Naturalness and dark matter predictions for the Higgs mass in MSSM and Beyond

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NPB 835 (2010) 110, arXiv:1103.4793, with G.G. Ross, S. Cassel.

NPB 848 (2011) 1, NPB 831 (2010) 133, with I. Antoniadis, E. Dudas, P. Tziveloglou.

- Standard Model (SM): best model so far.

  - Agrees with experiment. Open questions: hierarchy, EWSB, unification, DM, gravity,....

  - $\delta m_h^2 \sim \mathcal{F}(\alpha_i^0, m_j^0)\,\Lambda_{UV}^2$, $\Lambda_{UV} \sim M_{Planck}$: $\Rightarrow$ Hierarchy problem $\Leftrightarrow$ fine tuning.

    - two faces of the same problem.

- MSSM. SUSY searches.

  - $\delta m_h^2 \sim m_{susy}^2 \log \Lambda_{UV}^2/m_{susy}^2$ $m_{susy} \sim$ TeV; $m_{susy} \sim \Lambda_{UV} \Rightarrow$ SM fine-tuning

$$\mathcal{L} = \int d^4\theta \sum_{\Phi} \mathcal{Z}_\Phi\, \Phi^\dagger e^V \Phi + \Big\{ \sum_{i=1,2,3.} \int d^2\theta\, \frac{1}{g_i^2}\, (1 + m_{1/2}\theta\theta)\, \mathrm{Tr}\, W^\alpha\, W_\alpha\vert_i + h.c. \Big\}$$

$$+ \int d^2\theta \Big[H_2\, Q\, \lambda_U\, U^c + Q\, \lambda_D\, D^c\, H_1 + L\, \lambda_E\, E^c\, H_1 + \mu\, H_1\, H_2 \Big] + h.c., \;\; \Phi: H_{1,2}, Q, U^c, D^c, E^c, L$$

$$\mathcal{Z}_\Phi(S, S^\dagger) = 1 - S\, S^\dagger,\; S = \theta\theta\, m_0;\;\; m_0 = \frac{\langle F_{hid}\rangle}{M_P},\;\; \lambda_F(S) = \lambda_F(0)(1 + A_0\, S),\;\; \mu(S) = \mu_0\,(1 + B_0 S)$$

$$A_0, B_0, \mu_0, m_0, m_{1/2}, \tan\beta = v_2/v_1$$

• MSSM scalar potential:

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

$$\text{Tree-level: } \lambda_{1,2} = (g_1^2+g_2^2)/4, \quad \lambda_3 = (g_2^2-g_1^2)/4, \quad \lambda_4 = -g_2^2/2, \quad \lambda_{5,6,7}=0$$

$$m^2 \equiv m_1^2\,\cos^2\beta + m_2^2\,\sin^2\beta - B_0\,\mu_0\,\sin 2\beta, \quad \text{UV}: m_{1,2}^2 = m_0^2 + \mu_0^2$$
$$\lambda \equiv \frac{\lambda_1}{2}\cos^4\beta + \frac{\lambda_2}{2}\sin^4\beta + \frac{\lambda_{345}}{4}\sin^2 2\beta + \sin 2\beta\,\big(\lambda_6\cos^2\beta + \lambda_7\sin^2\beta\big)$$

• The Problem:

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

• "residual" fine-tuning (little hierarchy). Tree level: $m_h < m_Z$, LEP2: > 114.4 GeV

• Need: large quantum corrections (QC) $\Rightarrow$ large m_{susy}. But QC can also increase λ and $m_h^2 \propto \lambda\, v^2$

• This is not only a problem of scales but of couplings (λ_{MSSM} small). $\delta\lambda > 0$ vs. $m_{susy}^2 \sim m^2$

• EW fine-tuning measures as a test of SUSY [Ellis et al 1986, Barbieri, Giudice 1988]

$$\Delta \equiv \max \big|\Delta_p\big|_{p=\{\mu_0^2, m_0^2, m_{1/2}^2, A_0^2, B_0^2\}}, \qquad \text{or} \quad \Delta' \equiv \Big(\sum_p \Delta_p^2\Big)^{1/2}, \qquad \Delta_p \equiv \frac{\partial \ln v^2}{\partial \ln p}$$

$$v^2 = -m^2/\lambda, \quad 2\lambda \frac{\partial m^2}{\partial \beta} = m^2 \frac{\partial \lambda}{\partial \beta}, \quad \Rightarrow \quad m^2, \lambda = F(p, \beta(p)),$$

• Exact formula:

$$\Delta_p = -\frac{p}{z}\left[\left(2\frac{\partial^2 m^2}{\partial \beta^2} + v^2 \frac{\partial^2 \lambda}{\partial \beta^2}\right)\left(\frac{\partial \lambda}{\partial p} + \frac{1}{v^2}\frac{\partial m^2}{\partial p}\right) + \frac{\partial m^2}{\partial \beta}\frac{\partial^2 \lambda}{\partial \beta \partial p} - \frac{\partial \lambda}{\partial \beta}\frac{\partial^2 m^2}{\partial \beta \partial p}\right]$$

$$z \equiv \lambda\left(2\frac{\partial^2 m^2}{\partial \beta^2} + v^2 \frac{\partial^2 \lambda}{\partial \beta^2}\right) - \frac{v^2}{2}\left(\frac{\partial \lambda}{\partial \beta}\right)^2, \qquad \Delta_p = \frac{p}{m_Z^2(1+\delta)} + \mathcal{O}\left[\frac{1}{\tan\beta}\right], \;\; \delta : \mathrm{QC\,top\;Y.}$$

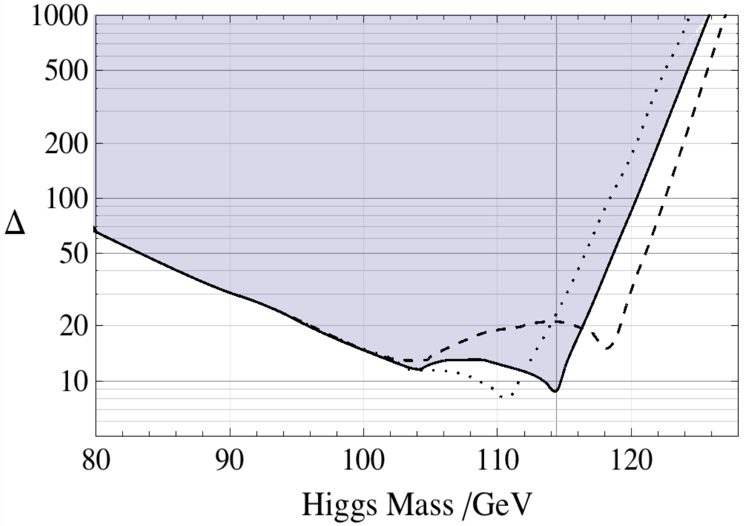
• $p_i \sim 1/\Delta$: "effective prior" emerges automatically in Bayesian fits [Casas et al 2008]

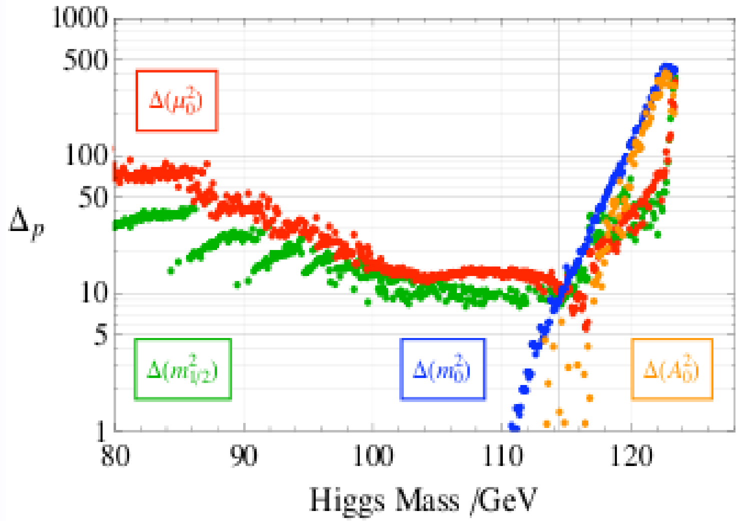
• if Δ too large: SUSY fails... Wanted: Δ minimal, for low UV sensitivity.

• Many studies: Δ: 1-loop. $\Delta \sim 100$ but $\Delta \sim m_0^2 \sim \exp(m_h^2/v^2)\,!$. [Pokorski, Ellis et al]

• 2-loop study (SoftSusy, micrOMEGAs: 6years 30×3 GHz). Impose usual constraints: TH + EXP but NO LEP bound on m_h!

• 2-loop results in CMSSM: min $\Delta \Rightarrow \ m_h = ?$ [S. Cassel, DG, G. Ross]





$(\alpha_3, m_t) = (0.1176, 173.1)$.

$\Delta \equiv \max |\Delta_p|, \quad p = \mu_0^2, m_0^2, A_0^2, B_0^2, m_{1/2}^2,$

$\Delta_{\mu_0^2}$, $\Delta_{m_0^2}$ dominant (EW vs. QCD)

$\Rightarrow$ minimal $\Delta \propto \exp(m_h^2/v^2) \Rightarrow$ 2-loop effects important!

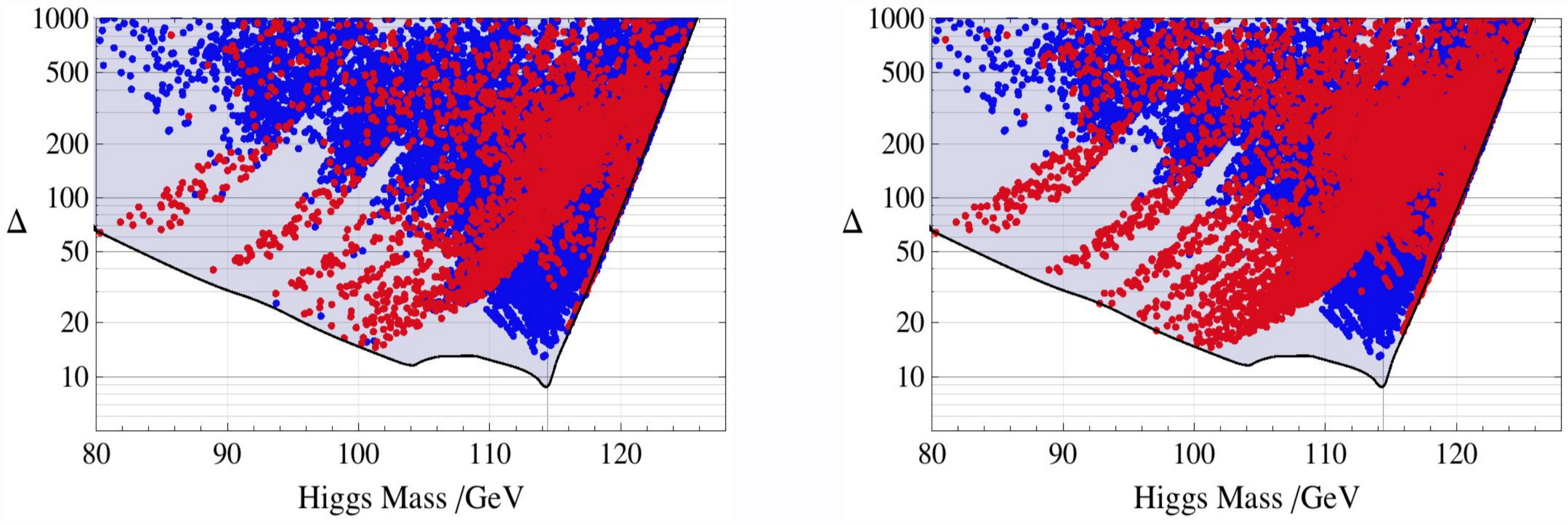
$\Rightarrow$ without LEP2 bound on m_h, min Δ: $\Delta \approx 9 \ \Rightarrow \ m_h = 114 \pm 2$ GeV, (just above LEP2 bound!)

$\Rightarrow$ CMSSM: Δ less than usually thought, when using the correct, 2-loop Δ.

$\Rightarrow$ Same result (m_h) and behaviour if using min of $\Delta' = \sqrt{\sum_p \Delta_p^2}$, (1 to 2 GeV variations).

$\Rightarrow$ dotted line: increase α_3 (1σ), reduce m_t (1σ) $\Rightarrow$ QCD does not like large m_h! (fine-tuning cost)

• 2-loop results in CMSSM: min Δ + dark matter $\Rightarrow$ $m_h = ?$ [S. Cassel, DG, G. Ross]



LSP: good dark matter candidate $\Rightarrow$ dark matter constraint:

WMAP: $\Omega h^2 = 0.1099 \pm 0.0062$; blue: Ωh^2 not-saturated; red: Ω saturated: 1σ (left); 3σ (right).

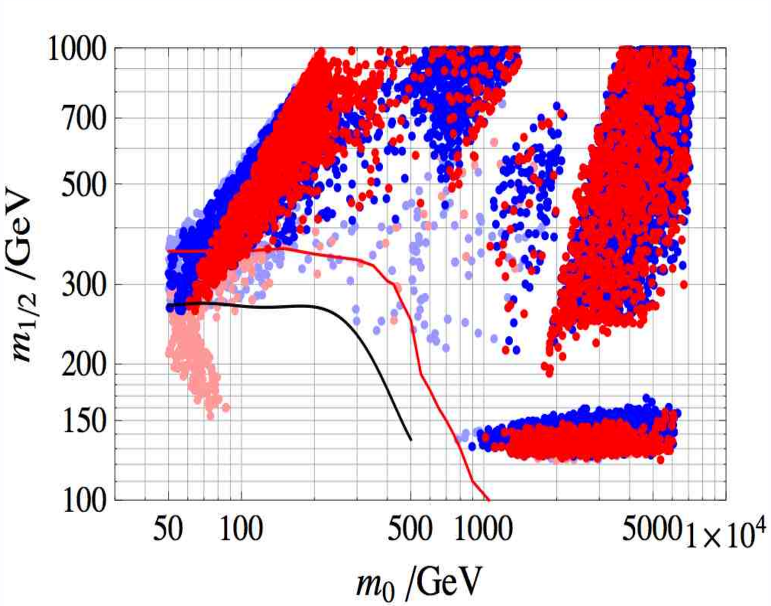
$\Rightarrow$ Prediction from: Min Δ + "right" dark matter abundance, (no LEP2 bound):

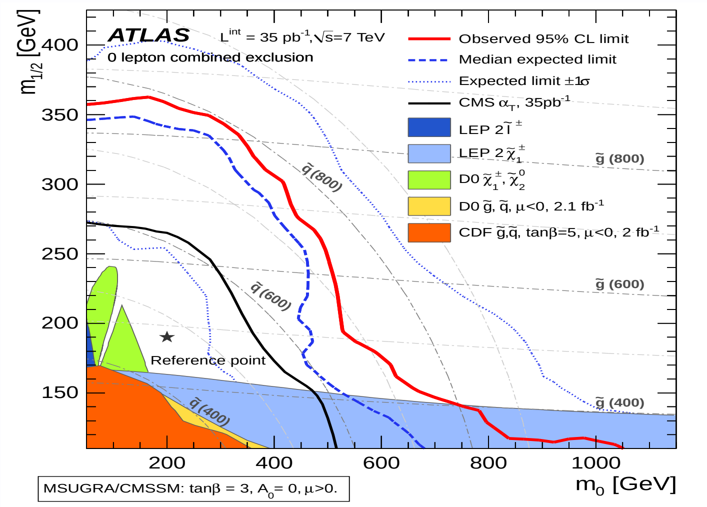
$$m_h = 114.7 \pm 2 \text{ GeV}, \quad \Delta = 15.0, \quad \text{(consistent with WMAP bound).}$$
$$m_h = 115.9 \pm 2 \text{ GeV}, \quad \Delta = 17.8, \quad \text{(saturating WMAP within } 3\sigma\text{).}$$

• an upper bound on Δ $\Rightarrow$ bounds on SUSY spectrum. $\Delta < 1000 \Rightarrow m_h < 126$ GeV ($\pm$ 2 to 3 GeV)

$\Delta < 100 \Rightarrow m_h < 121$ GeV ($\pm$ 2 to 3 GeV)

• 2-loop results in CMSSM: min Δ & the LHC @ 7 TeV reach. [S. Cassel, DG, G. Ross]





$\Rightarrow$ Left: points $\Delta < 1000$: blue: consistent with WMAP (3σ deviation); red: saturate it within 3σ.

Points in lighter (darker) red/blue have m_h below (above) LEP2 bound for m_h.

$\Rightarrow$ Right: Atlas exclusion limits (red curve, observed) for $\tan\beta = 3$, $A_0 = 0$, $\mu > 0$. arXiv:1102.5290.

Atlas is already testing CMSSM points with $\Delta < 100$ and $m_h > 114$ GeV. ($\pm$ 2 to 3 GeV)

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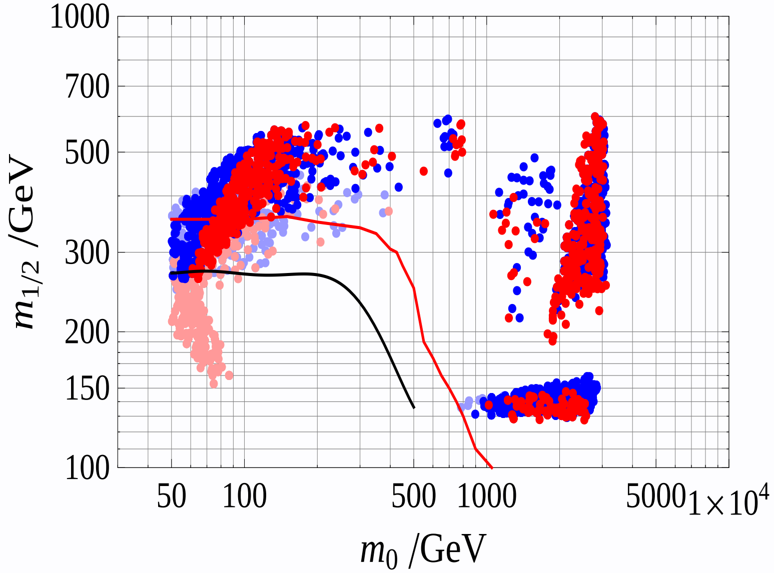
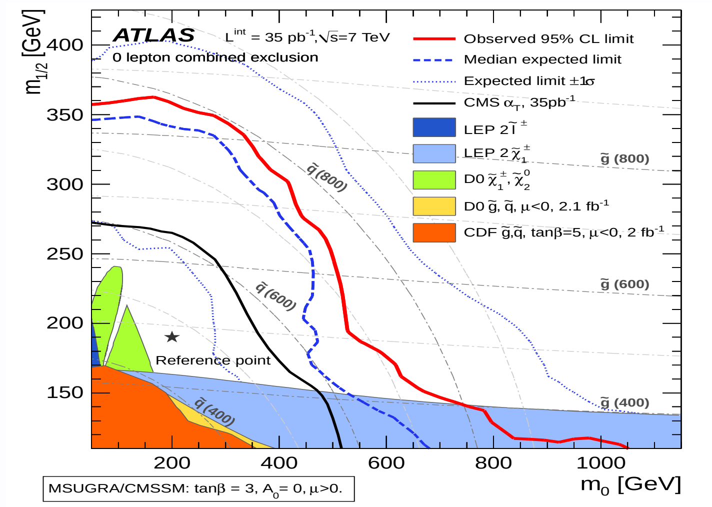




⇒ Left: points $\Delta < 100$: blue: consistent with WMAP (3σ deviation); red: saturate it within 3σ.

Points in lighter (darker) red/blue have m_h below (above) LEP2 bound for m_h.

⇒ Right: Atlas exclusion limits (red curve, observed) for $\tan\beta = 3$, $A_0 = 0$, $\mu > 0$. arXiv:1102.5290.

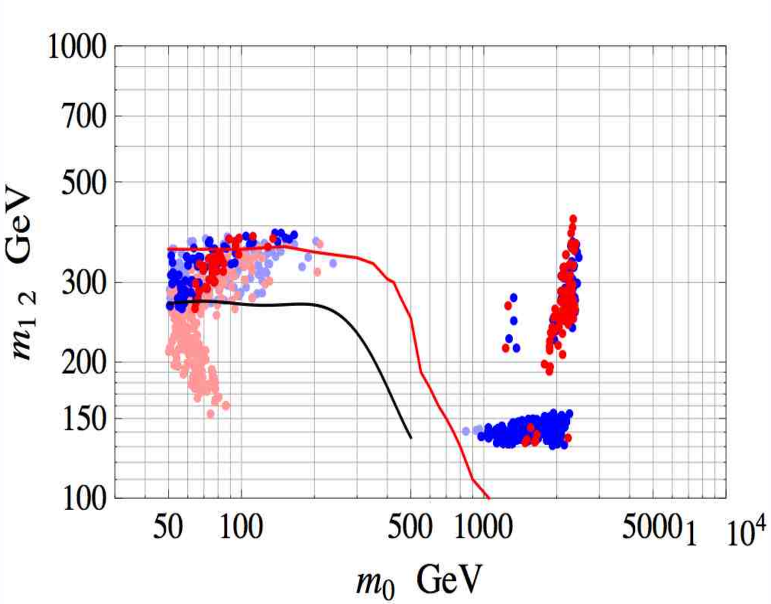
Atlas is already testing CMSSM points with $\Delta < 100$ and $m_h > 114$ GeV.

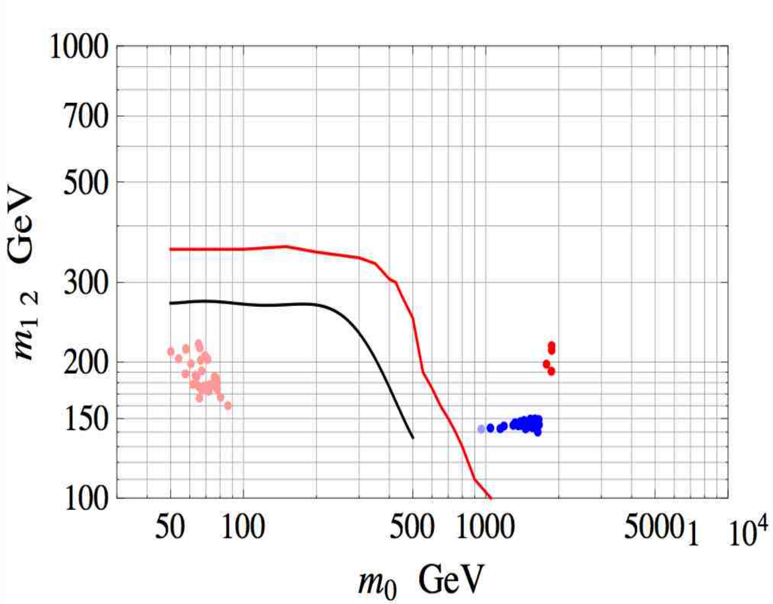
⇒ $m_h < 121$ GeV, $m_0 < 3200$, $120 < m_{1/2} < 720$, $\mu < 680$, $-2000 < A_0 < 2500$, GeV, $\tan\beta > 5.5$

$\chi_1^0 < 305$, $\chi_2^0 < 550$, $\chi_3^0 < 660$, $\chi_4^0 < 665$, $\chi_1^\pm < 550$, $\chi_2^\pm < 670$, $\tilde{g} < 1700$, $\tilde{t}_1 < 2080$, $\tilde{t}_2 < 2660$

$\tilde{b}_1 < 2660$, $\tilde{b}_2 < 3140$ GeV

• 2-loop results in CMSSM: min Δ & the LHC @ 7 TeV reach. [S. Cassel, DG, G. Ross]





⇒ Left: points $\Delta < 50$: blue: consistent with WMAP (3σ deviation); red: saturate it within 3σ.

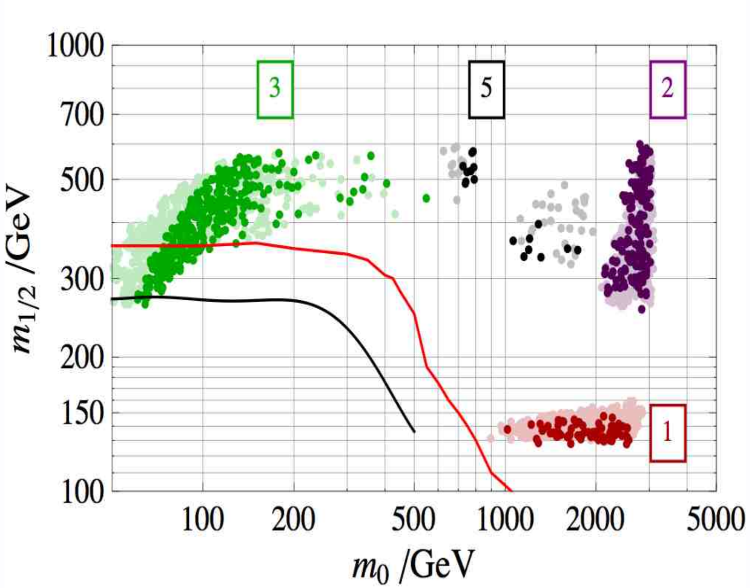
Points in lighter (darker) red/blue have m_h below (above) LEP2 bound for m_h.

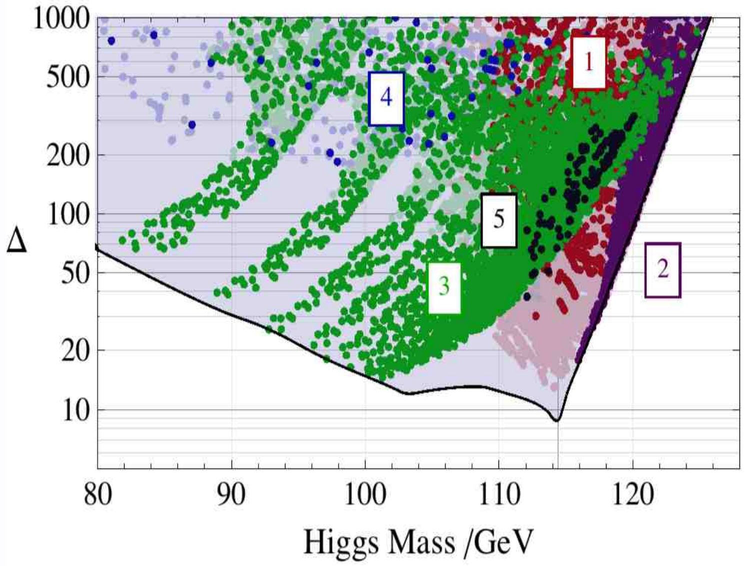
⇒ Right: points $\Delta < 20$.

⇒ small(er) area in moduli space $(m_0, m_{1/2})$: not an indication/measure of (large) fine-tuning!

"moduli fixing" $\neq$ fine tuning

- Two-loop results in CMSSM: min Δ and LHC @ 7 TeV reach; $m_h > 114$ GeV.





$\Delta < 100$; dark colours: Ωh^2 within 3σ; light colours: below this bound.

LHC 7 TeV: $\mathcal{O}(1)$ fb^{-1}; $m_{\tilde{g}} \sim 1.1$ TeV if $m_{\tilde{q}} \sim m_{\tilde{g}}$; $m_{\tilde{g}} \sim 620$ GeV, $m_{\tilde{q}} \gg m_{\tilde{g}}$ [Baer, Barger, Tata, Lessa]

- purple: LSP: higgsino 10%, heavy squarks
- red: LSP: bino-like, heavy squarks (TeV), focus point region.
- green: LSP: bino-like. light squarks. [S. Cassel, DG, S. Kraml, G. Ross, A. Lessa]

• How do these results m_h change under "new physics" ?

- large(r) m_h at low Δ ?

(a). to relax CMSSM constraints (gaugino univ); symmetries... [Kane, King, Ross, Horton, 09]

(b). "new physics" beyond MSSM, that increases m_h and reduces Δ: $U(1)'$, extra S, D of SU(2)...

Effective approach: MSSM Higgs+ effective operators $(X_{n,i})$

$$\mathcal{L} = \mathcal{L}_{MSSM}^{Higgs} + \sum_{n\geq 1,i} \frac{\rho_{n,i}}{M_*^n} X_{n,i}, \quad \rho_{i,n} \sim \mathcal{O}(1); \quad M_* : \text{scale of ''new physics''}$$

$X_{n,i}$ effective operators, parametrize new physics beyond MSSM Higgs sector.

- generated in renormalisable theories, after integrating some massive states.

• We consider: (d=5), (d=6) operators; corrections to m_h?

$$\mathcal{L}_{MSSM}^{Higgs} + \mathcal{L}_i(\propto 1/M_*) + \mathcal{O}_i(\propto 1/M_*^2)$$

- d=5 operators beyond MSSM Higgs: [DG, Antoniadis, Dudas, Tziveloglou]

$$\mathcal{L}_1 = \frac{1}{M_*}\int d^2\theta\; \zeta(S)\,(H_2.H_1)^2 + h.c., \qquad [S,T]$$

$$\mathcal{L}_2 = \frac{1}{M_*}\int d^4\theta\; \Big\{ a(S,S^\dagger) D^\alpha\Big[b(S,S^\dagger)\, H_2\, e^{-V_1}\Big] D_\alpha\Big[c(S,S^\dagger)\, e^{V_1}\, H_1\Big] + h.c.\Big\}, \quad [D]$$

- d=6 operators:

$$\mathcal{O}_i = \frac{1}{M_*^2}\int d^4\theta\; \mathcal{Z}_i(S,S^\dagger)\;(H_i^\dagger\, e^{V_i}\, H_i)^2, \qquad i=1,2. \qquad (T,U(1))$$

$$\mathcal{O}_3 = \frac{1}{M_*^2}\int d^4\theta\; \mathcal{Z}_3(S,S^\dagger)\;(H_1^\dagger\, e^{V_1}\, H_1)\,(H_2^\dagger\, e^{V_2}\, H_2), \qquad (T,U(1))$$

$$\mathcal{O}_4 = \frac{1}{M_*^2}\int d^4\theta\; \mathcal{Z}_4(S,S^\dagger)\;(H_2\, H_1)\,(H_2\, H_1)^\dagger, \qquad (S)$$

$$\mathcal{O}_5 = \frac{1}{M_*^2}\int d^4\theta\; \mathcal{Z}_5(S,S^\dagger)\;(H_1^\dagger\, e^{V_1}\, H_1)\,(H_2\, H_1 + h.c.), \qquad (2\,D,S)$$

$$\mathcal{O}_6 = \frac{1}{M_*^2}\int d^4\theta\; \mathcal{Z}_6(S,S^\dagger)\;(H_2^\dagger\, e^{V_2}\, H_2)\,(H_2\, H_1 + h.c.), \qquad (2\,D,S)$$

$$\mathcal{O}_7 = \frac{1}{M_*^2}\int d^2\theta\; \frac{1}{16\kappa\, g_i^2}\mathcal{Z}_7(S,0)\;\mathrm{Tr}\, W_i^\alpha\, W_{i,\alpha}\,(H_2\, H_1) + h.c.,$$

$$\mathcal{O}_8 = \frac{1}{M_*^2}\int d^4\theta\; \Big[\mathcal{Z}_8(0,S^\dagger)\;(H_2\, H_1)^2 + h.c.\Big]$$

- Other operators:

$$\mathcal{O}_9 = \frac{1}{M_*^2}\int d^4\theta\ \mathcal{Z}_9(S,S^\dagger)\ H_1^\dagger\,\overline{\nabla}^2\,e^{V_1}\,\nabla^2\,H_1$$

$$\mathcal{O}_{10} = \frac{1}{M_*^2}\int d^4\theta\ \mathcal{Z}_{10}(S,S^\dagger)\ H_2^\dagger\,\overline{\nabla}^2\,e^{V_2}\,\nabla^2\,H_2$$

$$\mathcal{O}_{11} = \frac{1}{M_*^2}\int d^4\theta\ \mathcal{Z}_{11}(S,S^\dagger)\ H_1^\dagger\,e^{V_1}\,\nabla^\alpha\,W_\alpha^{(1)}\,H_1$$

$$\mathcal{O}_{12} = \frac{1}{M_*^2}\int d^4\theta\ \mathcal{Z}_{12}(S,S^\dagger)\ H_2^\dagger\,e^{V_2}\,\nabla^\alpha\,W_\alpha^{(2)}\,H_2$$

$$\mathcal{O}_{13} = \frac{1}{M_*^2}\int d^4\theta\ \mathcal{Z}_{13}(S,S^\dagger)\ H_1^\dagger\,e^{V_1}\,W_\alpha^{(1)}\nabla^\alpha\,H_1$$

$$\mathcal{O}_{14} = \frac{1}{M_*^2}\int d^4\theta\ \mathcal{Z}_{14}(S,S^\dagger)\ H_2^\dagger\,e^{V_2}\,W_\alpha^{(2)}\nabla^\alpha\,H_2$$

$$\mathcal{O}_{15} = \frac{1}{M_*^2}\int d^4\theta\ \mathcal{Z}_{15}(S,S^\dagger)\ \mathrm{Tr}\,e^V\,W^\alpha\,e^{-V}\,D^2\,e^V\,W_\alpha\,e^{-V}$$

where $\nabla_\alpha H_i \equiv e^{-V_i}\,D_\alpha\,e^{V_i}\,H_i$, $\quad V_i = V_W^a\,\sigma^i/2 + (\mp 1/2)\,V_Y; \quad i=1,2$.

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

$\Rightarrow$ $\mathcal{L}_2$, $\mathcal{O}_{9,\ldots,15}$ removed by field redefinitions up to wavefunction ren, redefinition of soft terms, μ!

$$\Rightarrow \quad \mathcal{L}_{total} = \mathcal{L}_{MSSM}^{Higgs} + \mathcal{L}_1 + \sum_{i=1}^{8}\mathcal{O}_i$$

• Comment: removing redundant operators: [DG, Antoniadis, Dudas]

$$\mathcal{O}_9 \;=\; \frac{1}{M_*^2}\int d^4\theta\; \mathcal{Z}_9(S,S^\dagger)\; H_1^\dagger\,\overline{\nabla}^2\, e^{V_1}\,\nabla^2\, H_1 \sim \frac{1}{M_*^2}\int d^4\theta\, H_1^\dagger \Box\, H_1 \supset -(1/M_*^2)\, h_1^*\Box^2\, h_1 - h_1^*\Box h_1 \cdots .....$$

• $\mathcal{L} = \int d^4\theta\; \Phi^\dagger\,(1+\Box/M_*^2)\,\Phi + \Big[\int d^2\theta\; W(\Phi) + h.c.\Big],\qquad \Phi^\dagger\Box\Phi \to (-1/16)\overline{D}^2\Phi^\dagger D^2\Phi$

$$\Phi = a_1\Phi_1 + a_2\Phi_2$$

$$(1/m)\,\overline{D}^2\Phi^\dagger = b_1\Phi_1 + b_2\Phi_2 \;\;\Rightarrow\qquad \delta\mathcal{L} = \int d^2\theta\,\Big[(1/m)\,\overline{D}^2(a_1\,\Phi_1 + a_2\,\Phi_2)^\dagger - (b_1\Phi_1 + b_2\,\Phi_2)\Big]\Phi_3\,\frac{m^2}{4\,M_*}$$

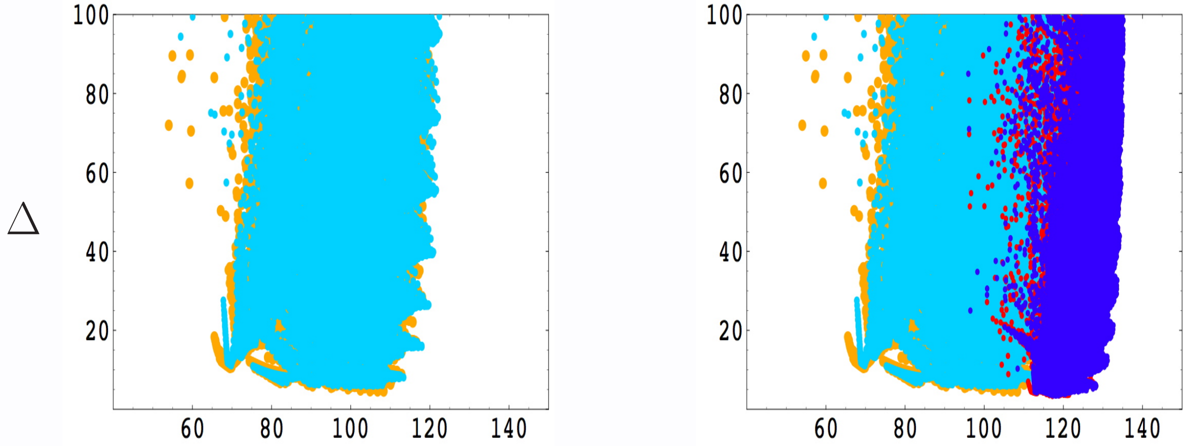
$$\Rightarrow\;\; \mathcal{L}+\delta\mathcal{L} = \int d^4\theta\Big[\tilde\Phi_1^\dagger\tilde\Phi_1 - \tilde\Phi_2^\dagger\tilde\Phi_2 - \tilde\Phi_3^\dagger\tilde\Phi_3\Big] + \int d^2\theta\;\Big[(-M_*)\,\tilde\Phi_2\tilde\Phi_3 + W(\Phi(\tilde\Phi_{1,2}))\Big] + h.c. + \mathcal{O}(1/M_*^3)$$

where $\Phi = \tilde\Phi_2 - \tilde\Phi_1$; then integrate $\tilde\Phi_{1,2}$ (massive):

$$\mathcal{L}+\delta\mathcal{L} = \int d^4\theta\Big[\tilde\Phi_1^\dagger\tilde\Phi_1 - \frac{1}{M_*^2}W'^\dagger(\tilde\Phi_1)W'(\tilde\Phi_1)\Big] + \int d^2\theta\, W(\tilde\Phi_1) + h.c.$$

MSSM+$\mathcal{O}_9$: $\int d^4\theta\, W'^\dagger\, W' \to \int d^4\theta\,(\mu^2/M_*^2)\;H_2^\dagger\, H_2$: wavefunc ren (Susy broken: soft terms ren)

- Fine-tuning in MSSM + (d=5) operator: $\mathcal{L}_1 = \int d^2\theta\, (\zeta_0 + \zeta_1 S)(H_1.H_2)^2$ [Cassel, DG, Ross]



MSSM m_h MSSM+$\mathcal{L}_1$, $\mu_0\zeta_0 = 0.035$, $\zeta_1 = 0$

$$m^2_{h,H} = \left(m_h^2 \right)^{1-loop}_{MSSM} + 2\zeta_0\, \mu_0\; v^2 \sin 2\beta \left(1 \pm \frac{m_A^2 + m_Z^2}{\sqrt{w}}\right) + \zeta_1\, m_0 v^2 \left(1 \mp \frac{(m_A^2 - m_Z^2)\cos^2 2\beta}{\sqrt{w}}\right) + \delta m_h^2$$

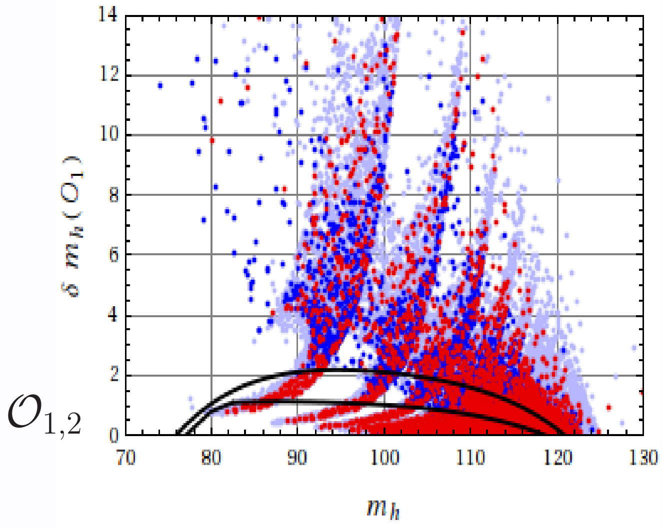
where $\zeta_0,\ \zeta_1 \sim \mathcal{O}(1/M_*)$, $\delta m_h^2 = \mathcal{O}(1/M_*^2)$, $w \equiv [m_A^2 + m_Z^2]^2 - 4 m_A^2 m_Z^2 \cos^2 2\beta$

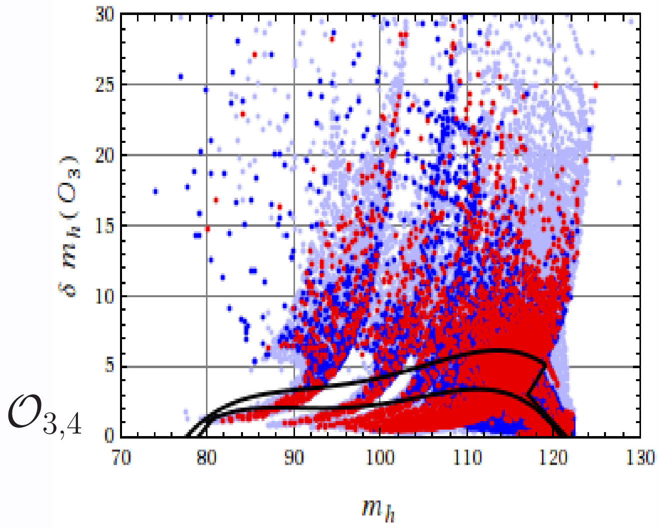
$\Rightarrow$ $\Delta < 10$, $114.4 \leq m_h \leq 130$ GeV, $M_* \approx 1/\zeta_0 \approx 65 \times \mu_0 = 5$ to 10 TeV, $\tan\beta < 6$.

$\Rightarrow$ (d=5) op: massive singlet: $S\, H_1\, H_2 + M_* S^2$. Re-do analysis in NMSSM with $M_* S^2$ F-term.

$\Rightarrow$ At large $\tan\beta$: d=6 operators relevant: $\lambda \propto (2\mu_0\, \zeta_0)^2 \sim (2\, \zeta_0 \mu_0)/\tan\beta \Rightarrow (2\mu_0\zeta_0) < 1/\tan\beta$

- d=6 effective operators: corrections to m_h $(\alpha_{jk} \sim 1/M_*^2)$





$$\delta\, m_h^2 \;=\; -2\,v^2 \Big[\alpha_{22}\, m_0^2 + (\alpha_{30}+\alpha_{40})\mu_0^2 + 2\alpha_{61}\, m_0\,\mu_0 - \alpha_{20}\, m_Z^2\Big] - \frac{(2\,\zeta_0\,\mu_0)^2\;v^4}{m_A^2 - m_Z^2}$$
$$+\frac{v^2}{\tan\beta}\bigg[\frac{1}{(m_A^2-m_Z^2)}\Big(4\,m_A^2\,\big((2\alpha_{21}+\alpha_{31}+\alpha_{41}+2\alpha_{81})\,m_0\,\mu_0+(2\alpha_{50}+\alpha_{60})\,\mu_0^2+\alpha_{62}\,m_0^2\big)$$
$$-(2\alpha_{60}-3\alpha_{70})\,m_A^2\,m_Z^2-(2\alpha_{60}+\alpha_{70})\,m_Z^4\Big)+\frac{8\,(m_A^2+m_Z^2)\;(\mu_0\,m_0\,\zeta_0\,\zeta_1)\,v^2}{(m_A^2-m_Z^2)^2}\bigg]+\mathcal{O}\Big[\frac{\tilde m^2}{M_*^2\tan^2\beta}\Big]$$

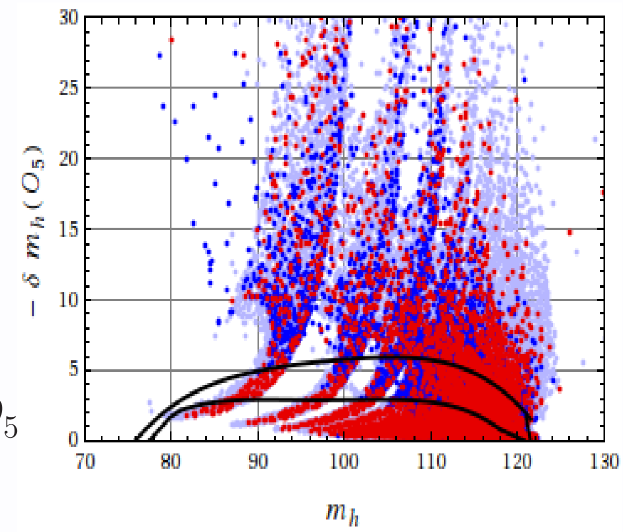
$\Rightarrow \quad \delta m_h = \big(m_h^2 + \delta m_h^2\big)^{1/2} - m_h = (1/2)\ (\delta m_h^2/m_h) + \mathcal{O}(1/M_*^4) \qquad m_h$: MSSM 2-loop LL value

$\Rightarrow$ lower curve: $\Delta < 100$: $m_h < 121$ GeV, $\delta m_h < 4$ GeV. $M_* = 8$ TeV. note: $\alpha_{j0}\tilde m \leq 1/4$

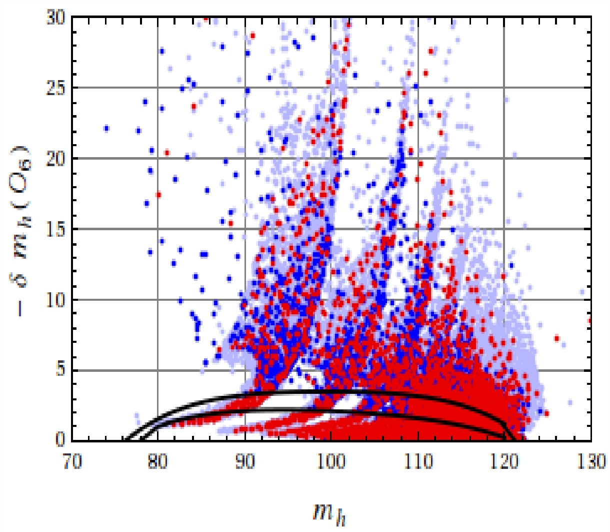
$\Rightarrow$ top curve: $\Delta < 200$: $m_h < 122$ GeV, $\delta m_h < 6$ GeV. $\pm 1\,\mathrm{GeV}\ (\delta m_h) \leftrightarrow \mp 1$ TeV (δM_*).

• d=6 effective operators: corrections to m_h, $(\alpha_{jk} \sim 1/M_*^2)$

$\mathcal{O}_5$



$\mathcal{O}_6$



$\rho - 1 = -(v^2/M_*^2)\left[\alpha_{10}\cos^4\beta + \alpha_{20}\sin^4\beta - \alpha_{30}\sin^2\beta\cos^2\beta\right] + \mathcal{O}(v^4/M_*^4)$, $M_* \sim 8$ TeV [Blum et al]

$\Rightarrow$ large $\tan\beta$: larger α_{30}, α_{10} allowed $\Rightarrow$ α_{30}, α_{40} largest SUSY correction to m_h

$$\mathcal{O}_3 \sim \alpha_{30} \int d^4\theta\ (H_1^\dagger e^{V_1} H_1)(H_2^\dagger e^{V_2} H_2),\ [T, U(1)] \quad \mathcal{O}_4 \sim \alpha_{40} \int d^4\theta\ (H_2 H_1)(H_2 H_1)^\dagger,\ [S]$$

$\Rightarrow$ difficult to generate α_{30}, α_{40} with the "right" sign, by integrating massive $T, U(1), S$ in ren model

$\Rightarrow$ neutralino mass corrections very small (LSP): $\sim \mu/M_* \sim$ few (≤ 1 to 2 GeV)!

$\Rightarrow$ $\Delta = 18$ (3σ WMAP), $m_h = 115.9 \pm 2$ GeV $\Rightarrow$ $m_h + \delta m_h = 119.9 \pm 2$ GeV, $\Delta' = \Delta \frac{m_h^2}{(m_h + \delta m_h)^2}$

- Conclusions:

- Hierarchy problem $\leftrightarrow$ fine tuning. Test of SUSY.

$\Rightarrow$ min Δ + DM consistency, in constrained MSSM, but no LEP2 bound on m_h:

$$m_h = 114 \pm 2 \quad \text{GeV}, \quad \Delta \approx 9, \quad \text{(no DM constraint)}.$$
$$m_h = 115.9 \pm 2 \;\; \text{GeV}, \quad \Delta = 17.8, \quad \text{(WMAP within } 3\sigma\text{)}.$$

$\Rightarrow$ Δ minimal at LEP2 bound! similar result if using Δ' (quadrature).

$\Rightarrow$ QCD does not like large m_h without fine-tuning cost: $\Delta < 100$ (1000), $m_h < 121$ (126) GeV.

- Beyond MSSM Higgs with all effective operators of d=5, d=6 (new U(1)'s, S, D...):

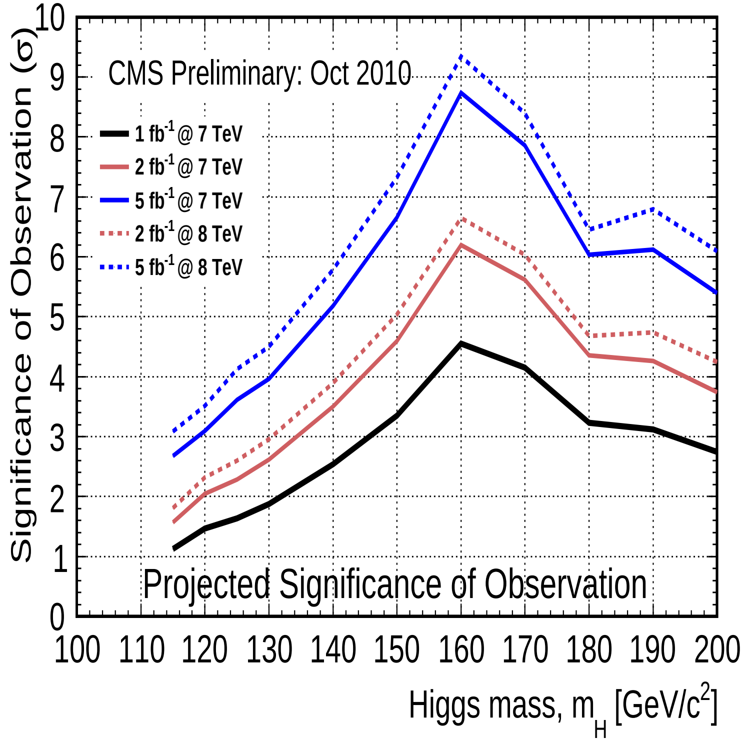
$\Rightarrow$ d=5 operators: small $\Delta < 10$ allowed for $114.4 \leq m_h \leq 130$ GeV. Massive S? NMSSM with $M_* S^2$

$\Rightarrow$ d=6 operators:

Points of $\Delta < 100$ (200) $\Rightarrow$ SUSY $\delta m_h \leq 4$ GeV (6 GeV). $M_* = 8$ TeV; (± 1 GeV for ∓ 1 TeV)

Extra U(1) or S ?

- CMS significance of observation



- Our CMSSM spectrum and parameter space.

	SUG0	SUG1	SUG2	SUG3	SUG5
m_0	1455	1508	2270	113	725
$m_{1/2}$	160	135	329	383	535
A_0	238	1492	30	-220	1138
$\tan\beta$	22.5	22.5	35	15	50
μ	191	433	187	529	581
$m_{\tilde{g}}$	482	414	900	898	1252
$m_{\tilde{u}_L}$	1469	1509	2331	826	1315
$m_{\tilde{t}_1}$	876	831	1423	602	1000
$m_{\tilde{\chi}_1^+}$	106	104	168	293	416
$m_{\tilde{\chi}_2^0}$	108	104	181	293	416
$m_{\tilde{\chi}_1^0}$	60	53	123	155	222
Δ	9	50	45	68	84
$\Omega_{\tilde{\chi}_1^0} h^2$	0.41	0.13	0.10	0.13	0.10
10^4 BR$(b \to s\gamma)$	3.4	3.7	3.4	3.2	3.2
10^9 BR$(B_s \to \mu\mu)$	3.0	2.9	2.9	3.4	1.7
$\delta a_\mu \times 10^{10}$	4.5	3.2	3.2	22.5	16.6

CMSSM parameters, sparticle masses (GeV) for regions 1,...5

- The favoured CMSSM spectrum of minimal $\Delta = 15$ consistent with Ωh^2.

h^0	114.7	$\tilde{\chi}_1^0$	79	$\tilde{b}_1$	1147	$\tilde{u}_L$	1444
H^0	1264	$\tilde{\chi}_2^0$	142	$\tilde{b}_2$	1369	$\tilde{u}_R$	1446
$H^\pm$	1267	$\tilde{\chi}_3^0$	255	$\tilde{\tau}_1$	1328	$\tilde{d}_L$	1448
A^0	1264	$\tilde{\chi}_4^0$	280	$\tilde{\tau}_2$	1368	$\tilde{d}_R$	1446
$\tilde{g}$	549	$\tilde{\chi}_1^\pm$	142	$\tilde{\mu}_L$	1406	$\tilde{s}_L$	1448
$\tilde{\nu}_\tau$	1366	$\tilde{\chi}_2^\pm$	280	$\tilde{\mu}_R$	1406	$\tilde{s}_R$	1446
$\tilde{\nu}_\mu$	1404	$\tilde{t}_1$	873	$\tilde{e}_L$	1406	$\tilde{c}_L$	1444
$\tilde{\nu}_e$	1404	$\tilde{t}_2$	1158	$\tilde{e}_R$	1406	$\tilde{c}_R$	1446

(focus point region).

- Generating d=5 operators beyond the MSSM the Higgs sector:

- $\mathcal{L}_1$?: massive gauge singlet Σ or SU(2) triplet ($M_* \gg \mu$):

$$\mathcal{L} \supset \int d^4\theta\, \Sigma^\dagger \Sigma + \int d^2\theta\, \Big[\mu\, H_1.H_2 - M_*\, \Sigma^2 + \lambda\, \Sigma\, H_1\, H_2\Big] + h.c. \quad \Rightarrow \quad \mathcal{L}_1 = \frac{1}{4M_*}\int d^2\theta\ \lambda^2\ (H_1.H_2)^2 + h.c.$$

- $\mathcal{L}_2$?: massive Higgs doublets $H_{3,4}$ beyond MSSM $H_{1,2}$

$$\begin{aligned}\mathcal{L} \;=\;& \int d^4\theta\, \Big[\sum_{j=1,3} \big(H_j^\dagger\, e^{V_1}\, H_j + H_{j+1}^\dagger\, e^{V_2}\, H_{j+1}\big) + \big(\nu_1 H_1^\dagger\, e^{V_1}\, H_3 + \nu_2\, H_2^\dagger\, e^{V_2}\, H_4 + h.c.\big)\Big];\\ &+ \int d^2\theta\, \big[\mu\, H_1\, H_2 + M_*\, H_3\, H_4\big] + h.c.; \qquad -\frac{1}{4}\overline{D}^2\big[H_3^\dagger\, e^{V_1}\big] - \frac{1}{4}\overline{D}^2\big[\nu_1\, H_1^\dagger\, e^{V_1}\big] + M_*\, H_4 = 0\ (H_3)\end{aligned}$$

$$\Rightarrow\ \mathcal{L}_2 = \int d^4\theta\Big[\sum_{j=1,2} H_j^\dagger\, e^{V_j}\, H_j + \Big(\frac{\nu_1\,\nu_2}{4\,M_*}\ H_2\, e^{-V_1}\, D^2\, e^{V_1}\, H_1 + h.c.\Big)\Big] + \Big[\int d^2\theta\ \mu\, H_1.\, H_2 + h.c.\Big]$$

$$H_2\, e^{-V_1}\, D^2\, e^{V_1}\, H_1 \;\sim\; D^\alpha\,\big[H_2\, e^{-V_1}\big]\, D_\alpha\, e^{V_1}\, H_1.$$

- ? “onshell”: $D^2\,\big[\,e^{V_1}\, H_1\,\big] = 4\,\mu\, H_2^\dagger \quad \Rightarrow$ wavefunc ren only. [Politzer, Georgi, Dixon, Taylor]

• Removing redundant operators by field redefinitions: [Antoniadis, Dudas, DG, Tziveloglou]

$$\mathcal{L}_1 = \frac{1}{M_*}\int d^2\theta\ \zeta(S)\,(H_2.H_1)^2 + h.c., \qquad [S,T]$$
$$\mathcal{L}_2 = \frac{1}{M_*}\int d^4\theta\ \Big\{ a(S,S^\dagger) D^\alpha\Big[b(S,S^\dagger)\,H_2\,e^{-V_1}\Big] D_\alpha\Big[c(S,S^\dagger)\,e^{V_1}\,H_1\Big] + h.c.\Big\}, \quad [D]$$

$$\frac{1}{M_*}\zeta(S) = \zeta_0 + \zeta_1\,m_0\,\theta\theta, \qquad \zeta_0,\ \zeta_1 \sim 1/M_*,$$
$$a(S,S^\dagger) = a_0 + a_1\,S + a_1^*\,S^\dagger + a_2\,S\,S^\dagger, \qquad S = \theta\theta\,m_0,\ \text{spurion}$$

$\Rightarrow$ $\mathcal{L}_2$ removed by general non-linear, field redefinitions in $\mathcal{L}_{MSSM}$

$$H_1 \to H_1 - \frac{1}{M_*}\overline{D}^2\Big[\delta_1(S,S^\dagger)\ H_2^\dagger\,e^{V_2}\,(i\sigma_2)\Big]^T$$
$$H_2 \to H_2 + \frac{1}{M_*}\overline{D}^2\Big[\delta_2(S,S^\dagger)\,H_1^\dagger\ e^{V_1}\,(i\sigma_2)\Big]^T$$

$\delta_1 = s_0 + s_1\,S + s_2\,S^\dagger + s_3\,S\,S^\dagger$, $\quad \delta_2 = s_0' + s_1'\,S + s_2'\,S^\dagger + s_3'\,S\,S^\dagger$, $\quad F$: U^c, D^c, E^c

$\mathcal{L}_2$ removed by suitably chosen s_i, s_i'. $\Rightarrow$ soft terms & μ-term redefinition: $\Rightarrow$ only $\mathcal{L}_1$ left (d=5)

- Other physical consequences:

$$\mathcal{L}_{MSSM} \supset \int d^2\theta \left[H_2\, Q\, \lambda_U(S)\, U^c + Q\, \lambda_D(S)\, D^c\, H_1 + L\, \lambda_E(S)\, E^c\, H_1 + \mu(S)\, H_1\, H_2\right] + h.c.$$

$$H_1 \;\rightarrow\; H_1 - \frac{1}{M_*}\overline{D}^2\left[\delta_1(S,S^\dagger)\; H_2^\dagger\, e^{V_2}\,(i\sigma_2)\right]^T$$
$$H_2 \;\rightarrow\; H_2 + \frac{1}{M_*}\overline{D}^2\left[\delta_2(S,S^\dagger)\, H_1^\dagger\; e^{V_1}\,(i\sigma_2)\right]^T$$

$$\Rightarrow\;\; \mathcal{L}_{eff} \;\supset\; -\frac{1}{M_*}\int d^4\theta\,\left[H_1^\dagger\, e^{V_1}\, Q\,\lambda_U(S) U^c + H_2^\dagger\, e^{V_2}\,(Q\,\lambda_D(S) D^c) + H_2^\dagger\, e^{V_2}\,(L\,\lambda_E(S) E^c) + h.c.\right]$$

$\Rightarrow$ "wrong"-Higgs couplings:

$$\frac{m_0}{M_*}(\lambda_U(0))_{ij}\;(h_1^\dagger\, q_{L\,i})\; u^c_{R\,j} + \frac{m_0}{M_*}(\lambda_D(0))_{ij}\;(h_2^\dagger\, q_{L\,i})\; d^c_{R\,j} + \frac{m_0}{M_*}(\lambda_E(0))_{ij}\;(h_2^\dagger\, l_{L\,i})\; e^c_{R\,j} + h.c.,$$

$$\Rightarrow\;\; m_b = \frac{v\cos\beta}{\sqrt{2}}\,\lambda_b\left(1 + \frac{\delta\lambda_b}{\lambda_b} + \frac{\Delta\lambda_b\tan\beta}{\lambda_b}\right)$$

"Wrong"-Higgs couplings also in MSSM at 1-loop:

[Haber, Mason; Pokorski, Hall, Pierce, Katz].