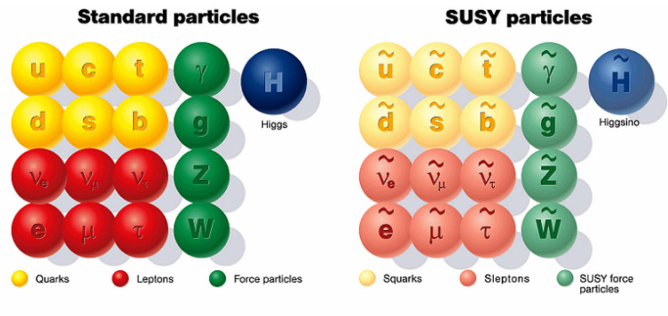
SUSY af†ter the Higgs discovery

G. Ross, Madrid, September 2013

Low scale SUSY

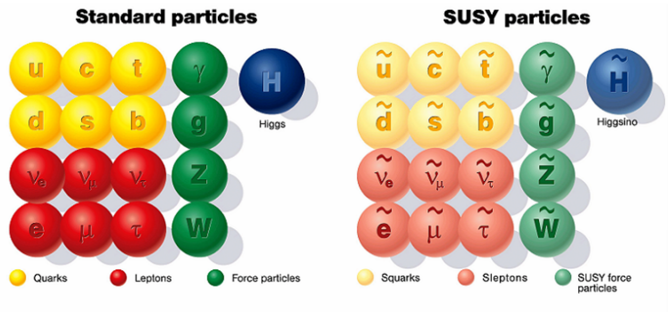
MSSM:



...motivation?

Low scale SUSY

MSSM:



GUTS:

$$e.g. \quad SO(10) \supset \underset{g_5}{SU(5)} \supset \underset{g_3}{SU(3)} \otimes \underset{g_2}{SU(2)} \otimes \underset{g_1}{U(1)}$$

Georgi Glashow 1974

$(\bar{5})_L$:

$SU(3)$

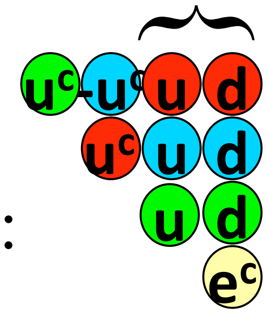
$SU(2)$

$$3Q_? + Q_{e^-} = 0$$

$$Q_{d^c} = 1/3$$

LH states SU(2) doublets

$(10)_L$:

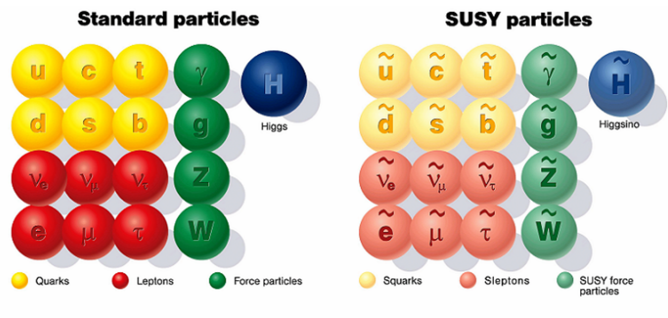


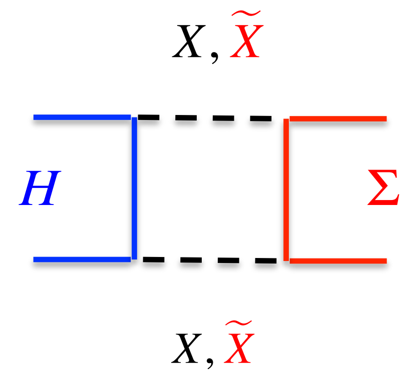
$$(16)_L = (10)_L + (\bar{5})_L + (1)_L$$

$$\nu_{e,L}{}^c \equiv \nu_{e,R}$$

Low scale SUSY

MSSM:





SUSY GUTS: the hierarchy problem

$$e.g.\quad SO(10) \supset \underset{g_5}{SU(5)} \supset \underset{g_3}{SU(3)} \otimes \underset{g_2}{SU(2)} \otimes \underset{g_1}{U(1)}$$

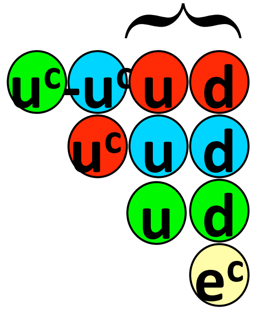
$(\bar{5})_L$: d^c, d^c, d^c } $SU(3)$; e, ν_e } $SU(2)$

$$3Q_? + Q_{e^-} = 0$$

$$Q_{d^c} = 1/3$$

LH states SU(2) doublets

$(10)_L$:



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Low scale SUSY

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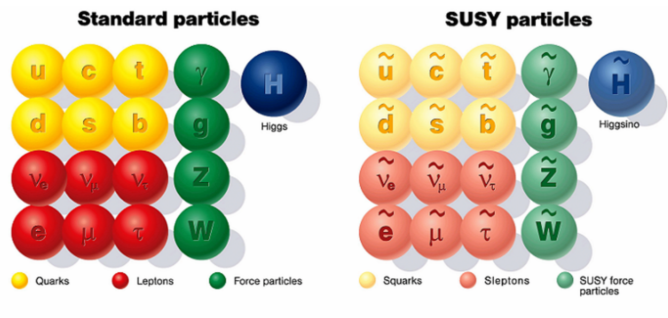
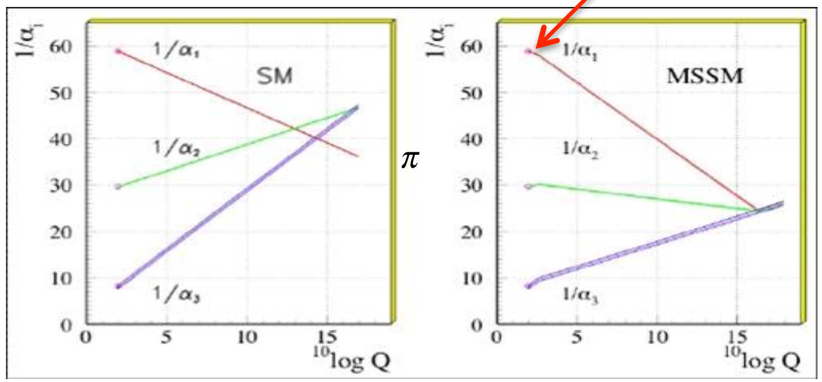


SUSY GUTS:

$\sim TeV$



✔

The (SUSY) Standard Model as an EFT:

A_μ ✔, Ψ ✔ H ✔ ?

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

CMSSM fits after the Higgs: $\gamma_i = \mu_0, m_0, m_{1/2}, A_0, B_0$

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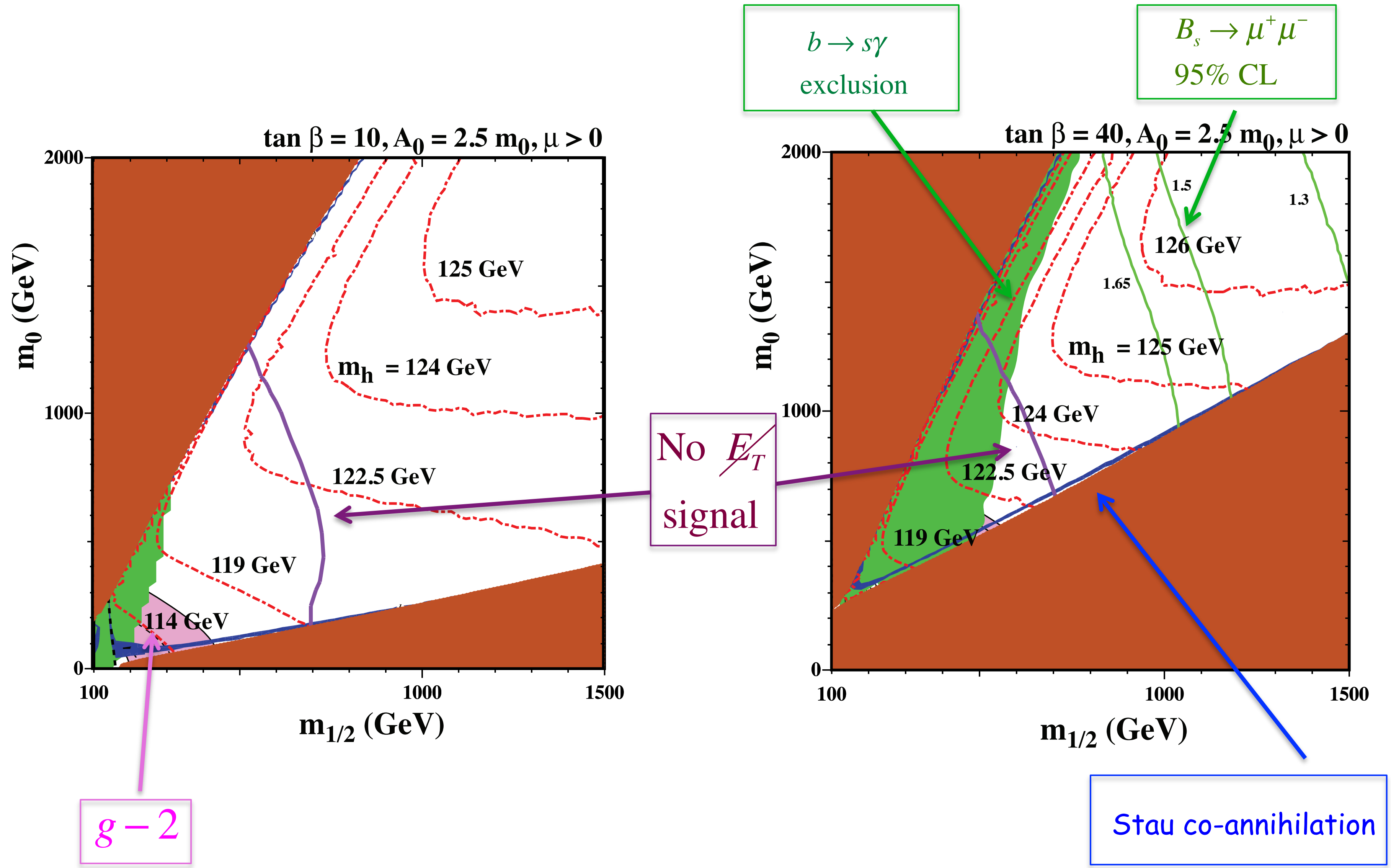
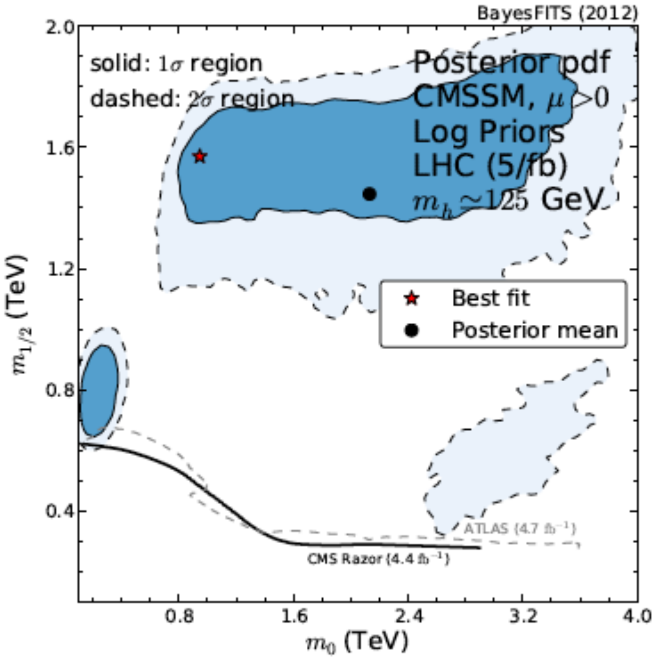


Under pressure!

Ellis et al

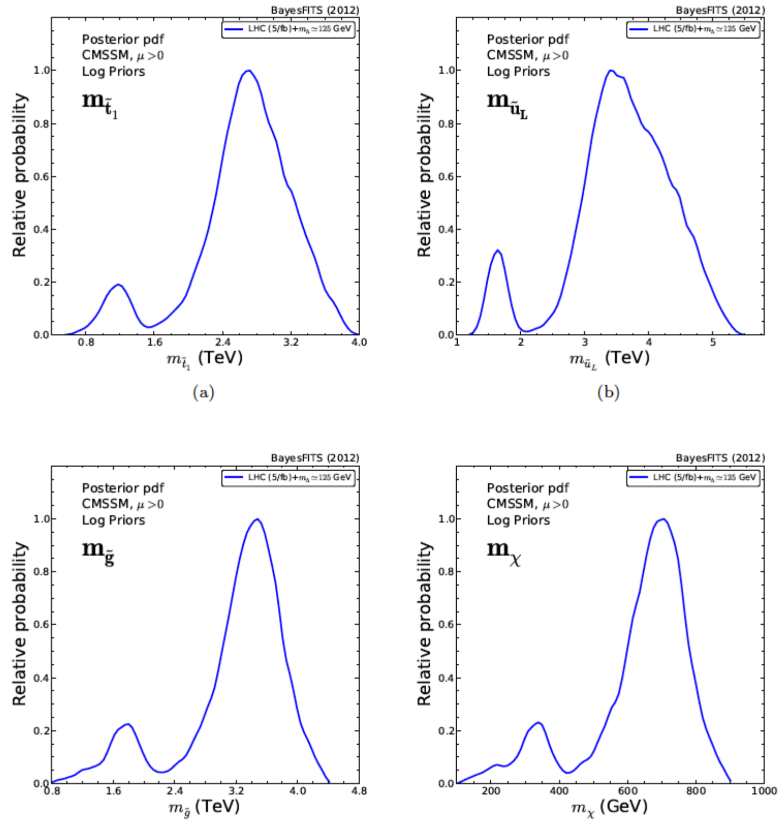
SUSY spectrum : CMSSM

$m_{1/2}$



m_0

$\tilde{t}$ $\tilde{u}_L$

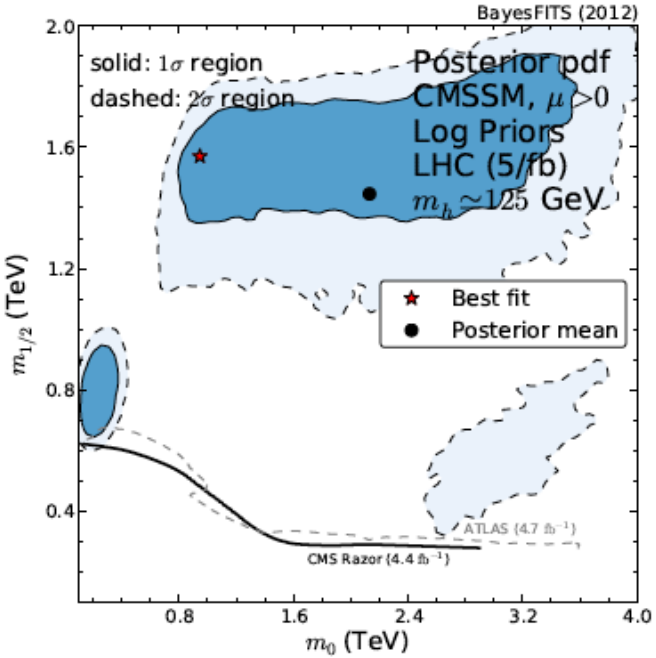


$\tilde{g}$ $\tilde{\chi}$

Fowlie et al

SUSY spectrum : CMSSM

$m_{1/2}$



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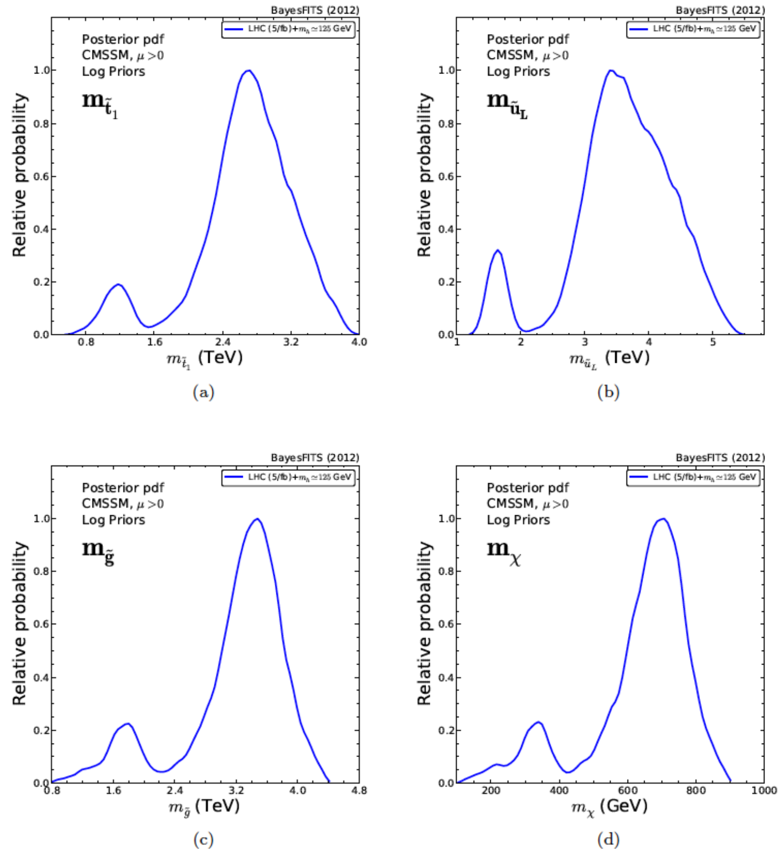

$\tilde{g}$ $\tilde{\chi}$

Little hierarchy problem:

This talk $\Lambda \sim M_{GUT}$

$$v^2 \sim \delta m_{H_u}^2 \simeq -\frac{3y_t^2}{4\pi^2}\left(m_{stop}^2 + \frac{g_s^2}{3\pi^2} m_{gluino}^2 \log\left(\frac{\Lambda}{m_{gluino}}\right)\right)\log\left(\frac{\Lambda}{m_{stop}}\right) \quad ?$$

breaking

Little hierarchy problem $\Rightarrow$ definite SUSY ^ structure

MSSM: 105 +(19) Parameters

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

$$M_{\tilde{g}} > 1TeV \quad \Rightarrow \quad \Delta > b\frac{\widetilde{M}^2}{M_Z^2} \sim 100$$

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

Little hierarchy problem $\Rightarrow$ definite SUSY ^breaking^ structure

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

Fine Tuning measure:

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

$$\Delta_m = Max_{a_i} \Delta(a_i), \quad \Delta_q = \left(\sum \Delta_{\gamma_i}^2\right)^{1/2}$$

Ellis, Enquist, Nanopoulos, Zwirner

Barbieri, Giudice

Fine tuning from a likelihood fit:

If v included as a "Nuisance" variable

$$L(\text{data} \mid \gamma_i) \propto \int d\text{v}\, \delta\left(m_Z - m_Z^0\right) \delta\left(\text{v-}\left(-\frac{m^2}{\lambda} \right)^{1/2} \right) L(\text{data} \mid \gamma_i; \text{v})$$

$$= \frac{1}{\Delta_q} \delta\left(n_q (\ln \gamma_i - \ln \gamma_i^S)\right) L(\text{data} \mid \gamma_i; \text{v}_0)$$

Fine tuning

Ghilencea, GGR
Cabrera, Casas, de Austri

Fine tuning from a likelihood fit:

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$$= \frac{1}{\Delta_q}\delta\left(n_q(\ln\gamma_i - \ln\gamma_i^S)\right)L\left(\text{data} \mid \gamma_i;\text{v}_0\right)$$

Fine tuning

Probabilistic interpretation:

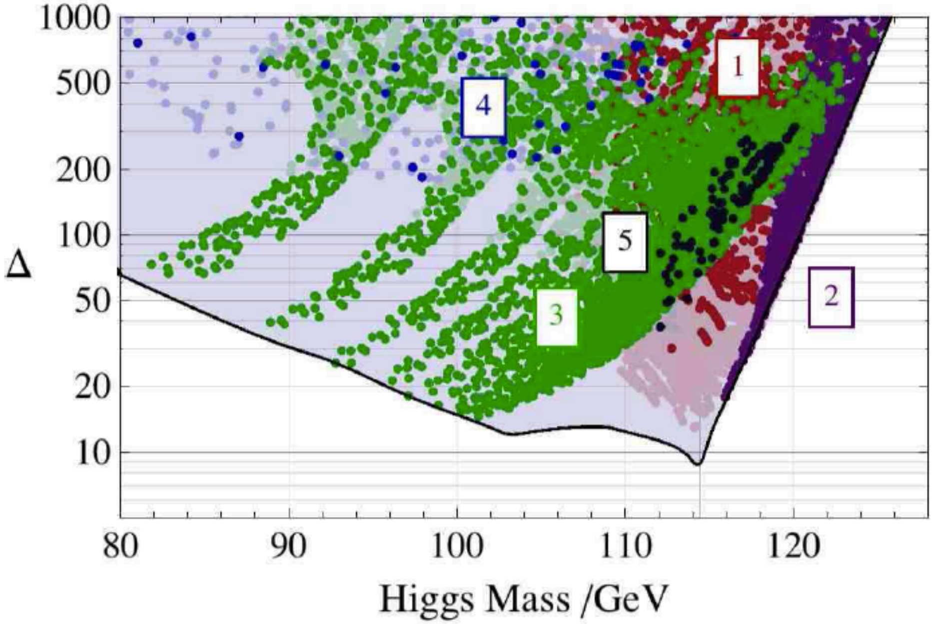
$$\chi^2_{new} = \chi^2_{old} + 2\ln\Delta_q$$

$$\Delta_q \ll 100$$

The CMSSM - before LHC

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

$$v^2 = -\frac{m_{eff}{}^2}{\lambda_{eff}}$$



Relic density restricted

1 h^0 resonant annihilation

2 $\tilde{h}$ t-channel exchange

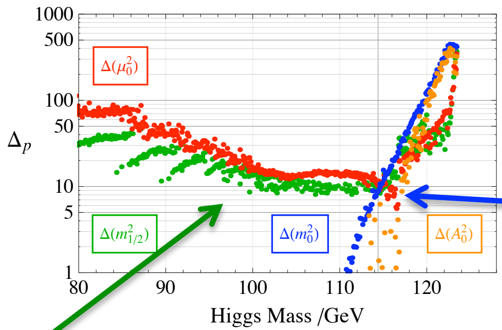
3 $\tilde{\tau}$ co-annihilation

4 $\tilde{t}$ co-annihilation

• 5 A^0 / H^0 resonant annihilation

Within 3σ WMAP:
$\Delta^{EW}_{Min} = 15, \quad m_h = 114.7 \pm 2GeV$

< 3σ WMAP:
$\Delta^{EW}_{Min} = 18, \quad m_h = 115.9 \pm 2GeV$



$\Delta(m_0^2)$

Limit of focus point

λ_{eff} increases with m_H

$$\Delta^{\Omega} = \max \left| \frac{\partial \ln \Omega h^2}{\partial \ln q} \right|_{q=m_0, m_{1/2}, A_0, B_0}$$

$$\Delta^{EW+\Omega}_{Min} = 29, \quad m_h = 117 \pm 2GeV$$

Cassel, Ghilencea, GGR

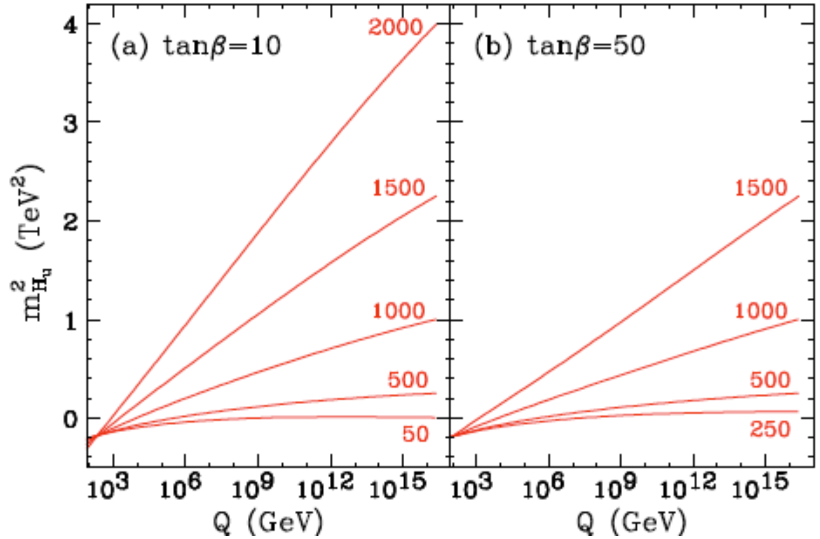
Focus Point

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

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

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

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



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

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

"Focus point": $m^2_{H_u}(0)=m^2_{Q_3}(0)=m^2_{\bar u 3}(0)\equiv m^2$

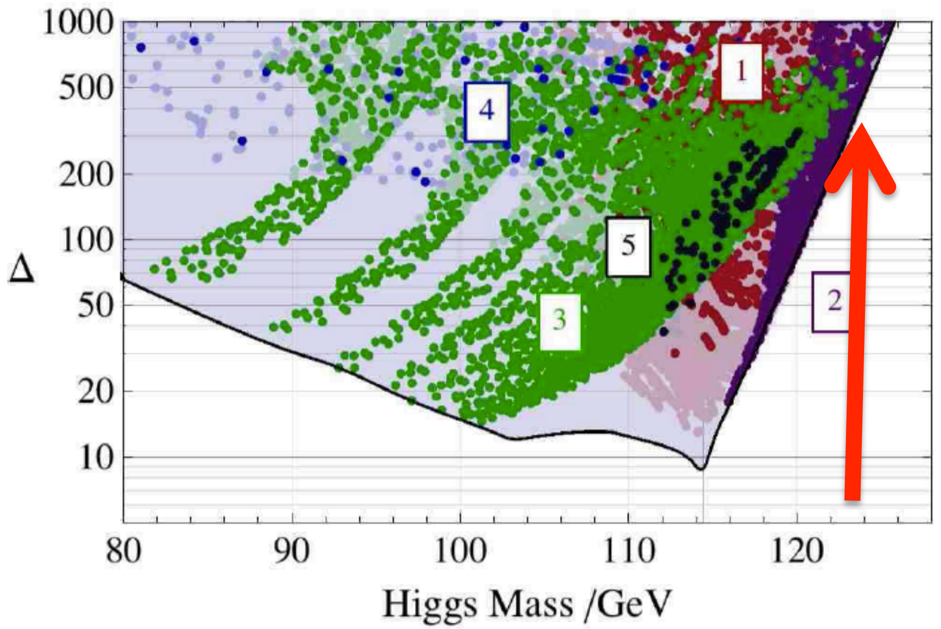
$$m^2_{H_u}(t_0)=a_0\,m^2+..,\ a_0\le 0.1$$

Natural choice

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

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

● The CMSSM - after Higgs discovery



$M_S^2 = m_{q_3} m_{U_3}$

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

$$\Delta_{Min} > 350 , \quad m_h = 125.6 \pm 3 GeV$$

Reduced fine tuning (c.f. CMSSM)

- New focus points?

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

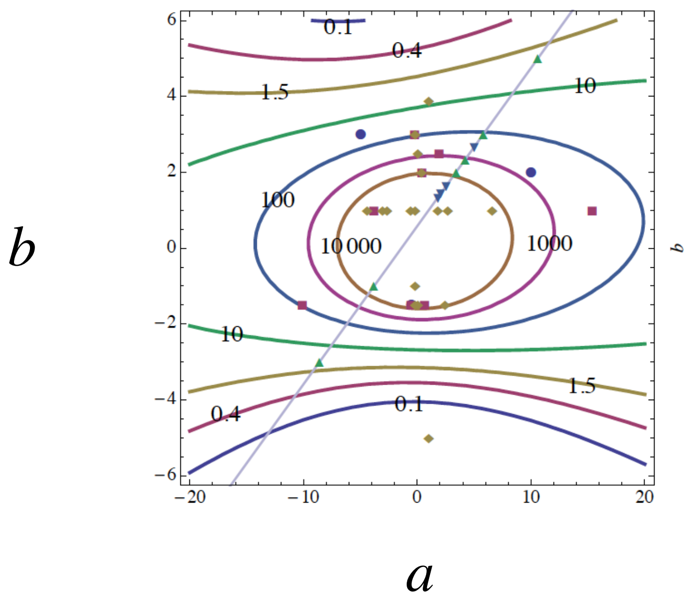
- New degrees of freedom

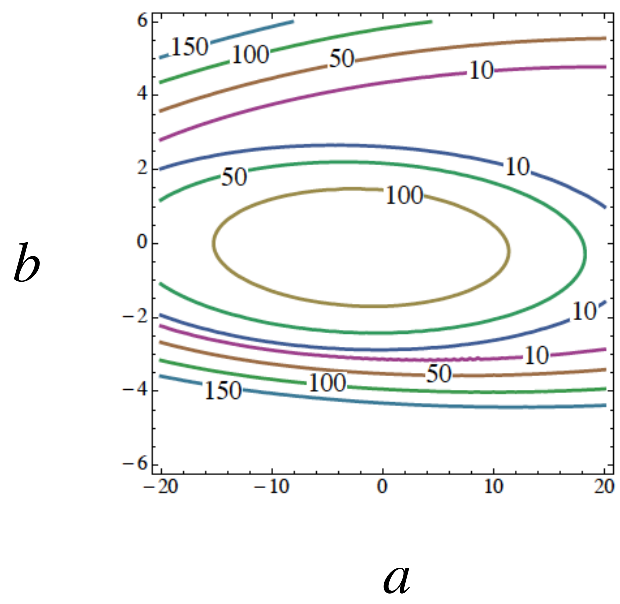
I. Reduced fine tuning : nonuniversal gaugino masses

$$16\pi^2 \frac{d}{dt} m_{H_u}^2 = 3\left(2\,|y_t|^2\,(m_{H_u}^2 + m_{Q_3}^2 + m_{\bar{u}_3}^2) + 2\,|a_t|^2\right) - 6 g_2^2\,|M_2|^2 - \frac{6}{5} g_1^2\,|M_1|^2$$

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

Horton, GGR
Choi et al…





$$M_3 : M_2 : M_1 = 1 : b : a$$

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$$\Delta_{Min}^{(C)MSSM} = 60\ (500), \quad m_h = 125.6 \pm 3GeV$$

LHC8 SUSY bounds ✔

DM relic abundance ✔

DM searches ✗

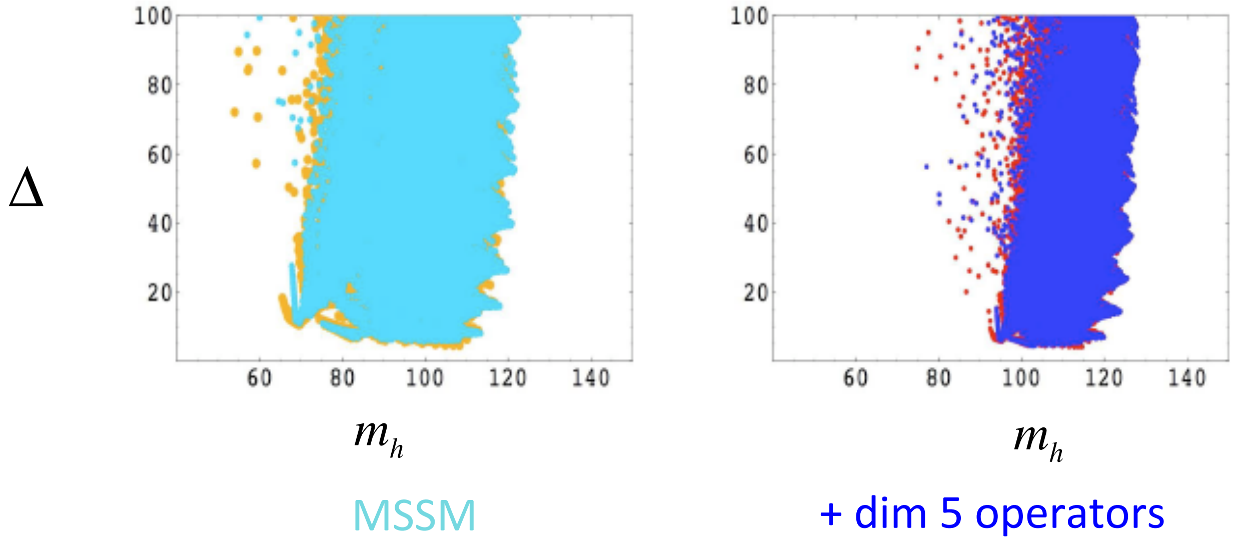
Kaminska, GGR, Schmidt-Hoberg

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

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

Dimension 5

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



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

Even for $M_*=65\ \mu_0$ a significant shift of m_h for constant Δ

…effect mainly comes from ς_1 term

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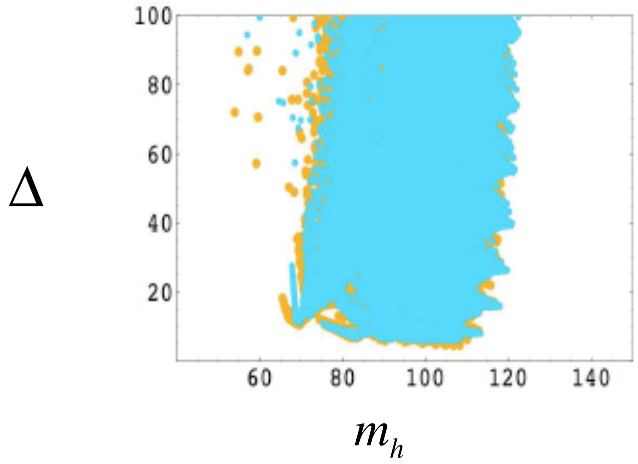
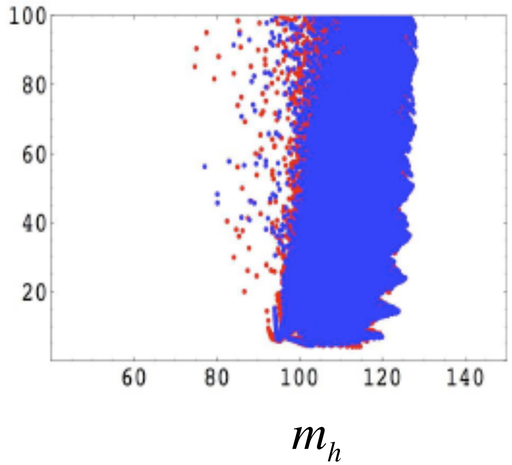


MSSM



+ dim 5 operators

Cassel, Ghilencea, GGR
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Even for M_*=65 μ_0 a significant shift of m_h for constant Δ

...effect mainly comes from ς_1 term ... origin?

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$$\varsigma_2 \propto \frac{m_0^2}{M_*^2}$$

but see Lu et al

Singlet extensions

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

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

$$\mu_S >> m_{3/2} : \quad W_{eff}^{GNMSSM} = (H_u H_d)^2 / \mu_s + \mu H_u H_d$$

$$\delta V = \frac{\mu}{\mu_S}\left(|H_u|^2 + |H_d|^2\right) H_u H_d$$ ✔

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$$\delta V = \frac{\mu}{\mu_S}\left(|H_u|^2 + |H_d|^2\right)H_u H_d$$ ✔

but are μ, μ_s naturally small?

SUSY extensions of the Standard Model

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

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

$$+ \frac{1}{M}\left(QQQL + QQQH_d + Q\overline{U}\,\overline{E}H_d + LLH_uH_u\right)$$

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

$$+ \frac{1}{M}\left(QQQL + QQQH_d + Q\overline{U}\,\overline{E}H_d + LLH_uH_u\right)$$

R-parity: Z_2

Z_N^R R-symmetry

N=4,6,8,12,24

Discrete gauge symmetry
-anomaly free

Ibanez, GGR

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

$SU(5), SO(10)$
compatible

Lee, Raby, Ratz, GGR, Schieren, Schmidt-Hoberg, Vaudrevange
Chen, Fallbacher, Ratz

SUSY extensions of the Standard Model

$$W = h^E L H_d \overline{E} + h^D Q H_d \overline{D} + h^U Q H_u \overline{U} + \mu H_d H_u + \mu_s S^2$$

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R-parity: Z_2

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

SUSY breaking: Domain walls safe

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

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

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

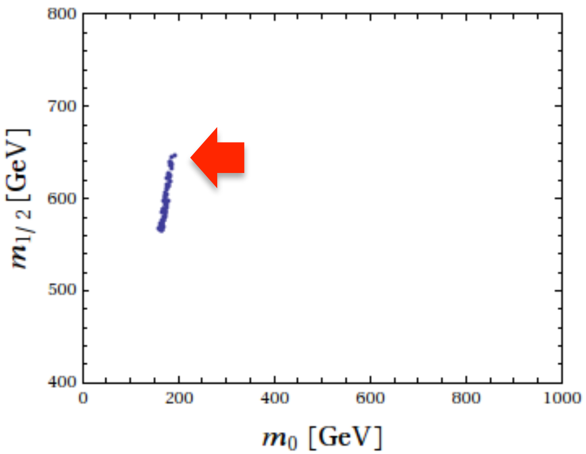
Fine tuning in the CGNMSSM $(\lambda \leq 0.7)$

$$\Delta_{Min} = 60\ (500), \quad m_h = 125.6 \pm 3 GeV$$

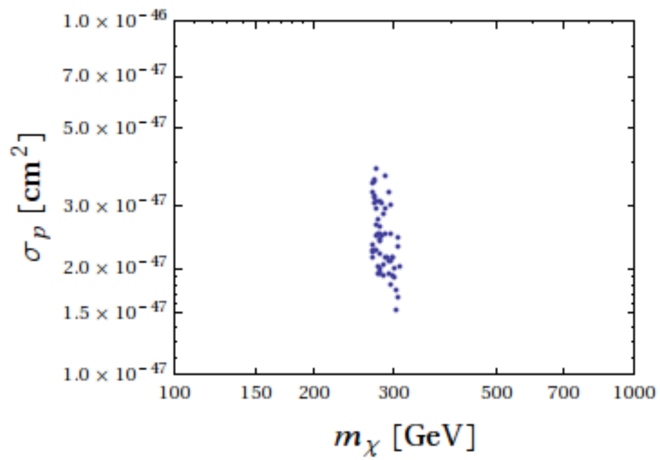
LHC8 SUSY bounds ✗

DM relic abundance ✔

DM searches ✔



Stau co-annihilation



DM searches insensitive

GGR, Schmidt-Hoberg , Staub

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

Non-universal gaugino masses

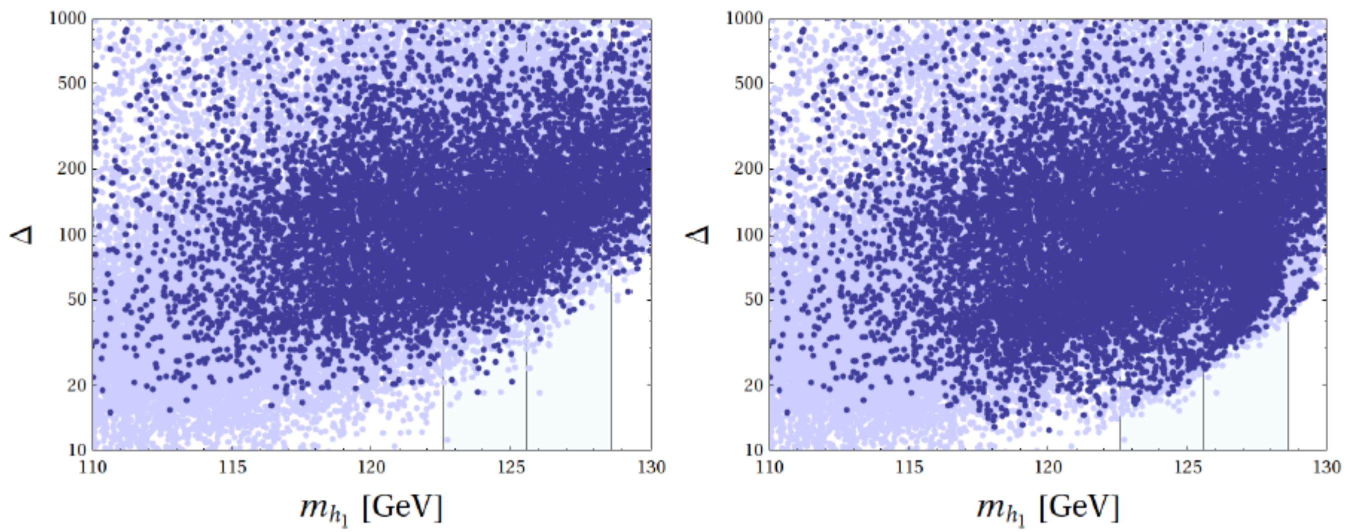
$$\Delta_{Min} = 20, \quad m_h = 125.6 \pm 3GeV$$

LHC8 SUSY bounds ✔

DM relic abundance ✔

DM searches ✔

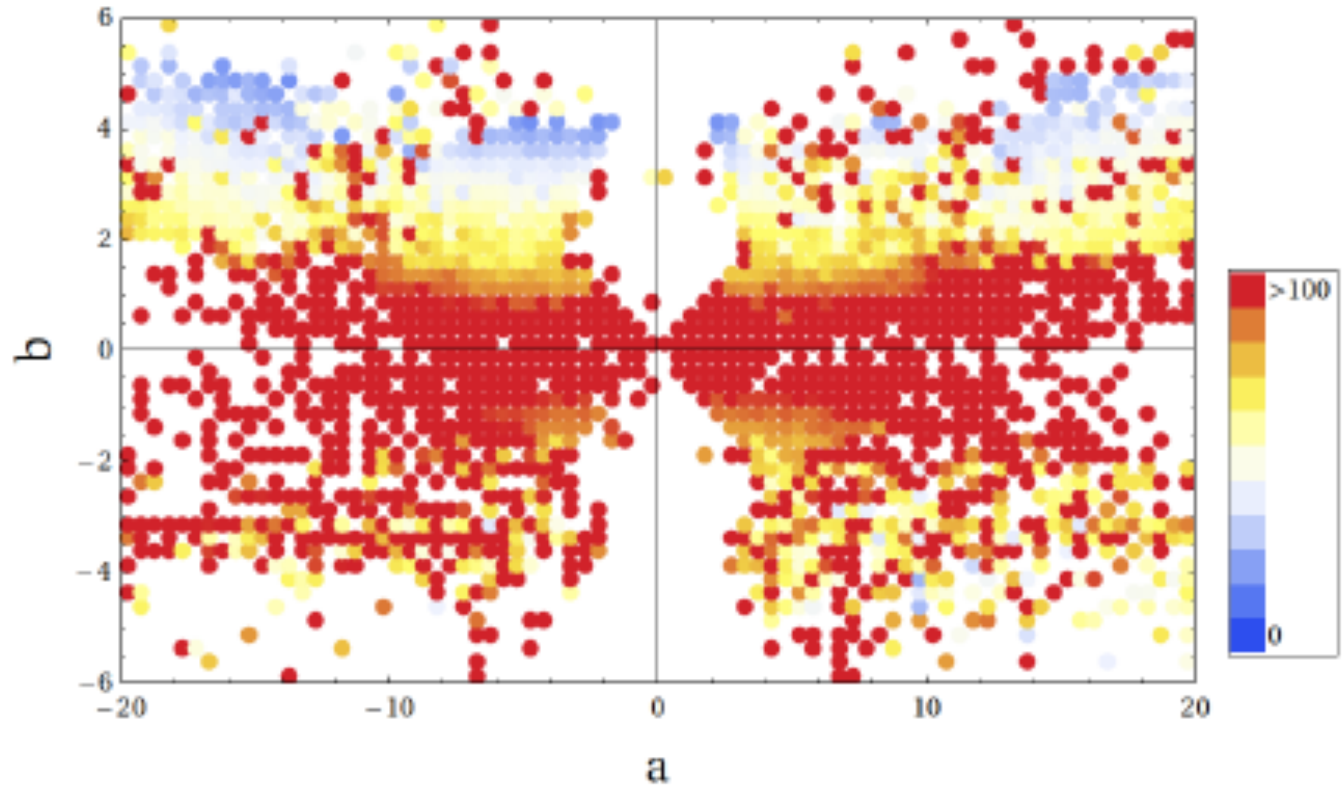
Δ



(uniform scan)

GGR, Kaminska, Schmidt-Hoberg

Fine tuning v/s gaugino mass ratios



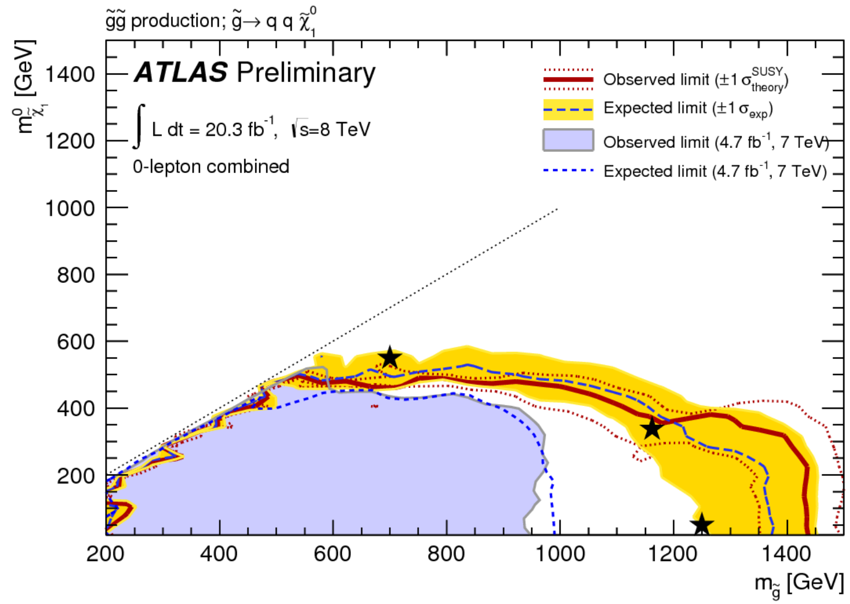
F.T.

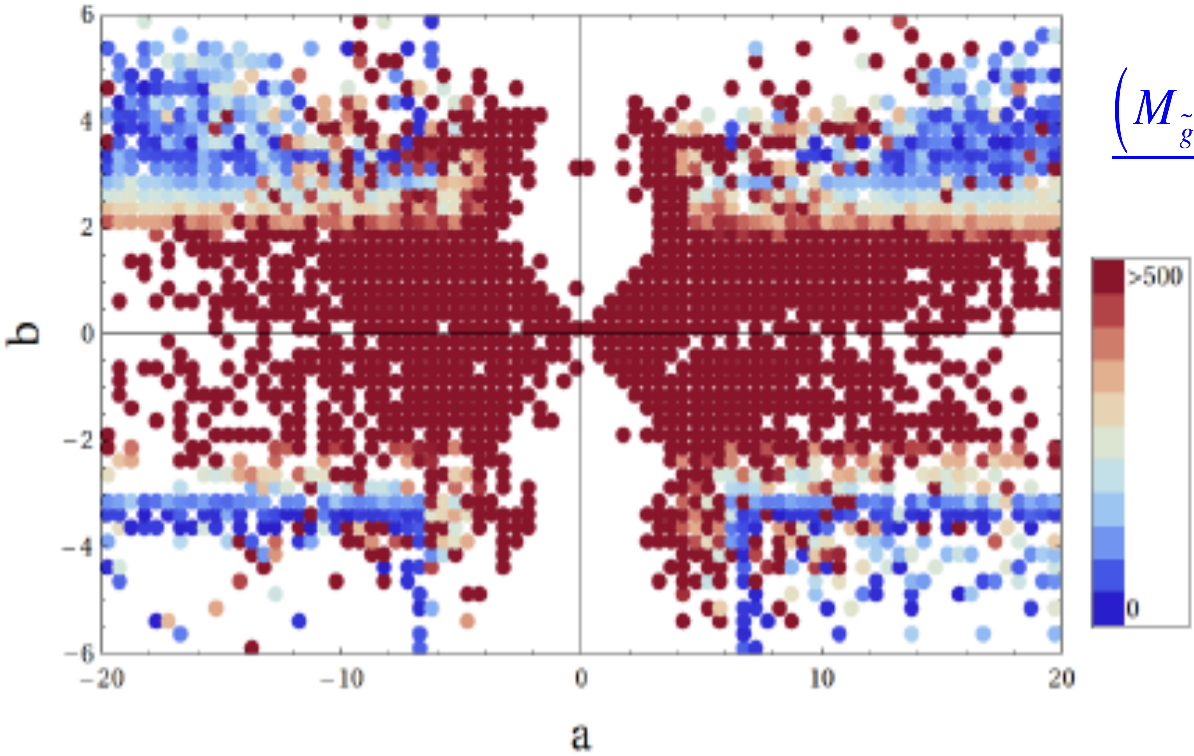
>100

0

$$M_3 = m_{1/2}, M_2 = b.m_{1/2}, M_1 = a.m_{1/2}$$

Compressed spectrum





$$\frac{\left(M_{\tilde{g}} - M_{LSP}^{neutralino}\right)}{GeV}$$

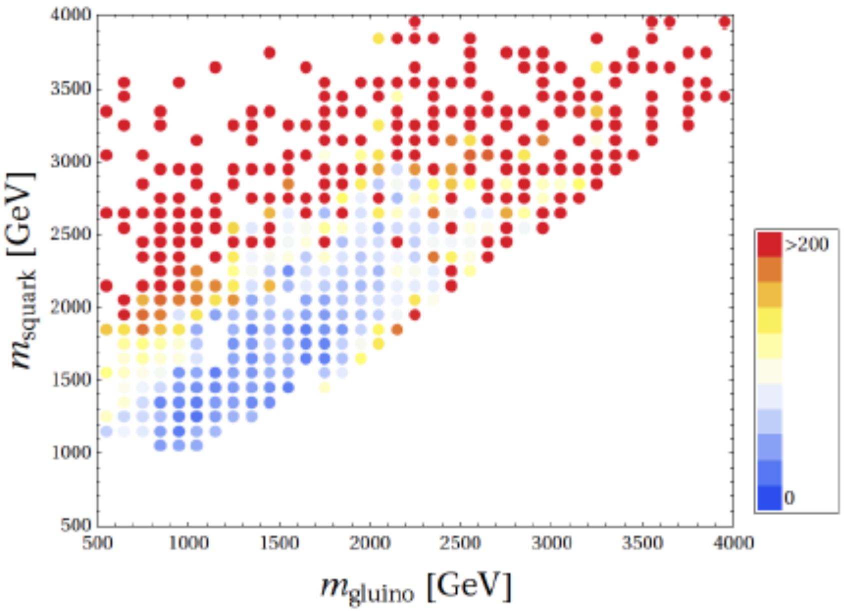
> 500

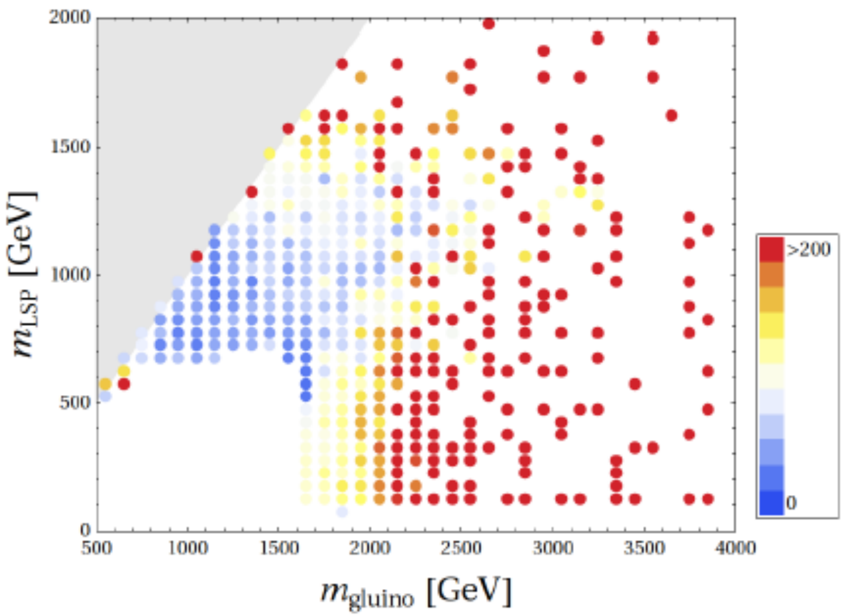
0

Masses v/s fine tuning

m_{squark}

m_{LSP}



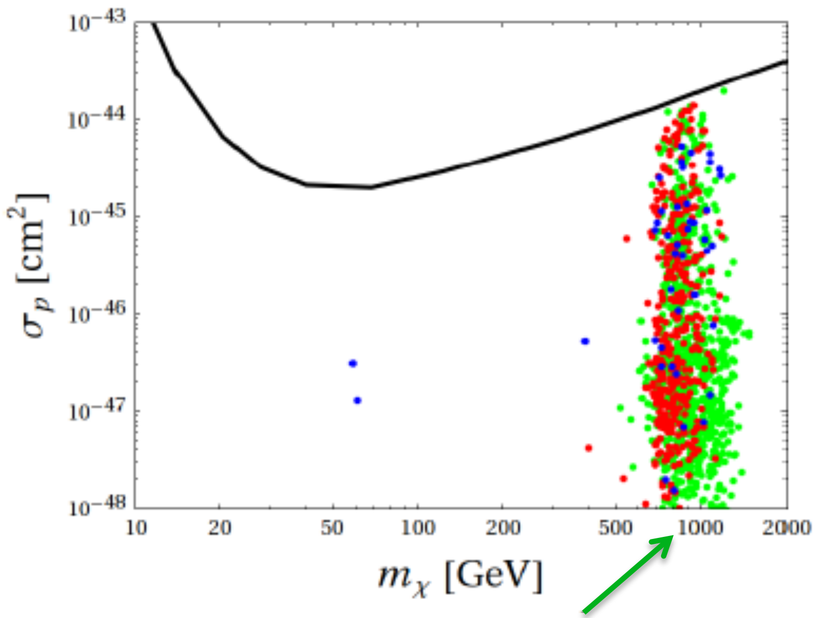


> 500

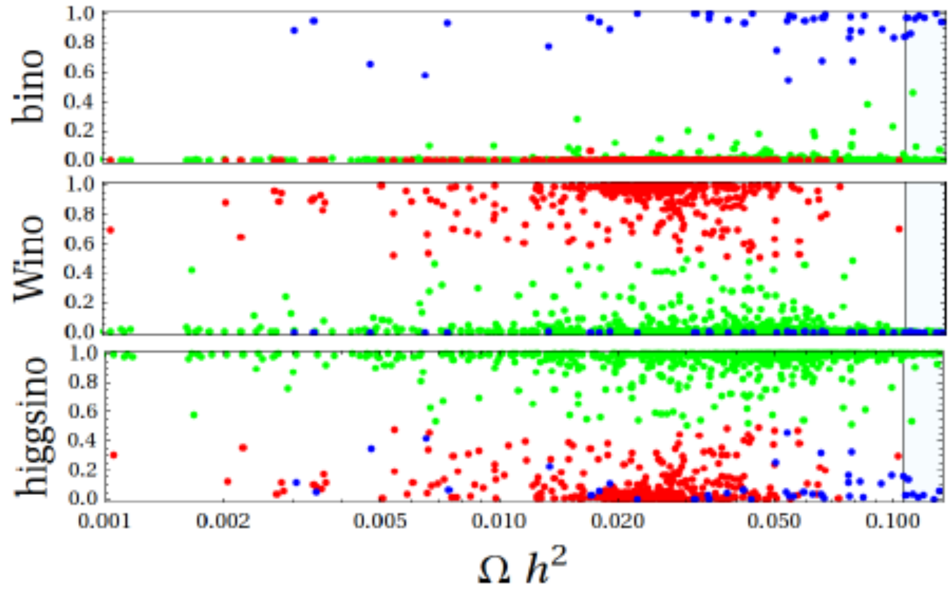
0

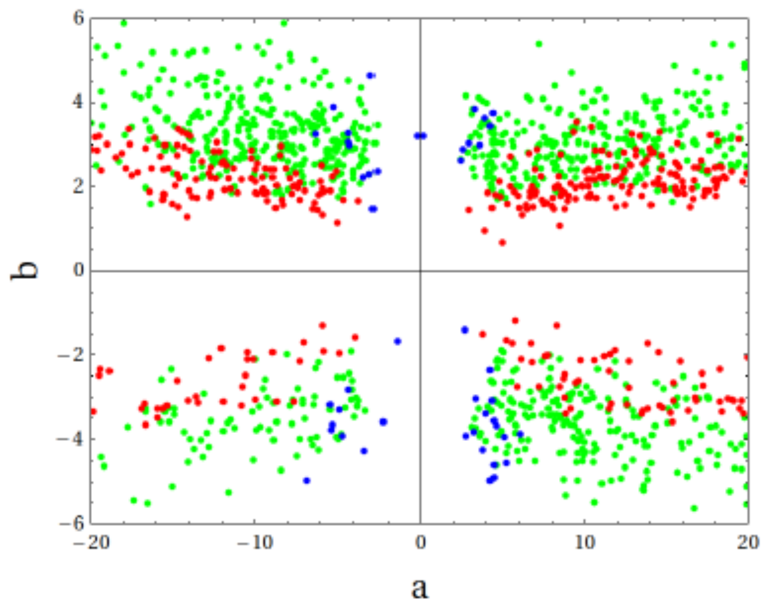
M_{gluino}

Dark matter



c.f. Roszkowski,Ruiz de Austria,
Trotta, Tsai, Varley





Summary

- GUTs $\Longrightarrow$ SUSY-GUTS (hierarchy problem)

- Fine tuning sensitive to SUSY spectrum

  ...scalar and gaugino focus points

- $\Delta^{CMSSM} > 350$ ✗ $\Delta^{(C)MSSM} > 60$ ✗

  $\Delta^{CGMSSM} > 60$ ✗ $\Delta^{(C)GNMMS} > 20$ ✔

$$c.f. \quad \Delta^{CMSSM}_{Low\ scale} = (10-30), \quad m_{\tilde{t}} = (1-5)TeV$$

Barger et al

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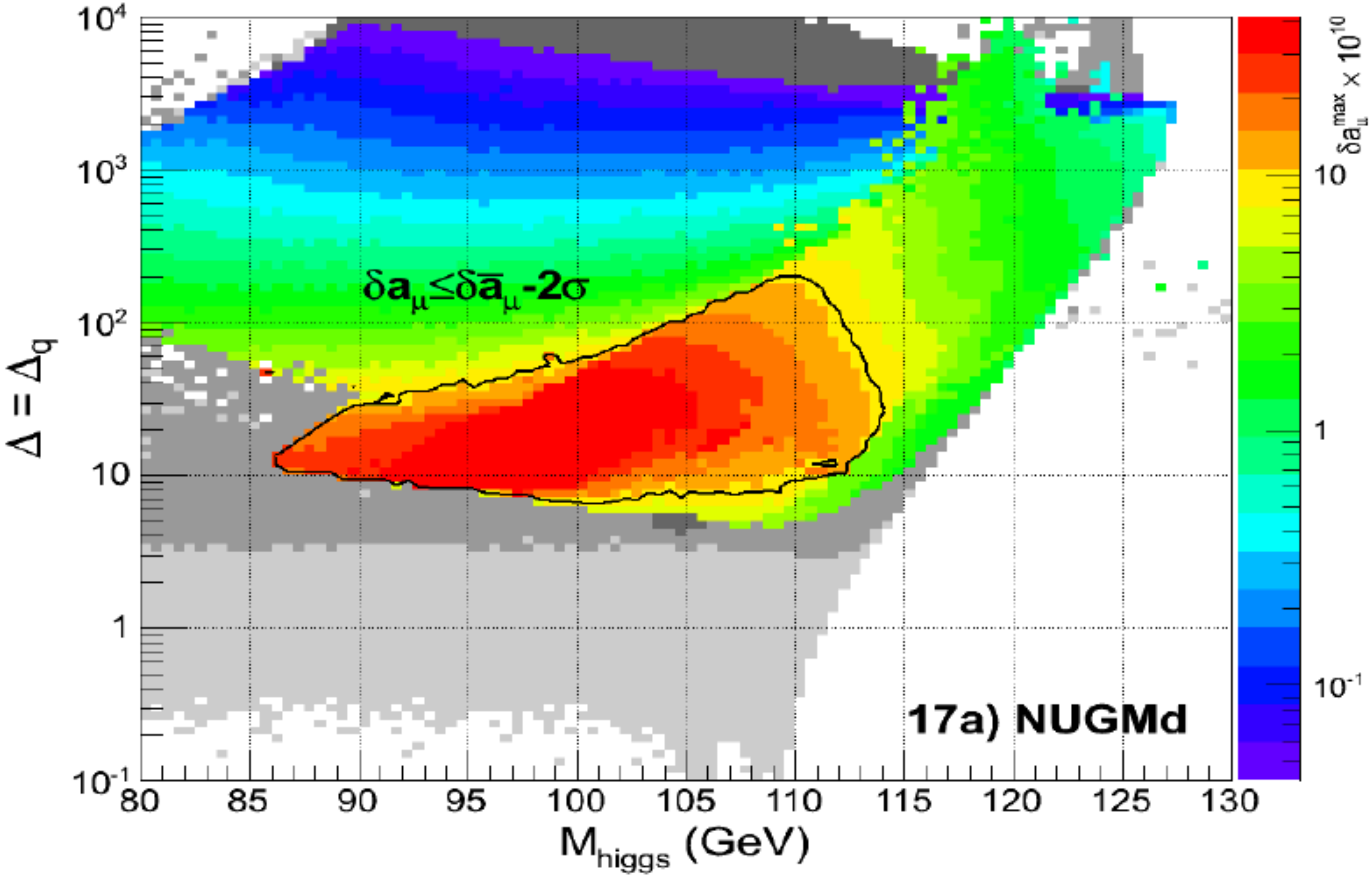
- Well motivated SUSY models remain to be tested

  LHC14?

  Compressed spectra, TeV squarks and gluinos



2-loop fine tuning in 75 case

Ghilencea, Lee, Park

Muon g-2

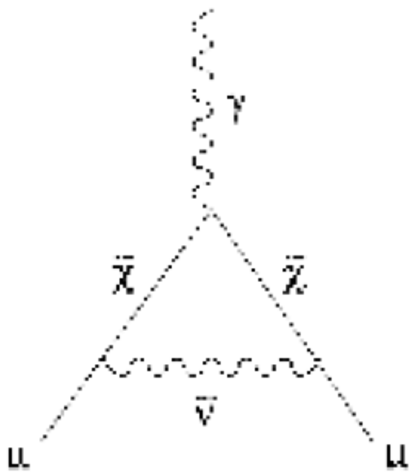
a_μ is a plausible location for a new physics signal!!

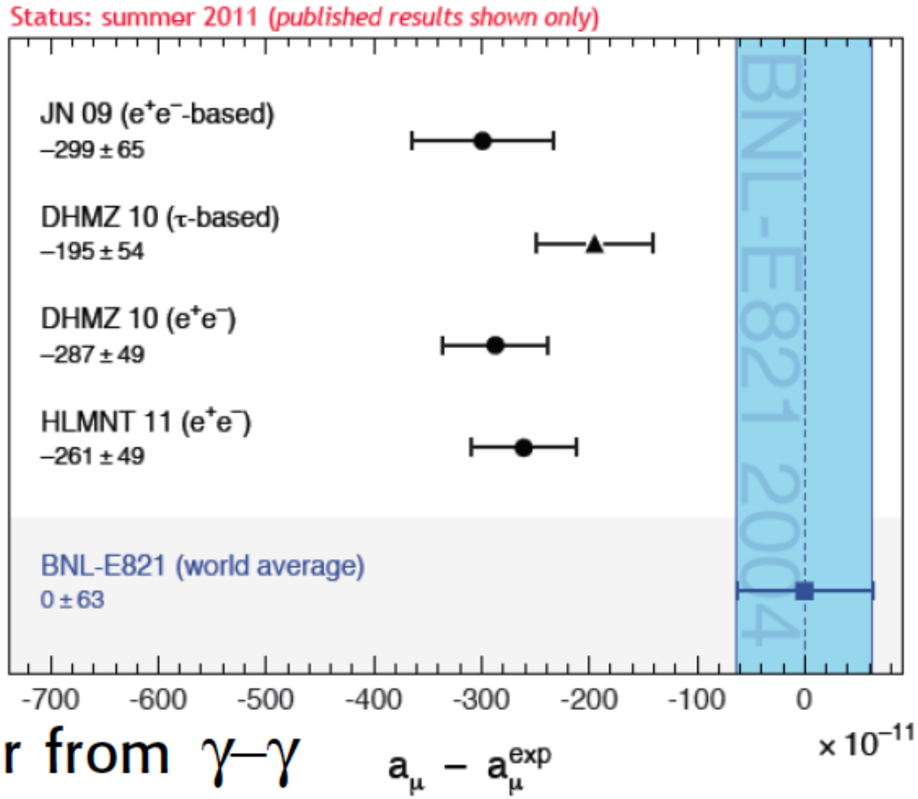
eg could be light SUSY
(now tension with LHC)

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

- ➡ 3.6 "standard deviations" (e^+e^-)
- ➡ 2.4 "standard deviations" (τ)

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

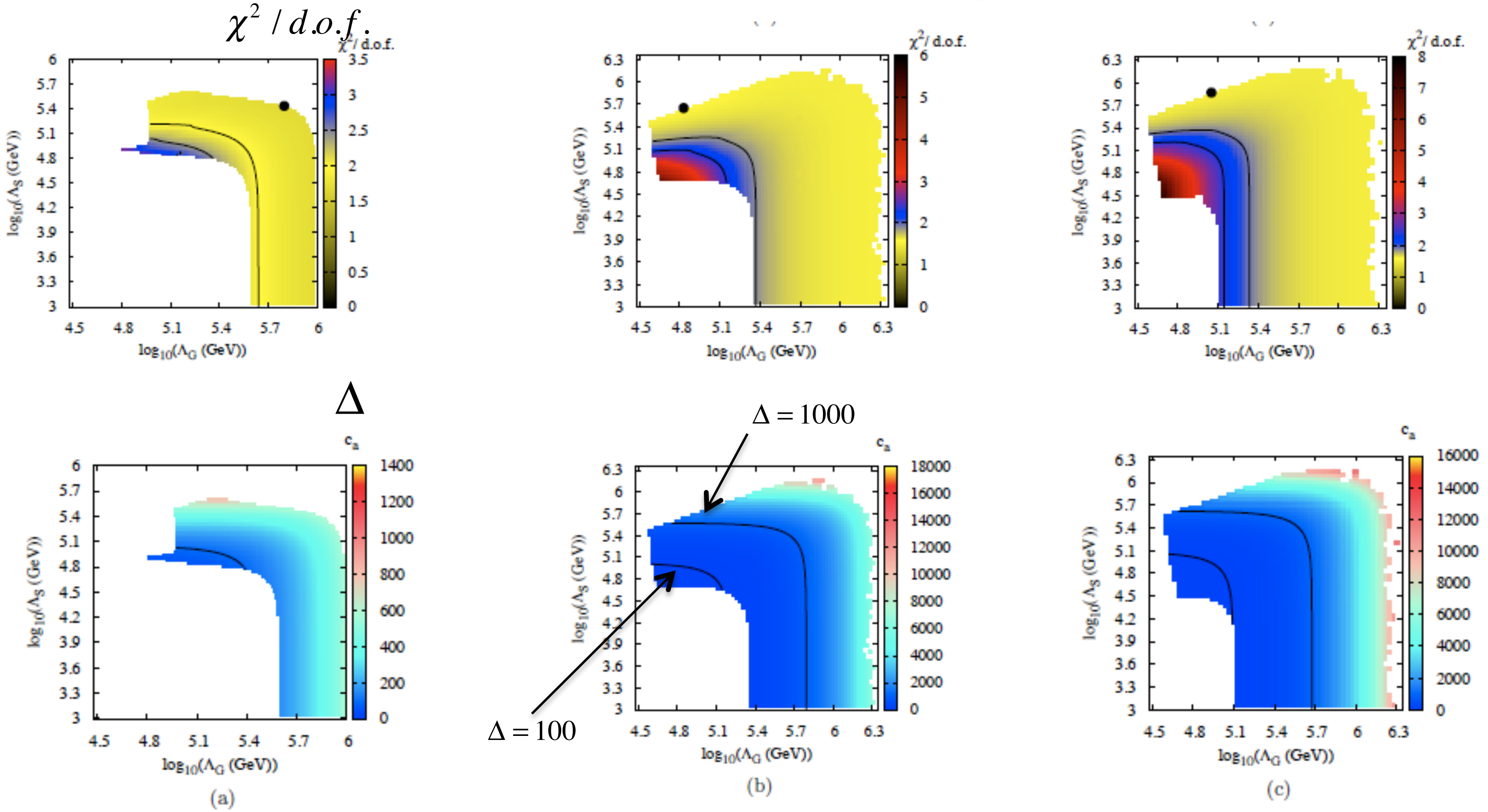




⊕ Error dominated by th error from γ–γ

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)