low energy

Is Λ SUSY alive ?

G. Ross, Madrid, September 2016

OUTLINE

Low scale SUSY: Hierarchy problem †

Little hierarchy problem: Definite SUSY (breaking) structure

Context: SUSY GUTS

† LHC 13Tev estimates:
+ Florian Staub, Kai Schmidt-Hoberg

MSSM: 105 +(19) Parameters

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

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

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

Fine Tuning measure:

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

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

Ellis, Enquist, Nanopoulos, Zwirner

Barbieri, Giudice

Fine tuning from a likelihood fit:

If v included as a "Nuisance" variable

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

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

Fine tuning

Ghilencea, GGR
Cabrera, Casas, Ruiiz de Austri

Probabilistic interpretation:

$$\chi^2_{new} = \chi^2_{old} + 2\ln\Delta_q \qquad \Delta_q < 100, \quad \delta\left(\frac{\chi^2}{d.f.}\right) < 1$$

Soft parameters?

Fine tuning sensitive to correlations between them

$e.g.$ $\gamma_i = \mu_0, m_0, m_{1/2}, A_0, B_0$ CMSSM

Soft parameters?

Fine tuning sensitive to correlations between them

$e.g.$ $\gamma_i = \mu_0, m_0, m_{1/2}, A_0, B_0$ CMSSM

Focus point $Z_{h_u}^{m_0}(M_Z) \simeq 0$

$$m_{h_u}^2(Q) = z_{h_u}^{m_0}(Q) m_0^2 + z_{h_u}^{m_{1/2}}(Q) m_{1/2}^2 + z_{h_u}^{A_0}(Q) A_0^2 + 2 z_{h_u}^{m_{1/2} A_0}(Q) m_{1/2} A_0$$

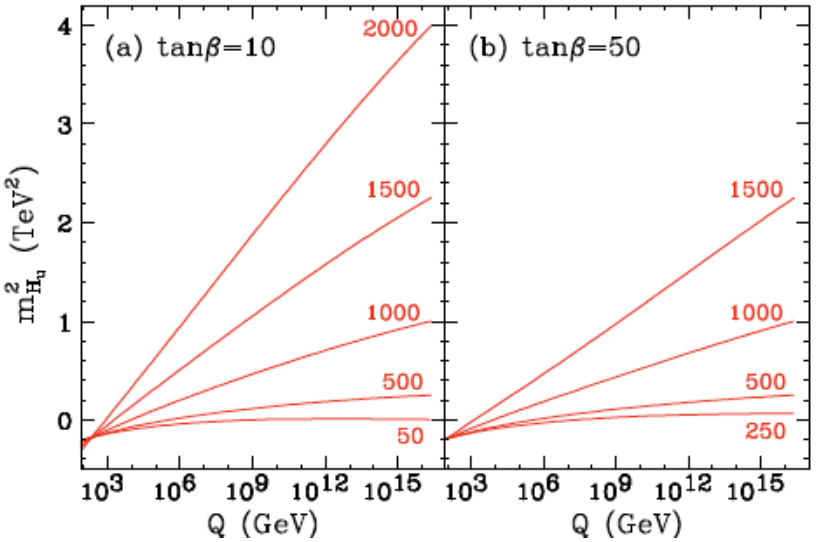
Focus Point

$2\,|\,y_t\,|^2\,(m^2_{H_u}+m^2_{Q_3}+m^2_{\bar{u}_3})+2\,|\,a_t\,|^2$

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

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

$$16\pi^2\frac{d}{dt}m^2_{\bar{u}_3}=2X_t-\frac{32}{3}g_3^2\,|\,M_3\,|^2-\frac{32}{15}g_1^2\,|\,M_1\,|^2$$



$$m^2_{H_u}\left(Q^2\right)=m^2_{H_u}\left(M_P^2\right)+\frac{1}{2}\left(m^2_{H_u}\left(M_P^2\right)+m^2_{Q_3}\left(M_P^2\right)+m^2_{\bar{u}_3}\left(M_P^2\right)\right)\left[\left(\frac{Q^2}{M_P^2}\right)^{\frac{3y_t^2}{4\pi^2}}-1\right]$$

m_0^2 $\qquad$ $3m_0^2$

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

"Focus point": $m^2_{H_u}\left(0\right)=m^2_{Q_3}\left(0\right)=m^2_{\bar{u}_3}\left(0\right)\equiv m^2$ $\qquad$ $m^2_{H_u}\left(t_0\right)=a_0\,m^2+..,\ a_0\le 0.1$

Natural choice

$i.e.\ m^3_{Q_3},m^2_{\bar{u}_3}\gg M_Z^2$ possible

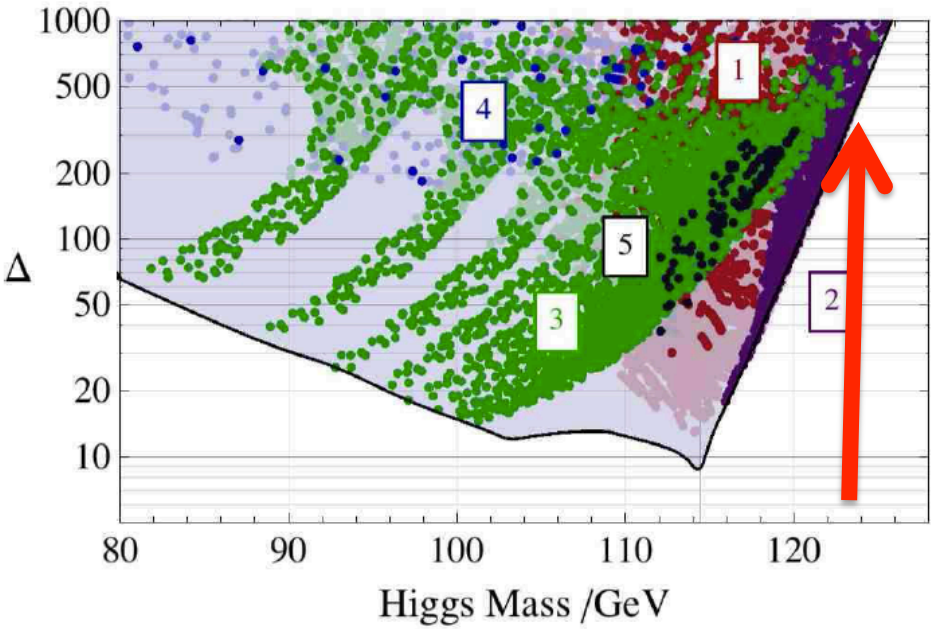
(sensitivity to h_t small)

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

The CMSSM – after Higgs discovery

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

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



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:

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

< 3σ WMAP:

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

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

†

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

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

† (requiring gauge coupling unification $\Delta \propto \log(M_{GUT}^2 / Q^2)$)

Soft parameters?

Fine tuning sensitive to correlations between them

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

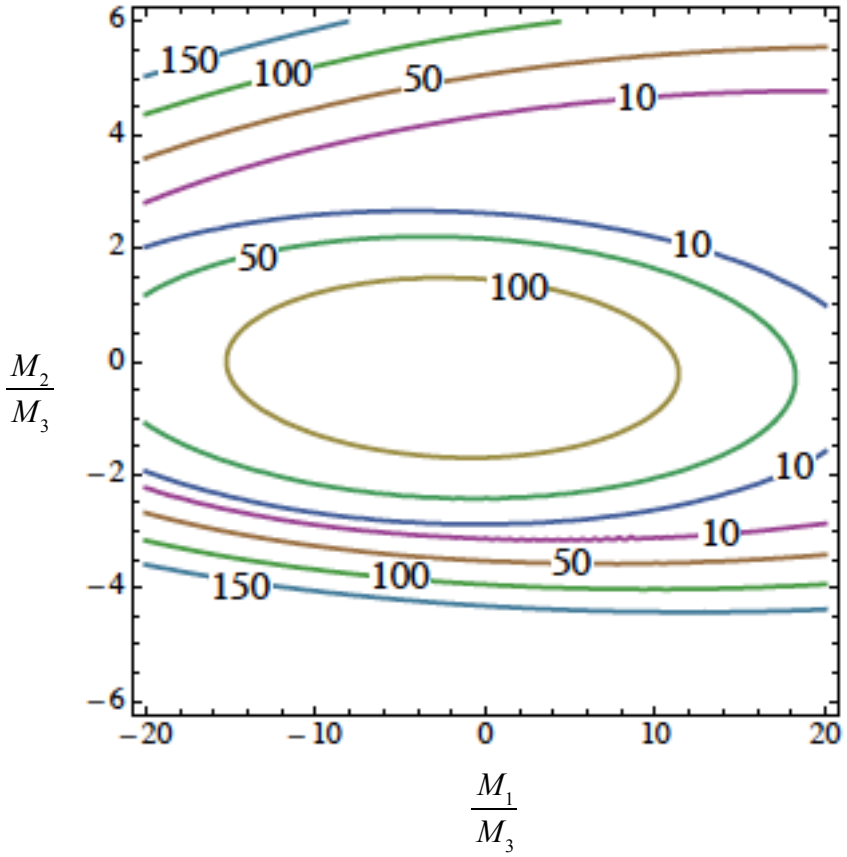
Focus point $Z_{h_u}^{m_{1/2}}(M_Z) \simeq 0$?

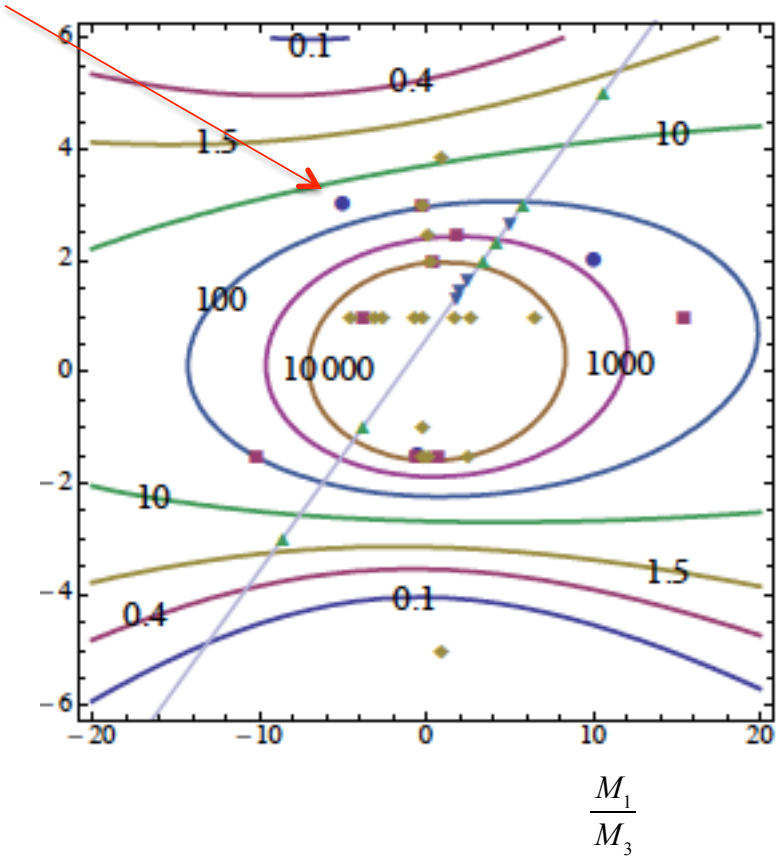
$$m_{h_u}^2(Q) = z_{h_u}^{m_0}(Q) m_0^2 + z_{h_u}^{m_{1/2}}(Q) m_{1/2}^2 + z_{h_u}^{A_0}(Q) A_0^2 + 2 z_{h_u}^{m_{1/2} A_0}(Q) m_{1/2} A_0$$

Δ

$SU(5): 75$

Focus point (TeV)





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

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

Horton, GGR

GGR, Kaminska, Schmidt-Hoberg

(Also improves precision of gauge coupling unification)

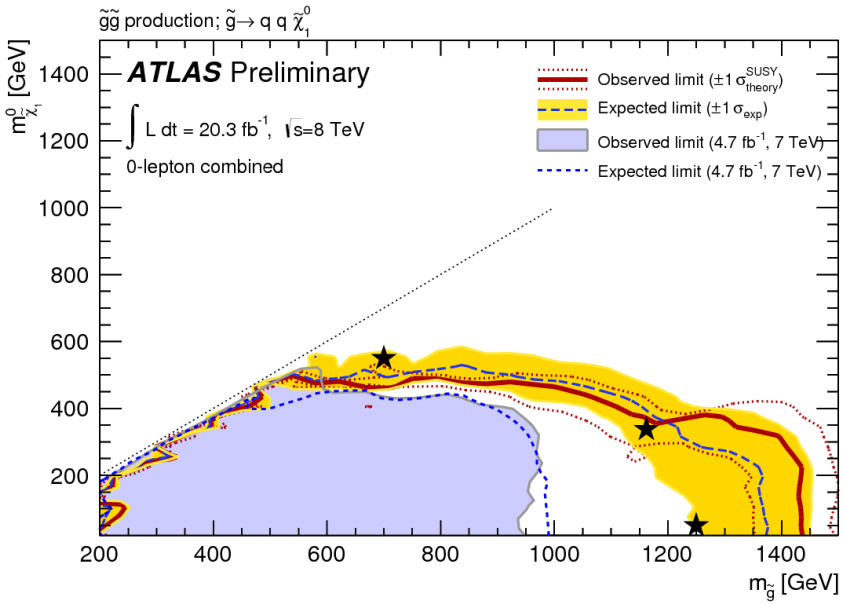
Shifman, Roszkowski

Krippendorf, Nilles, Ratz, Winkler

Fine tuning in the (C)MSSM

Non-universal gaugino masses

LHC 8TeV



$$\Delta^{EW+\Omega}_{Min} = 60\,(500), \quad m_h = 125.6 \pm 3 GeV$$

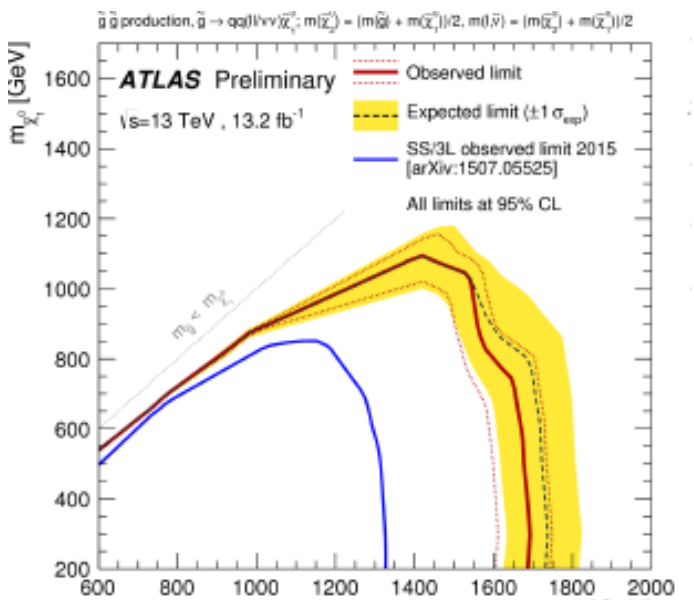
LHC8 SUSY bounds ✔

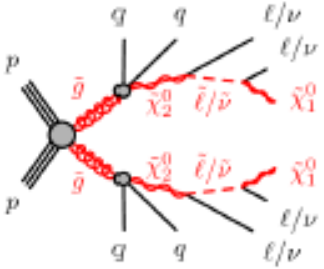
DM relic abundance ✔

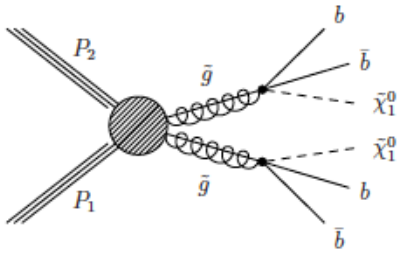
DM searches ✔

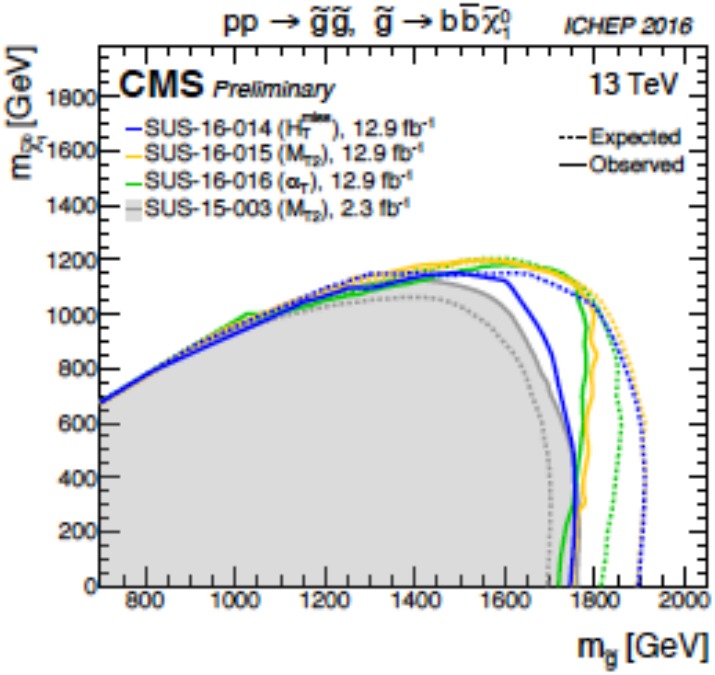
GGR, Kaminska, Schmidt-Hoberg

LHC 13 TeV

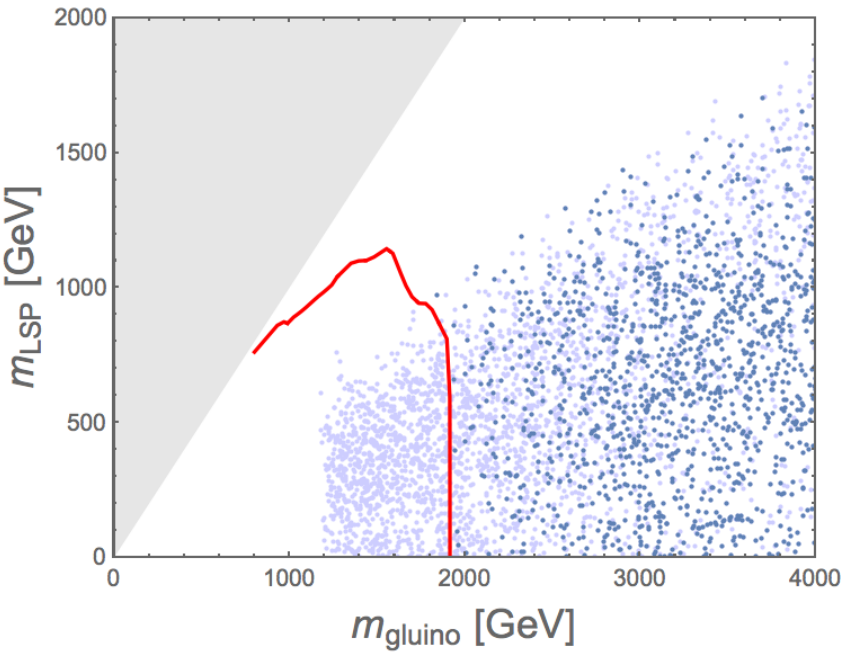




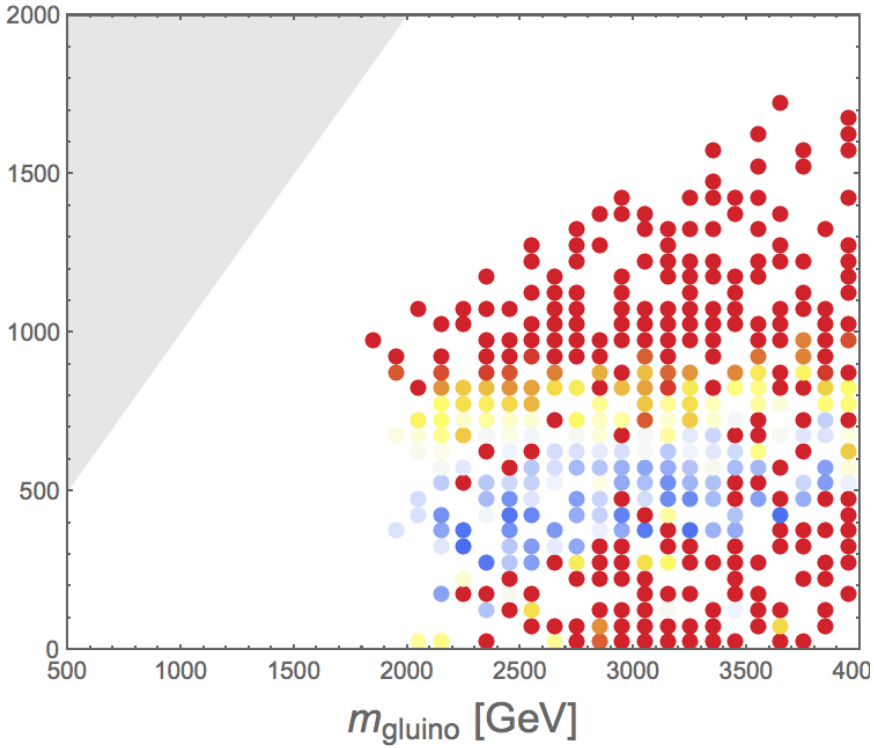


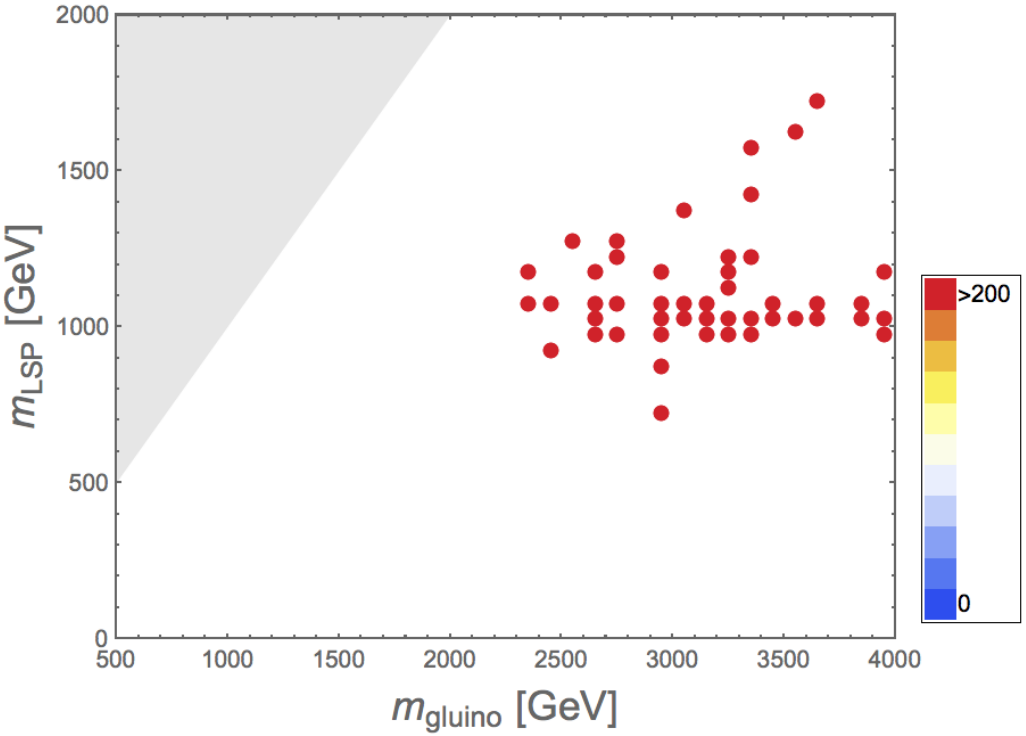


(C)MSSM



(C)MSSM





$$\left(\Omega h^2\right)^{SUSY} \leq \left(\Omega h^2\right)^{Observed}$$

$$\left(\Omega h^2\right)^{SUSY} = \left(\Omega h^2\right)^{Observed}$$

$$\Delta_{Min}^{EW} = 40, \quad m_h = 125.6 \pm 3GeV$$

Soft parameters?

Fine tuning sensitive to correlations between them

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

$$\mu_0 \rightarrow \langle S \rangle$$

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

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

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

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

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

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

$$\delta V = \frac{\mu}{\mu_S}\left(|H_u|^2 + |H_d|^2\right)H_u H_d$$ ✔ $(Z_8^R \Rightarrow \mu, \mu_s$ naturally small$)$

SUSY extensions of the Standard Model

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

R-parity: Z_2 $\mu H_u H_d, \frac{1}{M} QQQL$ ✗ SUSY states odd

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

$Q_W^R = 2$

MSSM spectrum
Commutes with SU(5)
Anomaly cancellation
No perturbative μ term

$$\mu, \mu_S \sim \frac{\langle W \rangle}{M_P^2} = m_{3/2}$$

N=8 No quadratic divergence

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

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

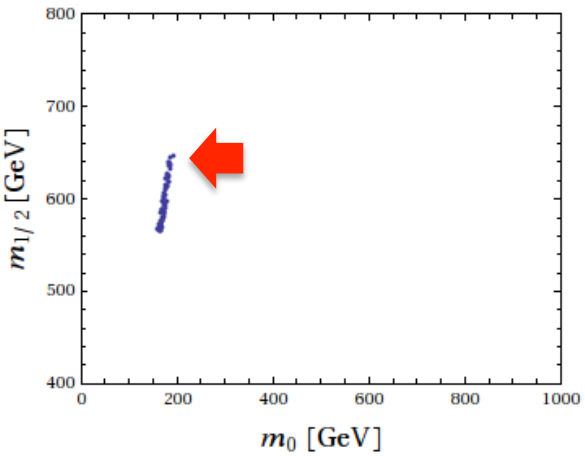
Fine tuning in the CGNMSSM $(\lambda \leq 0.7)$

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

LHC8 SUSY bounds ✗

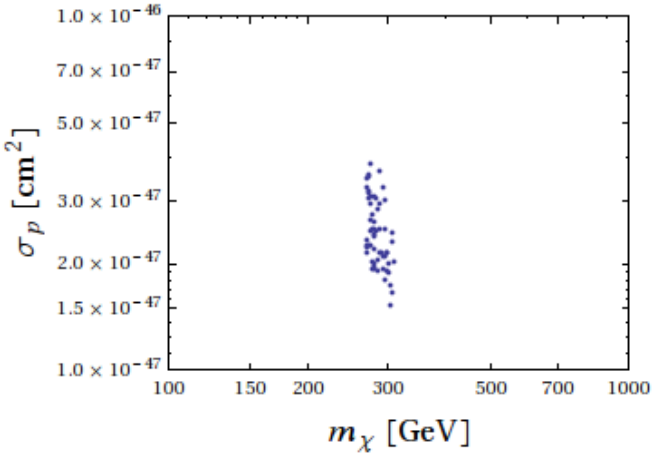
DM relic abundance ✔

DM searches ✔



LSP~Bino

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

16?

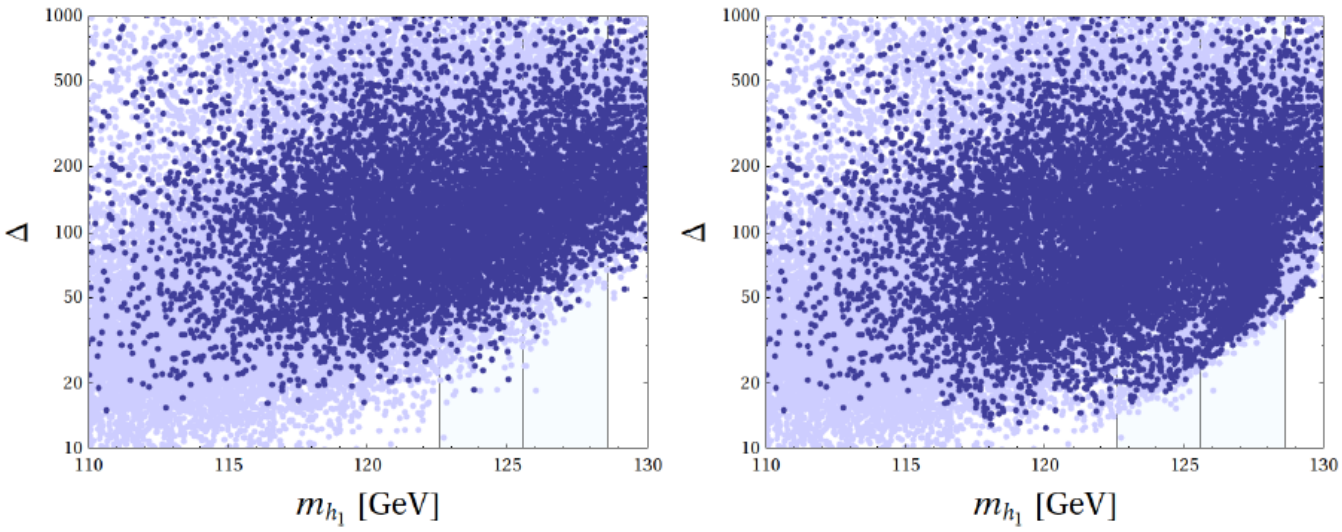
LHC8 SUSY bounds ✔

DM relic abundance ✔

DM searches ✔

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

Δ



(uniform scan)

GGR, Kaminska, Schmidt-Hoberg

Soft parameters?

Fine tuning sensitive to correlations between them

$$\gamma_i = \tilde{\mu}_0, m_0, m_{1/2}, A_0, B_0$$

Soft Higgsino mass

$$m_H = 0, m_{\tilde{H}} = \mu_0 \quad \left(c.f. \quad \mu_0 H_u H_d \,|_{\theta\theta} - \mu_0^2 \left(\left| H_u \right|^2 + \left| H_d \right|^2 \right) \right)$$

Hard parameter – tadpole divergences

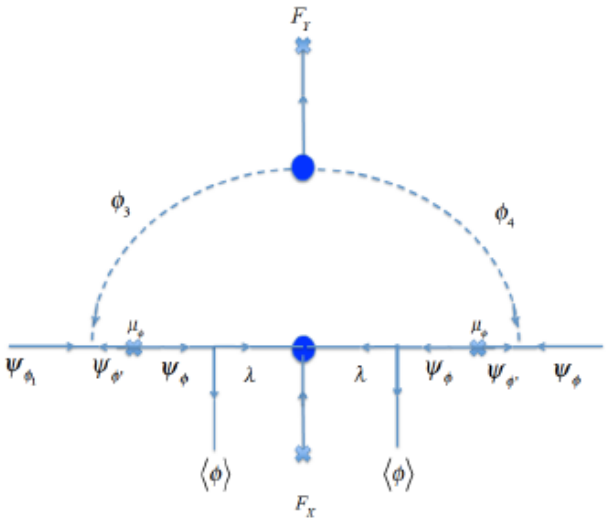
(Absent in MSSM)

Higgsino mass origin

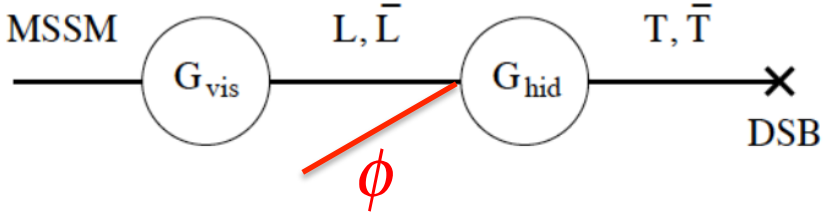
- Gaugino mediation

$$\int d^4\theta X X^\dagger \overline{D}_\alpha \left(\Phi_1^\dagger e^V\right) \overline{D}^\alpha e^{-V} \Phi_2^\dagger$$

$$m_{\psi_{\phi_1}\psi_{\phi_2}} \propto \frac{\mu_\phi^2 \langle \phi \rangle^2 F_Y F_X}{M^7}$$



ϕ link field coupled to hidden sector and visible sector via Higgs portal



- Sequestering

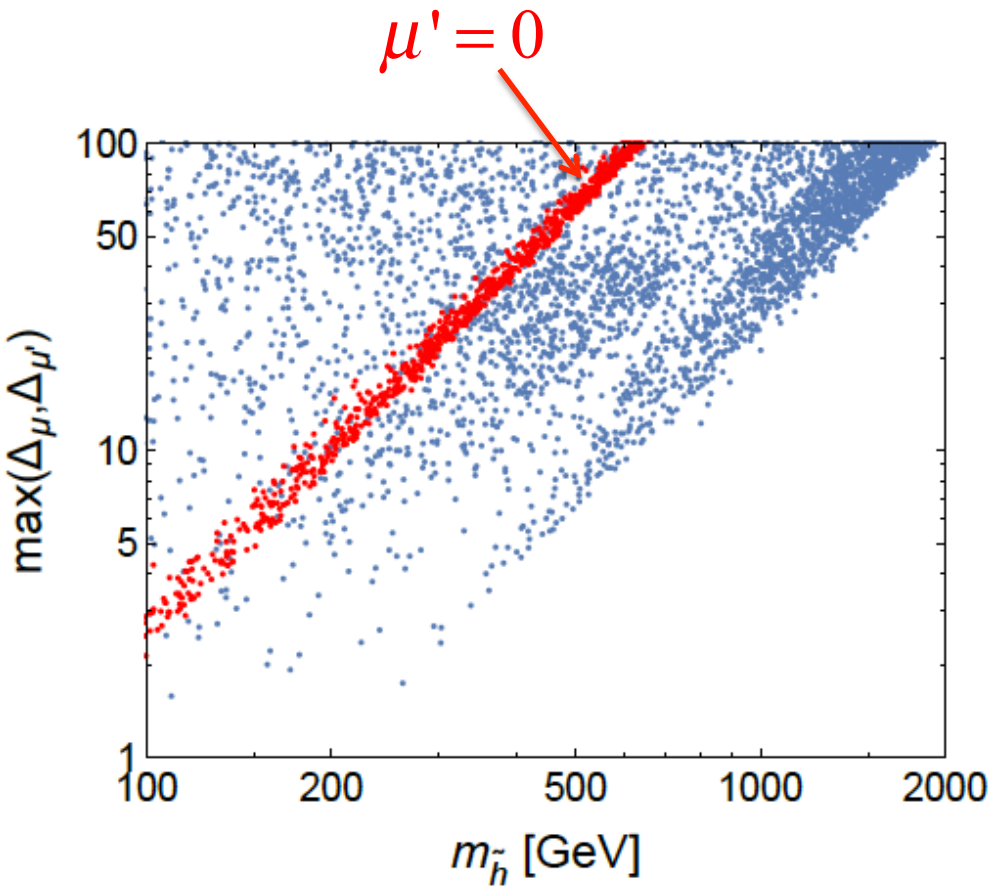
Hidden sector running drives Higgs mass to zero leaving Higgsino mass unchanged

Perez, Roy, Schmaltz

- New SUSY breaking soft terms

$$m_0, m_{1/2}, A_0, \tan\beta, \mu, B\mu, \mu'$$

$$\mathcal{L}_{NH} = T'_{u,ij} H_d^* \tilde{u}^*_{R,i} \tilde{q}_j + T'_{d,ij} H_u^* \tilde{d}^*_{R,i} \tilde{q}_j + T'_{e,ij} H_u^* \tilde{e}^*_{R,i} \tilde{l}_j + \mu' \tilde{H}_d \tilde{H}_u + \text{h.c.}$$

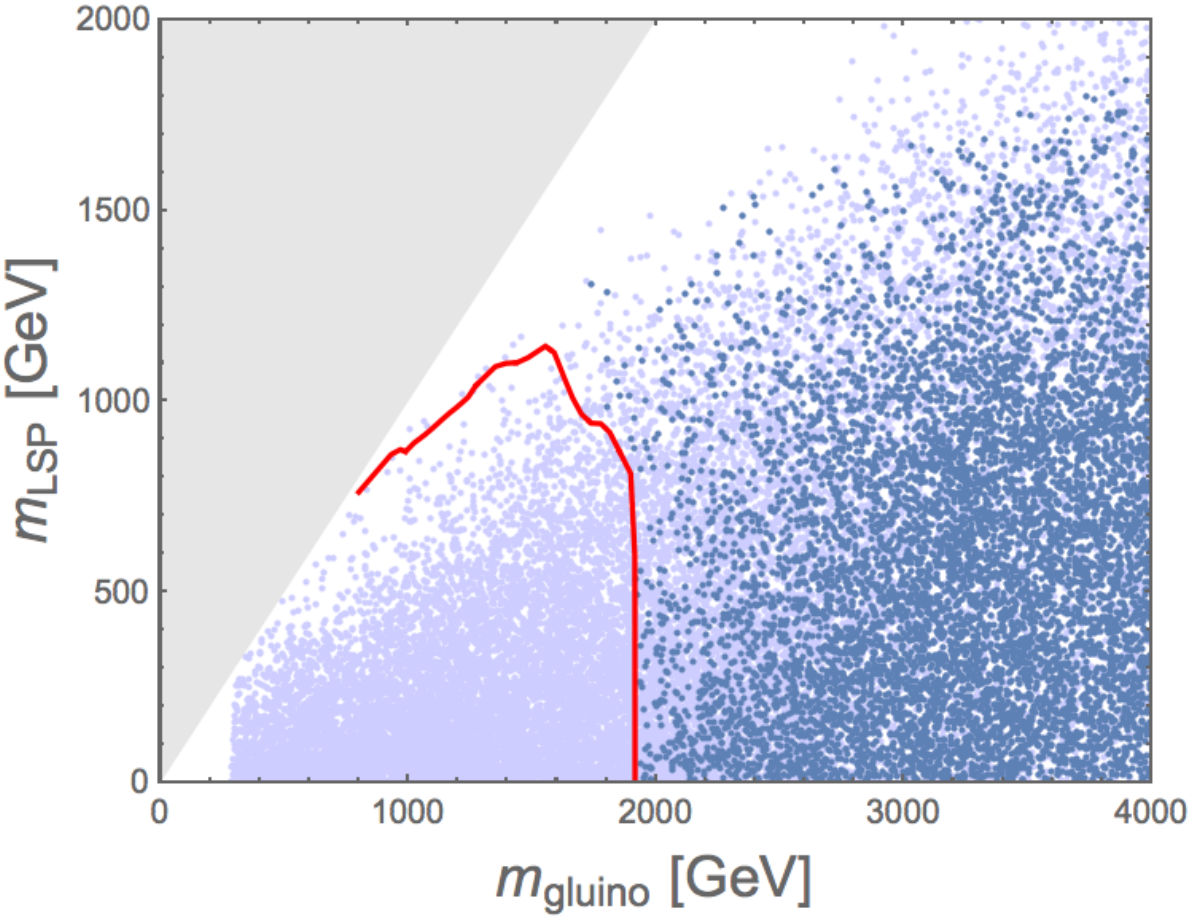


LHC 13 TeV

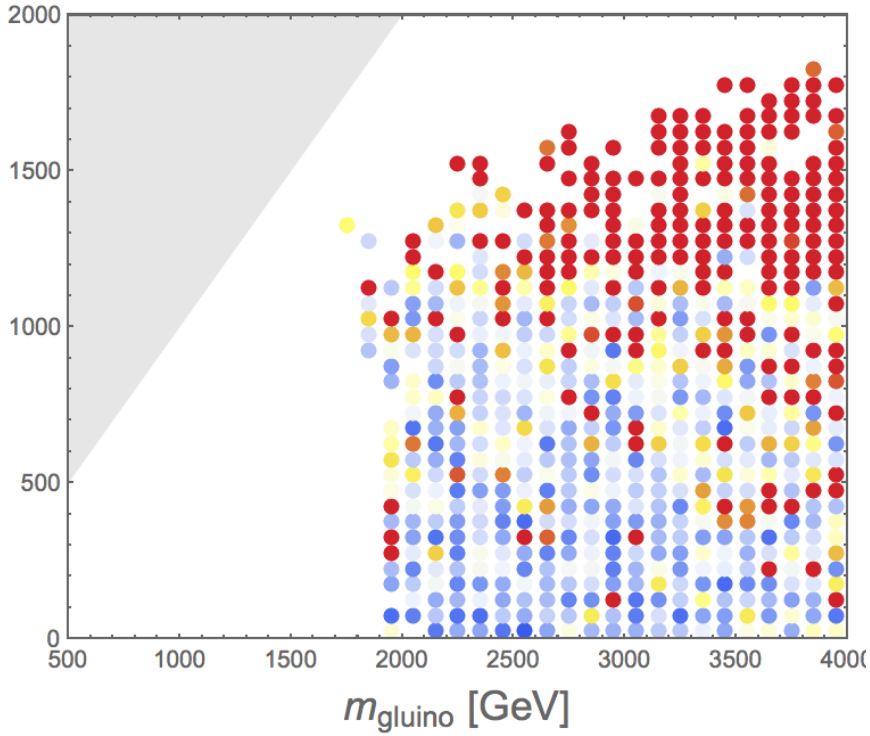
$\Delta_{CMSSM} \geq 350$

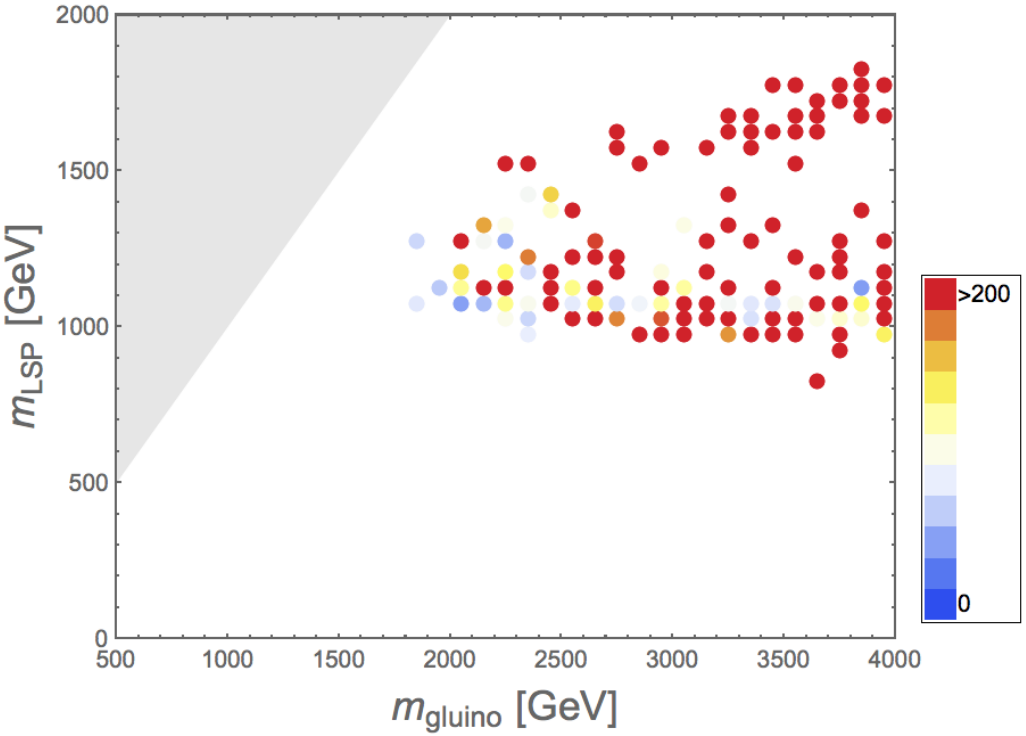
$\Delta_{CMSSM+\mu'} \geq 20$

(C)MSSM $+\mu'$


2000
1500
1000
500
0
m_{LSP} [GeV]
0
1000
2000
3000
4000
m_{gluino} [GeV]

(C)MSSM $+\mu'$

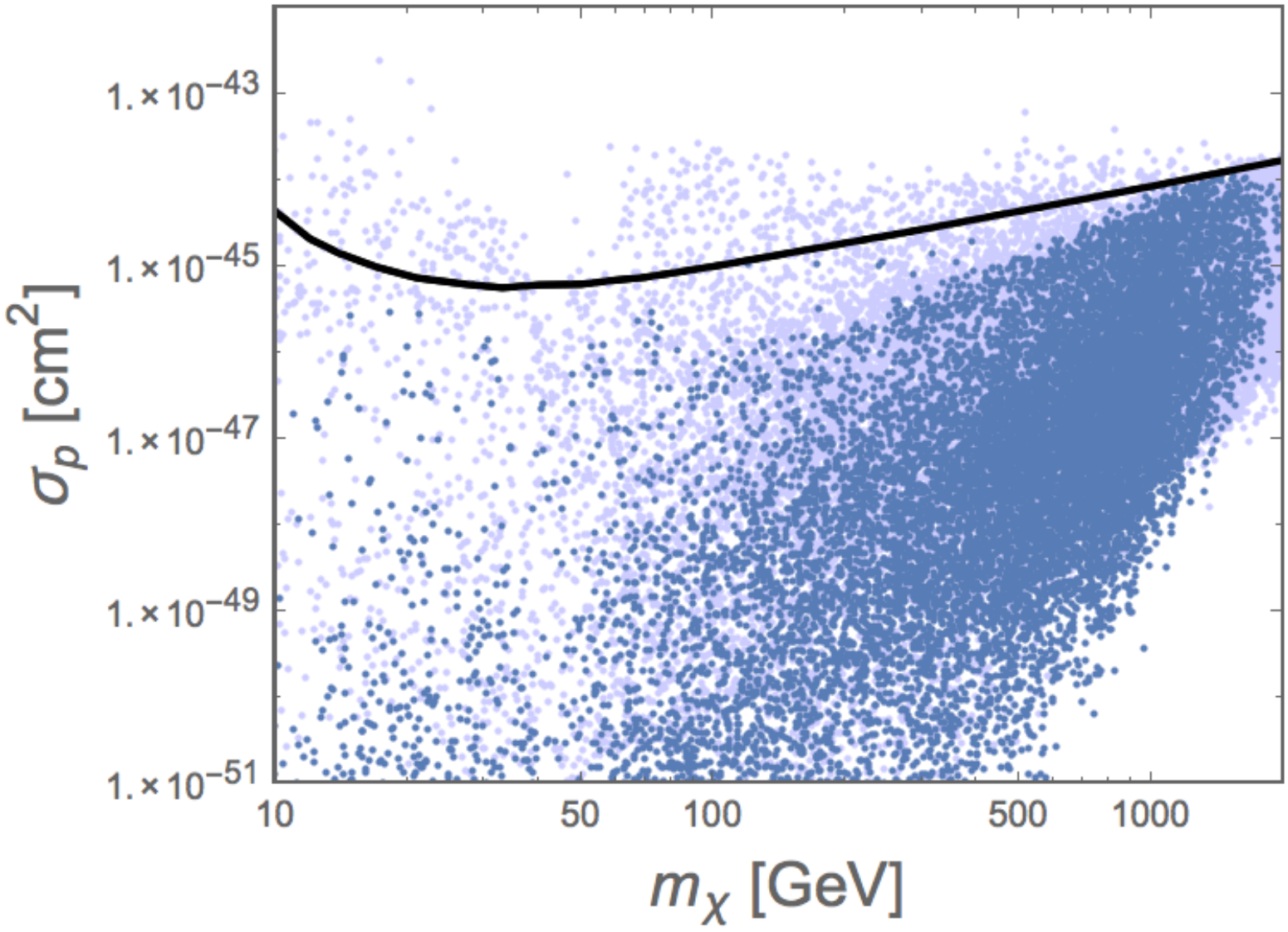




$$\left(\Omega h^2\right)^{SUSY} \leq \left(\Omega h^2\right)^{Observed}$$

$$\left(\Omega h^2\right)^{SUSY} = \left(\Omega h^2\right)^{Observed}$$

$$\Delta_{Min}^{EW\,(+\Omega)} = 20\ (40), \quad m_h = 125.6 \pm 3GeV$$



Direct detection DM cross section compared to LUX bound

SUMMARY

- GUTs $\Longrightarrow$ SUSY-GUTS (hierarchy problem)
- Fine tuning sensitive to SUSY spectrum

  ...scalar and gaugino focus points, Higgsino mass
- $\Delta^{CMSSM} > 350$ ✗ $\Delta^{(C)MSSM} > 40\,(200)^{SUSY\ DM}$

  $\Delta^{CGMSSM} > 60$ ✗ $\Delta^{(C)GNMMS} > 20$ ✔8TEV 13TEV?

  $\Delta^{(C)MSSM+\mu'} > 20\ (40)^{SUSY\,DM}$

low energy

Is Λ SUSY alive ?

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- $\Delta^{CMSSM} > 350$ ✗ $\Delta^{(C)MSSM} > 40\,(200)^{SUSY\ DM}$

  $\Delta^{CGMSSM} > 60$ ✗ $\Delta^{(C)GNMMS} > 20$ ✔8TEV?13TEV

  $\Delta^{(C)MSSM+\mu'} > 20\,(50)^{SUSY DM}$
- Yes (just) - Well motivated SUSY models remain to be tested