Naturalness and likelihood in SUSY models and their implications.

D. Ghilencea

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- Outline

I. The old story: scales hierarchy and naturalness

II. Naturalness versus likelihood in SUSY models

(or how to choose between models: unnatural but... v.likely and natural but less likely!)

III. Numerical results for naturalness in SUSY Models

IV. Naturalness beyond MSSM: NMSSM, GNMSSM, ...

I. The old story: scales hierarchy and naturalness

L. Susskind PRD 20 (1979), 2619

• why SM EW scale $v \sim M_Z \ll M_P$, stable under quantum corrections. $\left[\frac{G_f h^2}{G_N c^2} = 1.7 \times 10^{33} \right]$

$\delta v^2 \sim \delta m_h^2 \sim f(\alpha_j)\,\Lambda^2$, if $\Lambda \sim M_P$: tune coupling: $1:10^{33}\,(!)$.

Hierarchy Problem ⇔ Fine tuning. Unnatural. Ways out?

A physical parameter $\rho(\mu)$ is naturally v.small if $\rho(\mu) = 0$ increases the symmetry.

"Naturalness dogma": 't Hooft (1979)

- 3 options:

$a)$. Scale/conformal symmetry. Or: see for example Bardeen 1995

$b)$. SUSY: $\delta m_h^2 \sim m_S^2 \ln \Lambda / m_S$, $m_S \sim$TeV... no SUSY seen, $m_S \gg \mathrm{TeV} \rightarrow$ back to SM fine-tuning

.....why worry? worse (unrelated?) fine tunings: cosmological const: $\left[\frac{\rho_v}{\rho} \approx \frac{(2.3\times 10^{-12}\mathrm{GeV})^4}{(10^{19}\,\mathrm{GeV})^4} \right]$

$c)$. Forget it. Use an EFT approach, ignore the UV completion.

- Fine tuning and SUSY models:

$$V = m_1^2\,|H_1|^2 + m_2^2\,|H_2|^2 - (B_0\,\mu_0\,H_1\cdot H_2 + h.c.) + \lambda_1/2\,|H_1|^4 + \lambda_2/2\,|H_2|^4 + \lambda_3\,|H_1|^2\,|H_2|^2$$
$$+\ \lambda_4\,|H_1\cdot H_2|^2 + \Big[\lambda_5/2\,(H_1\cdot H_2)^2 + \lambda_6\,|H_1|^2\,(H_1\cdot H_2) + \lambda_7\,|H_2|^2\,(H_1\cdot H_2) + h.c.\Big]$$

$$m^2 \equiv m_1^2\cos^2\beta + m_2^2\sin^2\beta - B_0\,\mu_0\,\sin 2\beta, \quad \mathrm{UV}: m_{1,2}^2 = m_0^2 + \mu_0^2$$

$$\lambda \equiv \frac{\lambda_1}{2}\cos^4\beta + \frac{\lambda_2}{2}\sin^4\beta + \frac{\lambda_{345}}{4}\sin^2 2\beta + \sin 2\beta\,\big(\lambda_6\cos^2\beta + \lambda_7\sin^2\beta\big)$$

2 constraints: $v^2 + \frac{m^2}{\lambda} = 0, \quad \frac{\partial m^2}{\partial\beta} - m^2\frac{\partial\lambda}{\partial\beta} = 0,$

- Problem: scales vs. couplings "tension" (tuning):

$$v^2 = -m^2/\lambda, \ \text{with}\ v = \mathcal{O}(100\ \mathrm{GeV}), \quad \lambda < 1, \qquad \textbf{but} \quad m_{1,2}, B_0 \text{ and } m \sim \mathcal{O}(1\,\mathrm{TeV}).$$

- for $m_h > m_Z$ large loop effects needed i.e. large $m_{1,2}, B_0 ...$; also a problem of couplings (λ small)

⇒ Solution: increase λ by 1.- quantum corrections
2.- corrections from "new physics" beyond MSSM

- Measures of fine tuning. Fine-tuning vs likelihood.

$$\Delta_{max} \equiv \max_{\gamma} \left|\Delta_{\gamma}\right|, \qquad \Delta_{\gamma} \equiv \frac{\partial \ln v^2}{\partial \ln \gamma^2}, \quad \gamma = \{m_0, m_{1/2}, \mu_0, A_0, B_0\}, \quad v = \text{EW scale}$$

Ellis, Enqvist, Nanopoulos, Zwirner (1986)

Barbieri, Giudice (1988)

- based on physical grounds/intuition. Mathematical support?
- small Δ preferable (?) what is "small" Δ ? usually ≤ 20? ≤ 100?, 1000? sufficient/necessary?*
- many other definitions for $\Delta \Rightarrow$ different results? .... see: Anderson, Castano, hep-ph/9409419

$$\Delta_q = \Big[\sum_{\gamma} \Delta_{\gamma}^2\Big]^{1/2}, \qquad \text{"quadrature } \Delta\text{"}$$

- local in $\{\gamma\}$ space; to compare models, go global: $\int d\gamma$? $\int$ measure? $\Rightarrow$ Use Bayesian probability.
-*Take 2 models: model A: v. good χ^2/d.o.f. but large $\Delta = 1000 \rightarrow$ model v. likely but...unnatural!

model B: good χ^2/d.o.f. but small $\Delta = 10$. $\rightarrow$ model less likely, but ...natural!

$\Rightarrow$ So what model is better? same problem in Bayesian approach!

$\Rightarrow$ Fine-tuning (likelihood): tune γ_i to respect EW min (observables); they are part of same problem!

II. Naturalness versus likelihood in SUSY models:

D.G., G.G. Ross, arXiv:1208:0837.

Consider the likelihood to fit the EW observables: $O_j, \quad j=1,2....,$ parameters $\tilde{\gamma}_i$:

$$L(\text{data}|\tilde{\gamma}_i; v, \beta) = \prod_{j\geq 1} L(O_j|\tilde{\gamma}_i; v, \beta), \qquad \tilde{\gamma}_i = \gamma_i, y_t, y_b...; \qquad \gamma_i = m_0, m_{1/2}, A_0, B_0, \mu_0..(\text{susy})$$

Observables are independent, but parameters not **! EW min: $f_1 = f_2 = 0$ (theor), $m_Z = m_Z^0$ (exp).

$$f_1(\tilde{\gamma}_i, v, \beta) = v - (-m^2/\lambda)^{1/2} = 0,$$

$$f_2(\tilde{\gamma}_i, v, \beta) = \tan\beta - \tan\beta_0(\tilde{\gamma}_i) = 0.$$

$$L(\text{data}|\tilde{\gamma}_i) = m_Z^0 \int dv \; d(\tan\beta) \; \delta(m_Z - m_Z^0) \; \delta\left(f_1(\tilde{\gamma}_i; v, \beta)\right) \; \delta\left(f_2(\tilde{\gamma}_i; v, \beta)\right) \; L(\text{data}|\tilde{\gamma}_i; v, \beta)$$

$$= v_0 \left[L\big(\text{data}|\tilde{\gamma}_i;\, v_0,\, \beta\big) \; \delta\big[f_1\big(\tilde{\gamma}_i;\, v_0,\, \beta\big)\big]\right]_{\beta=\beta_0(\tilde{\gamma}_i)}, \qquad v_0 = 246\text{GeV}, m_Z^0 = 91.18\text{GeV}.$$

where we used $m_Z = gv/2;\ m_Z^0 = gv_0/2,\ g^2 = g_1^2 + g_2^2.$

$\Rightarrow$ ** consequence: (constrained L) = (unconstrained L) x (Dirac delta, to respect EW min!).

D.G., G.G. Ross, arXiv:1208:0837.

Further

$$\delta(f_1(\vec{z})) = \frac{1}{|\nabla_z f_1|_o}\,\delta\Big[\vec{n}.(\vec{z}-\vec{z}^0)\Big], \qquad z_j \to \ln\tilde{\gamma}_j, \quad n_j = \frac{\partial_{z_j} f_1}{|\nabla f_1|_o}$$

where $\vec{n}$ is the normal to the EW min surface $f_1 = 0$. So:

$$\Rightarrow\; L(\text{data}|\tilde{\gamma}_i) = \frac{1}{\Delta_q}\,\delta\Big(\sum_{j\geq 1} n_j\,(\ln\tilde{\gamma}_j - \ln\tilde{\gamma}_j^0)\Big)\; L\big(\text{data}|\tilde{\gamma}_i;\, v_0,\, \beta\big)\Big|_{\beta=\beta_0(\tilde{\gamma}_i)}$$

where

$$\Delta_q = \Big(\sum_j \Delta^2_{\tilde{\gamma}_j}\Big)^{1/2}, \quad \Delta_{\tilde{\gamma}_j} = \frac{\partial\ln\tilde{v}}{\partial\ln\gamma_j}, \quad \tilde{v} = (-m^2/\lambda)^{1/2}$$

$$\Rightarrow\quad L(\text{data}|\tilde{\gamma}_i^0) = \frac{1}{\Delta_q}\,L(\text{data}|\tilde{\gamma}_i; v_0, \beta)\Big|_{\beta=\beta_0(\tilde{\gamma}_i);\,\tilde{\gamma}_i=\tilde{\gamma}_i^0}$$

$\Rightarrow$ Large "constrained" L demands one maximize the ratio of old/unconstrained L and Δ_q !

$\Rightarrow$ answers how to compare (likely but ... unnatural) and (unlikely but ...natural) models!

$\Rightarrow$ similar results for the Bayesian approach (Bayesian "evidence")!

Using that $\chi^2 = -2\ln L + \text{constant}$: D.G., G.G. Ross, arXiv:1208:0837.

$$\chi^2_{\text{new}}(\tilde{\gamma}_i) = \Big[\ \chi^2_{\text{old}}(\tilde{\gamma}_i) + \underbrace{2\ln\Delta_q(\tilde{\gamma}_i)}_{\delta\chi^2}\ \Big]_{f_1=0, f_2=0}$$

- if y_t, y_b also fixed by m_t^0, m_b^0, then $L \to L\delta(m_t - m_t^0)\,\delta(m_b - m_b^0)$, so $\tilde{\gamma}_i \to \gamma_i$.
- Can also compute the profile likelihood.

$\Rightarrow$ Implications for χ^2 fits in SUSY models, with $m_h \approx 125$ GeV: (fine tuning cost of the likelihood):

$$\begin{aligned} \text{if} \qquad \Delta_q &\approx 10 \Rightarrow \delta\chi^2/\text{d.o.f} \approx 4.6/9 \\ \Delta_q &\approx 100 \Rightarrow \delta\chi^2/\text{d.o.f} \approx 9.2/9 \\ \Delta_q &\approx 500 \Rightarrow \delta\chi^2/\text{d.o.f} \approx 12.5/9 \end{aligned}$$

$\Rightarrow$ for χ^2/d.o.f.≈ 1 need small $\Delta_q \leq \mathcal{O}(10) \Rightarrow$ rule out models in probabilistic sense using only Δ_q!
$\Rightarrow$ current χ^2/d.o.f. in SUSY models: worse than thought (?). $\Delta_q \ll \exp(\text{d.o.f.}/2)$.

- So let us examine Δ_q in SUSY models (in the light of recent LHC results). Can we have $\Delta_q \sim 10$?

III. Numerical results for naturalness in SUSY models:

D.G., H. M. Lee, M. Park, arXiv:1203:0569

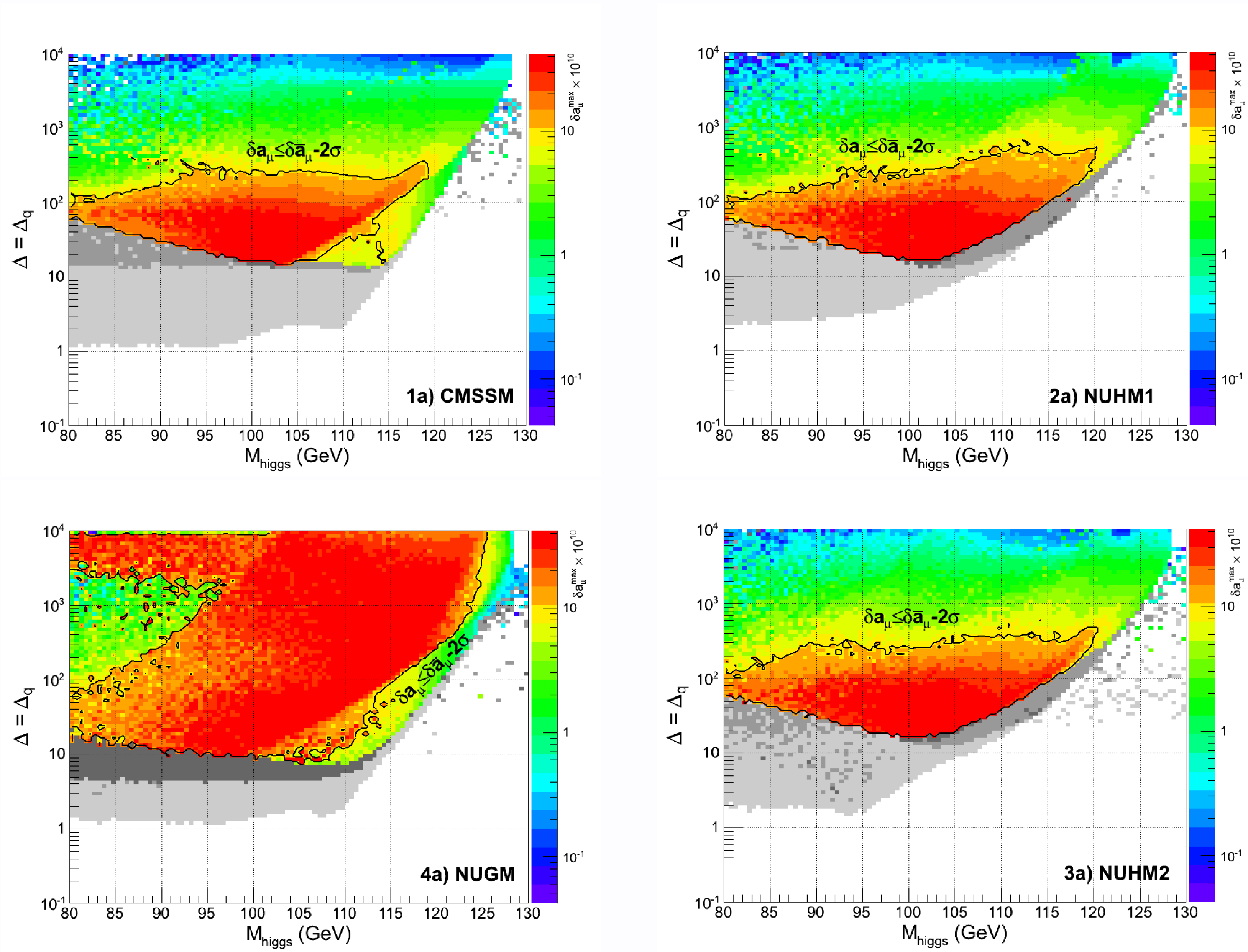
1) CMSSM (constrained MSSM) $\gamma = \{m_0, \mu_0, m_{1/2}, A_0, B_0\}$
2) NUHM1 (non universal Higgs Mass) $\gamma = \{m_0, \mu_0, m_{H_1}^{uv} = m_{H_2}^{uv}, m_{1/2}, A_0, B_0\}$
3) NUHM2 (non universal Higgs Mass) $\gamma = \{m_0, \mu_0, m_{H_1}^{uv}, m_{H_2}^{uv}, m_{1/2}, A_0, B_0\}$
4) NUGM (non universal gaugino masses) $\gamma = \{m_0, \mu_0, m_{\lambda_{1,2,3}}, A_0, B_0\}$

• Experimental Constraints:

- SUSY masses: micrOmegas 2.4.5, "MSSM/masslim.c"
- muon magnetic moment: $\delta a_\mu = (25.5 \pm 2 \times 8) \times 10^{-10}$ at 2σ
- $b \to s\,\gamma$ $3.03 < 10^4$ Br$(b \to s\gamma) < 4.07$ at 2σ
- $B_s \to \mu^+\mu^-$ Br$(B_s \to \mu^+\mu^-) < 1.08 \times 10^{-8}$ at 2σ
- ρ-parameter $-0.0007 < \delta\rho < 0.0033$ at 2σ
- dark matter $\Omega h^2 = 0.1099 \pm 3 \times 0.0062$ at 3σ
- ATLAS/CMS: $m_h \approx 126$ GeV and δa_μ not imposed.

• Tools: micrOMEGAs 2.4.5, SoftSUSY 3.2.4. Random scan. $\Rightarrow \Delta_q$, Δ_{max} at 2-loop LL.

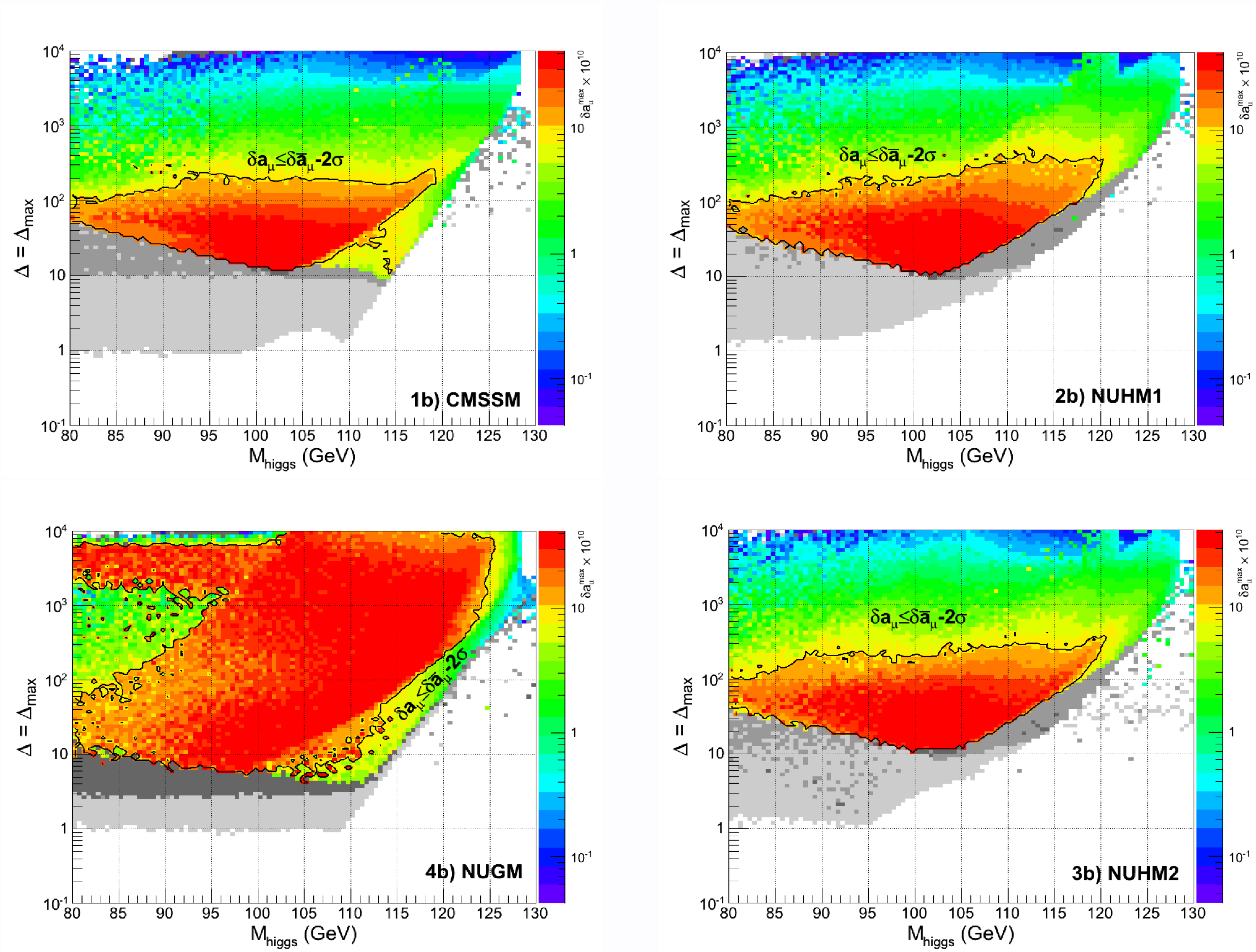
• Impact of m_h, δa_μ on Δ_q. [2-loop, all $\{\gamma, \tan\beta\}$ all values]   D.G., H. M. Lee, M. Park, arXiv:1203:0569



• grey 0: excluded by SUSY; grey 1: $b \rightarrow s\gamma$, $B_s \rightarrow \mu^+\mu^-$, $\delta\rho$; grey 2: excluded by $\delta a_\mu > 0$.

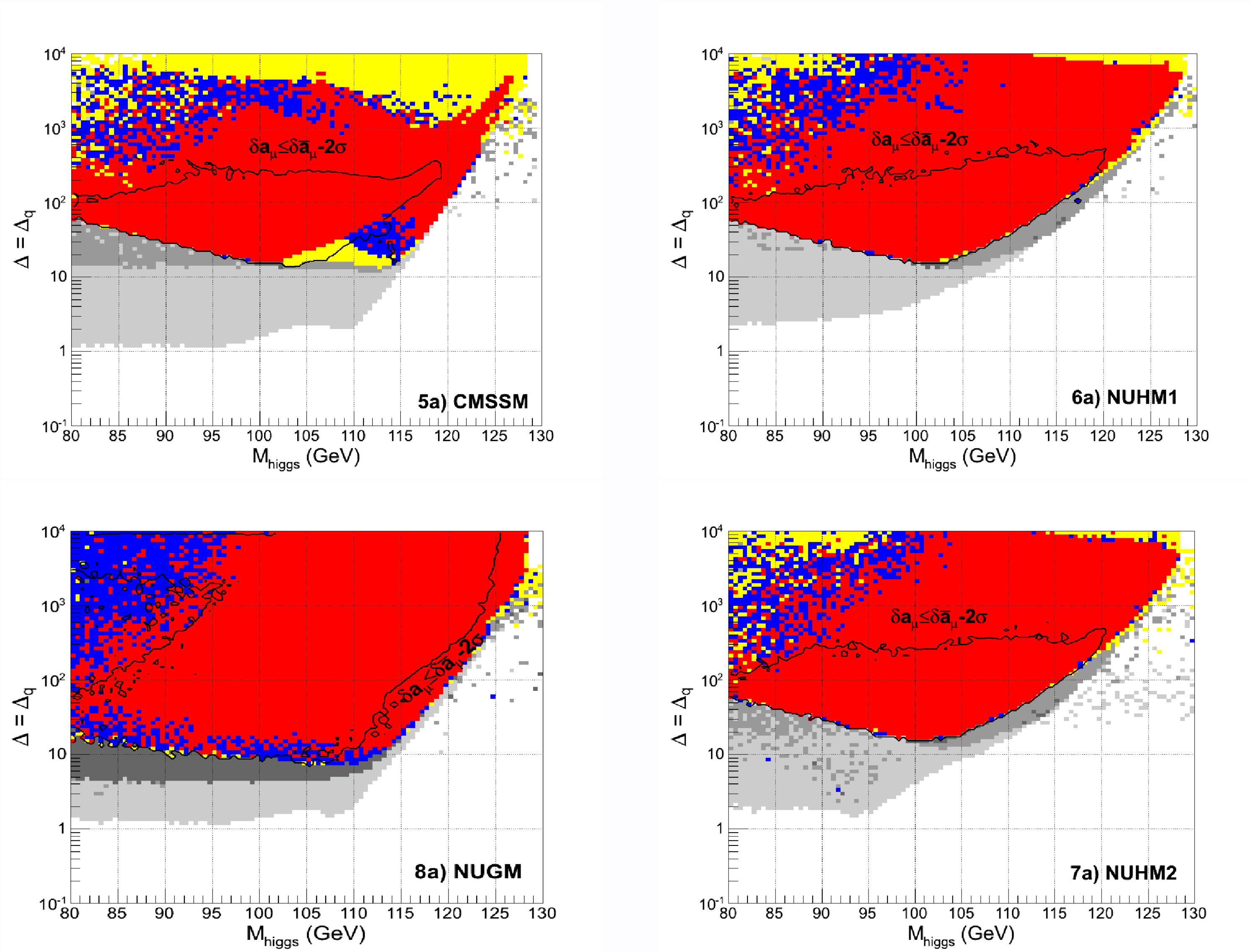
$\Rightarrow$ m_h strongest impact: $\Delta_q \sim e^{m_h}$. $\Delta_q \sim 1000$ (!) near 125 GeV. NUGM better behaviour.

- Impact of m_h, δa_μ on Δ_{max}. [2-loop, all $\{\gamma, \tan\beta\}$ all values]. D.G., H. M. Lee, M. Park, arXiv:1203:0569



- δa_μ: 2σ contour (red) [smaller δa_μ outside]. $\Rightarrow$ Δ_{max} identical behaviour to Δ_q (marginally smaller)

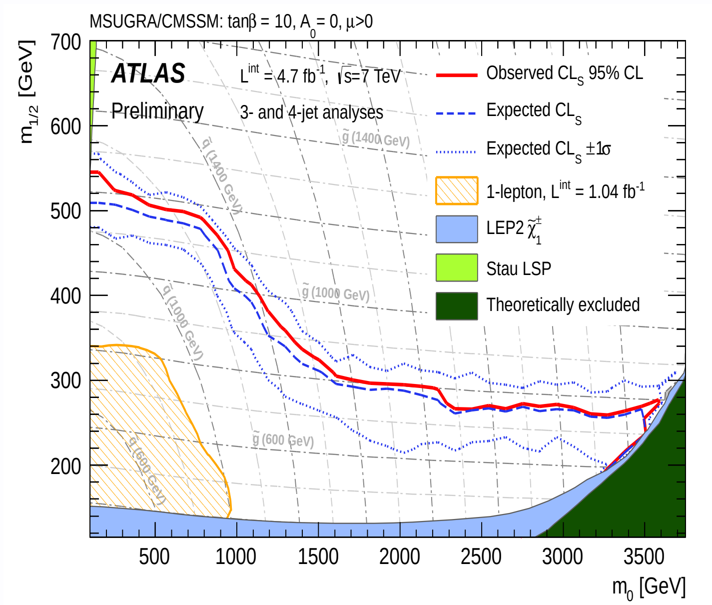
- Impact of m_h, dark matter on Δ_q: [2-loop, $\{\gamma, \tan\beta\}$ all values]. D.G., H. M. Lee, M. Park, arXiv:1203:0569

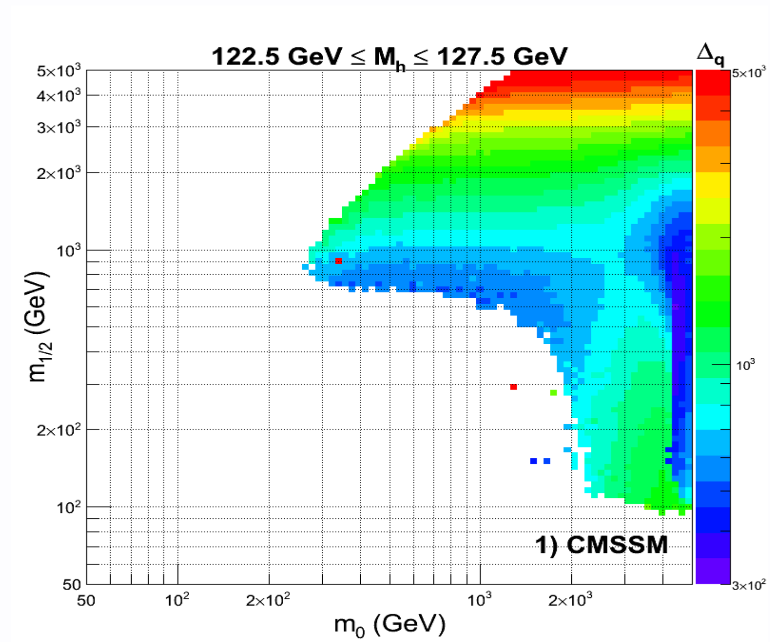


- blue: consistent with Ωh^2; Red: saturate Ωh^2 within 3σ. Grey areas ruled out by data.

$\Rightarrow$ Δ_{max} (not shown) nearly identical plots to Δ_q, (marginally smaller for same Higgs mass).

- SUSY searches from ATLAS and impact on parameter space (CMSSM only):





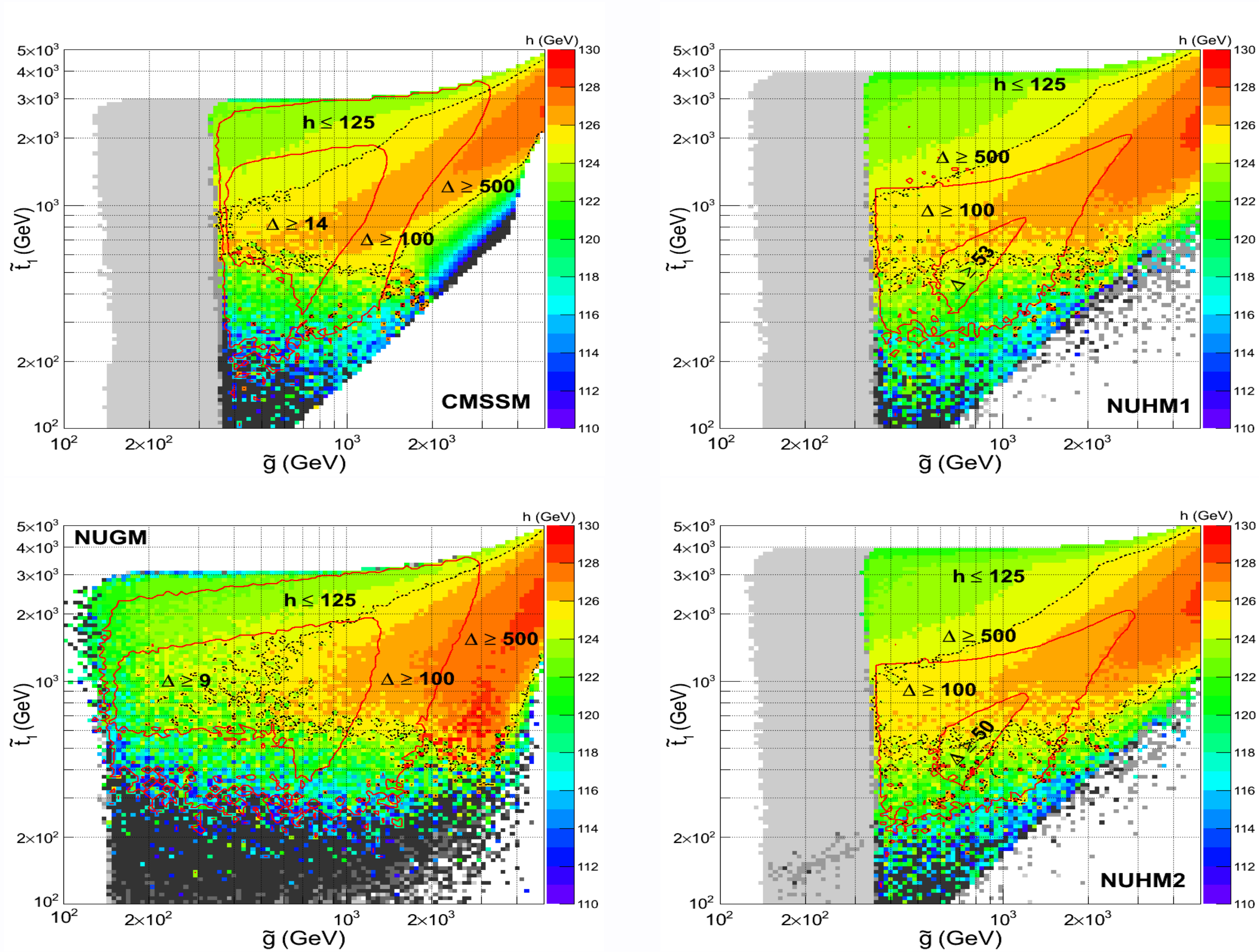
ATLAS-CONF-2012-041

CMSSM, $122.5 \leq m_h \leq 127.5$ GeV and Δ_q cost.

[all values for γ, $\tan\beta$]. $\Delta_q > 500$.

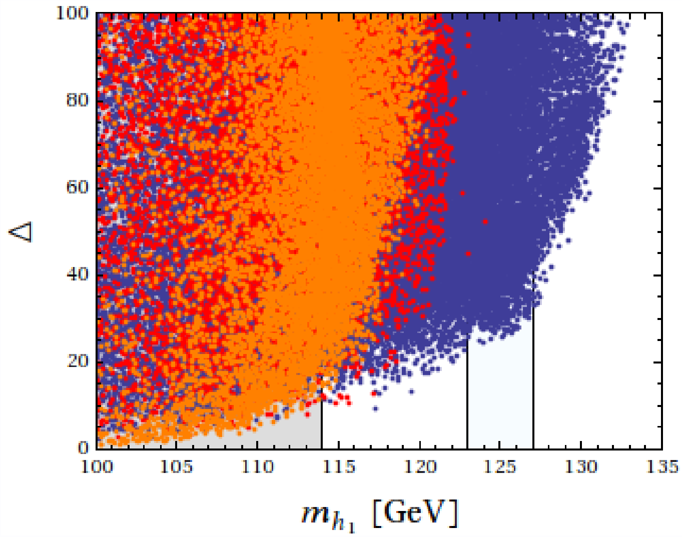
D.G., Hyun Min Lee, Myeonghun Park (2012)

- Stop vs Gluino with largest m_h and min Δ_q. $[\{\gamma, \tan\beta\}$ all values] D.G., H. M. Lee, M. Park, arXiv:1203:0569



$\Rightarrow$ constraints on m_h strongly reduce the viable regions.

IV. Fine tuning beyond MSSM: NMSSM, GNMSSM, ...



MSSM

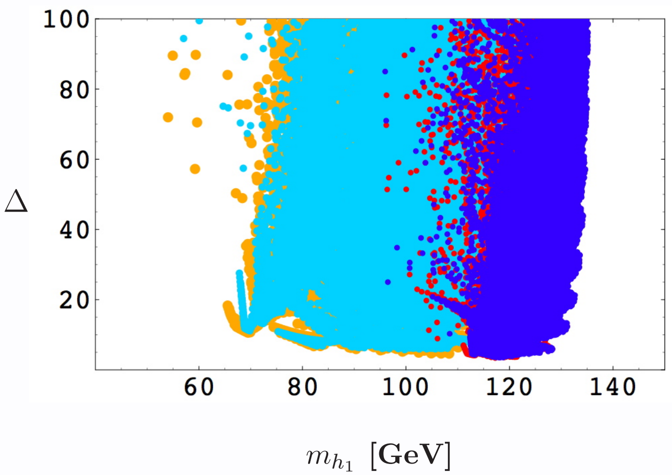
NMSSM: $W = W_Y + \lambda S H_1 H_2 + \kappa S^3$

GNMSSM: $W = W_Y + (\mu + \lambda S)\, H_1 H_2 + M_* \, S^2 + \kappa S^3$

$\Delta < 30$ for $m_h \leq 130\, GeV.$

G.G. Ross et al, arXiv:1205.1509

U. Ellwanger et al arXiv:1107.2472



Decoupling limit: MSSM with a massive gauge singlet:

$\Rightarrow$ MSSM + d=5 operator:

$$W = W_Y + \mu\, H_1 H_2 + \lambda\, S\, H_1\, H_2 + M_*\, S^2$$

$$\Rightarrow W = W_Y + \mu\, H_1 H_2 + \zeta_0\, (H_1 H_2)^2, \quad \zeta_0 \sim \lambda / M_*$$

$\Delta < 20$ for $m_h \leq 130\, GeV.$

S. Cassel, D.G., G.G. Ross, NPB 825(2010)

$\Rightarrow$ massive gauge singlet $\Rightarrow$ reduces fine tuning considerably, to $\Delta \sim 20$.

• Fine tuning beyond MSSM: MSSM + d=6 operators

$$\mathcal{O}_j = \int d^4\theta\ \mathcal{Z}_j\ (H_j^\dagger e^{V_j} H_j)^2, \quad (j=1,2). \qquad \mathcal{O}_3 = \int d^4\theta\ \mathcal{Z}_3\ (H_1^\dagger e^{V_1} H_1)(H_2^\dagger e^{V_2} H_2)$$

$$\mathcal{O}_4 = \int d^4\theta\ \mathcal{Z}_4\ (H_2 H_1)(H_2 H_1)^\dagger, \qquad \mathcal{O}_k = \int d^4\theta\ \mathcal{Z}_k\ (H_k^\dagger e^{V_k} H_k) H_2 H_1 + h.c., \text{ (k=5,6)}$$

$$\mathcal{O}_7 = \int d^2\theta\ \mathcal{Z}_7 \,\mathrm{Tr}\, W_i^\alpha W_{i,\alpha} (H_2 H_1) + h.c.,$$

where $\mathcal{Z}_j(S, S^\dagger) = \alpha_{j0} + \alpha_{j1} S + \alpha_{j1}^* S^\dagger + \alpha_{j2} m_0^2 S S^\dagger$, $\quad \alpha_{jk} \sim 1/M_*^2$, $\; S = m_0 \theta\theta$

$\mathcal{O}_{1,2,3}$: generated by massive T, U(1); $\mathcal{O}_4$: singlet, T. $\mathcal{O}_{5,6}$: 2 D, singlet.

$$\Rightarrow \delta m_h^2 = -2v^2 \left[(\alpha_{30}+\alpha_{40})\mu_0^2 - \alpha_{20} m_Z^2\right] - \frac{(2\zeta_0 \mu_0)^2 v^4}{m_A^2 - m_Z^2} + \frac{v^2 \cot\beta}{m_A^2 - m_Z^2}\Big[4 m_A^2 \mu_0^2 (2\alpha_{50}+\alpha_{60}) - (2\alpha_{60} - 3\alpha_{70}) m_A^2 m_Z^2 - (2\alpha_{60}+\alpha_{70}) m_Z^4\Big] + \mathcal{O}\big(1/(M_*^2 \tan^2\beta)\big)$$

$\Rightarrow \alpha_{j0}$ (choice?) $\Rightarrow$ increase m_h, reduce fine-tuning by:

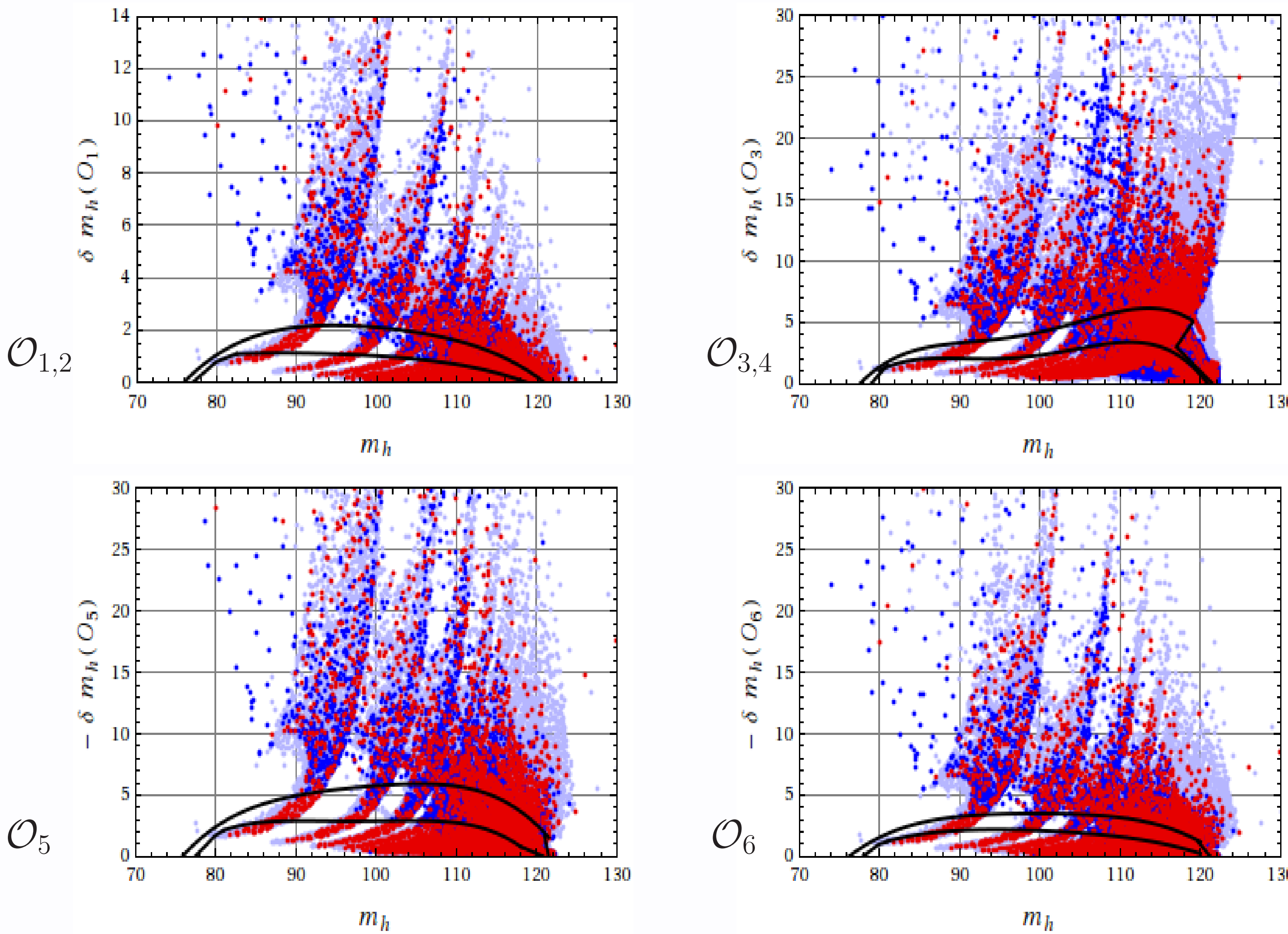
$$\Delta_q(m_h) \approx \exp(-\delta m_h/\text{GeV})\, \Delta_q(m_h)\big|_{\text{CMSSM}}$$

D.G. et al, NPB 848(2011), NPB 831(2010),

M. Carena et al, PRD 85(2012), PRD 81, 82(2010),

F. Boudjema et al, PRD 85 (2012)

- Corrections to m_h from MSSM + d=6 operators D.G., I. Antoniadis, E. Dudas, P. Tziveloglu, NPB B848(2011)1.



$\delta m_h = \left(m_h^2 + \delta m_h^2\right)^{1/2} - m_h$, m_h: 2-loop LL CMSSM. $M_* = 8$ TeV. take: $\alpha_{j0} \leq 1/4$

$\Rightarrow$ top curve: $\Delta < 200$: $m_h < 122$ GeV, $\delta m_h < 6$ GeV. $\pm 1\,\text{GeV}\ (\delta m_h) \leftrightarrow \mp 1$ TeV (δM_*).

$\Rightarrow$ largest δm_h: $\mathcal{O}_3$, $\mathcal{O}_4$. $\Delta_q(128\,\text{GeV}) \approx e^{-6}\,\Delta_q(128\,\text{GeV})_{\text{MSSM}} = \mathcal{O}(10)$.

• Final Remarks:

⇒ Fine tuning: probabilistic interpretation from EW/theoretical constraints (correlations of γ_i).

⇒ large $L_{new} = L_{old}/\Delta_q$ required, or equivalently $\chi^2_{new} = \chi^2_{old} + 2\ln\Delta_q$ (fine tuning cost of χ^2).

⇒ current χ^2/d.o.f. in SUSY models: worse than thought (?). $\Delta_q \ll \exp(\text{d.o.f.})$.

⇒ Numerical results: Δ_q: of all EW data, m_h strongest constraint.

⇒ Δ_q, Δ_{max}: similar, large: $\sim 500 - 1000$ in CMSSM, NUHM1,2, NUGM for $m_h \sim 125$ GeV.

⇒ expect L/Δ_q worsen for $m_h > 115$ as $\Delta_q \sim \exp(m_h/\text{GeV})$.

⇒ GNMSSM preferable?.

⇒ Beyond MSSM: with d=5, d=6 operators. ⇒ increase m_h, reduce Δ by $\exp(\delta m_h/\text{GeV})$.

⇒ best scenario: extra massive singlet, extra U(1).

V. Fine tuning from the Bayesian approach.

$$p(a|b)\,p(b) = p(a\cap b) = p(b|a)\,p(a)$$

Bayes theorem: [initial belief + data $\rightarrow$ updated belief].

Thomas Bayes (1761), Laplace (1812)

$$p(\gamma|\text{data}) = \frac{L(\text{data}|\gamma)\;p(\gamma)}{p(\text{data})}, \qquad p(\text{data}) = \int L(\text{data}|\gamma)\,p(\gamma)d\gamma, \qquad \gamma:\{m_0, m_{1/2}, \mu_0, A_0, B_0\}.$$

(CMSSM)

- $p(\text{data})$: "evidence". Models $1, 2$: $p_1(\text{data})/p_2(\text{data})$
- EW constraints: $f_1(\gamma; v, \beta, y_t, y_b) = f_2(\gamma; v, \beta, y_t, y_b) = 0$, $\Rightarrow$ $v(\gamma, ...), \tan\beta_0(\gamma...)$.

$$p(\text{data}) = \int d\gamma\; p(\gamma)\, dy_t\; dy_b\; p(y_t)\; p(y_b)\;\; dv\; d(\tan\beta)\; \delta(m_Z - m_Z^0)\; \delta(m_t - m_t^0)\; \delta(m_b - m_b^0)$$
$$\times\; \delta\left(f_1(\gamma; v, \beta, y_t, y_b)\right)\; \delta\left(f_2(\gamma; v, \beta, y_t, y_b)\right) L(\text{data}|\gamma; \beta, v, y_t, y_b)$$

$$p(\text{data}) = \int_{f_{1,2}=0} dS_\gamma\; \frac{L(\text{data}|\gamma)}{\Delta_q(\gamma)}\; p(\gamma)p\big(y_b(\gamma)\big)p\big(y_t(\gamma)\big), \qquad \Delta_q \equiv \Big[\sum_\gamma \Delta_\gamma^2\Big]^{1/2}$$

D.G., H. M. Lee, M. Park, arXiv:1203:0569

$\Rightarrow$ Δ_q fine-tuning induced in $p(\text{data})$ by two theoretical constraints (EW min).

• Fine-tuning from a Bayesian approach.

$\Rightarrow$ result below, integral version of the discussion in "frequentist" approach:

$$p(\text{data}) = \int_{f_{1,2}=0} dS_\gamma \, \frac{L(\text{data}|\gamma)}{\Delta_q(\gamma)} \times (\text{priors}), \qquad \delta(f_1)\,\delta(f_2) \to \frac{\delta(v-v_0)}{|\nabla_\gamma f_1|_{v_0}} \delta(\tan\beta - \tan\beta_0)$$

$\Rightarrow$ presence of Δ_q independent of priors!

$\Rightarrow$ to maximize global evidence $p(\text{data})$: small Δ (not sufficient!): large ratio L/Δ_q ($\times$ priors)

$\Rightarrow$ smaller Δ, good $L(\text{data}|\gamma)$ for $m_h \approx 115$ GeV.... increasing m_h ? $\Delta \sim \exp(m_h)$ dominates L?

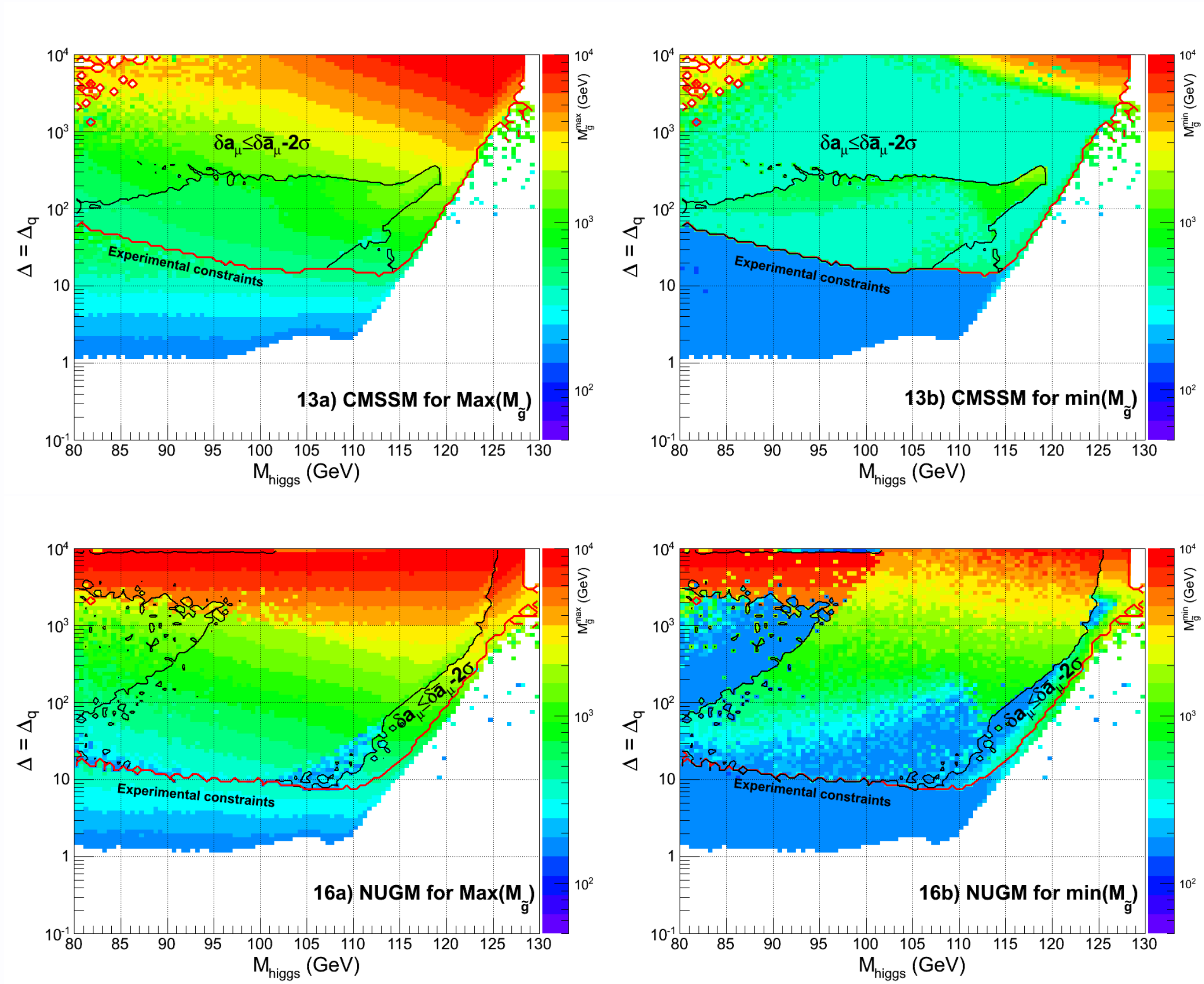
B.C. Allanach et al hep-ph/0601089, 0904.2548

J.A. Casas et al, M.E. Cabrera et al, 0812.0536

L. Roszkowski et al, C. Balazs et al, arXiv:1205.1568

- Δ_q vs m_h and gluino mass range, δa_μ: $[\{\gamma, \tan\beta\}$ all values$]$

D.G., H. M. Lee, M. Park, arXiv:1203:0569

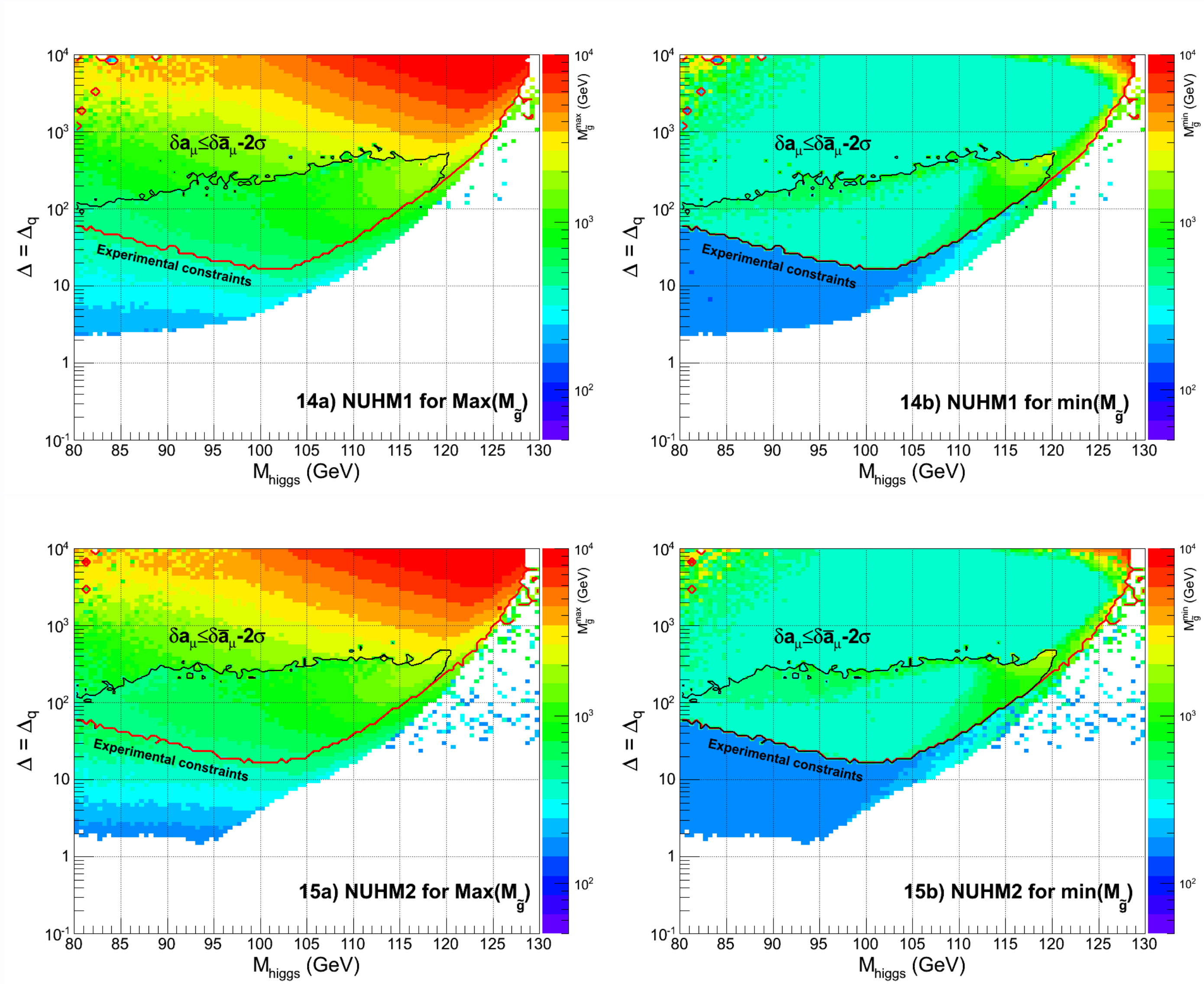


largest gluino mass

lowest gluino mass.

- Δ_q vs m_h and gluino mass range, δa_μ: $[\{\gamma, \tan\beta\}$ all values$]$

D.G., H. M. Lee, M. Park, arXiv:1203:0569

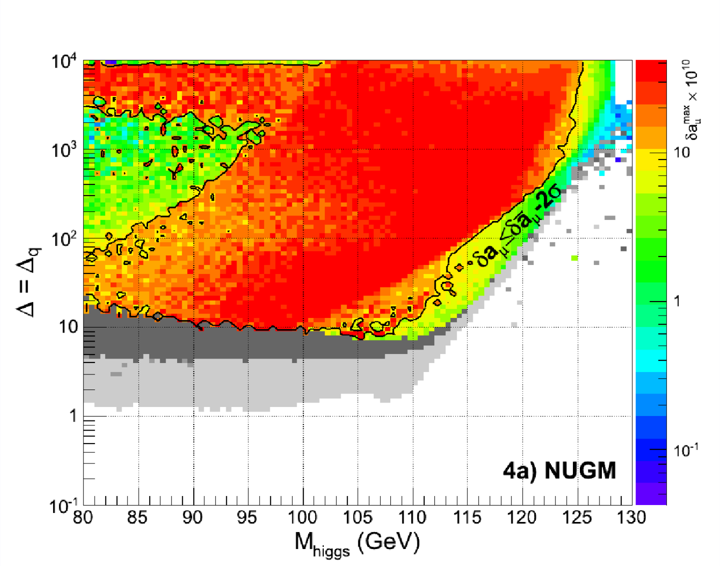


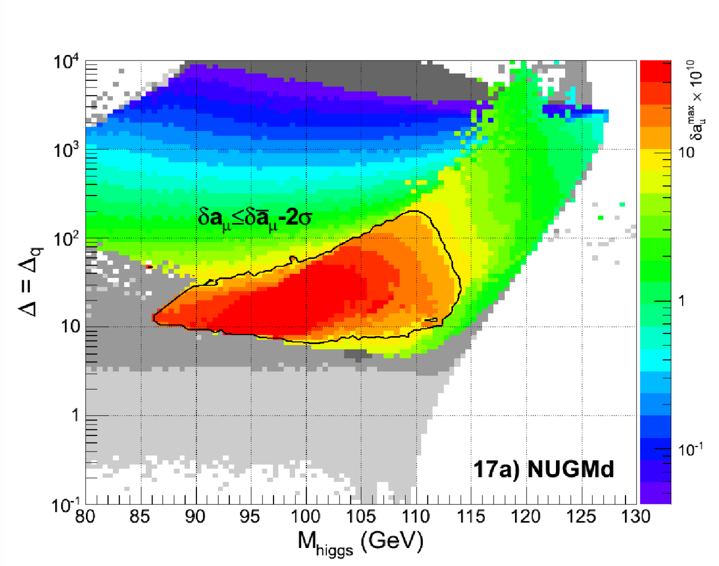
largest gluino mass

lowest gluino mass.

• NUGM versus NUGM with GUT-like gaugino mass relation (NUGMd):

D.G., H. M. Lee, M. Park, arXiv:1203:0569





non-univ gaugino mass with a GUT relation:

$$m_{\lambda_1} = 5/3 m_{1/2}, m_{\lambda_2} = m_{1/2}, m_{\lambda_3} = (1/3)\, m_{1/2}$$

Horton, Ross, arXiv:0908.0857 [hep-ph]

• NUGM better behaviour if δa_μ considered, near 125 GeV for m_h.