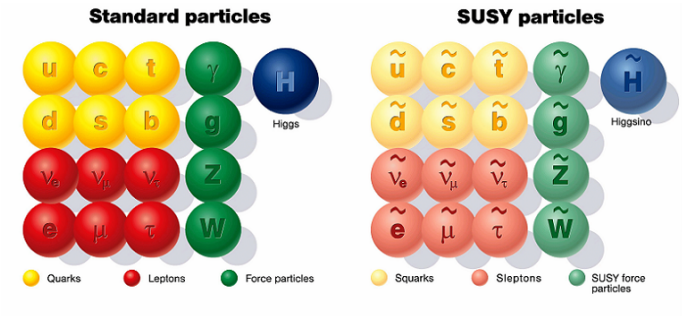
SUSY after Higgs

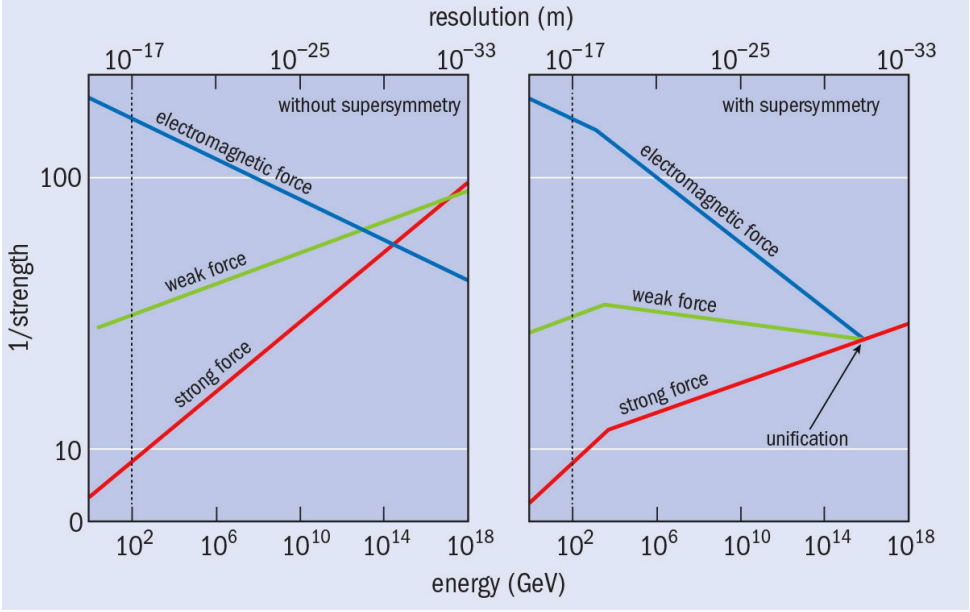
G.G.Ross, Bonn, May 2017

(Kai Schmidt-Hoberg, Florian Staub)

SUSY



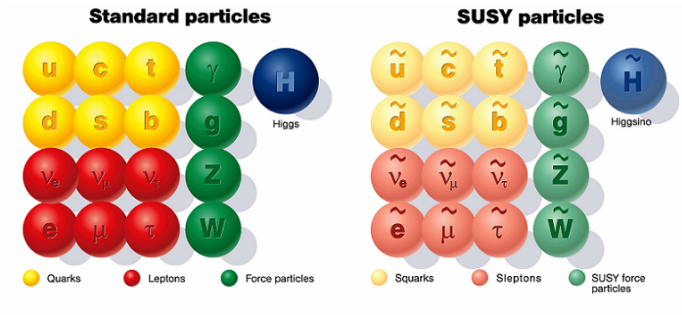
MSSM

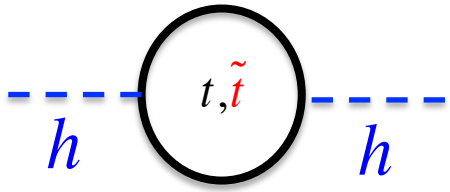


GUTs

Georgi, Quinn, Weinberg
Ibanez, GGR
Dimopoulos, Raby, Wilczek

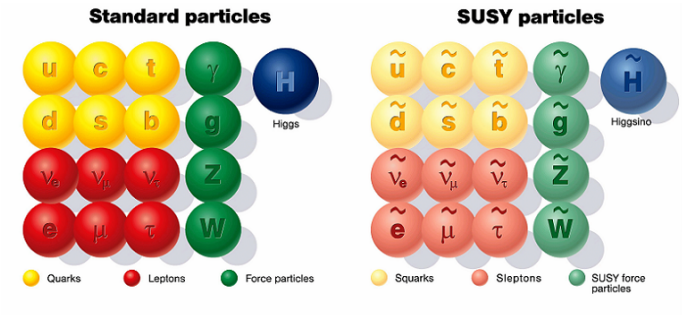
The Higgs mass and SUSY

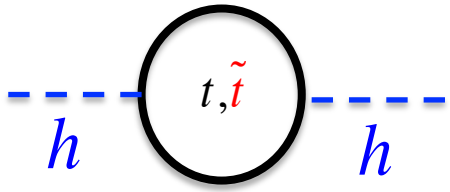




$$m_h^2 = M_Z^2 + \frac{3m_t^2 h_t^2}{4\pi^2}\left(\ln\left(m_{stop}^2 / m_t^2\right) + \delta_t\right) + \ldots < \sim 140\,GeV$$ ✔

The Higgs mass and SUSY





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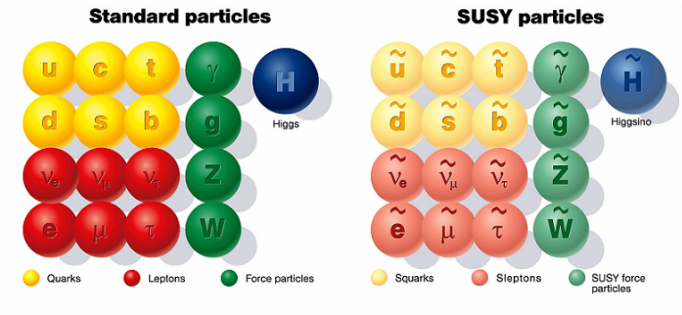
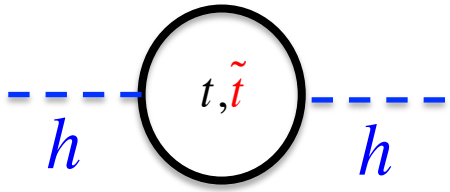
Tension:

$$\Lambda \sim M_{GUT}\,?$$

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

The Higgs mass and SUSY





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… the "Hierarchy problem" – has SUSY been fully tested ?

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:

$$\Delta(a_i) = \left|\frac{\partial \ln M_Z^2}{\partial \ln \gamma_i}\right|, \qquad \gamma_i = m_{i,}\, M_i \ldots$$

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

Ellis, Enquist, Nanopoulos, Zwirner

Barbieri, Giudice

Fine tuning from a likelihood fit:

SUSY parameters

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 measure $\Delta_q = \left(\sum \Delta_{\gamma_i}^2\right)^{1/2}$

Ghilencea, GGR

Probabilistic interpretation:

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

$$\Delta_q < 100, \quad \delta\left(\frac{\chi^2}{d.f.}\right) < 1$$

(should be averaged over #df)

Simplest case – the "Constrained" MSSM (CMSSM)

Soft SUSY breaking parameters:

$$\gamma_i(M_{GUT}) = \mu_0, m_0, m_{1/2}, A_0, B_0$$

- Parameters input at GUT scale (gauge coupling unification)
- SARAH/Spheno+FlavorKit Staub

  (2-loop: RGE & Higgs mass)

Higgsino mass term μ_0

Radiative corrections can reduce sensitivity:

$$\gamma_i(M_{GUT}) = \mu_0, m_0, m_{1/2}, A_0, B_0$$

$$\tfrac{1}{2} M_Z^2 = -\mu^2 - m_{H_u}^2 \rightarrow -\mu^2 - m_{H_u}^2 - \frac{\partial \Delta V}{\partial v^2}$$

$$\Delta_{FT}^{\mu} = -\frac{2\mu^2}{M_Z^2}\bigg|_{Tree} \rightarrow \geq \frac{\mu^2}{M_Z^2}\bigg|_{\text{Radiative corrections}}$$

GGR, Schmidt-Hoberg, Staub
Cassell, Ghilencea, GGR

Scalar mass term m_0

Fine tuning also sensitive to *correlations* between SUSY breaking terms

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

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

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

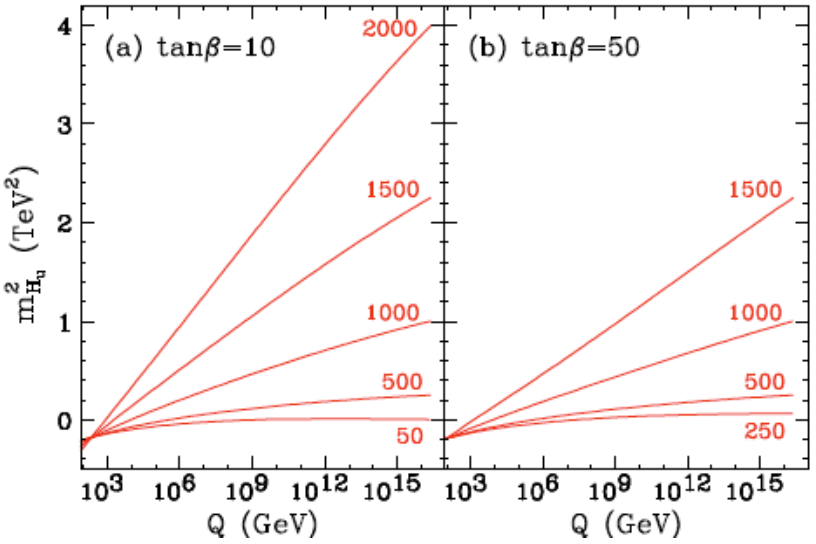
Focus Point

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

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

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

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



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

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

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

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

Natural choice

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

Feng, Sanford

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

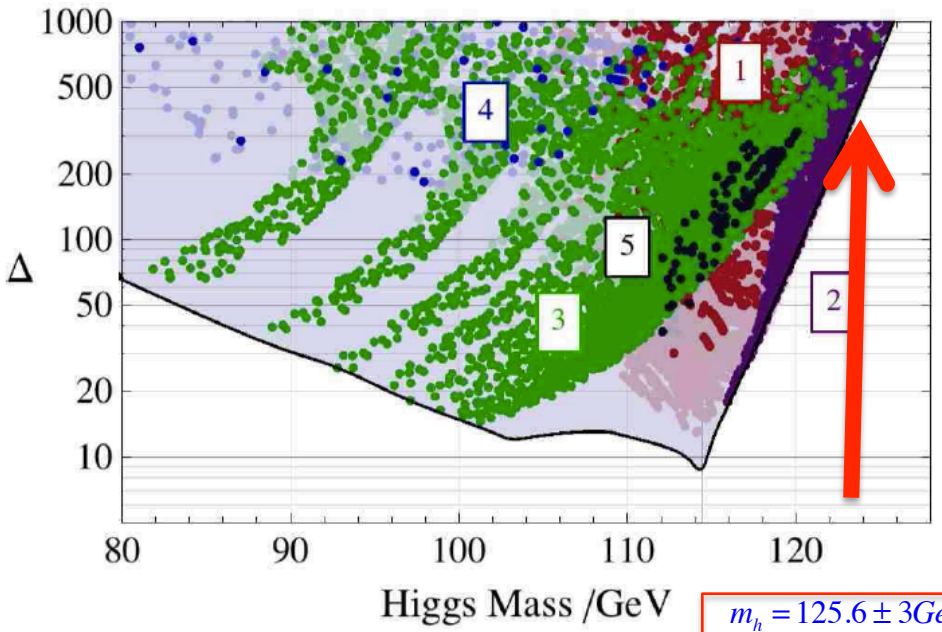
(sensitivity to y_t small)

Ciafaloni, Strumia

The CMSSM – after Higgs discovery

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

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



$m_h = 125.6 \pm 3 GeV$
e.g.1609.00371

Relic density restricted $\begin{cases} 1,3,4,5 : \tilde{B} \\ 2 : \tilde{H} / \tilde{B} \end{cases}$

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

Model	*LHC & Higgs*	*weak DM*	*strong DM*
CMSSM	134	216	276

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

Cassel, Ghilencea, GGR

GGR, Schmidt-Hoberg , Staub

Soft parameters?

Fine tuning sensitive to correlations between them

further

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

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

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

Correlation between SUSY breaking parameters

…non-universal gaugino masses

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

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

Abe, Kobayashi, Omura
Horton, GGR

(Also improves precision of gauge coupling unification)

Shifman, Roszkowski
Krippendorf, Nilles, Ratz, Winkler

Reduced fine tuning (the MSSM-NUGM)

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

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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}	$M_3 : M_2 : M_1$ 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

Younkin, Martin

STRING:

$\left(3+\delta_{GS}\right):\left(-1+\delta_{GS}\right):\left(-\frac{33}{5}+\delta_{GS}\right)$ δ_{GS} quantised (OII orbifold)

Brignole, Ibanez, Munoz

$M_a = m_{3/2}\left(\varrho + b_a g_a^2\right)$ ρ quantised (mixed moduli+anomaly..

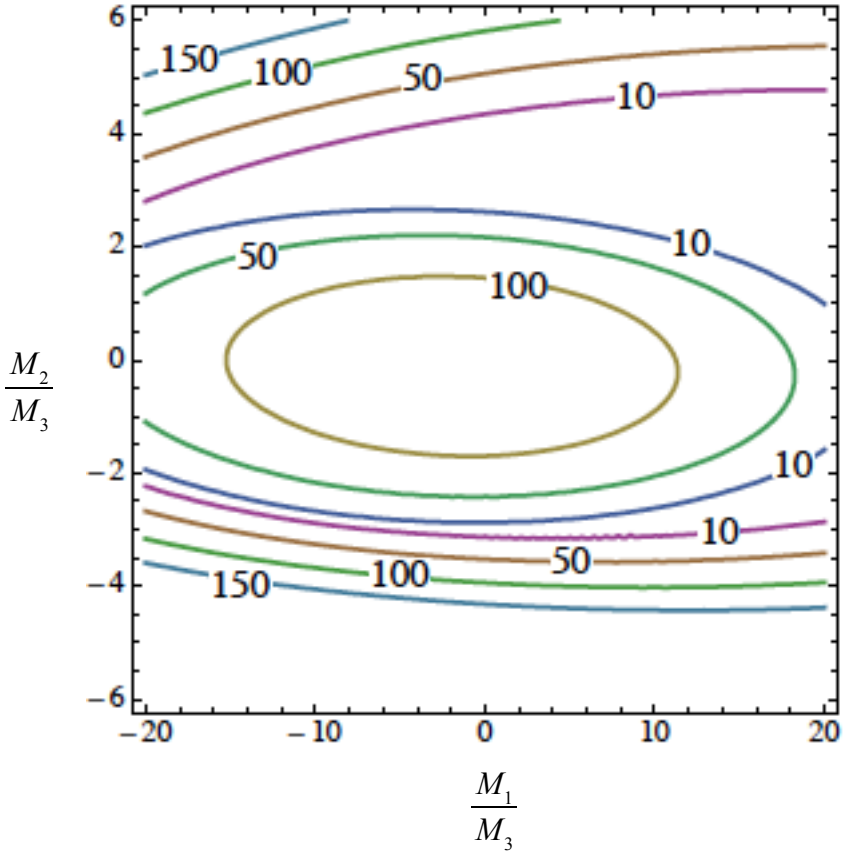
Choi, Nilles
Badziek, Krippendorf, Nilles, Winkler
Choi, Jeong, Okumura
• • •

..mirage, orbifold mini landscape, KKLT in IIB, hidden sector superptentials)

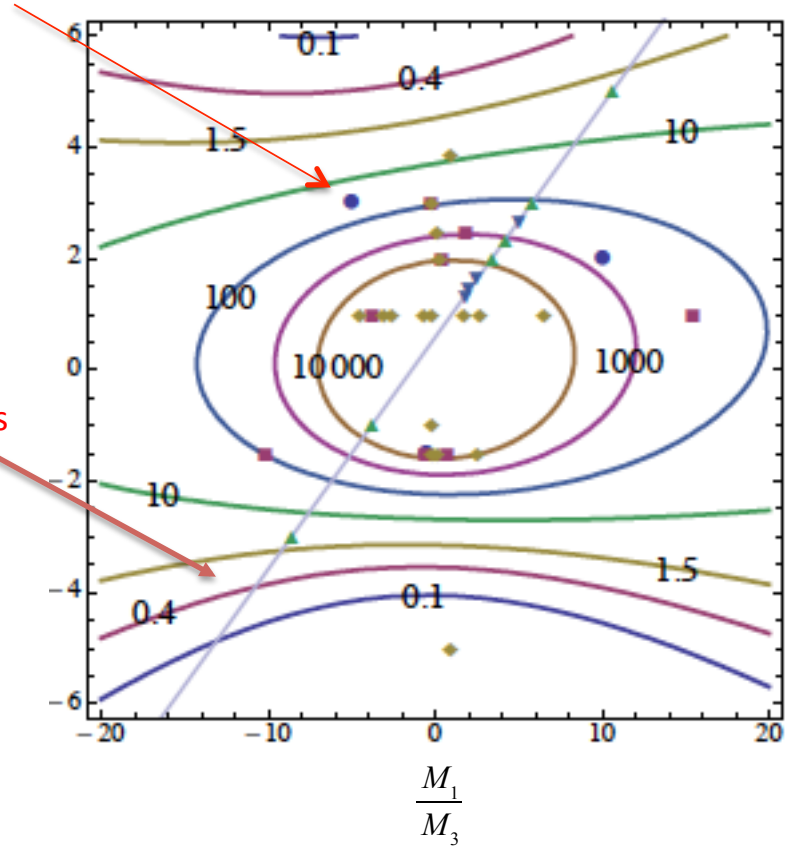
Δ

$SU(5):75$

Focus point (TeV)



String models



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

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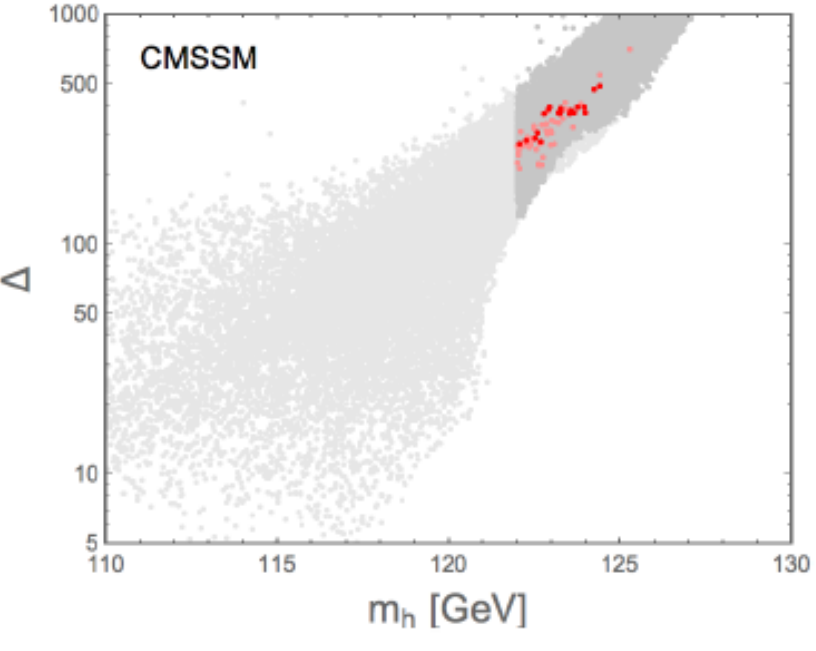
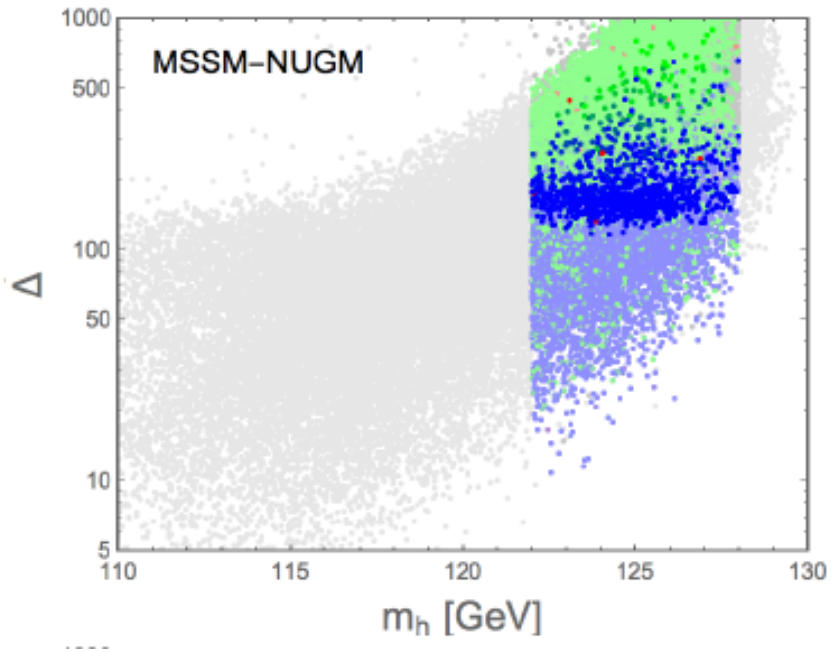
Fine tuning –effect of gaugino focus point

LHC 13 TeV

$\delta m_h = \pm 3GeV \rightarrow \pm 1GeV$ at high scales .... $\Delta m_h = -2GeV$





- $\widetilde{B}$
- $\widetilde{H}$
- $\widetilde{W}$

CMSSM

MSSM-NUGM

Model	*LHC & Higgs*	*weak DM*	*strong DM*
CMSSM	136	216	276
MSSM – NUGM	11	11	117

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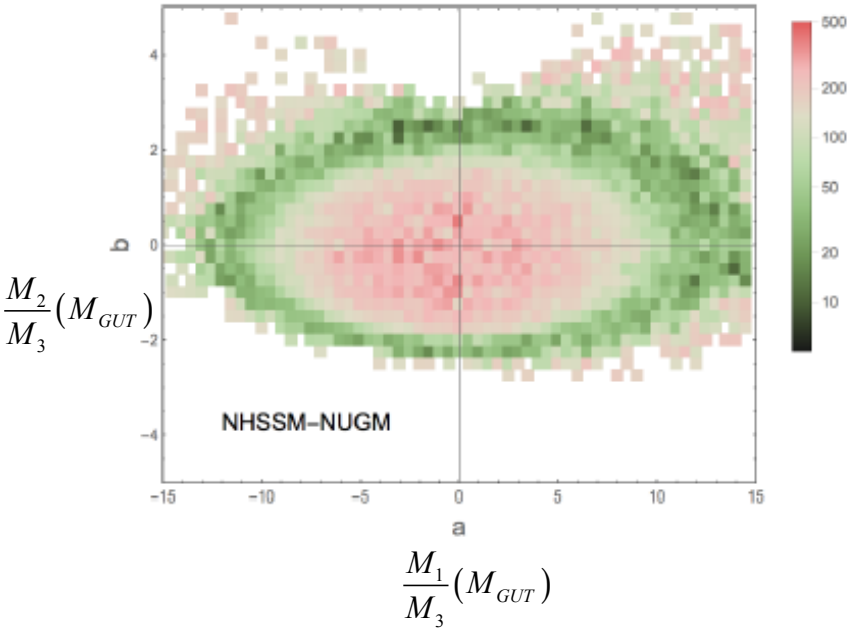
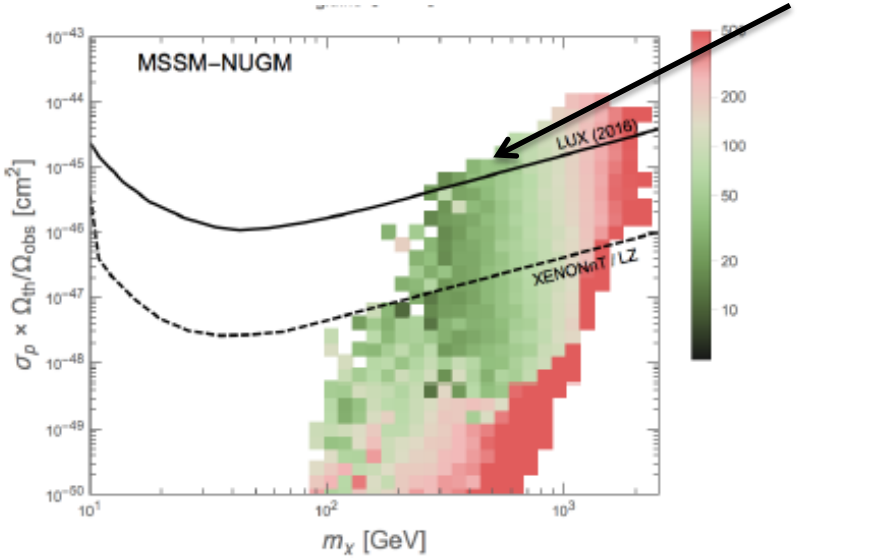


DM detection

LUX



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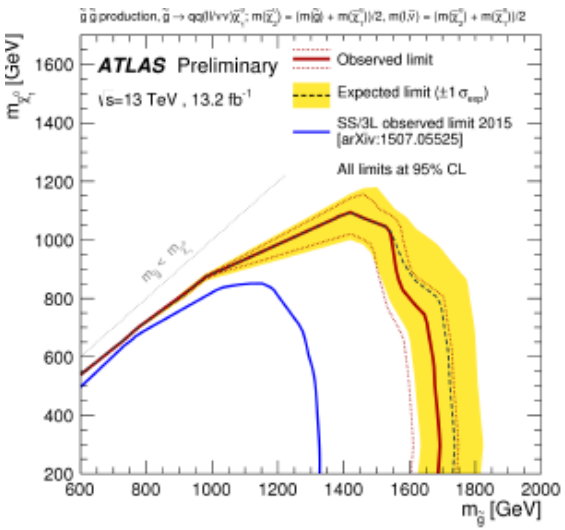
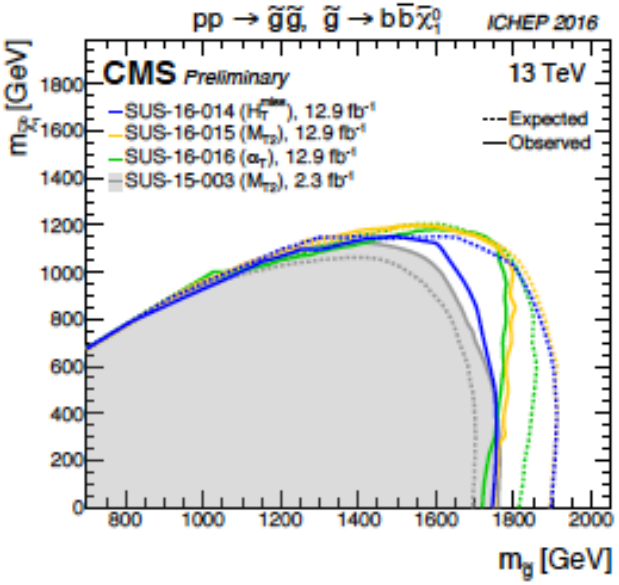
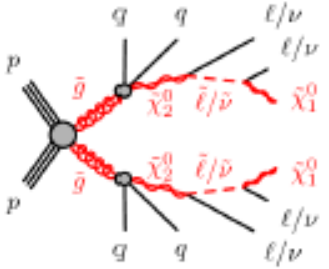
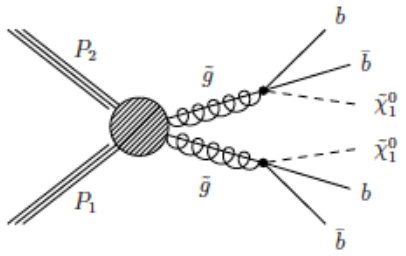
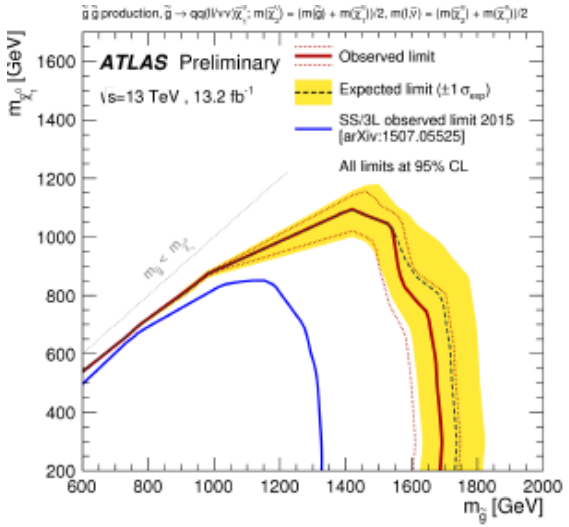

ATLAS Preliminary
√s=13 TeV , 13.2 fb-1
Observed limit
Expected limit (±1 σexp)
SS/3L observed limit 2015
[arXiv:1507.05525]
All limits at 95% CL
m(χ̃10) [GeV]
m(g̃) [GeV]

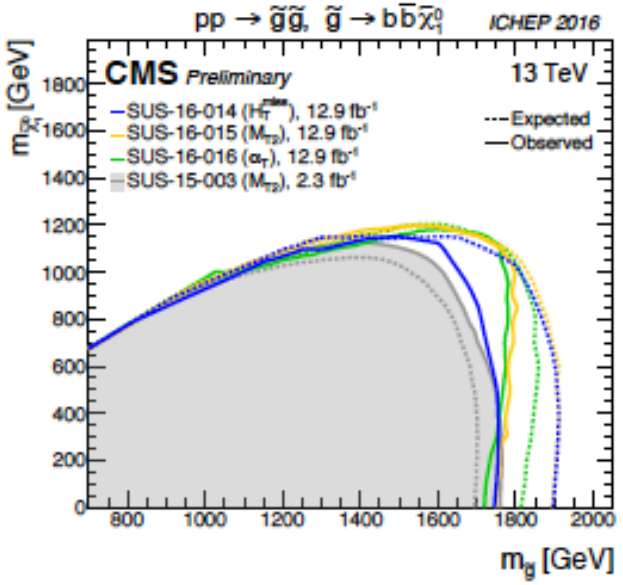

pp → g̃g̃, g̃ → bb̄χ̃10
ICHEP 2016
CMS Preliminary
13 TeV
SUS-16-014 (HTmiss), 12.9 fb-1
SUS-16-015 (MT2), 12.9 fb-1
SUS-16-016 (αT), 12.9 fb-1
SUS-15-003 (MT2), 2.3 fb-1
Expected
Observed
m(χ̃10) [GeV]
m(g̃) [GeV]

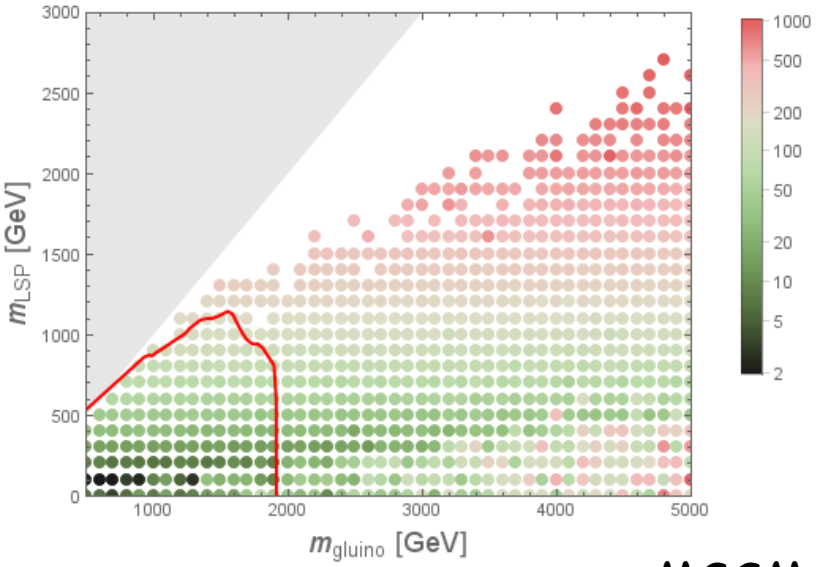

p
p
g̃
g̃
χ̃20
χ̃20
ℓ̃/ν̃
ℓ̃/ν̃
χ̃10
χ̃10
q
q
q
q
ℓ/ν
ℓ/ν
ℓ/ν
ℓ/ν

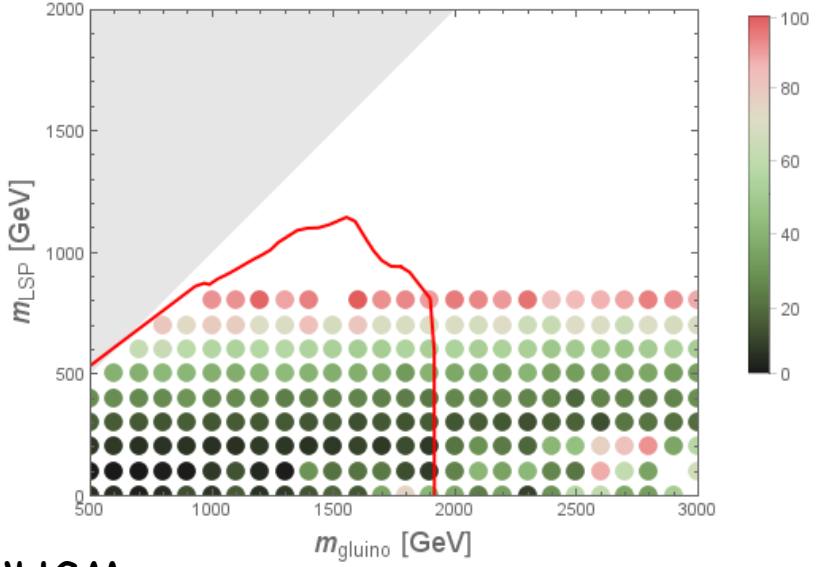

P2
P1
g̃
g̃
b
b̄
b
b̄
χ̃10
χ̃10

LHC 13 TeV





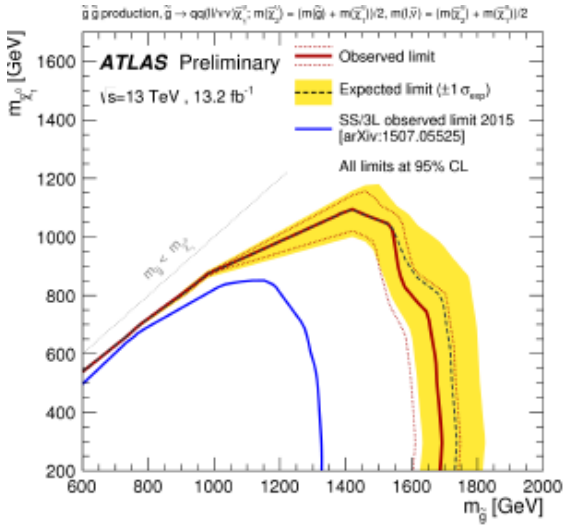


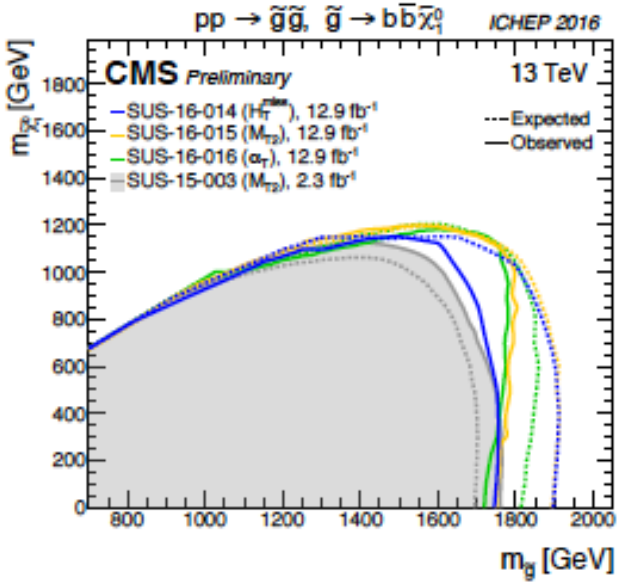


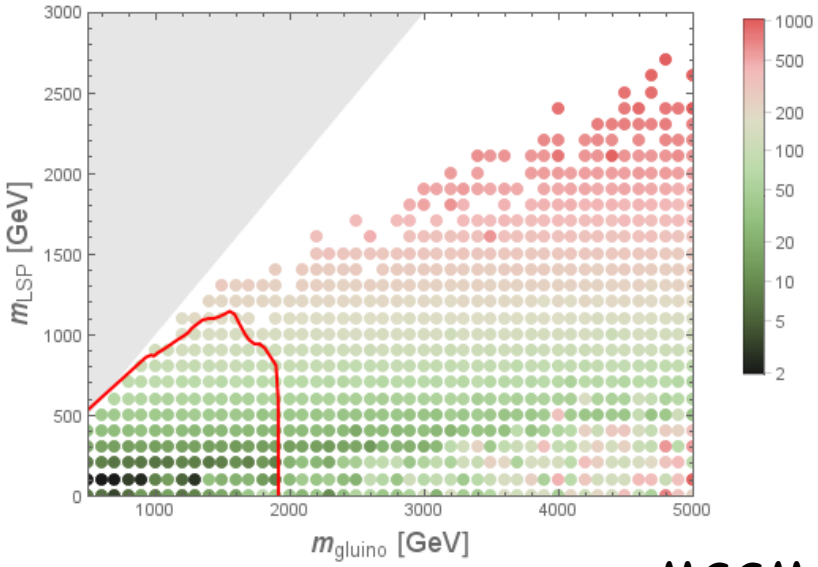
MSSM-NUGM

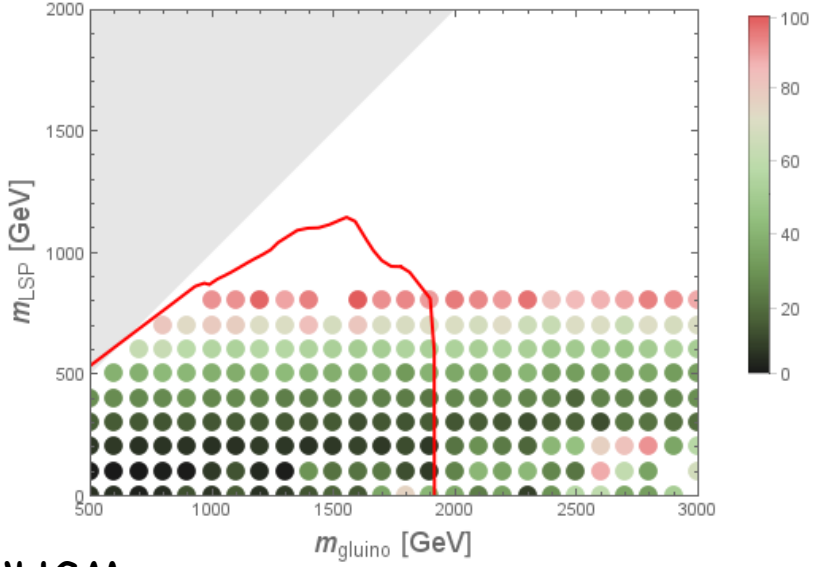
GGR, Schmidt-Hoberg , Staub

LHC 13 TeV







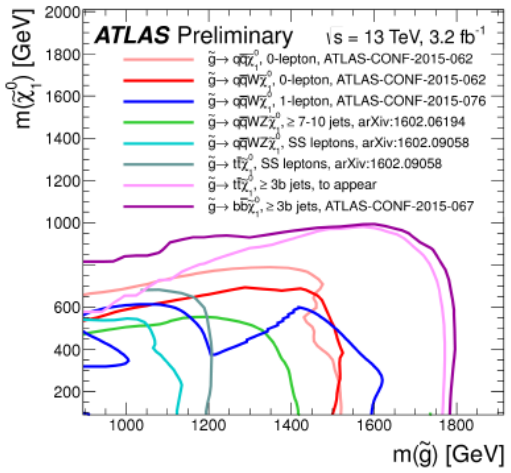


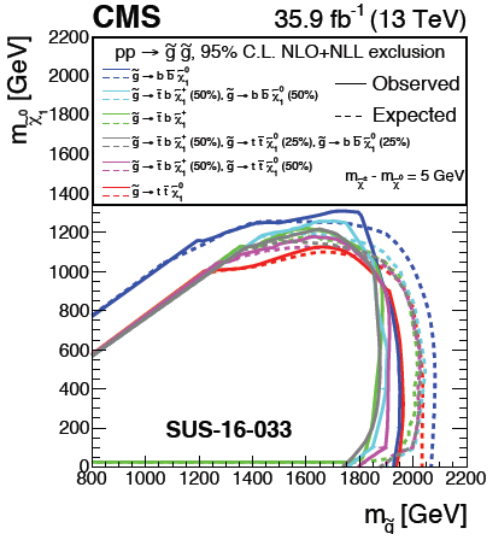
MSSM-NUGM

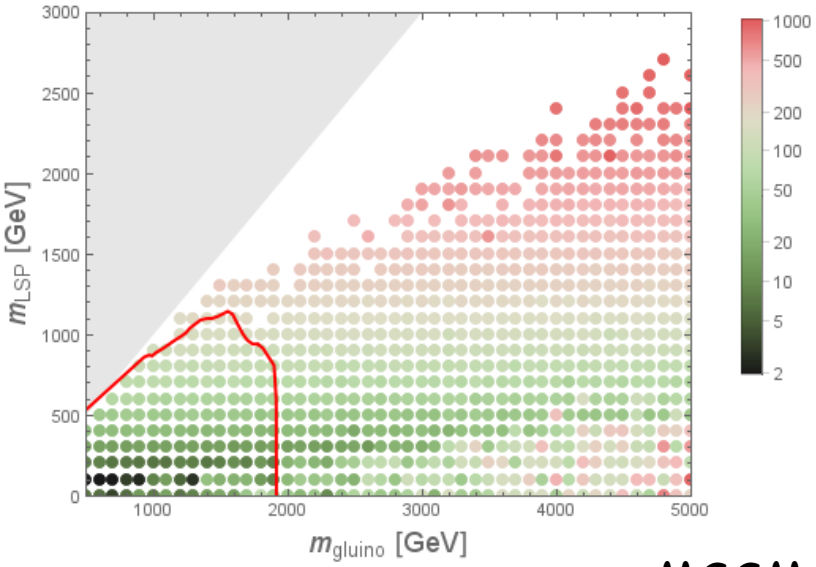
(Two-scale matching summing $\ln(M_{SUSY}/M_Z, M_h)$ can reduce Δ by further factor 2 and $\delta m_h = -2GeV$)

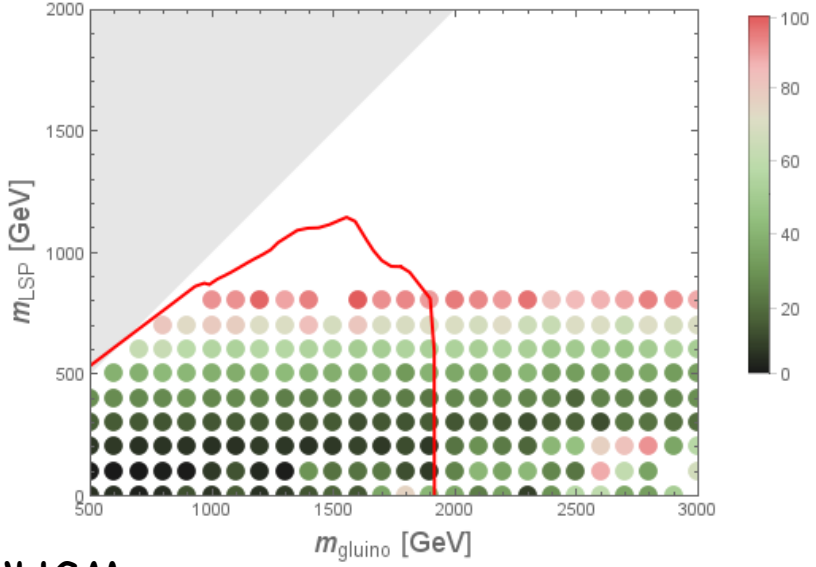
Porod, Staub

LHC 13 TeV









MSSM-NUGM

Soft parameters?

(No divergences introduced)

Fine tuning sensitive to correlations between them

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

Soft Higgsino mass?

$$m_H = 0, m_{\tilde{H}} = \mu'$$

Hard parameter – tadpole divergences

(Absent in MSSM)

Higgsino mass origin

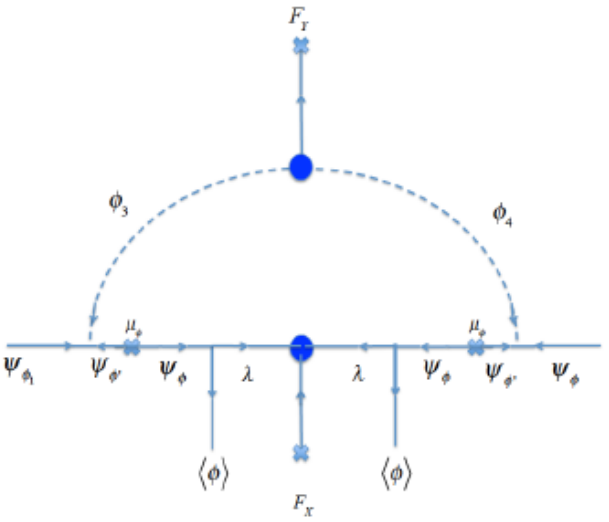
(c.f. Scherk-Schwarz …low compactification scale)

Garcia-Garcia, Howe, March Russell
Delgado, Garcia-Pepin, Quirosl
Dimopoulos, Howe, March-Russell

- Gaugino mediation

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

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



Martin;
GGR, Schmidt-Hoberg , Staub

- Sequestering

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

Perez, Roy, Schmaltz

$$\Rightarrow \mu_0 H_u H_d\,|_{\theta\theta} - \mu_0^2\left(|H_u|^2 + |H_d|^2\right)$$

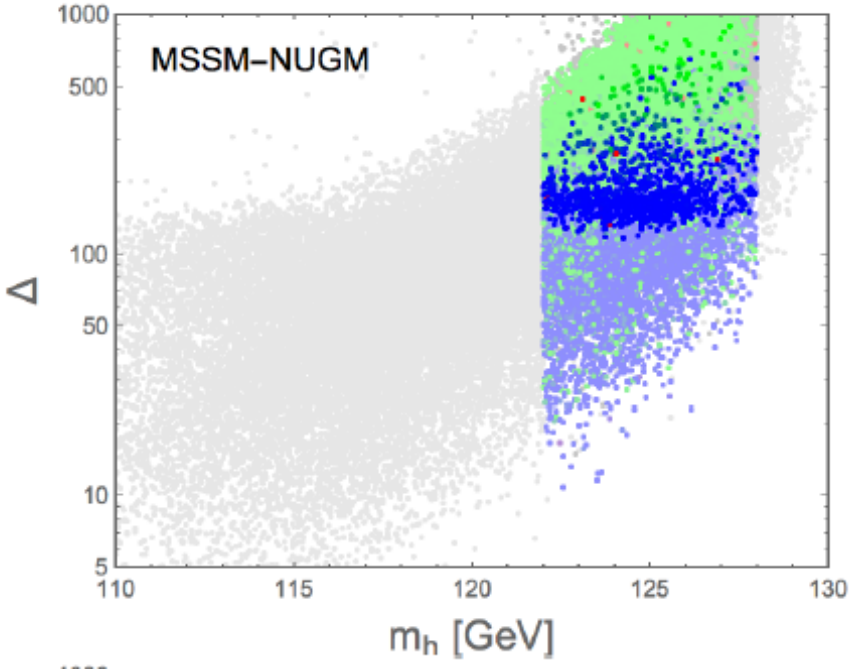
"Soft" even with singlets

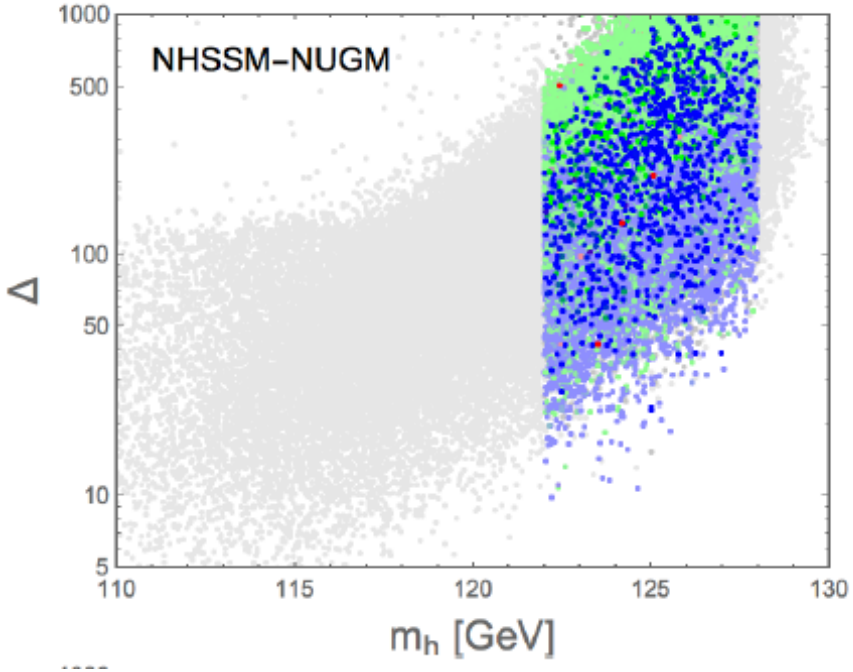
- New SUSY breaking soft terms

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

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

$+\mu'$





- $\widetilde{B}$
- $\widetilde{H}$
- $\widetilde{W}$

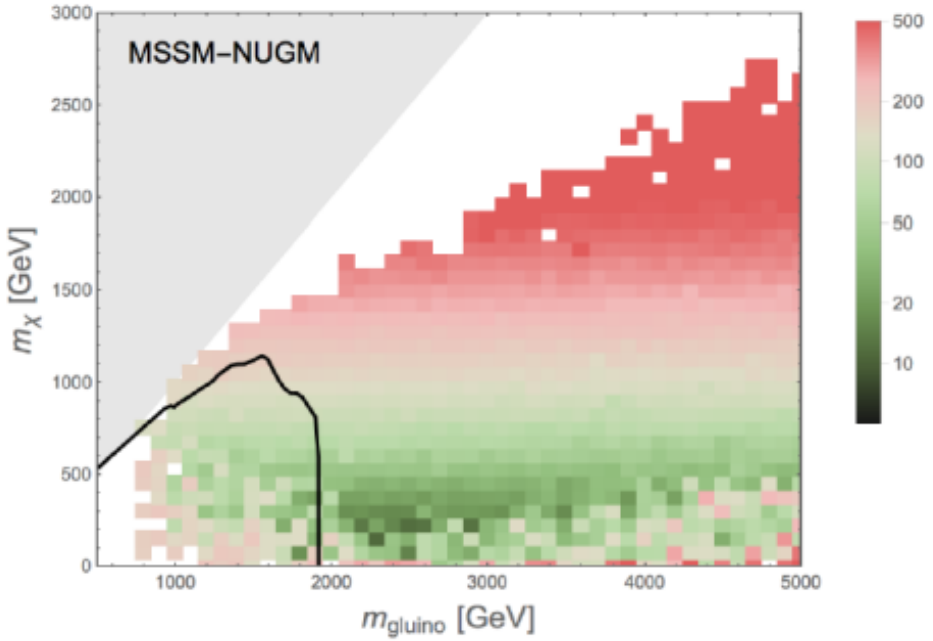
MSSM-NUGM

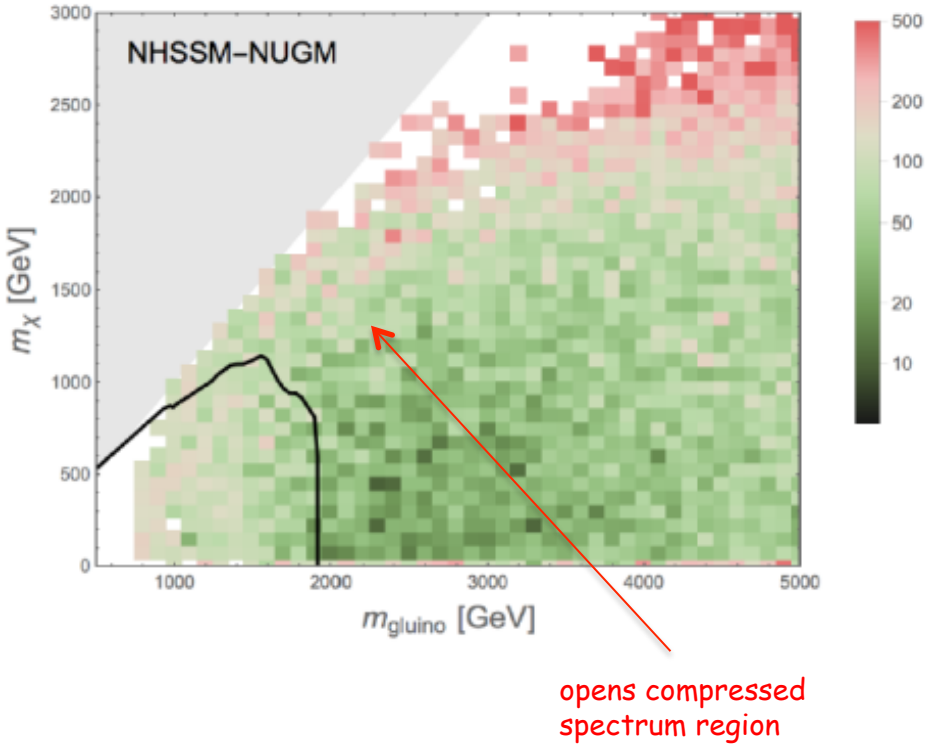
NHMSSM-NUGM

SUSY DM

MSSM-NUGM

$+\mu'$

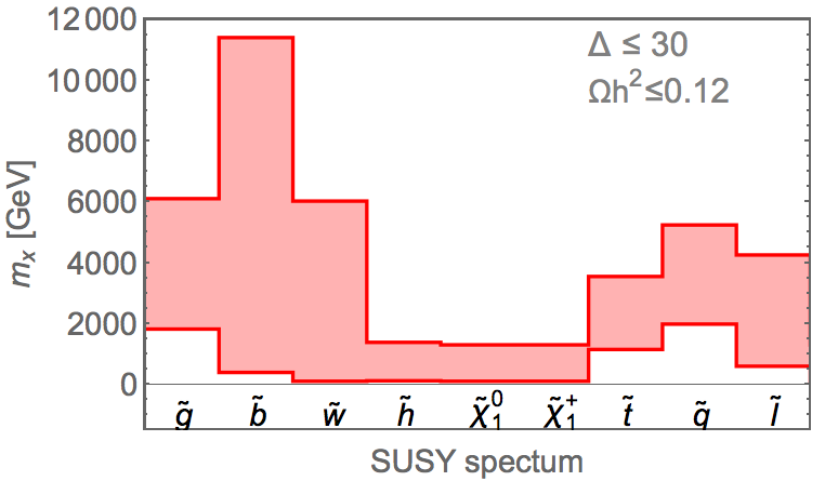


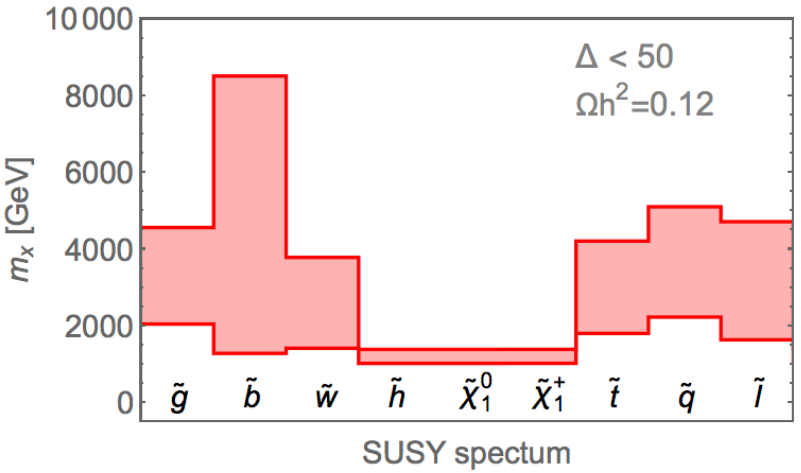


Model	*LHC & Higgs*	*weak DM*	*strong DM*
MSSM – NUGM	11	11	117
NHSSM – NUGM	10	10	23

GGR, Schmidt-Hoberg , Staub

Spectrum





$m_{\tilde{H}} \sim 1TeV$

Model	*LHC & Higgs*	*weak DM*	*strong DM*
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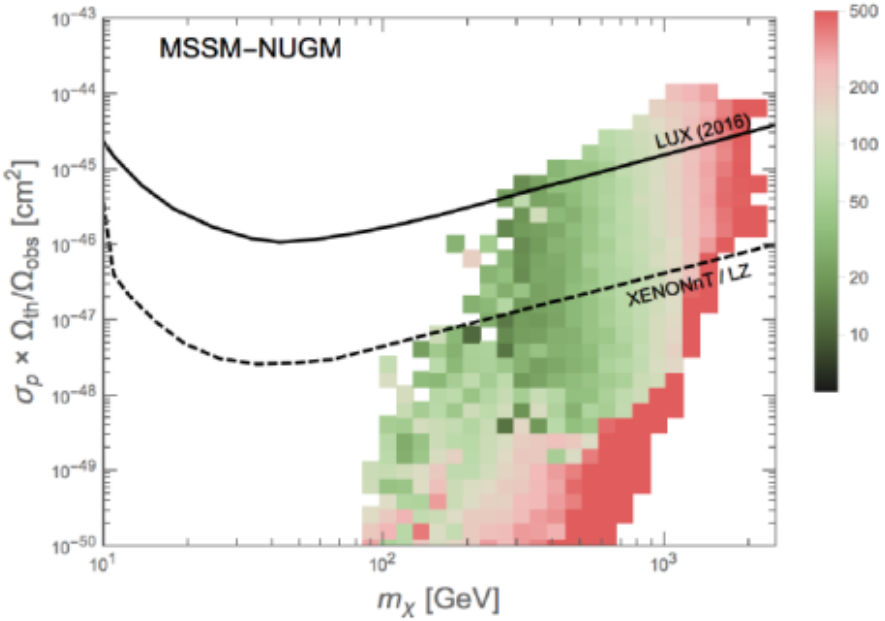
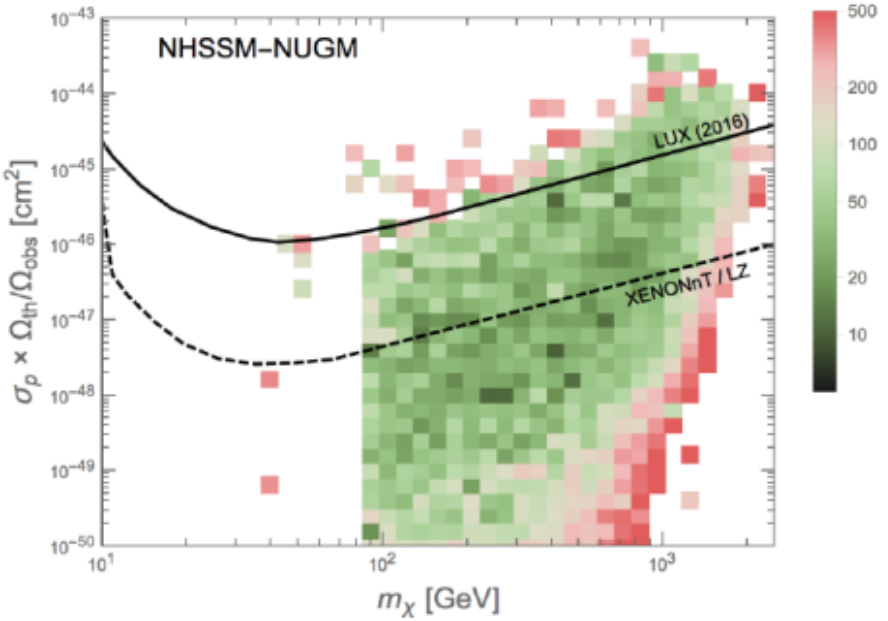
Dark Matter


MSSM–NUGM
LUX (2016)
XENONnT / LZ
$\sigma_p \times \Omega_{th}/\Omega_{obs}$ [cm^2]
m_χ [GeV]
500
200
100
50
20
10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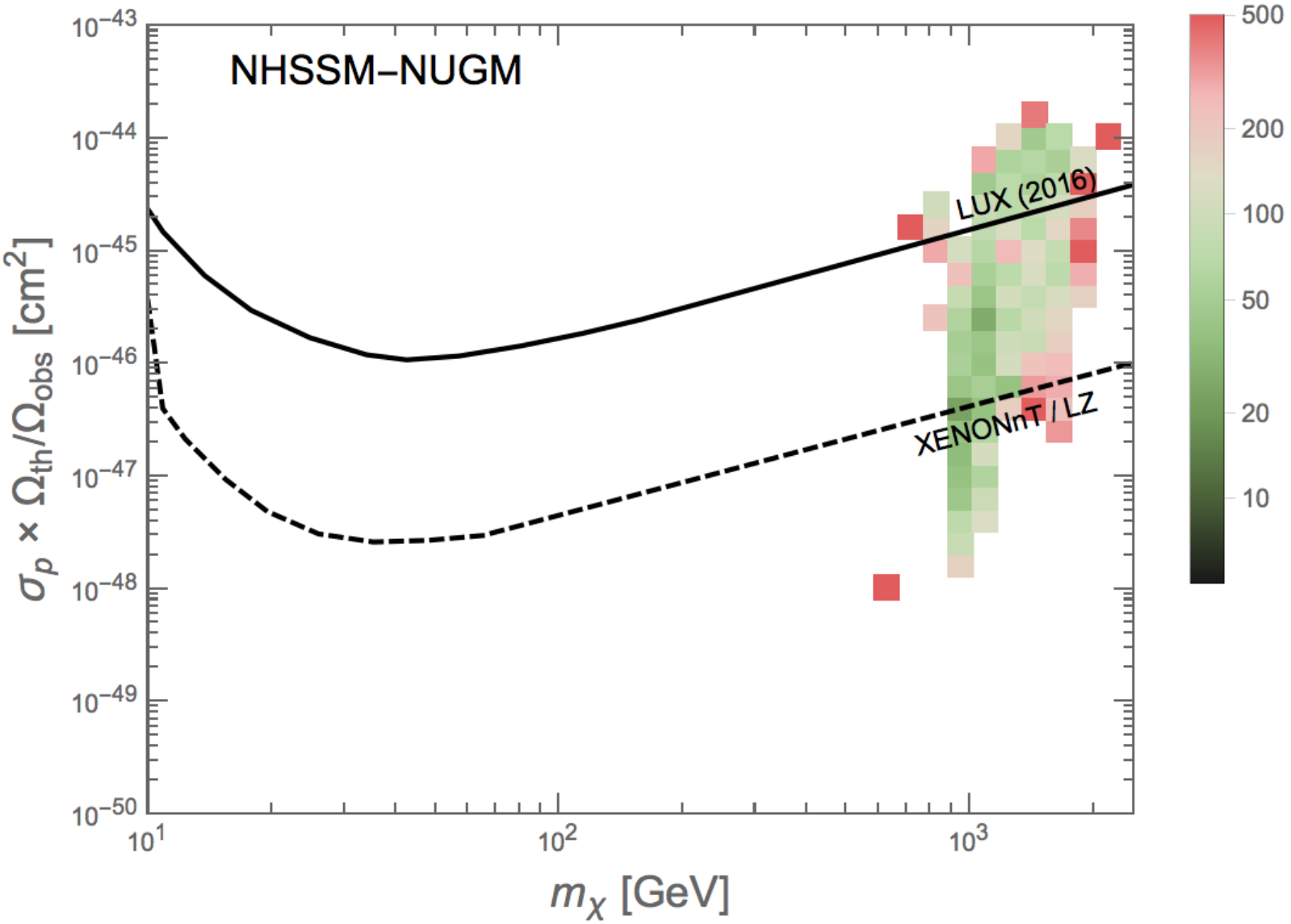
Thermal SUSY DM



SUMMARY

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

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- Fine tuning sensitive to SUSY spectrum

  …scalar and gaugino focus points, Higgsino mass

Model	*LHC & Higgs*	*soft DM*	*strong DM*
CMSSM	134	216	276
MSSM – NUGM	11	11	117
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... and non-minimal spectrum

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GNMSSM – NUGM	~10	~10	~30

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

Kaminska, GGR, Schmidt-Hoberg

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low energy

- Is SUSY alive ?

Yes (just) - Well motivated SUSY models remain to be tested

SUMMARY

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- Fine tuning sensitive to SUSY spectrum

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low energy

- Is SUSY alive ?

Can LHC fully test it?

Prospects:

CMSSM							
	current			prospects			
Cut	LHC & Higgs	soft DM	strong DM	$m_{\tilde{g}} \geq 3$ TeV	DD	$m_{\tilde{g}} \geq 5$ TeV	DD
$\Delta_{\min}$	134	216	276	231	271	686	-

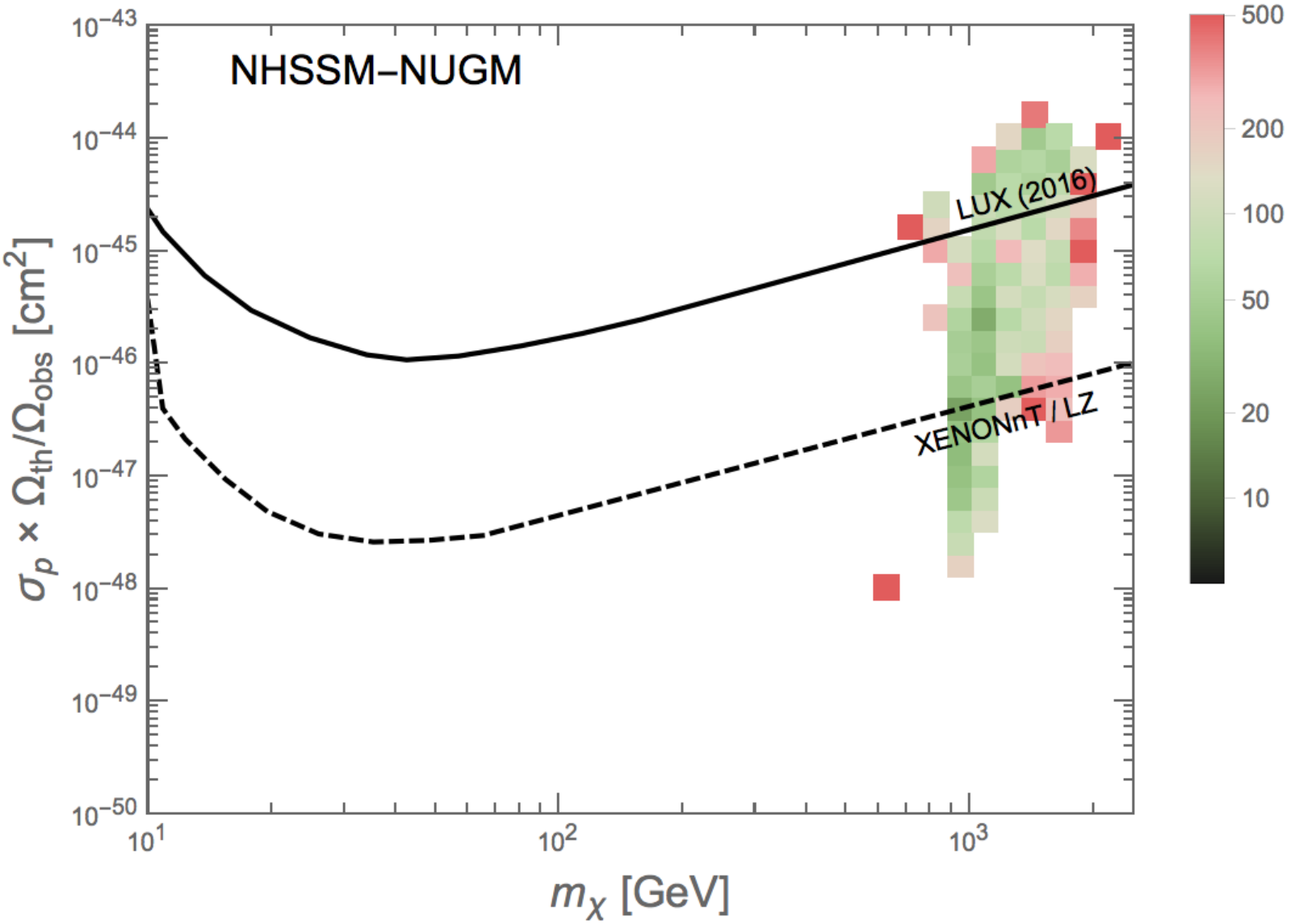
CNHSSM							
	current			prospects			
Cut	LHC & Higgs	soft DM	strong DM	$m_{\tilde{g}} \geq 3$TeV	DD	$m_{\tilde{g}} \geq 5$ TeV	DD
$\Delta_{\min}$	114	116	166	227	264	665	677

MSSM-NUGM							
	current			prospects			
Cut	LHC & Higgs	soft DM	strong DM	$m_{\tilde{g}} \geq 3$ TeV	DD	$m_{\tilde{g}} \geq 5$ TeV	DD
$\Delta_{\min}$	11	11	117	17	17	29	29

NHSSM-NUGM							
	current			prospects			
Cut	LHC & Higgs	soft DM	strong DM	$m_{\tilde{g}} \geq 3$ TeV	DD	$m_{\tilde{g}} \geq 5$ TeV	DD
$\Delta_{\min}$	10	10	23	11	11	23	23

(DD: Direct detection DM)

Thermal SUSY DM

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