# SUSY in the light of the Higgs discovery

Graham Ross, IPMU, December 2013

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Introduction

Derivation of fine tuning measure

Scalar and gluino focus points – the CMSSM and the ©MSSM

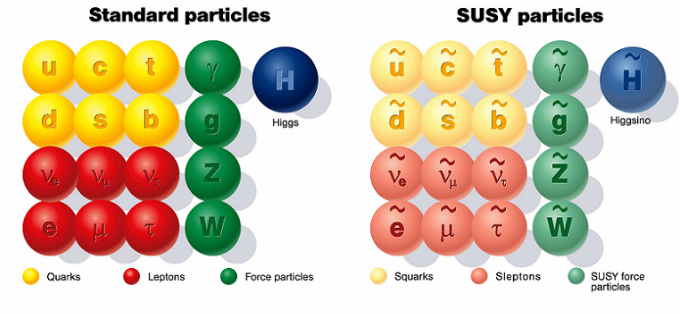
Beyond the MSSM – operator analysis and singlet extensions

Discrete R-symmetries

The GNMSSM (and Dirac NMSSM)

# Introduction

# Low energy SUSY ?



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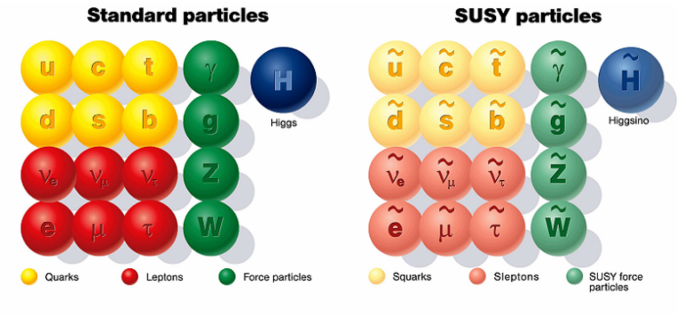
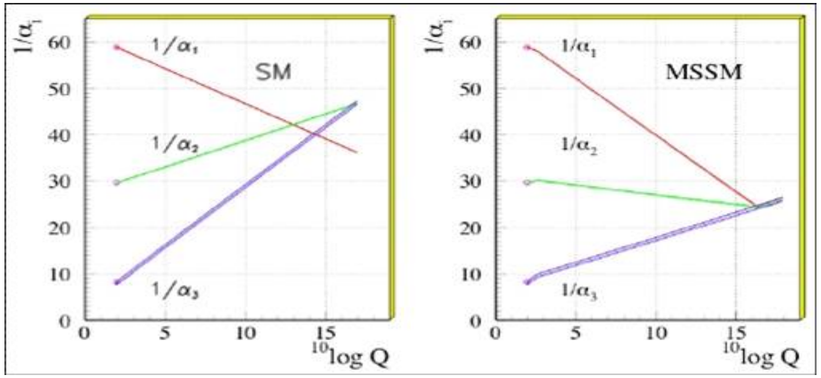


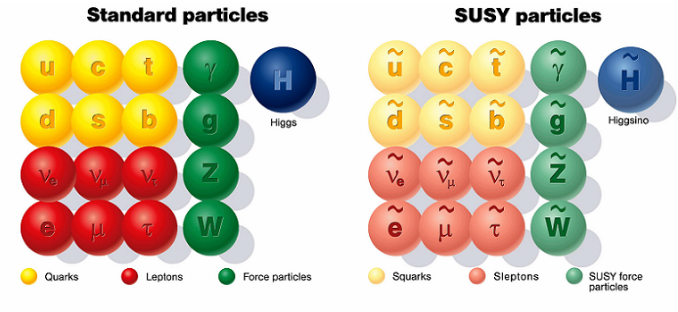

Unification:




✔

Only log sensitivity to SUSY scale

# Low energy SUSY ?

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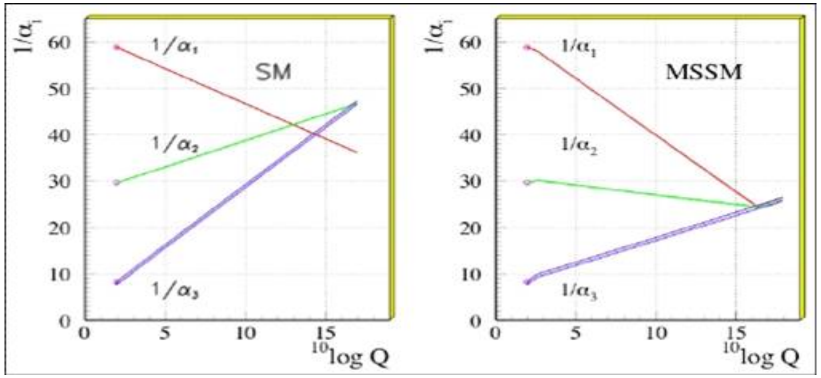
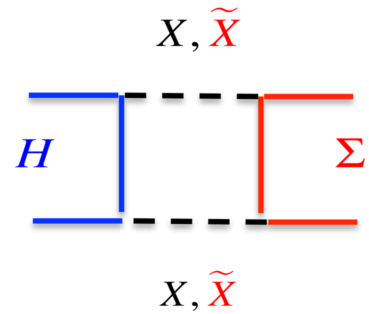



✔



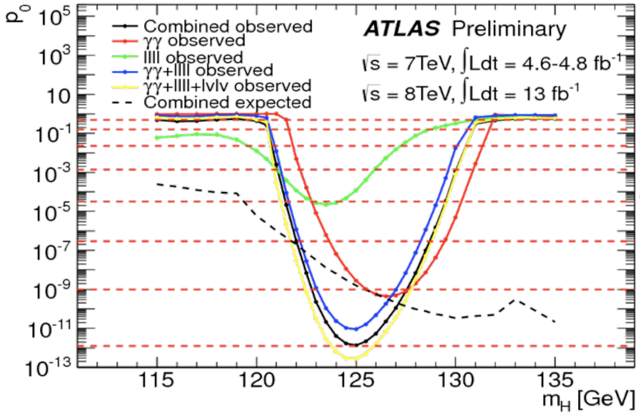

## The (SUSY) Standard Model as an EFT:

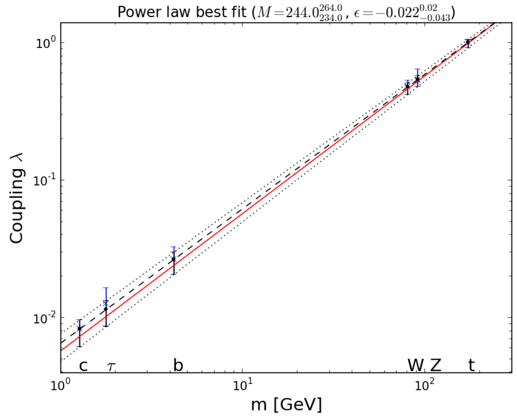
$A_\mu$ ✔, $\Psi$ ✔ H ✔ ?

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

**Solves the big hierarchy problem,** $M_{SUSY} < O(1TeV)$

# Higgs discovery! … completes the "Standard Model"



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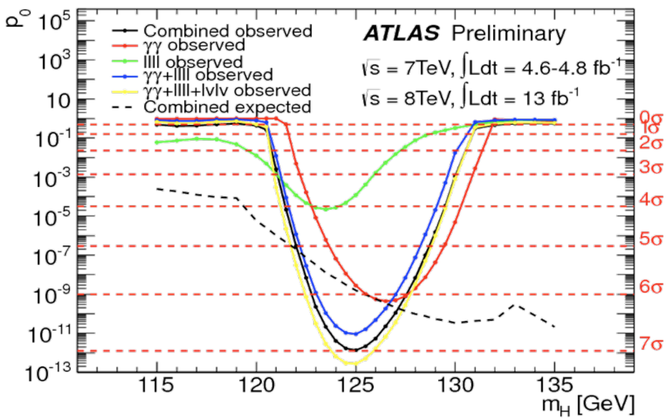
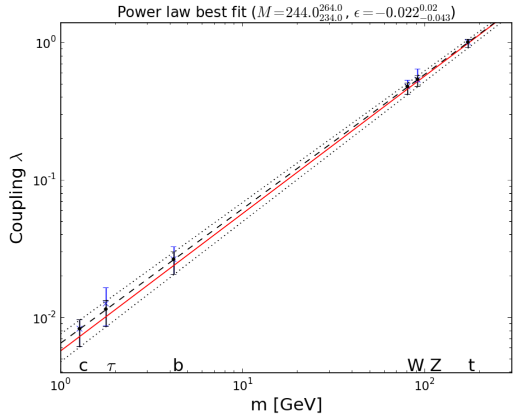
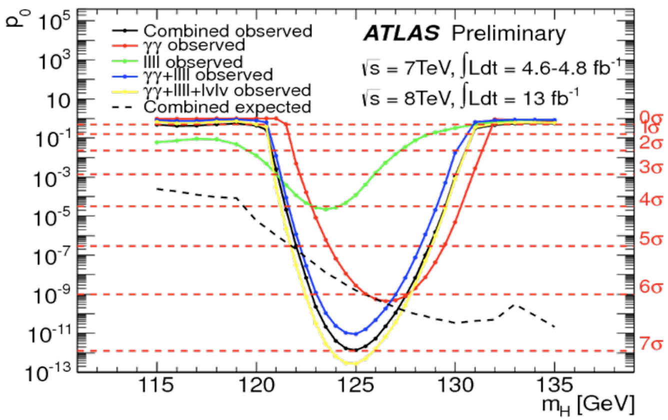
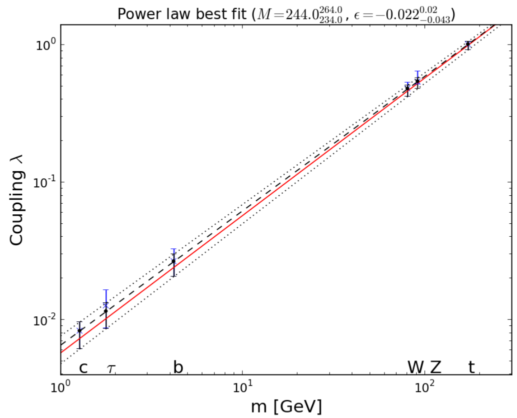



- "Light", weakly interacting SUSY ✔

Higgs discovery**!** ... completes the "Standard Model"




- "Light", weakly interacting SUSY ✔
- "Heavy", no evidence for sparticles SUSY ✗

$$m_h^2 = M_Z^2 + \frac{3m_t^2 h_t^2}{4\pi^2}\left(\ln\left(\frac{M_s^2}{m_t^2}\right) + \delta_t\right) + \ldots \simeq 126\, GeV$$

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

SUSY under pressure "Little hierarchy problem"

# The fine tuning measure

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

breaking

# MSSM:

105 +(19) Parameters

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

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

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

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

# 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:

"Nuisance" variable

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

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

Fine tuning not optional!

Ghilencea, GGR
Casas et al

## Probabilistic interpretation:

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

$$\Delta_q \ll 100$$

Scalar and gluino focus points –

The CMSSM and the ©MSSM

- The CMSSM

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

assumes correlation between SUSY breaking parameters

# Fine tuning in the CMSSM

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

Minimisation conditions:

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

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

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

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

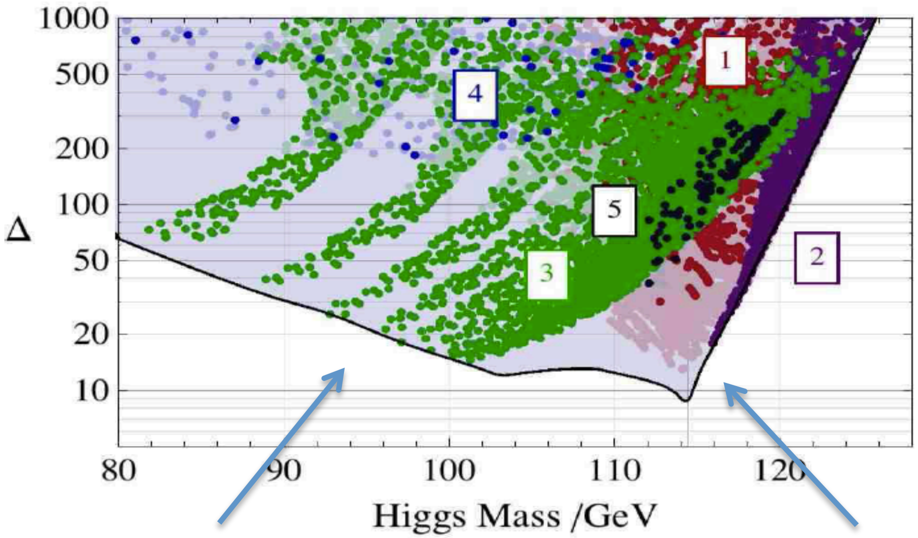
…enhanced sensitivity due to small tree-level $\lambda = \frac{1}{8}\left(g_1^2 + g_2^2\right)\cos^2 2\beta$

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

# The CMSSM - before LHC

$\gamma_i \supset \mu_0, m_0, m_{1/2}, A_0, B_0\big|_{M_{GUT}}$

Precision tests included
Gauge unification required
Relic density restricted




Λ increases

Focus point

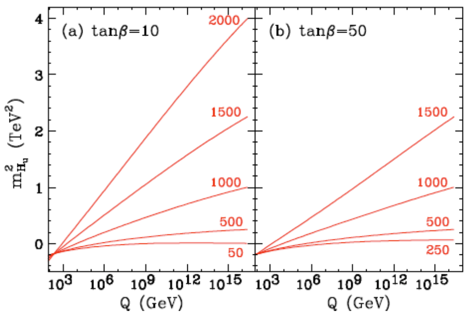
1 $h^0$ resonant annihilation
2 $\tilde{h}$ t-channel exchange
3 $\tilde{\tau}$ co-annihilation
4 $\tilde{t}$ co-annihilation
• 5 $A^0 / H^0$ resonant annihilation

Within $3\sigma$ WMAP:
$\Delta_{Min} = 15, \quad m_h = 114.7 \pm 2 GeV$

$< 3\sigma$ WMAP:
$\Delta_{Min} = 18, \quad m_h = 115.9 \pm 2 GeV$

Scalar focus point

$m_{H_u} = m_{\tilde{Q}_3} = m_{\tilde{u}3} = m_0$

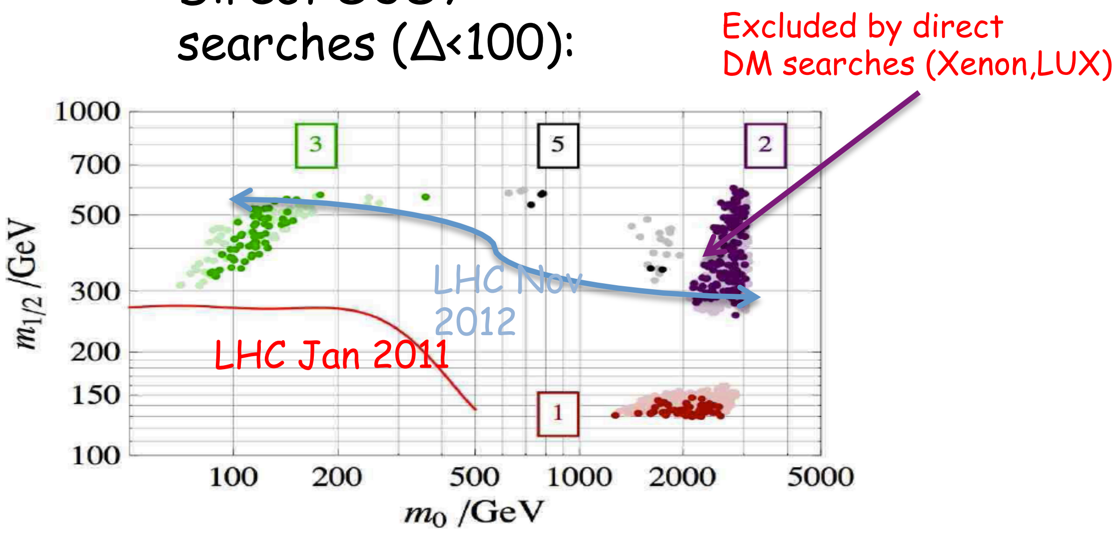



$$m^2_{H_u}\left(Q^2\right) = m^2_{H_u}\left(M_P^2\right) + \frac{1}{2}\left(m^2_{H_u}\left(M_P^2\right) + m^2_{Q_3}\left(M_P^2\right) + m^2_{\bar{u}3}\left(M_P^2\right)\right)\left[\left(\frac{Q^2}{M_P^2}\right)^{\frac{3y_t^2}{4\pi^2}} - 1\right]$$

Feng, Matchev, Moroi
Chan, Chattopadhyay, Nath

# The CMSSM - after LHC

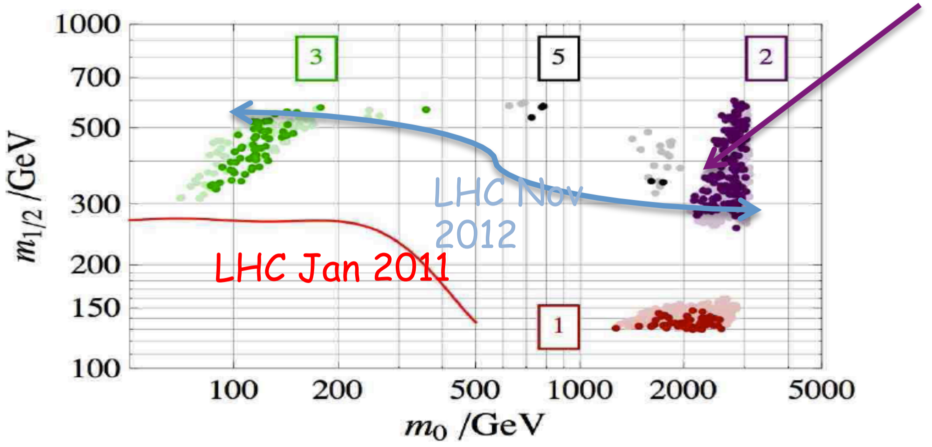
Direct SUSY searches (Δ<100):



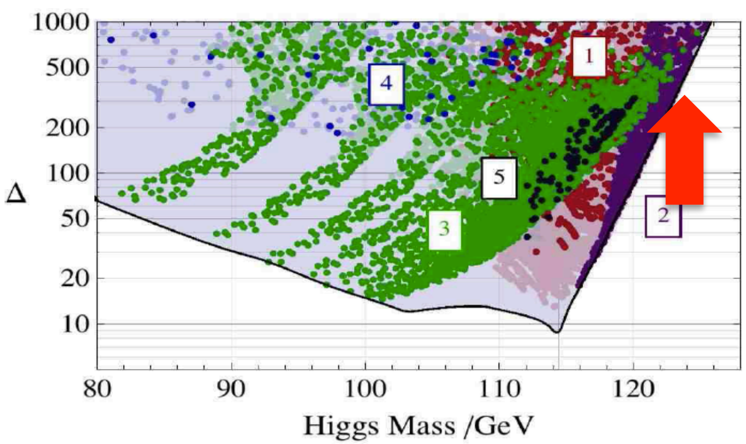
# The CMSSM - after LHC

Direct SUSY searches (Δ<100):

Excluded by direct DM searches (Xenon,LUX)




Higgs mass:




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

# Reduced fine tuning (the ©MSSM)

- New focus points?

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

# Reduced fine tuning (the ©MSSM)

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

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

Abe, Kobayashi, Omura
Horton, GGR

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Abe, Kobayashi, Omura
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Natural ratios? e.g.:

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

| Representation | $M_3 : M_2 : M_1$ at $M_{GUT}$ ($\eta_3 : 1 : \eta_1$) | $M_3 : M_2 : M_1$ at $M_{EWSB}$ ($2.7\eta_3 : 1 : 0.5\eta_1$) |
|---|---|---|
| **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 |

Younkin, Martin

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

Ibanez et al
Choi et al
Badziek et al

# Reduced fine tuning (the ©MSSM)

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

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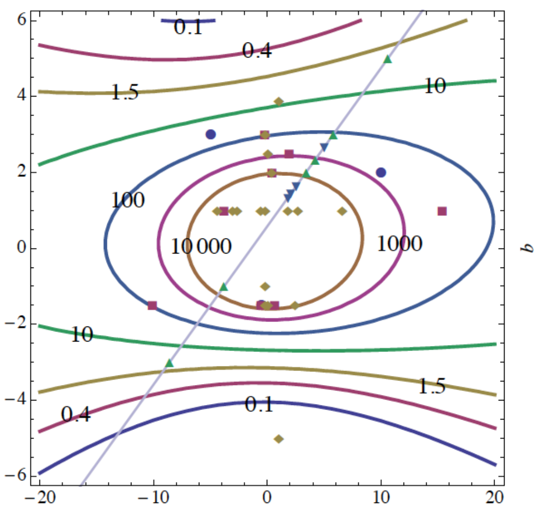
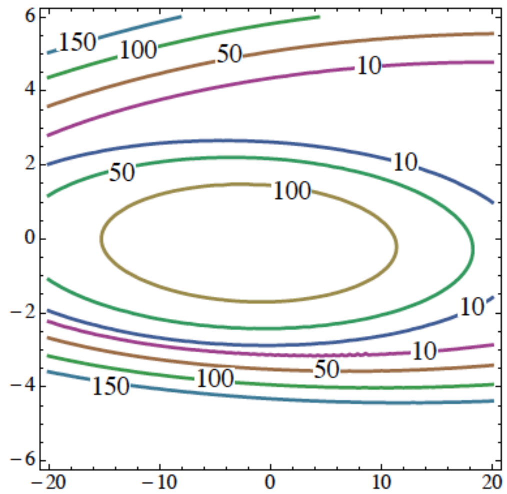
$b$




$a$

$b$




$a$

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

GGR, Kaminska, Schmidt-Hoberg

## 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 $M_{SUSY}$

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

LHC8 SUSY bounds ✔

DM relic abundance ✔

DM searches ✗

# Beyond the MSSM –

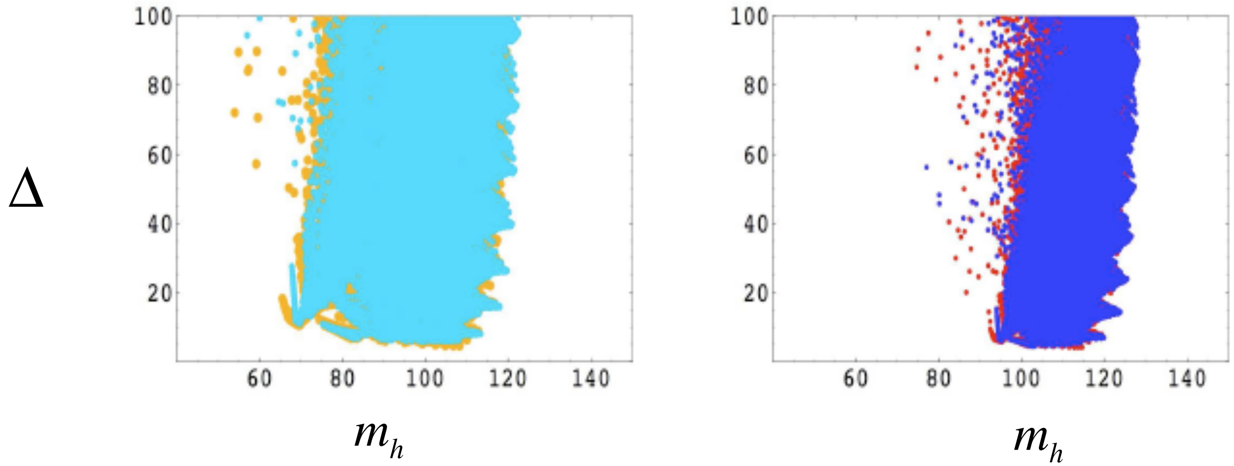
## operator analysis and singlet extensions

## Reduced fine tuning : New heavy states – higher dimension operators

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

Dimension 5

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




MSSM | + dim 5 operators

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 $\Delta$

…effect mainly comes from $\varsigma_1$ term … origin?

## Reduced fine tuning : New heavy states – higher dimension operators

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

Dimension 5

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

†

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

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

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

## Singlet extensions

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

NMSSM

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

GNMSSM

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

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

## 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

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

## Singlet extensions

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

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

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

but are $\mu, \mu_s$ naturally small?

# Discrete R-symmetries

# 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: $Z_2$ $\quad H_u, H_d \; +1$ $\quad$ SUSY states odd

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

Weinberg, Sakai

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R-parity: $Z_2$

SUSY states odd

Weinberg, Sakai

Baryon "parity": $Z_3$

| | |
|---|---|
| $Q$ | $1$ |
| $\overline{D}, H_u$ | $\alpha$ |
| $L, \overline{E}, \overline{U}, H_d$ | $\alpha^2$ |

LSP unstable

Discrete gauge symmetry
-anomaly free

Ibanez, GGR

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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

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$$W = h^E L H_d \overline{E} + h^D Q H_d \overline{D} + h^U Q H_u \overline{U} + \mu H_d H_u$$
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$$+ \frac{1}{M}\left( QQQL + QQQH_d + Q\overline{U}\,\overline{E} H_d + \ldots(\cancel{L}) \right)$$

$\mu$ term, GUTs?

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

Dreiner, Luhn, Thormeier

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$$W = h^E L H_d \overline{E} + h^D Q H_d \overline{D} + h^U Q H_u \overline{U} + \mu H_d H_u$$
$$+ \lambda L L \overline{E} + \lambda' L Q \overline{D} + \kappa L H_u + \lambda'' \overline{U}\,\overline{D}\,\overline{D}$$
$$+ \frac{1}{M}\left(QQQL + QQQH_d + Q\overline{U}\,\overline{E} H_d + \ldots(\not{L})\right)$$

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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

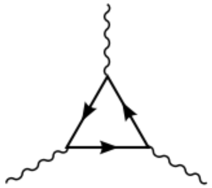
# A unique solution : $Z_4^R$ discrete R symmetry

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

| $N$ | $q_{10}$ | $q_{\bar{5}}$ | $q_{H_u}$ | $q_{H_d}$ | $q_N$ |
|---|---|---|---|---|---|
| 4 | 1 | 1 | 0 | 0 | 2 |

Green Schwarz term

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



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

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

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

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

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## D=5 operators

up and down Yukawas allowed

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

Weinberg operator

## SUSY breaking

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

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

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

Domain walls safe
Tadpole safe

$M_{higgs} \approx M_{SUSY}$

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

# The GNMSSM (and Dirac NMSSM)

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R-symmetry ensures Singlet extensions natural

# GNMSSM

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

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

Weinberg operator

## SUSY breaking

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

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

Domain walls and tadpoles safe Abel

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

$$\boxed{\begin{aligned} W &= W_{MSSM}+\lambda SH_uH_d+\kappa S^3+\Delta W \\ \Delta W_{Z^R_4} &\sim m_{3/2}H_uH_d+m^2_{3/2}S+m_{3/2}S^2 \\ \Delta W_{Z^R_8} &\sim m^2_{3/2}S \end{aligned}}$$

μ term and mass term

# Dirac NMSSM

$$W_{DiracNMSSM} \supset QuH_u,\ QdH_d,\ leH_d,\ NH_uH_d,\ m_{3/2}N\overline{N},\ l\nu_R H_u$$

(reduces F-term decoupling without FT increase)

Lu, Murayama, Ruderman, Tobioka

Discrete R-symmetry e.g.

| | $Q$ | $u$ | $d$ | $l$ | $e$ | $H_d$ | $H_u$ | $N$ | $\overline{N}$ | $X$ | $\nu_R$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $Z_8^R$ | 1 | 1 | 5 | 5 | 1 | 4 | 0 | 6 | 2 | 0 | 5 |
| $Z_5$ | 0 | –1 | 0 | –3 | 3 | 0 | 1 | –1 | 1 | 1 | 2 |

(Neutrino masses of correct magnitude)

Chen, Ratz, GGR, Takhistov

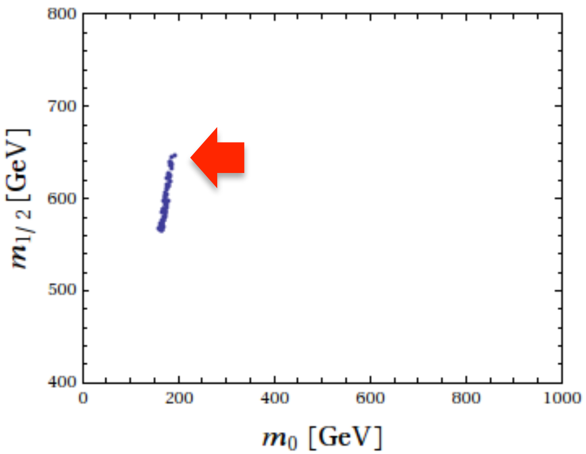
# Fine tuning in the CGNMSSM $(\lambda \leq 0.7^{\dagger})$

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

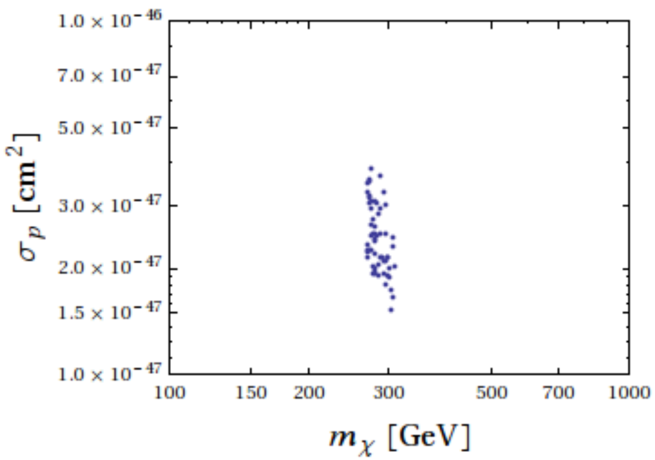
LHC8 SUSY bounds ✗

DM relic abundance ✔

DM searches ✔




Stau co-annihilation




DM searches insensitive

GGR, Schmidt-Hoberg , Staub

† c.f. Hall, Pinner, Ruderman

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

Non-unversal gaugino masses

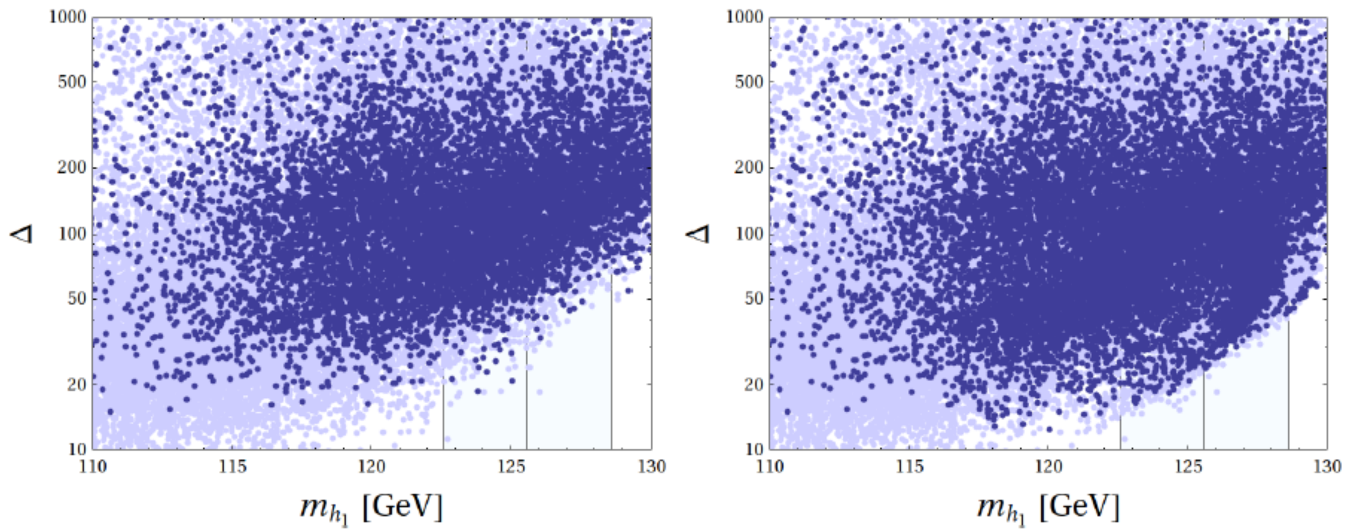
$$\boxed{\Delta_{Min} = 20\,, \quad m_h = 125.6 \pm 3 GeV}$$

LHC8 SUSY bounds ✔

DM relic abundance ✔

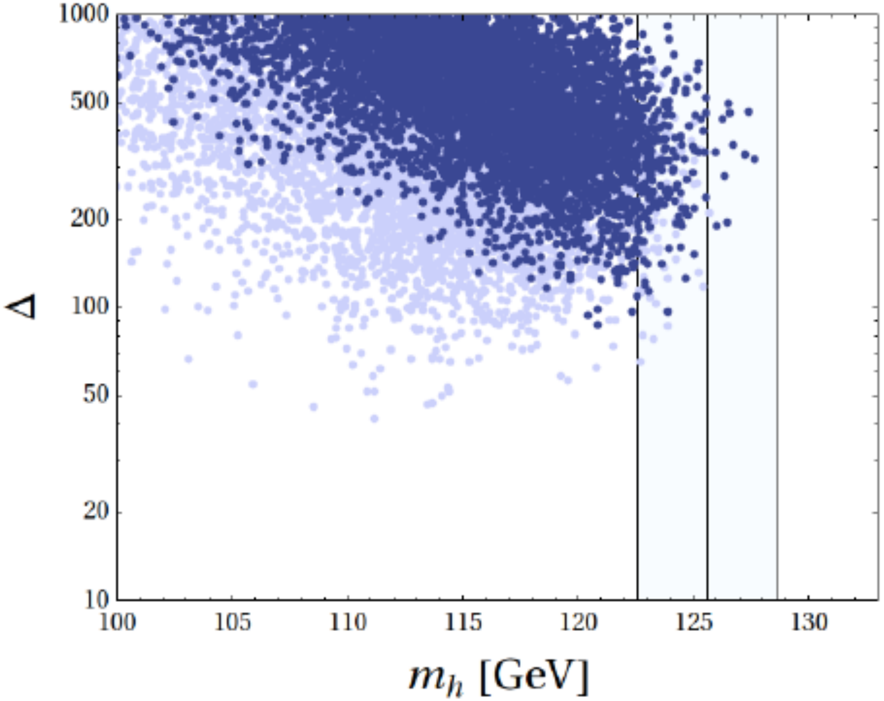
DM searches ✔

$\Delta$



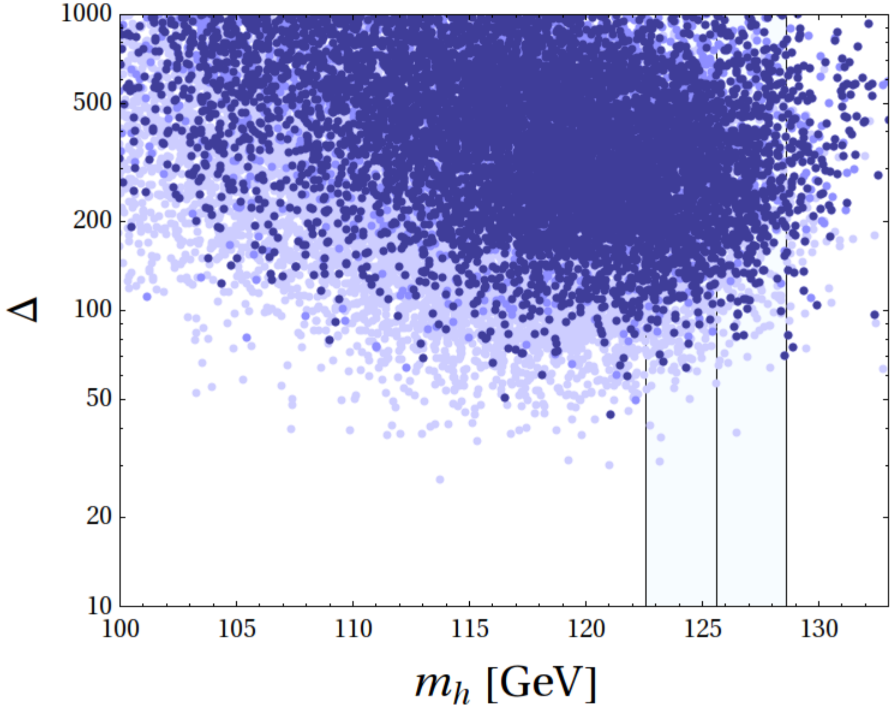

GGR, Kaminska, Schmidt-Hoberg

# Fine tuning in the DiracNMSSM




CDiracNMSSM

$$\Delta \geq 80$$




©DiracNMSSM

$$\Delta \geq 70$$

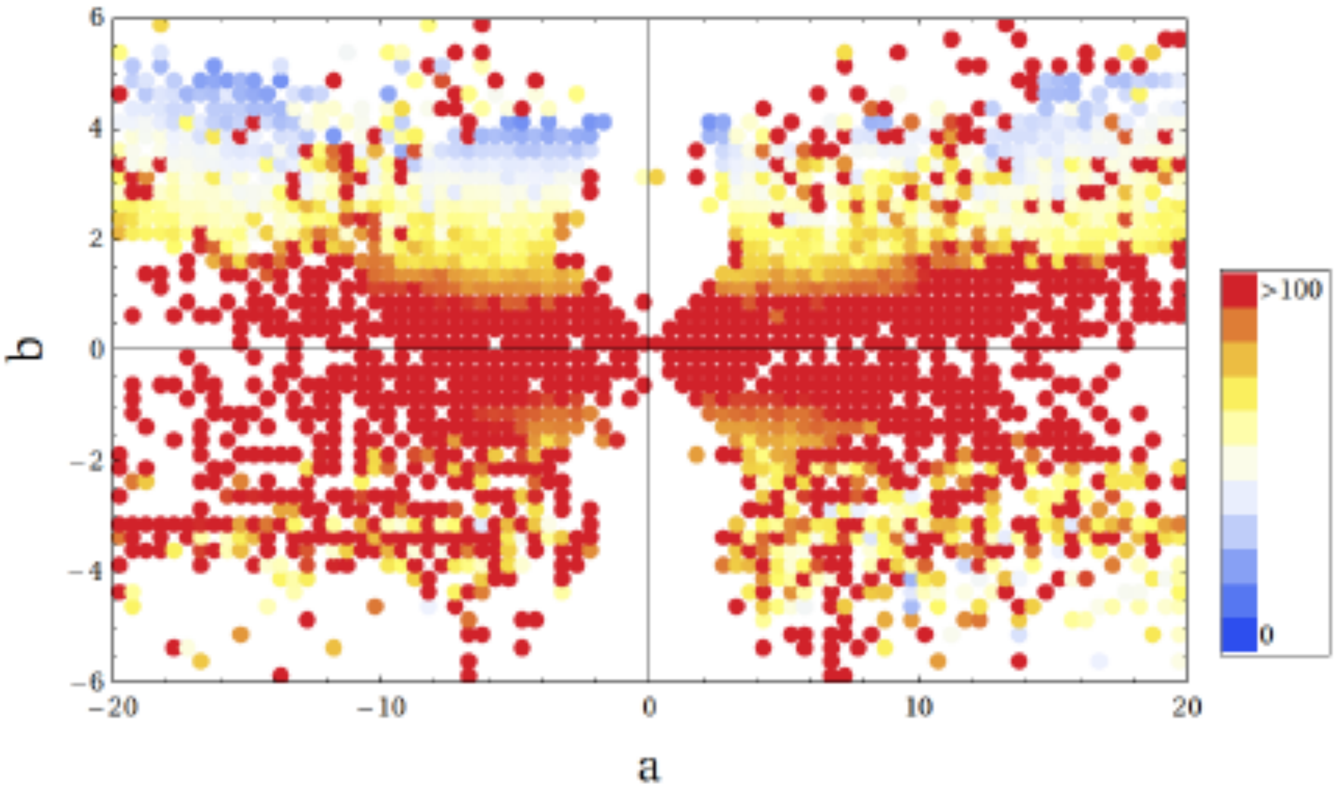
(1+leading 2-loop Higgs mass determination and full 2-loop RGE)

$$m_0, m_{1/2}, A_0, \tan\beta, \mu, b\mu, \lambda, A_\lambda, v_s, v_{\bar{s}}, M, b_s, m_{h_u}^2, m_{h_d}^2, m_s^2, m_{\bar{s}}^2, \xi_S, \xi_{\bar{S}}$$

Kaminska, Schmidt-Hoberg, GGR, Staub
(Preliminary)

# Back to the ©GNMSSM

…fine tuning v/s gaugino mass ratios



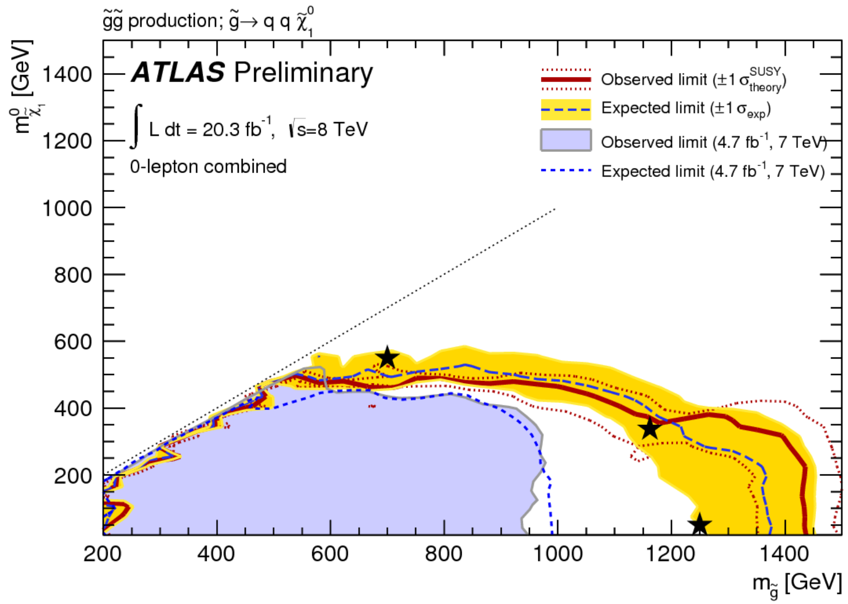

F.T.

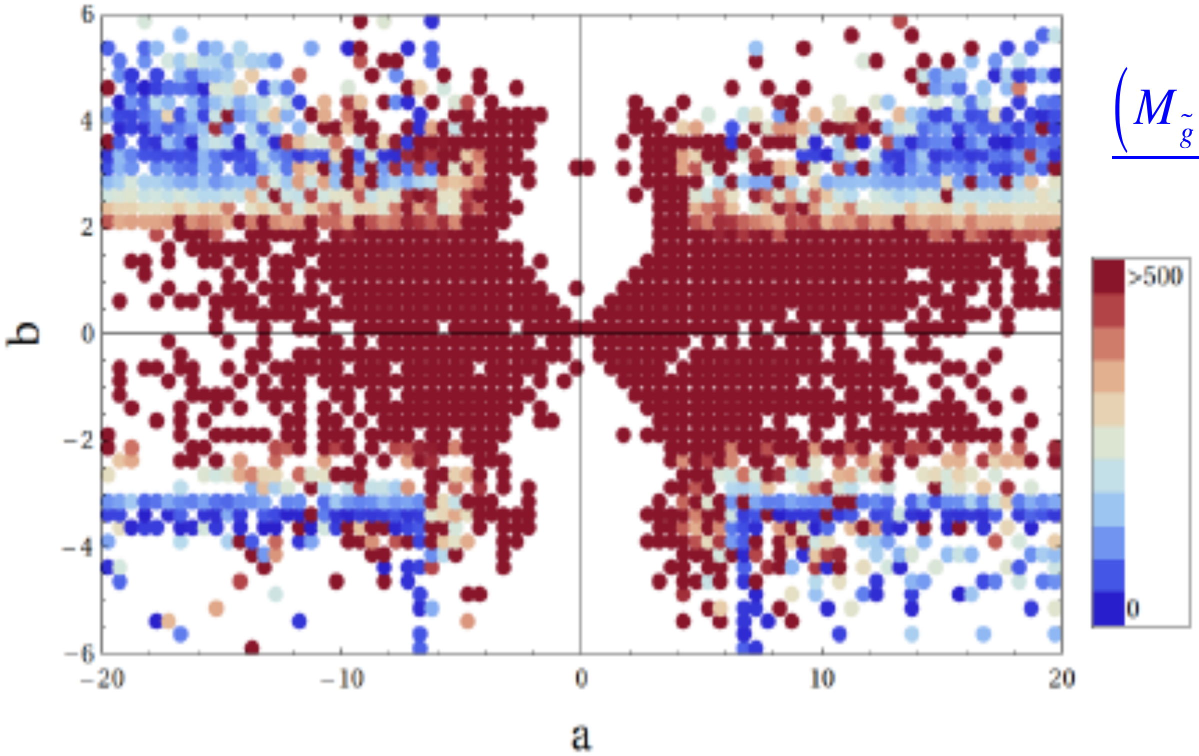
$> 100$

$0$

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

# Compressed spectrum



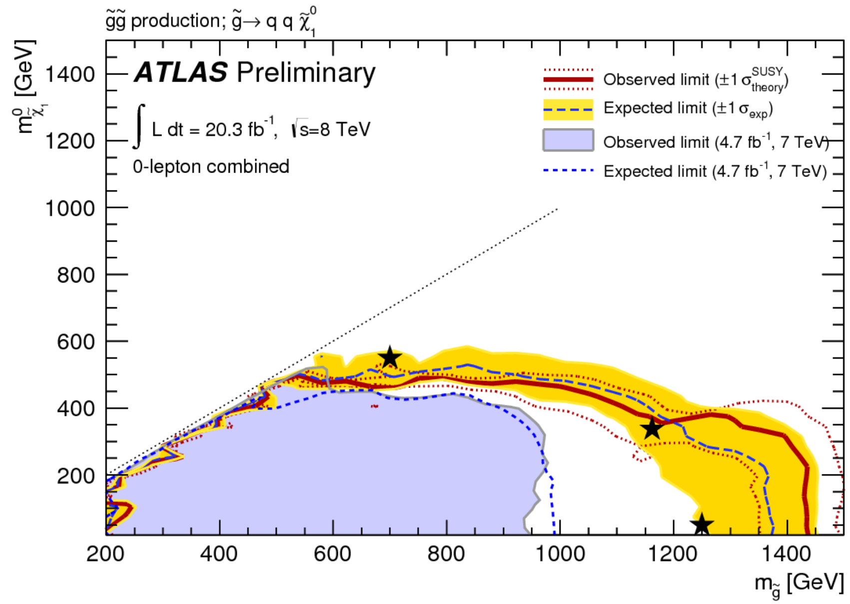



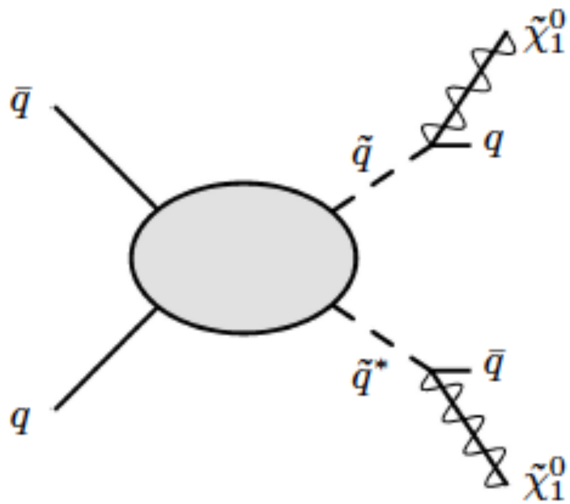

$$\frac{\left(M_{\tilde{g}} - M_{LSP}^{neutralino}\right)}{GeV}$$

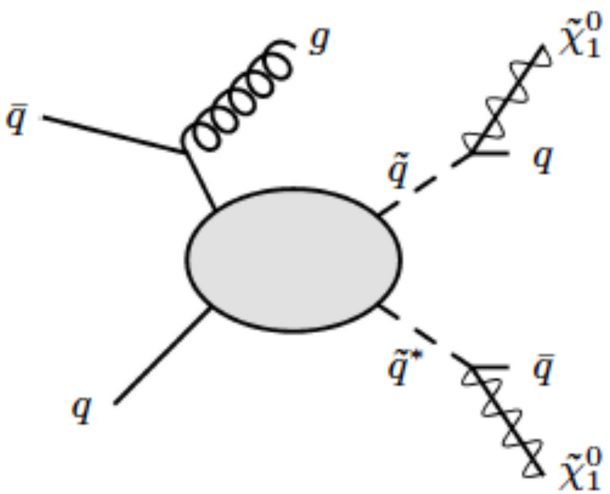
$> 500$

$0$

# Compressed spectrum





$$m_{\tilde{q}} > 370\ GeV$$

$$m_{\tilde{g}} > 530\ GeV$$

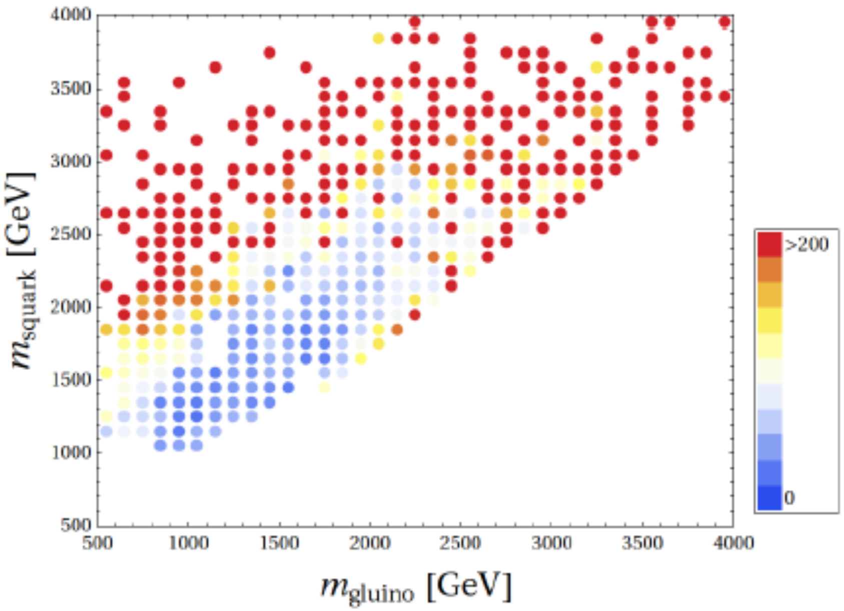
$$m_{\tilde{q}} \sim m_{\tilde{g}} > 680\ GeV$$

Tag with hard initial QCD radiation

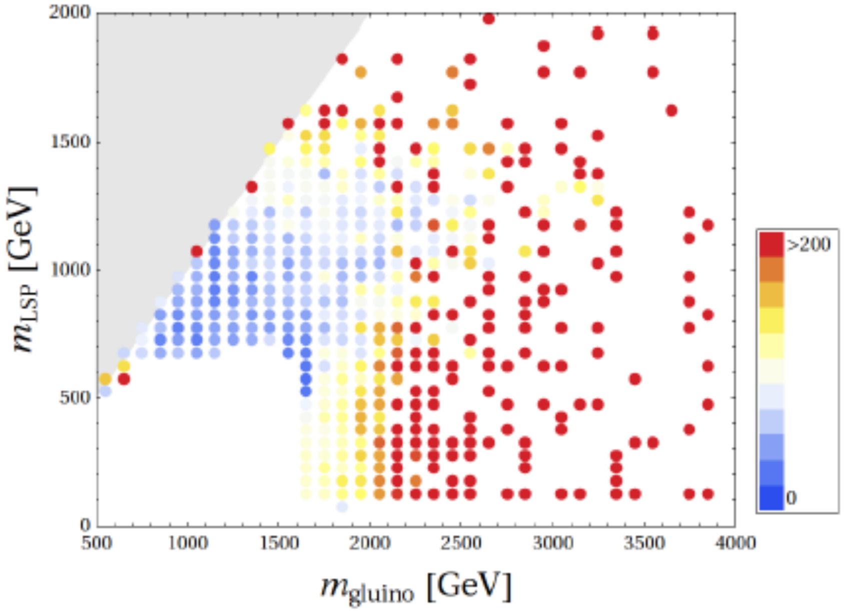
Dreiner, Kramer, Tattersall

# Masses v/s fine tuning

$m_{squark}$




$m_{LSP}$

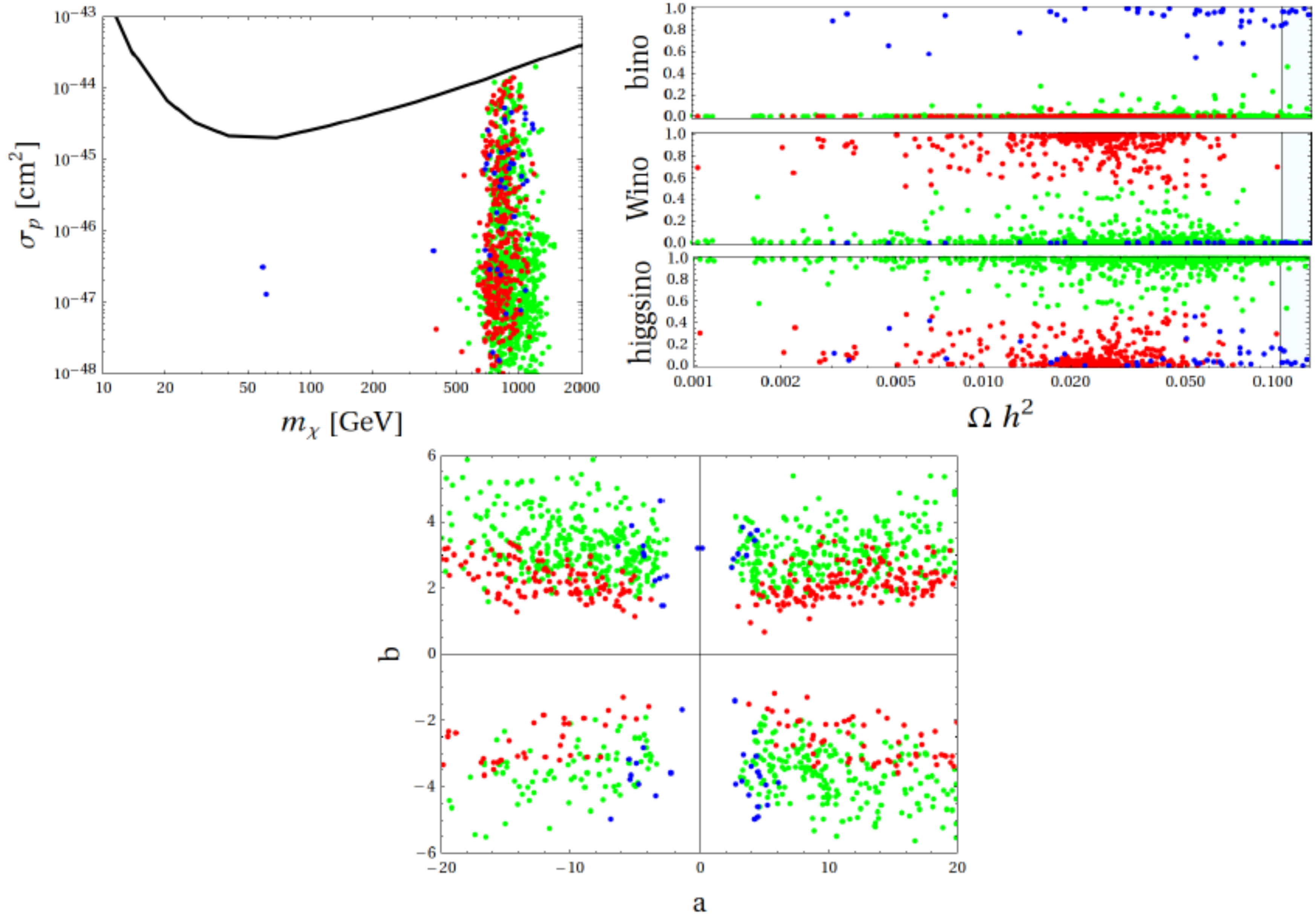



$> 500$

$0$

$M_{gluino}$

# Dark matter



$10^{-43}$
$10^{-44}$
$10^{-45}$
$10^{-46}$
$10^{-47}$
$10^{-48}$
$\sigma_p$ [cm$^2$]
10 20 50 100 200 500 1000 2000
$m_\chi$ [GeV]
bino
Wino
higgsino
0.0 0.2 0.4 0.6 0.8 1.0
0.001 0.002 0.005 0.010 0.020 0.050 0.100
$\Omega\ h^2$
b
a
−20 −10 0 10 20
−6 −4 −2 0 2 4 6

# Summary

- GUTs $\Longrightarrow$ SUSY-GUTS (hierarchy problem)
- Low fine tuning not optional
- Fine tuning sensitive to SUSY spectrum

  ...scalar and gaugino focus points

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

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

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

Barger et al

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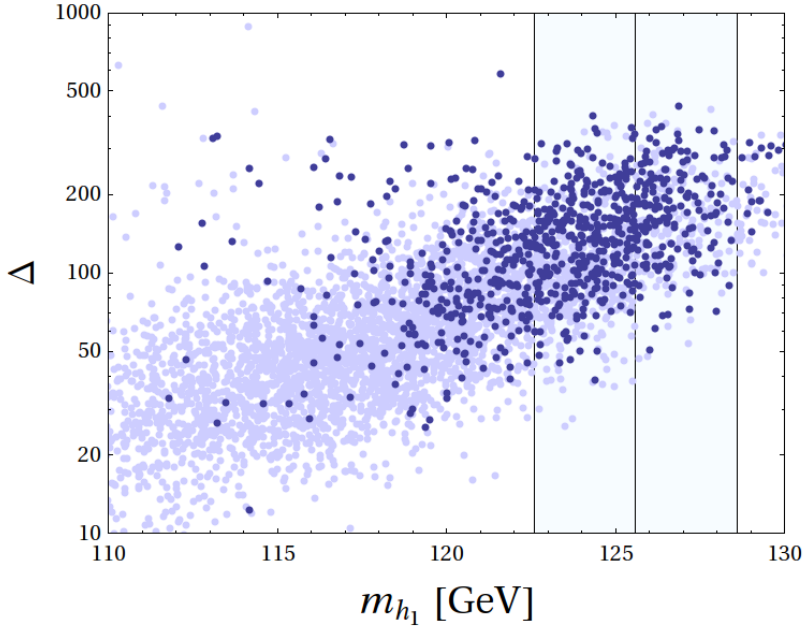
a, b not fixed

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- Well motivated SUSY models remain to be tested

  LHC14?

  Compressed spectra, TeV squarks and gluinos