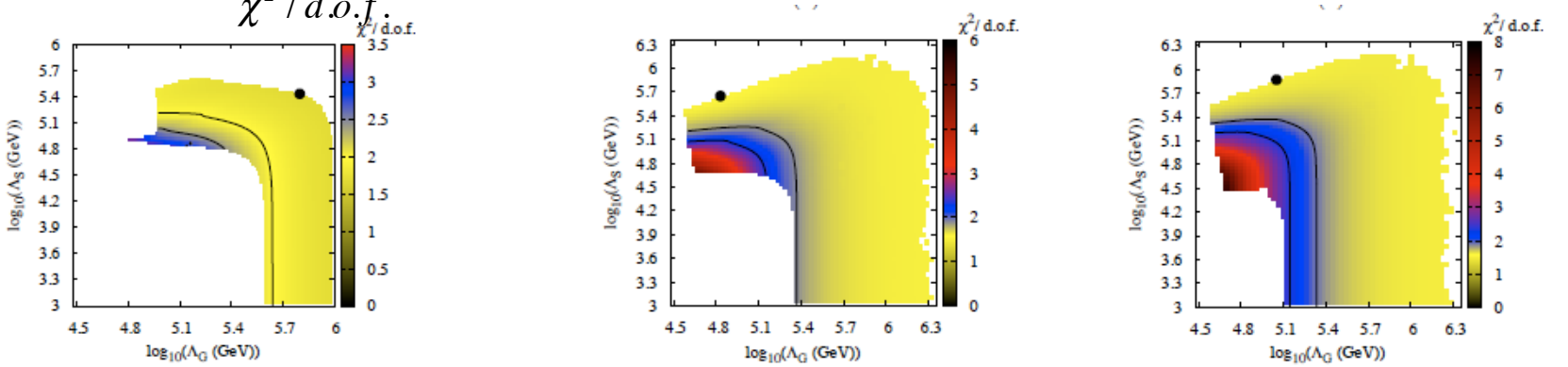
(Ordinary gauge mediation $\Lambda_G = \Lambda_S$)

Meade, Seiberg, Shih

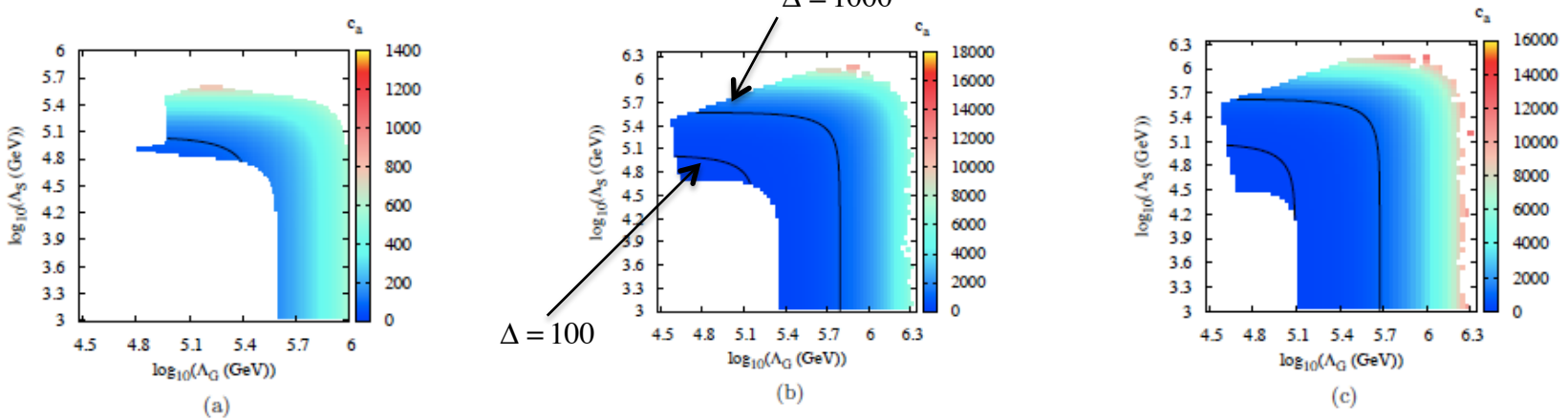
Fine tuning in General Gauge Mediation

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

$\chi^2 / d.o.f.$



Δ



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

$\Delta >> 100$ no focus point

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

Reduced fine tuning (c.f. CMSSM)

- New degrees of freedom

- 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

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

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

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

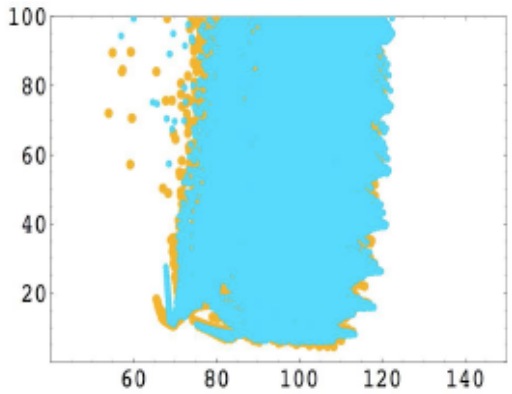
I. Reduced fine tuning : New heavy states – higher dimension operators

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

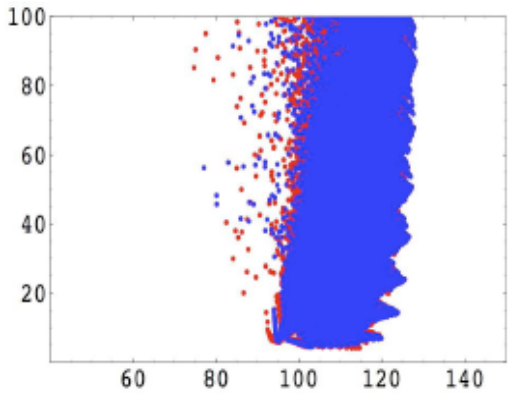
Dimension 5

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

Δ



MSSM



+ dim 5 operators

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

Even for M_*=65 μ_0 a significant shift of m_h for constant Δ

…effect mainly comes from ς_1 term … origin?

Reduced fine tuning : singlet extensions

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

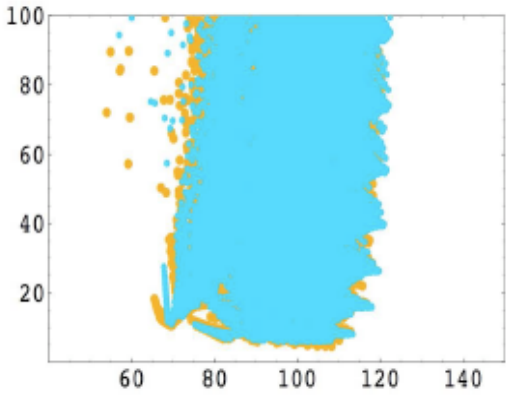
$\mu_S >> m_{3/2}$

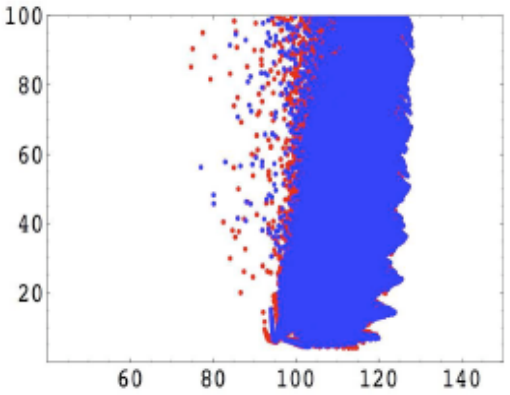
$W_{eff}^{GNMSSM} = (H_u H_d)^2 / \mu_s + \mu H_u H_d$

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

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

Δ





Reduced fine tuning in GNMSSM (but not NMSSM)

SUSY extensions of the Standard Model

R-symmetry ensures Singlet extensions natural

SUSY extensions of the Standard Model

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

Can be embedded in SO(10)

R-symmetry ensures singlets light

D=5 operators

up and down Yukawas allowed

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

Weinberg operator

SUSY breaking

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

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

Domain walls and tadpoles safe Abel

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

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

Domain walls and tadpoles safe Abel

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

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

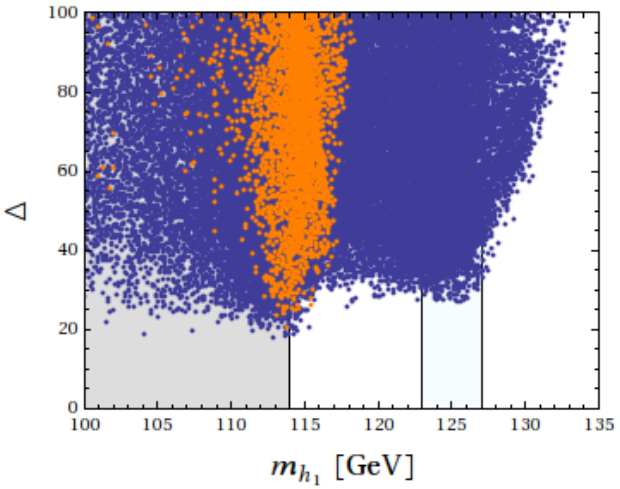
$$\Delta W_{Z_4^R} \sim m_{3/2} H_u H_d + m_{3/2}^2 S + m_{3/2} S^2$$

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

← μ term and mass terms "natural"

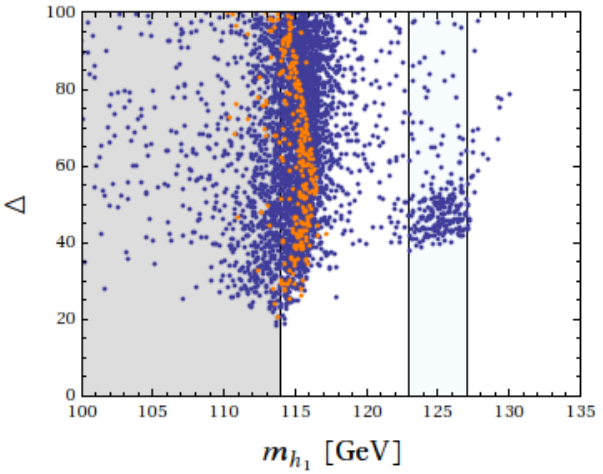
GNMSSM (c.f. NMSSM)

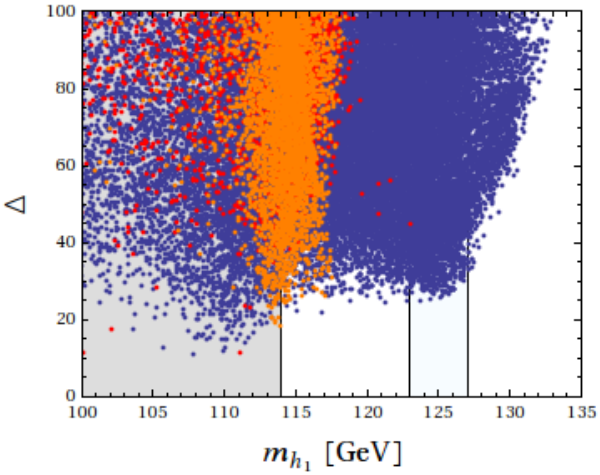
Fine tuning in the GNMSSM $(\lambda \leq 0.7^{\dagger})$



- CMSSM
- CGNMSSM

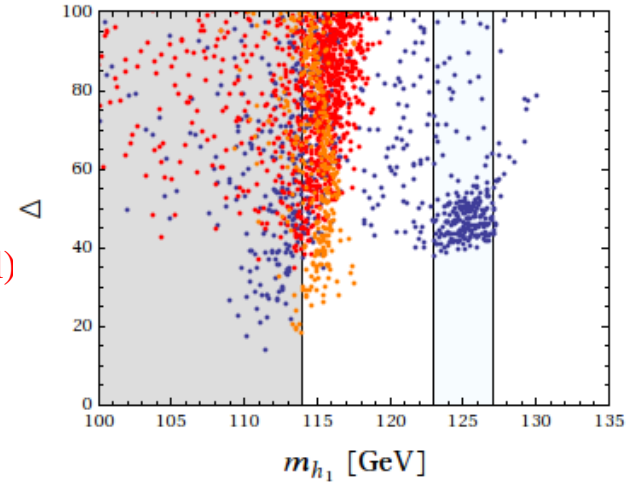
(universal masses)





- CMSSM
- CGNMSSM
- CNMSSM

(Higgs not universal)



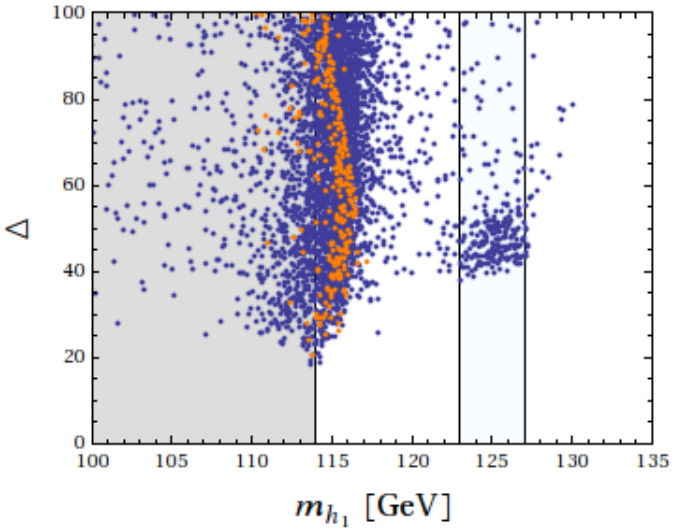
LHC constraints applied

LHC +DM constraints applied

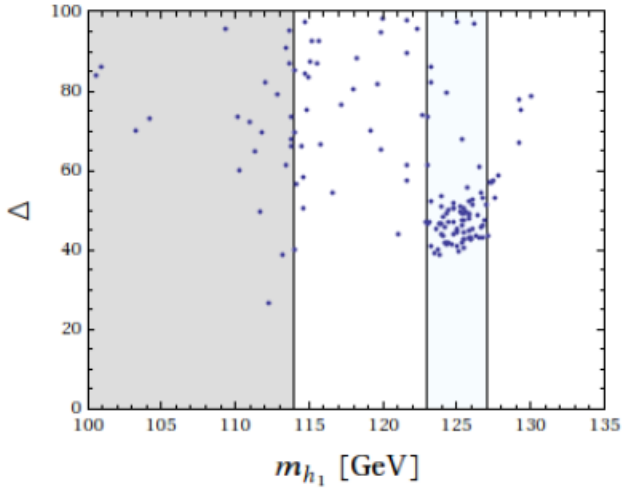
GGR, Schmidt-Hoberg , Staub

† c.f. Hall, Pinner, Ruderman

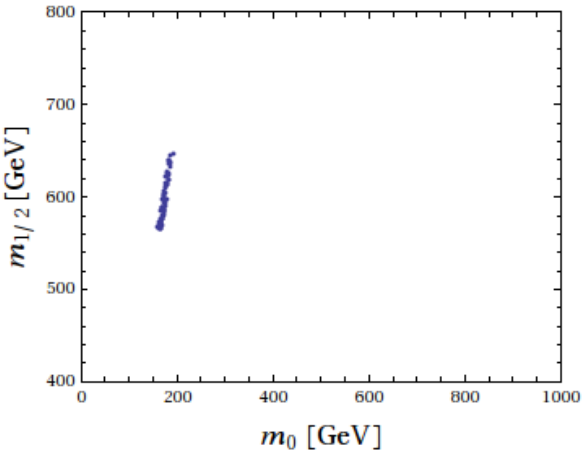
Dark Matter structure



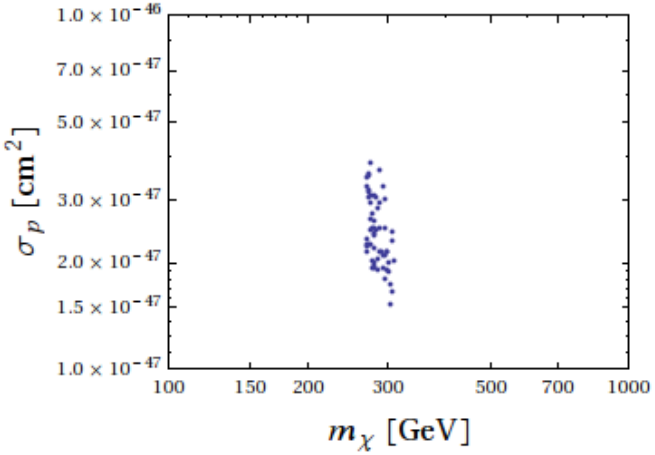
$\rho_{LSP} \leq \rho_{DM}$



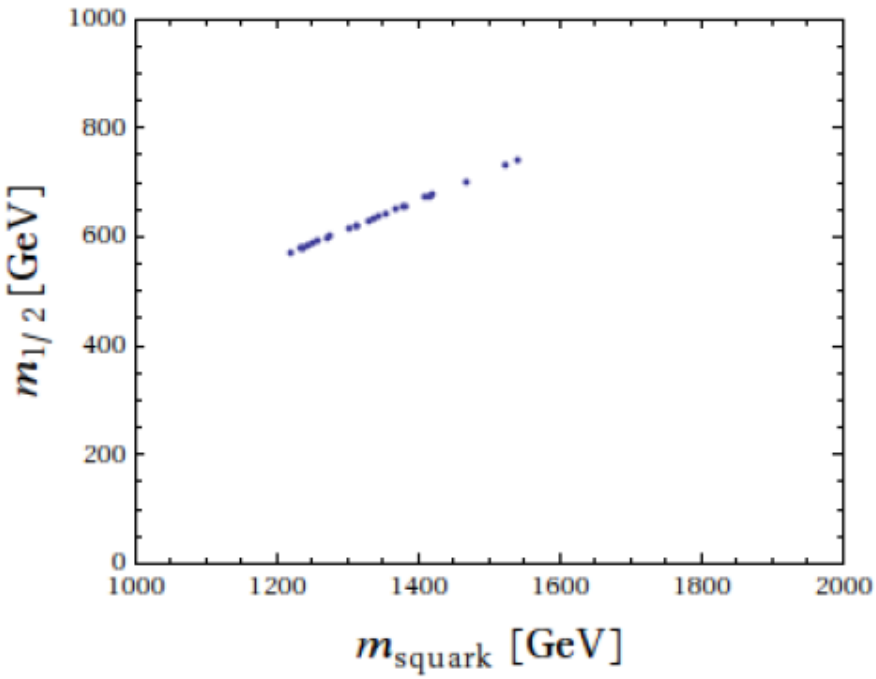
$\rho_{LSP} \approx \rho_{DM}$

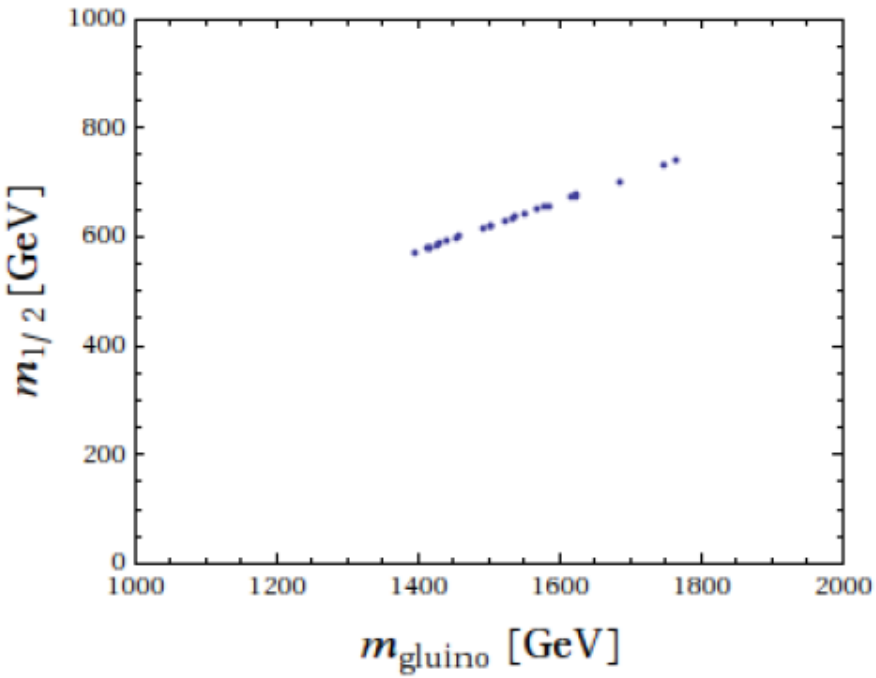


Stau co-annihilation



DM searches insensitive


1000
800
600
400
200
0
1000
1200
1400
1600
1800
2000
$m_{1/2}$ [GeV]
m_{squark} [GeV]


1000
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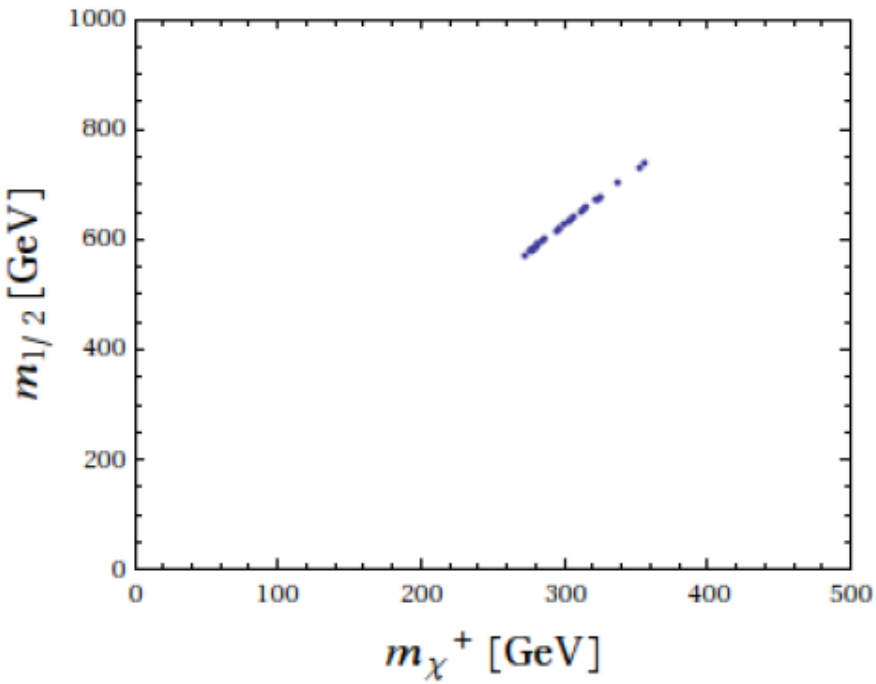
$m_{1/2}$ [GeV]
m_{gluino} [GeV]


1000
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0
100
200
300
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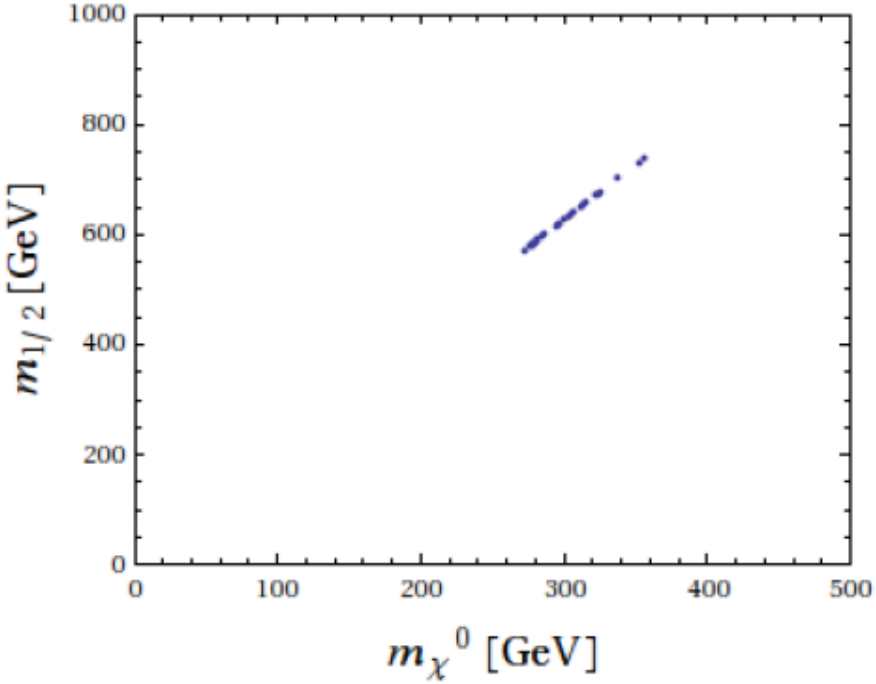
500
$m_{1/2}$ [GeV]
m_{χ^+} [GeV]


1000
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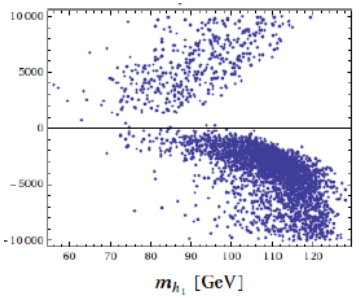
200
300
400
500
$m_{1/2}$ [GeV]
m_{χ^0} [GeV]

GENERAL-NMSSM PHENOMENOLOGY

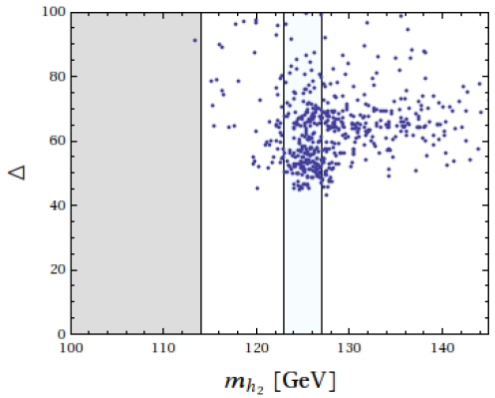
Higgs structure (h_u, h_d, s)

- $\mu_s \gg \mu$ MSSM SUSY structure with heavy Higgs

- $\mu_s, m_s, b_s \sim \mu$ $h_1 \simeq H_{u,d} + \varepsilon S, \quad h_2 = S - \varepsilon H_{u,d}$



...h_2 may be lighter than LEP bound



m_{h_1} v/s Δ for the case $m_{h_2} < m_{h_1}$

Benchmark points

	BP1	BP2	BP3	BP4	BP5
m_0 [GeV]	746	163	957	573	752
$m_{1/2}$ [GeV]	476	568	557	482	472
$\tan\beta$	2.7	2.9	2.8	3.4	2.8
A_0 [GeV]	1433	1666	782	27	-198
λ	1.43	1.47	1.58	1.34	1.12
κ	-0.1	0.09	-0.005	1.52	1.03
A_λ [GeV]	A_0	A_0	A_0	400	192
A_κ [GeV]	A_0	A_0	A_0	-323	-326
v_S [GeV]	-841	-190	-929	390	281
μ_S [GeV]	-5931	-5354	-5799	131	-37
$m^2_{h_d}$ [GeV^2]	m_0^2	m_0^2	m_0^2	$9.1\cdot10^5$	$5.4\cdot10^5$
$m^2_{h_u}$ [GeV^2]	m_0^2	m_0^2	m_0^2	$2.3\cdot10^6$	$2.4\cdot10^6$
m^2_s [GeV^2]	m_0^2	m_0^2	m_0^2	$2.8\cdot10^6$	$1.7\cdot10^6$
μ [GeV]	-750	-1136	-934	-33	10
$b\mu$ [GeV^2]	$-2.4\cdot10^6$	$-1.2\cdot10^6$	$-2.3\cdot10^6$	147	26
b_s [GeV^2]	$-1.9\cdot10^7$	$-5.4\cdot10^6$	$-1.4\cdot10^7$	326	144
ξ_s [GeV^3]	$2.2\cdot10^9$	$1.5\cdot10^9$	$3.0\cdot10^9$	22	-8
m_{squark} [GeV]	1256-1293	1207-1263	1507-1548	1211-1248	1280-1315
$m_{\tilde{g}}$ [GeV]	1219	1389	1416	1242	1235
m_{h_1} [GeV]	124	123.5	125	93.5	78
m_{h_2} [GeV]	1002	856	1257	125	124
h_1 singletfraction	$\mathcal{O}(10^{-4})$	$\mathcal{O}(10^{-6})$	$\mathcal{O}(10^{-4})$	0.8	0.85
$\text{Br}(h\to\gamma\gamma)$	$2.29\cdot10^{-3}$	$2.28\cdot10^{-3}$	$2.2\cdot10^{-3}$	$2.5\cdot10^{-3}$	$2.66\cdot10^{-3}$
$\text{Br}(b\to s\gamma)$	$3.1\cdot10^{-4}$	$3.1\cdot10^{-4}$	$3.1\cdot10^{-4}$	$3.1\cdot10^{-4}$	$3.3\cdot10^{-4}$
Δa_μ	$-7.8\cdot10^{-11}$	$-2.5\cdot10^{-10}$	$-5.4\cdot10^{-11}$	$1.7\cdot10^{-10}$	$8\cdot10^{-11}$
$\delta\rho$	$6.2\cdot10^{-5}$	$6.6\cdot10^{-5}$	$7.5\cdot10^{-5}$	$1.9\cdot10^{-4}$	$3.1\cdot10^{-4}$
$m_{\tilde{\chi}_1^0}$ [GeV]	229	270	168	99	70
$\tilde{\chi}_1^0$ singlinofraction	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-5})$	0.1	0.2
Ωh^2	7.5	0.10	7.4	0.017	0.11
$\sigma_p[cm^2]$	$2.8\cdot10^{-47}$	$2.2\cdot10^{-47}$	$6\cdot10^{-47}$	$1.2\cdot10^{-44}$	$1.3\cdot10^{-45}$
Δ (Fine-tuning)	34.9	51.0	51.8	44.9	52.7

Table 1: Benchmark scenarios for the GNMSSM for the universal (BP1-BP3) and the general (BP4-BP5) case. m_{squark} shows the range of squark masses of the first two generations. For the last two points the second lightest Higgs is mostly MSSM-like.

GENERAL-NMSSM PHENOMENOLOGY

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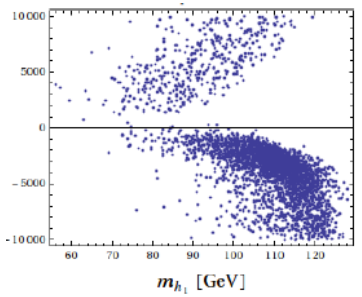
- $\mu_s \gg \mu$ MSSM SUSY structure with heavy Higgs

- $\mu_s, m_s, b_s \sim \mu$ $h_1 \simeq H_{u,d} + \varepsilon S, \quad h_2 = S - \varepsilon H_{u,d}$

  ... h_2 may be lighter than LEP bound $h_1 \to h_2 h_2$ large

  ... h_1 may have enhanced $\gamma\gamma$ rate (later)

  ... DM and SUSY phenomenology modified

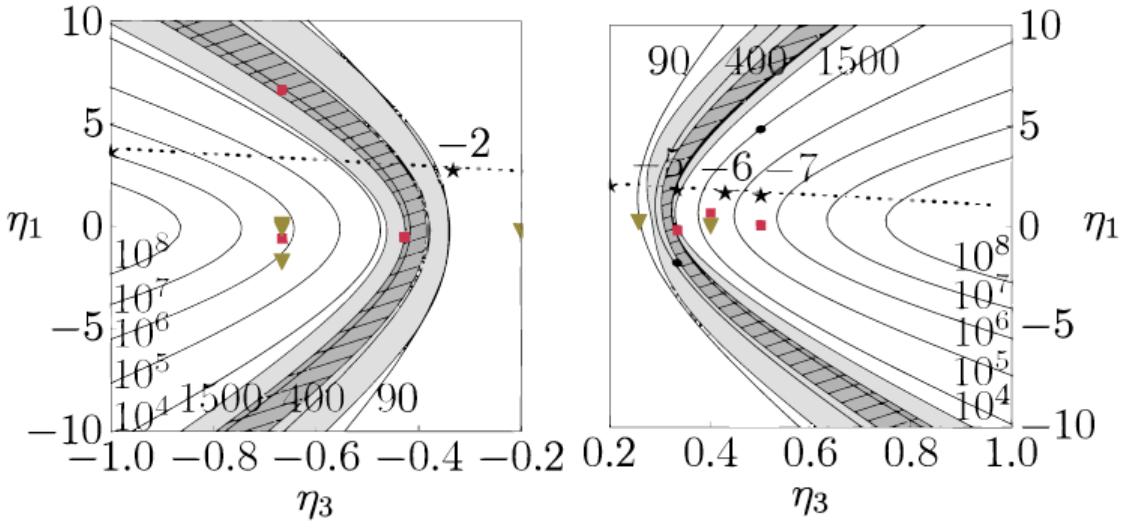


II. Reduced fine tuning : nonuniversal gaugino masses

Reduced fine tuning : nonuniversal gaugino masses

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

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

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Natural ratios? e.g.:

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

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

Phenomenology

- Gaugino mass ratios

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

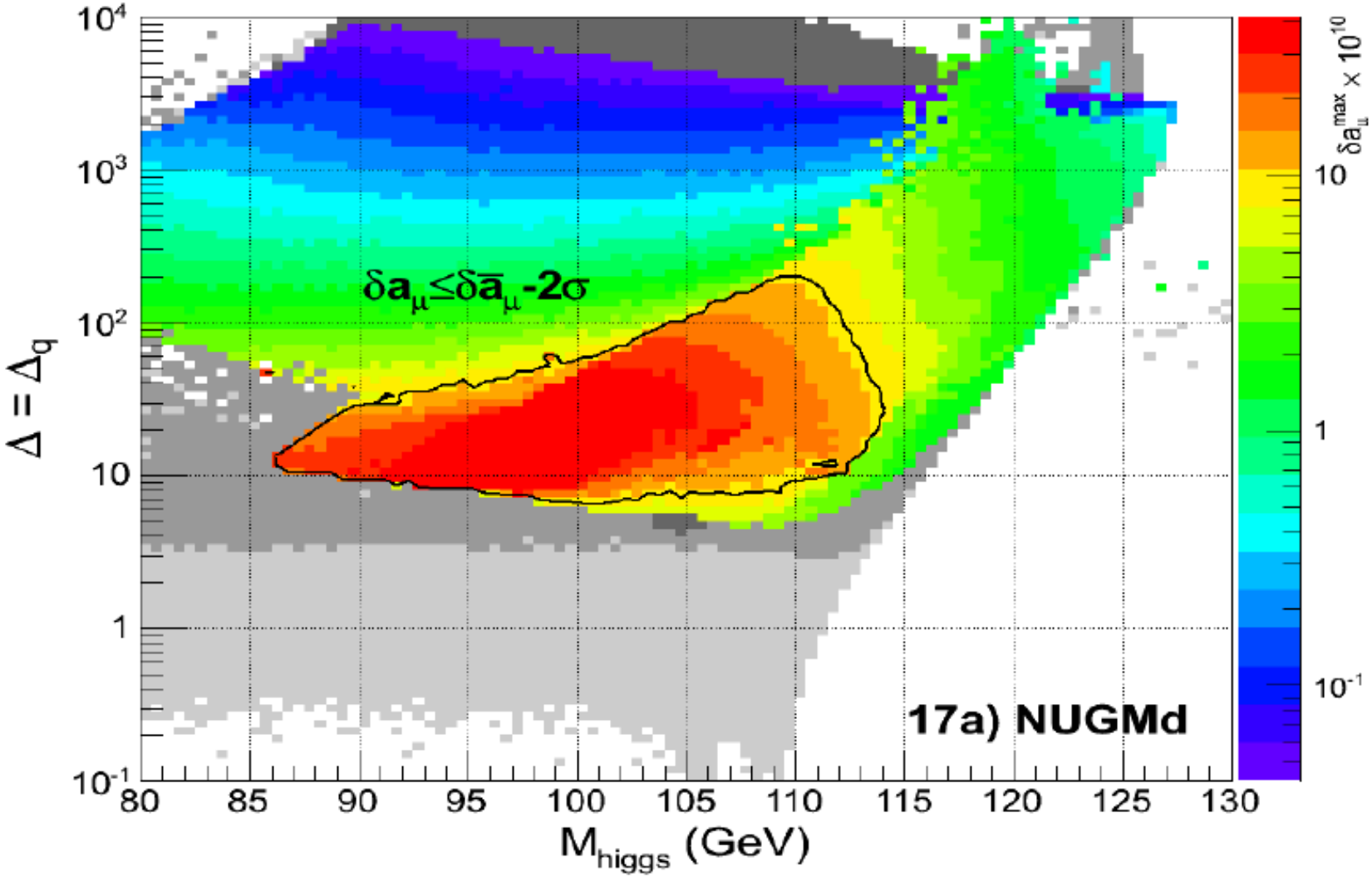
…. gauginos can be very heavy

- Light neutralino and 2 charginos nearly degenerate

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

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

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



2-loop fine tuning in 75 case

Ghilencea, Lee, Park

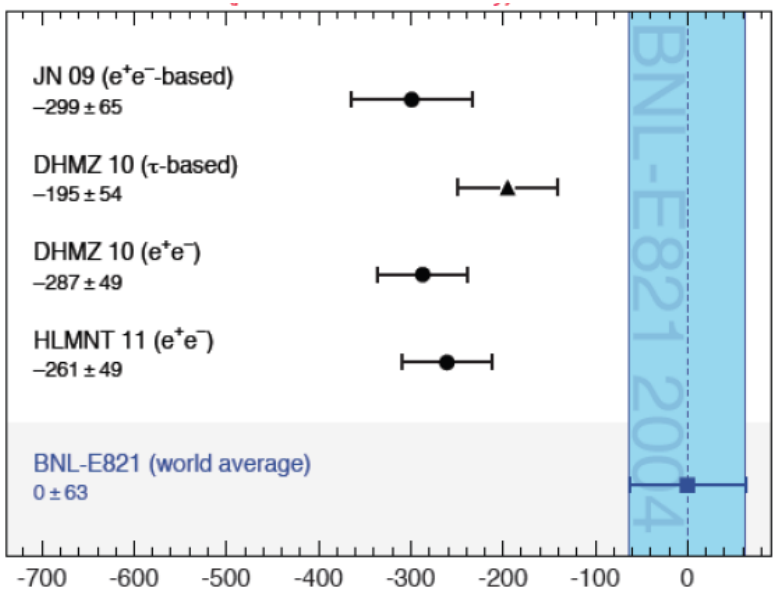
Muon g-2

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

Theory error from hadronic contribution:

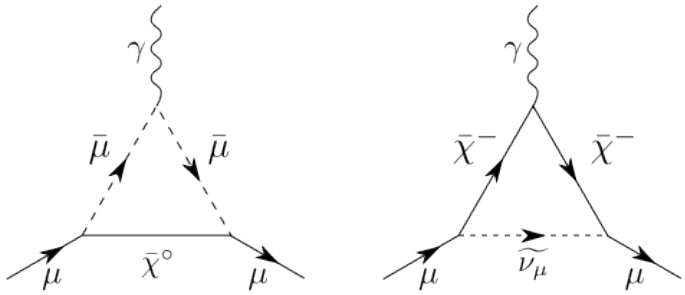
$$\delta a_\mu^{e^+e^-} = 3.6\,\sigma$$

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



SUSY

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



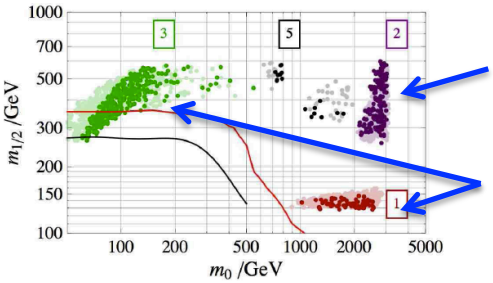
Needs light sleptons – anomaly/mirage spectrum?

Summary (before Higgs discovery)

- 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 $\quad \Delta \le 100 \quad$ Sensitivity $\times (10 - 100)$

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

(Gauge mediation $\Delta >> 100$)

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

  SUSY states can be (slightly)heavier

  $m_h \rightarrow 130GeV$

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

  Characteristic η_i

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

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

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

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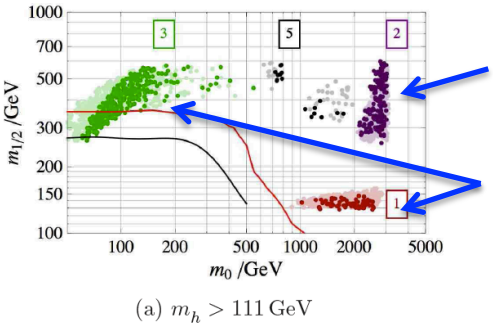
- Hierarchy problem $\Longrightarrow$ SUSY breaking structure and/or further states

- 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 $\times (10-100)$ (Now achieved!)

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

$\Delta_{MSSM} > 300$ for $m_H = 126GeV$

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

  Further light/invisible Higgs a possibility

- Gaugino focus point

  Mixed anomaly mediation, mirage mediation …

  Light sleptons…g-2!

- Natural SUSY, SPLIT SUSY…