Natural Electroweak Symmetry Breaking in NMSSM

and Higgs at 100 GeV

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EWSB in MSSM

Minimum of the Higgs potential:

$$\frac{1}{2} m_Z^2 = -\mu^2 + \frac{m_{H_d}^2 - \tan^2\beta\, m_{H_u}^2}{\tan^2\beta - 1}\,, \qquad \tan\beta = \frac{v_u}{v_d}$$

$\tan\beta = 10$:

$$\begin{aligned} m_Z^2 \simeq\ & -2.0\ \mu^2(0) + 5.9\ M_3^2(0) + 0.8\ m_Q^2(0) + 0.6\ m_u^2(0) \\ & -1.2\ m_{H_u}^2(0) - 0.7\ M_3(0) A_t(0) + \ldots \end{aligned}$$

Without specific relations between SSB parameters and/or μ:

$$m_Z \sim M_3(0),\ m_Q(0),\ m_u(0) \sim m_{\tilde{g}},\ m_{\tilde{t}}$$

natural EWSB $\rightarrow$ light gluino and stop!

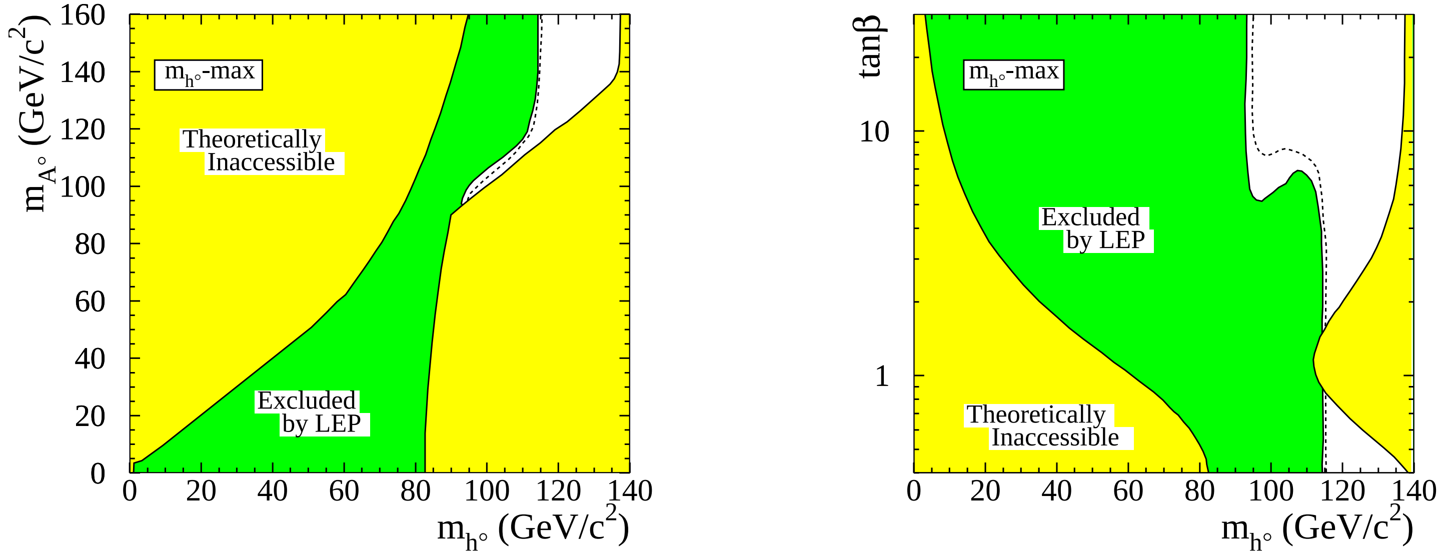
Higgs Mass in MSSM

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} v^2 y_t^4 \sin^4 \beta \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \dots$$

$$m_h^2 \simeq (91\mathrm{GeV})^2 + (38\mathrm{GeV})^2 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

LEP limit: $m_h \gtrsim 115$ GeV

LHWG-Note 2004-01



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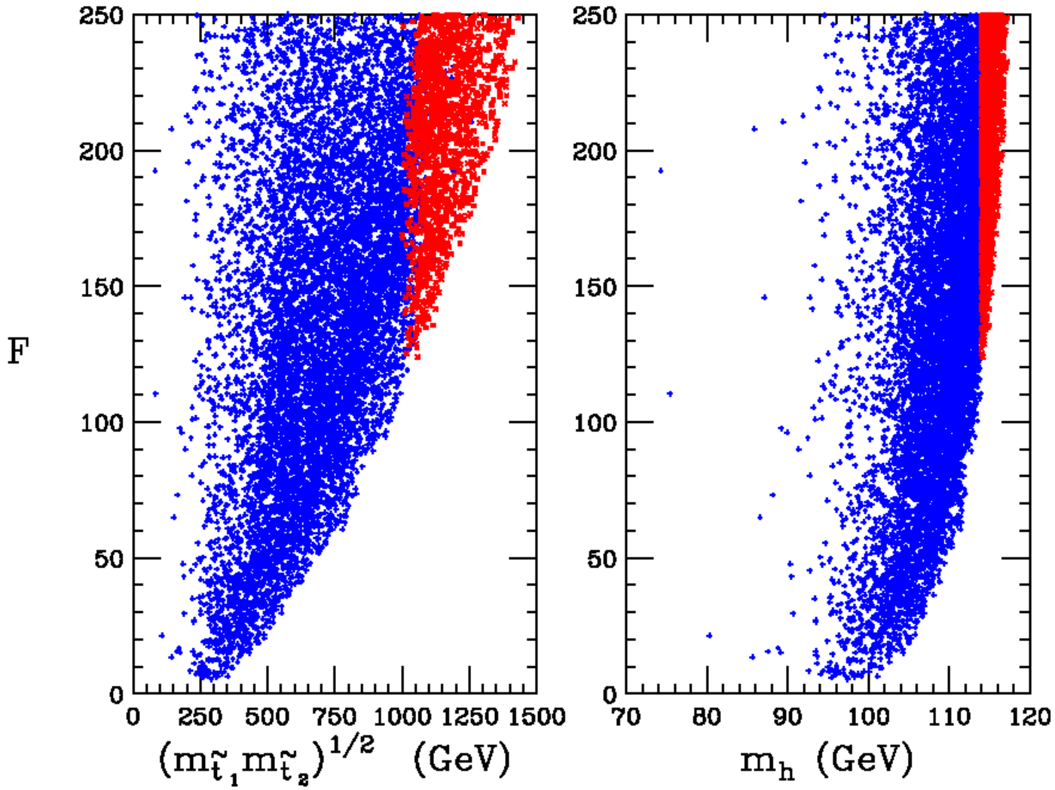
$$m_h^2 \simeq (91\mathrm{GeV})^2 + (38\mathrm{GeV})^2 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

LEP limit: $m_h \gtrsim 115$ GeV

$$m_{\tilde{t}_1} m_{\tilde{t}_2} \gtrsim (\ 900\,\mathrm{GeV}\ )^2$$

LEP $\rightarrow$ heavy stop!

Little Hierarchy Problem in MSSM



$+\ m_h < 115$ GeV

$\times\ m_h > 115$ GeV

$M_1(m_Z) = 100$ GeV

$M_2(m_Z) = 200$ GeV

$M_3(m_Z) = 300$ GeV

$\tan\beta = 10$

other SSB parameters

randomly generated

$$m_Z^2 = \frac{1}{2}(g_2^2 + g'^2)(v_u^2 + v_d^2)$$
$$v_u = v_u(a),\ v_d = v_d(a)$$

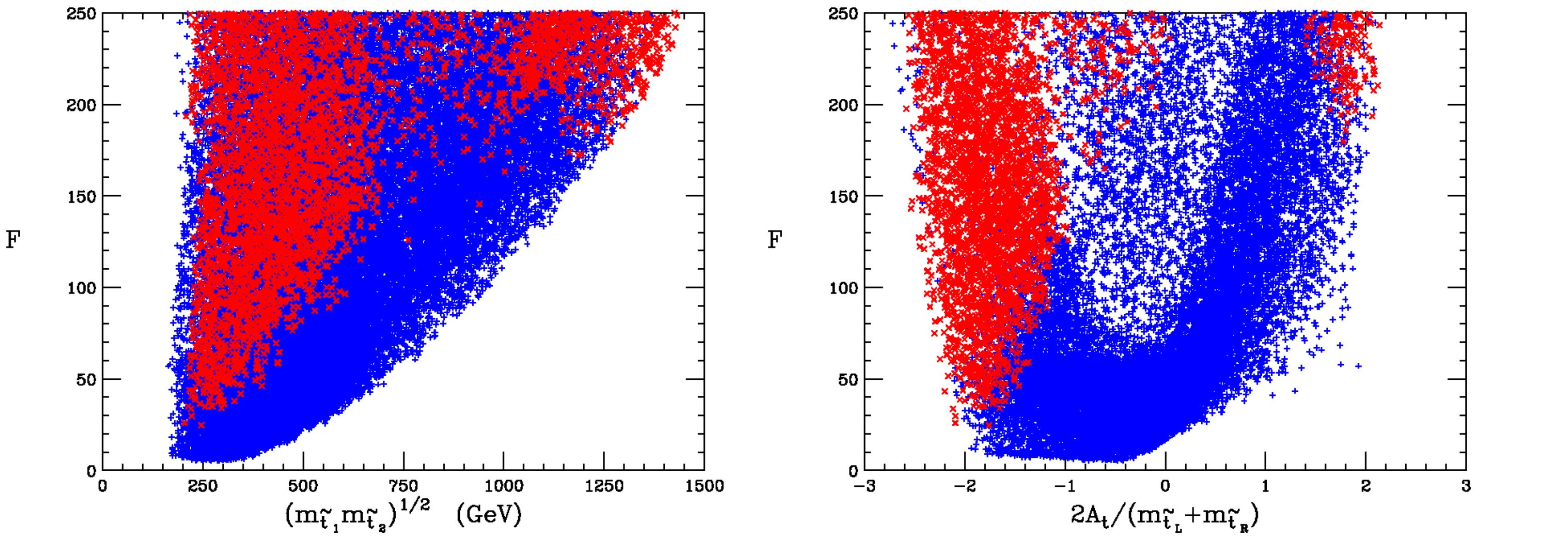
Fine tuning measure:

$$F = \max_p F_p = \max_p \left| \frac{p}{m_Z} \frac{dm_Z}{dp} \right|$$

$$p \in \{M_i(0), i = 1,2,3; m_s^2(0), s = Q, u, d, L, e, H_u, H_d; A_t(0), \mu(0), B_\mu(0)\}$$

Little Hierarchy Problem in MSSM

Large A_t: $\mathcal{L}^{SSB} \supset \lambda_t A_t \tilde{Q} \tilde{\bar{u}} H_u$



NMSSM - brief review

MSSM + one additional singlet superfield (results in one CP-even and one CP-odd neutral Higgs bosons, and one additional neutralino):

$$W = W_{MSSM} + \lambda \, \widehat{S} \widehat{H}_u \widehat{H}_d + \frac{\kappa}{3} \, \widehat{S}^3$$

$$\mathcal{L}^{SSB} = \mathcal{L}^{SSB}_{MSSM} + \lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3 + m_S^2 S S^*$$

$$\tan\beta = \frac{v_u}{v_d}\,, \quad \mu_{eff} = \lambda s$$

$$m_Z^2 = \tfrac{1}{2}(g_2^2 + g'^2)(v_u^2 + v_d^2)$$

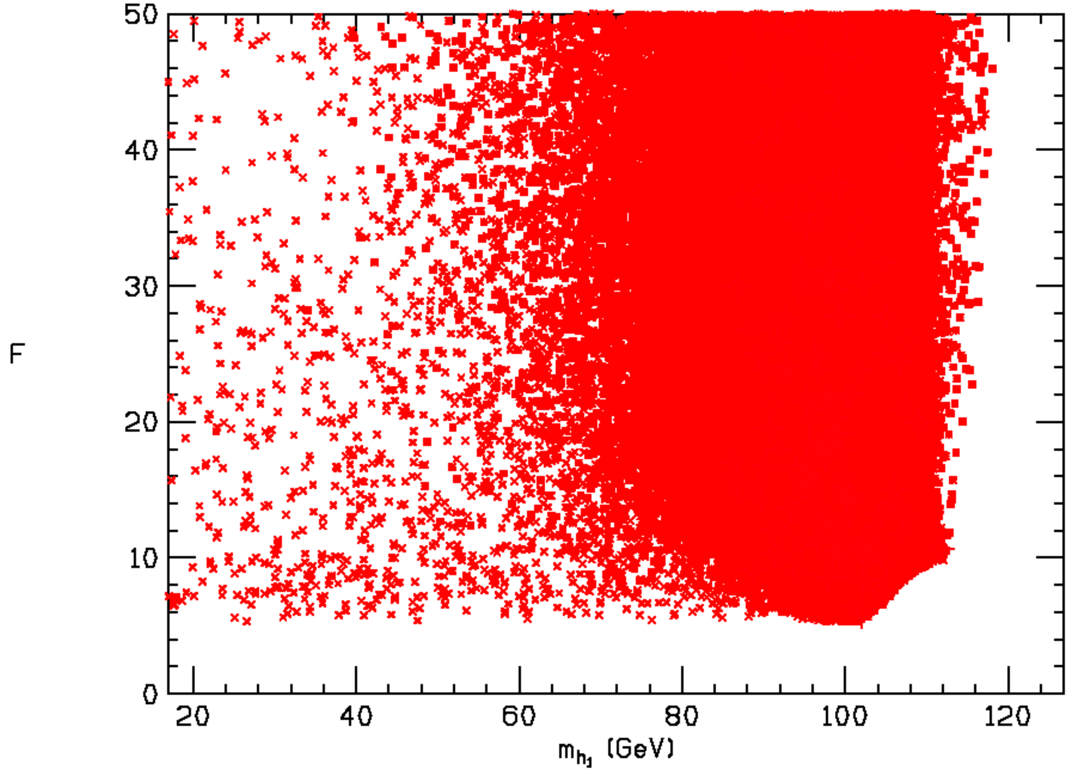
$m_{H_u}^2$, $m_{H_d}^2$, m_S^2 determined by 3 minimization eqs. of the scalar potential

Higgs mass at tree level:

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + m_Z^2 \frac{2\lambda^2}{g_2^2 + g'^2} \sin^2 2\beta$$

Natural Higgs mass in NMSSM

$\tan\beta = 10,\ M_3(M_Z) = 300$ GeV



- no constraints

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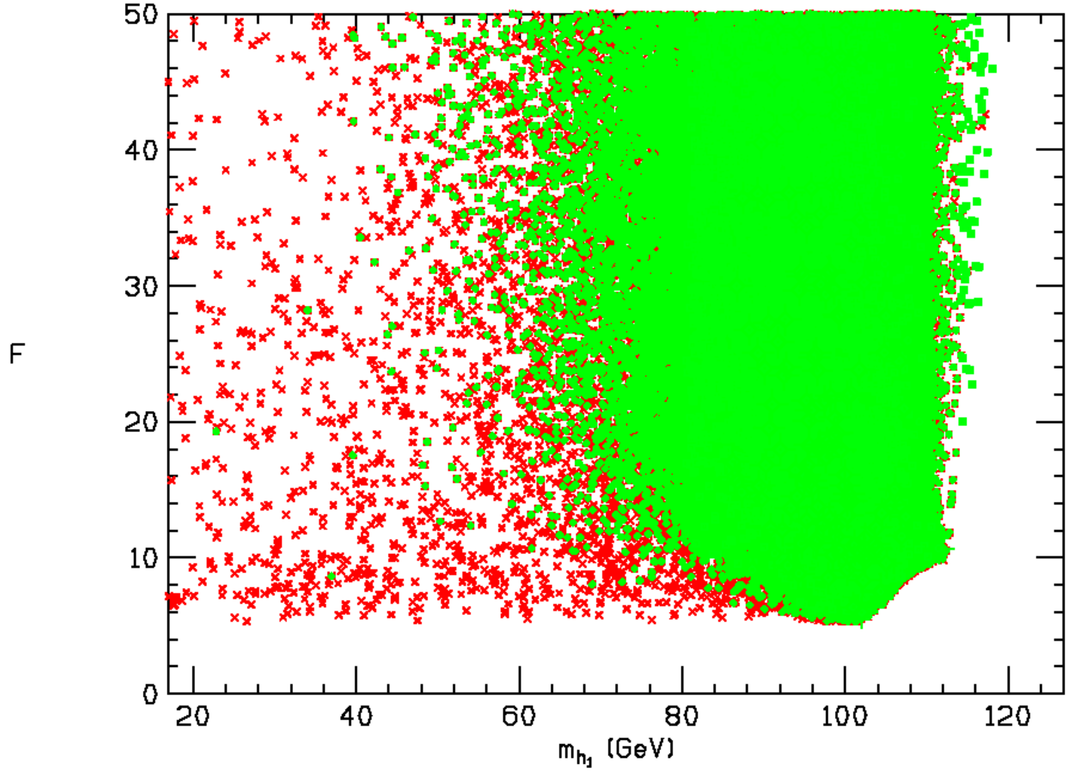

• no constraints

• SUSY constraints

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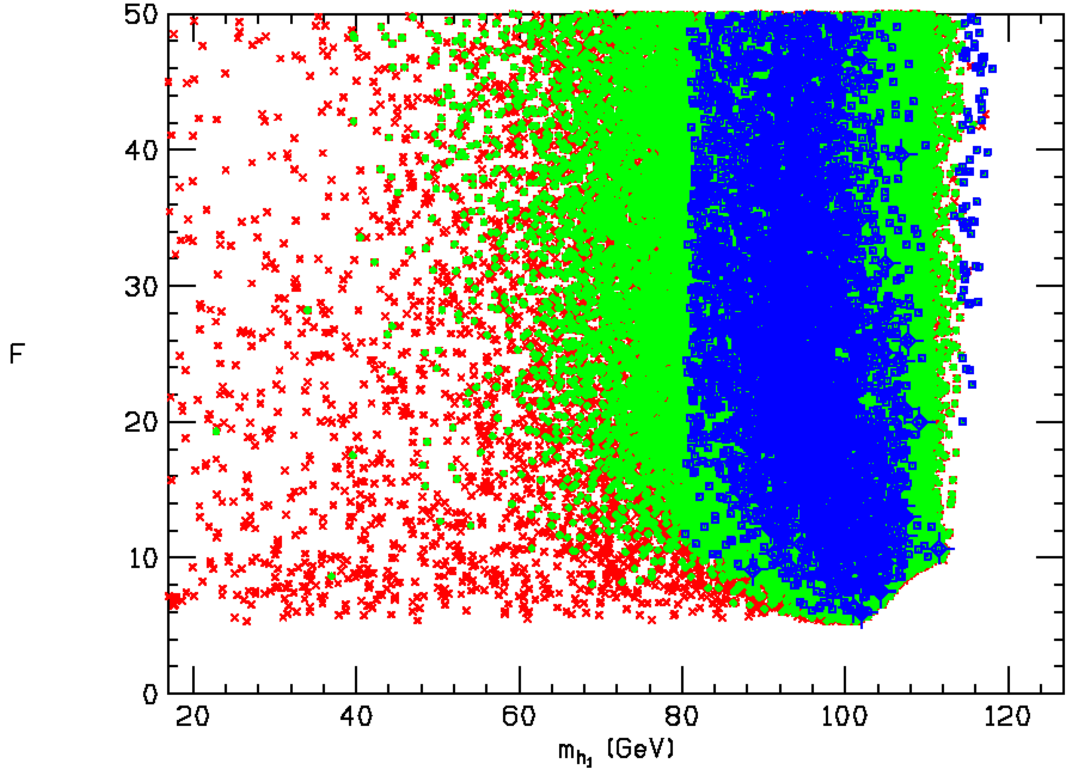

- no constraints
- SUSY constraints
- $m_h > 114$ GeV or $h \to aa$

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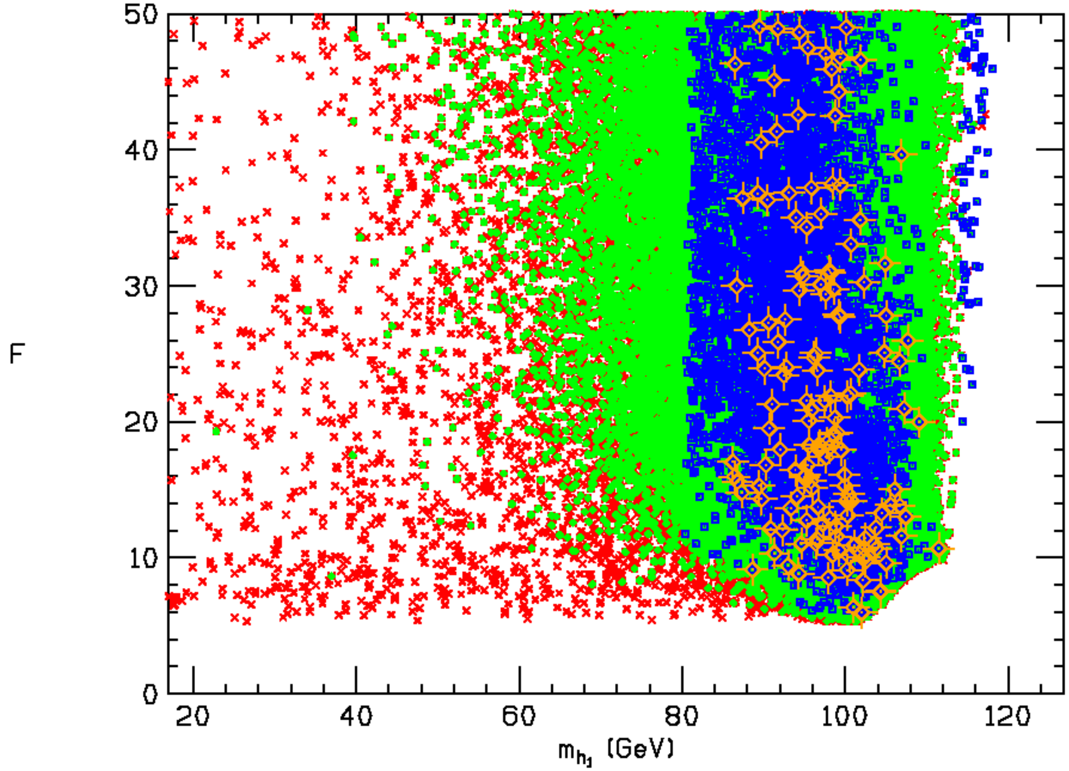

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- $h \to aa,\ m_a < 2m_b$

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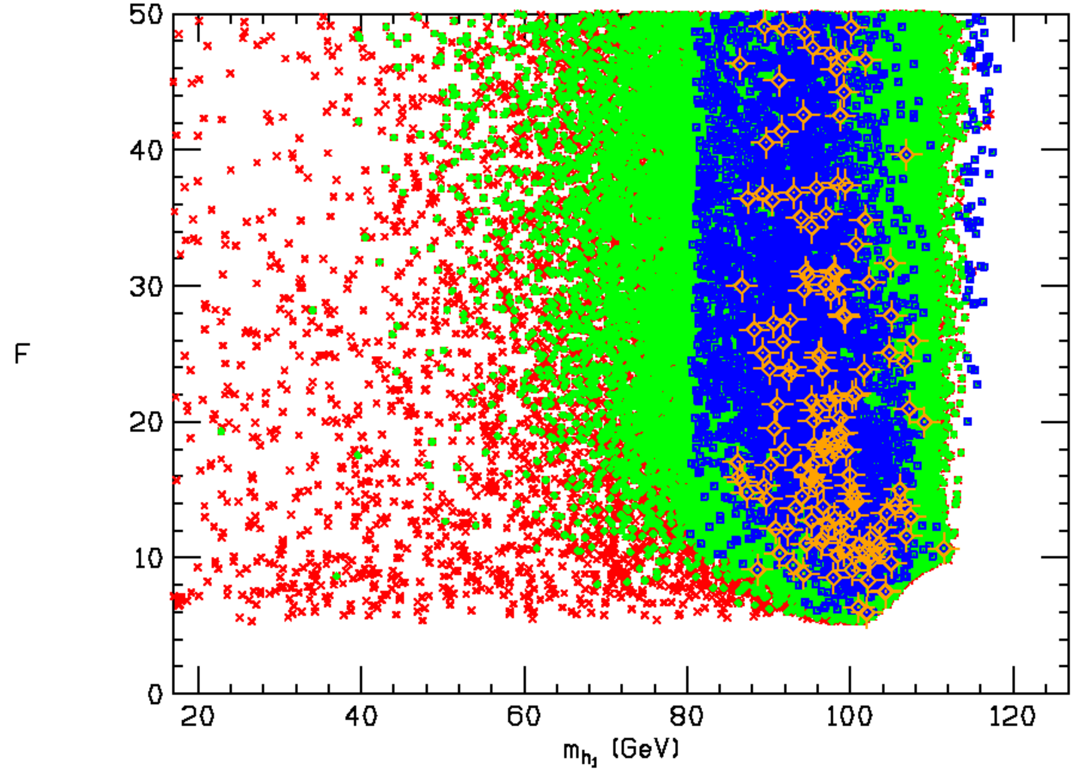

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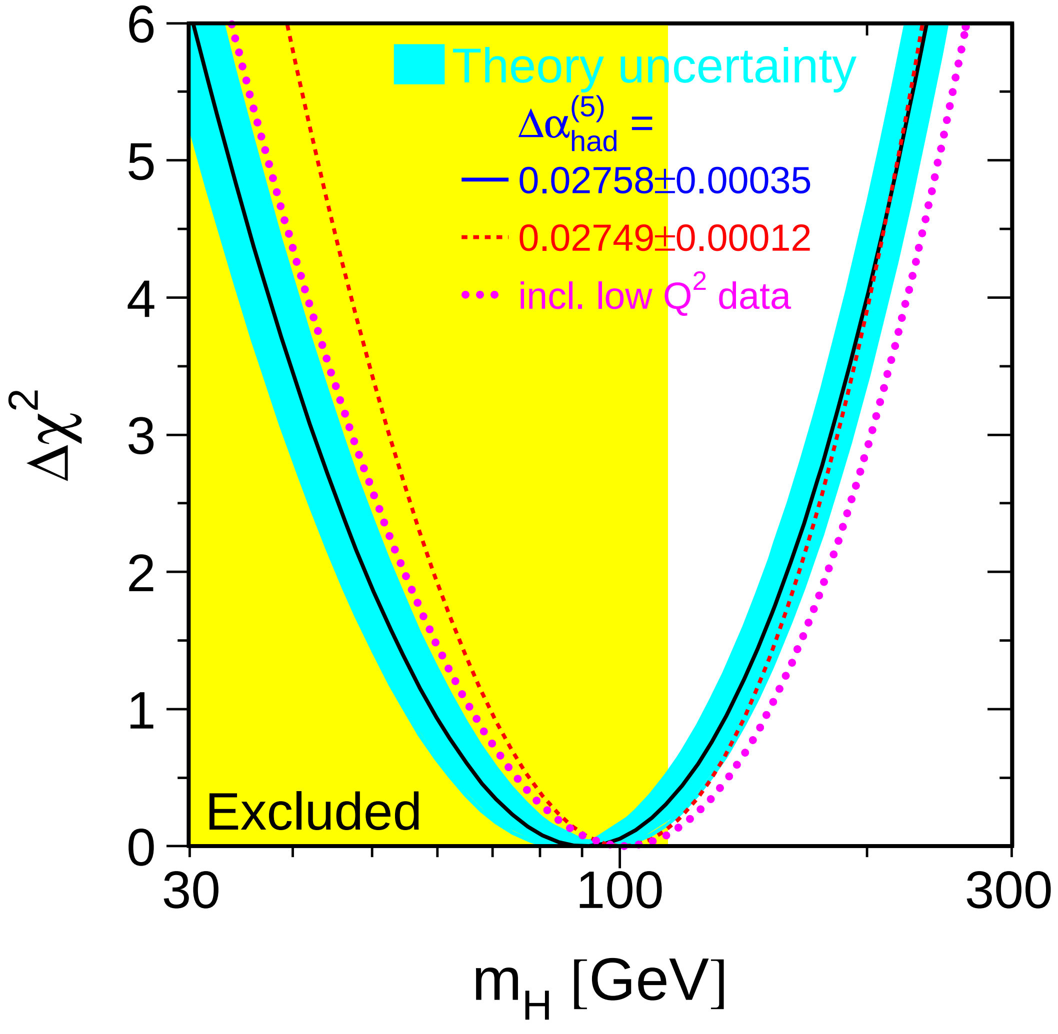
Maybe Higgs is at ~ 100 GeV

Precision electroweak data



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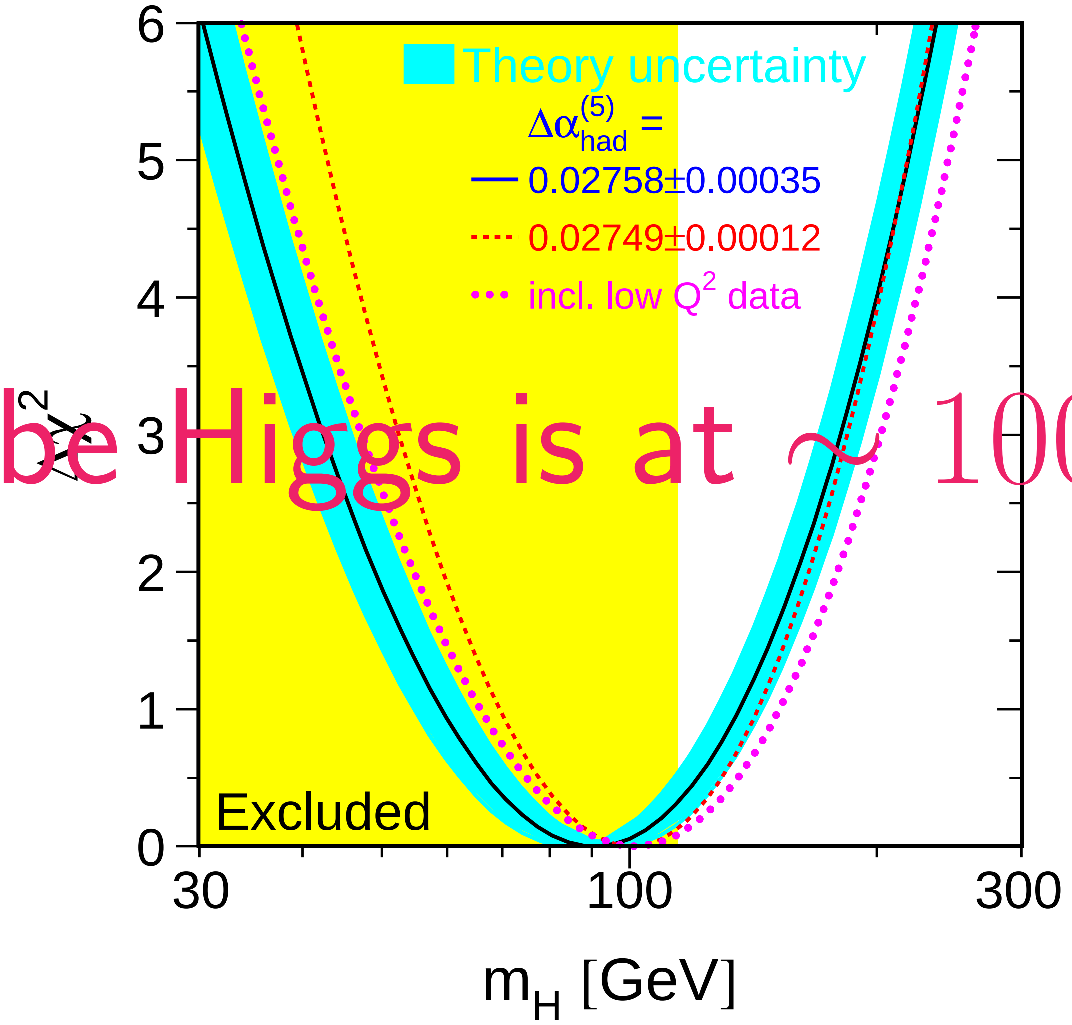
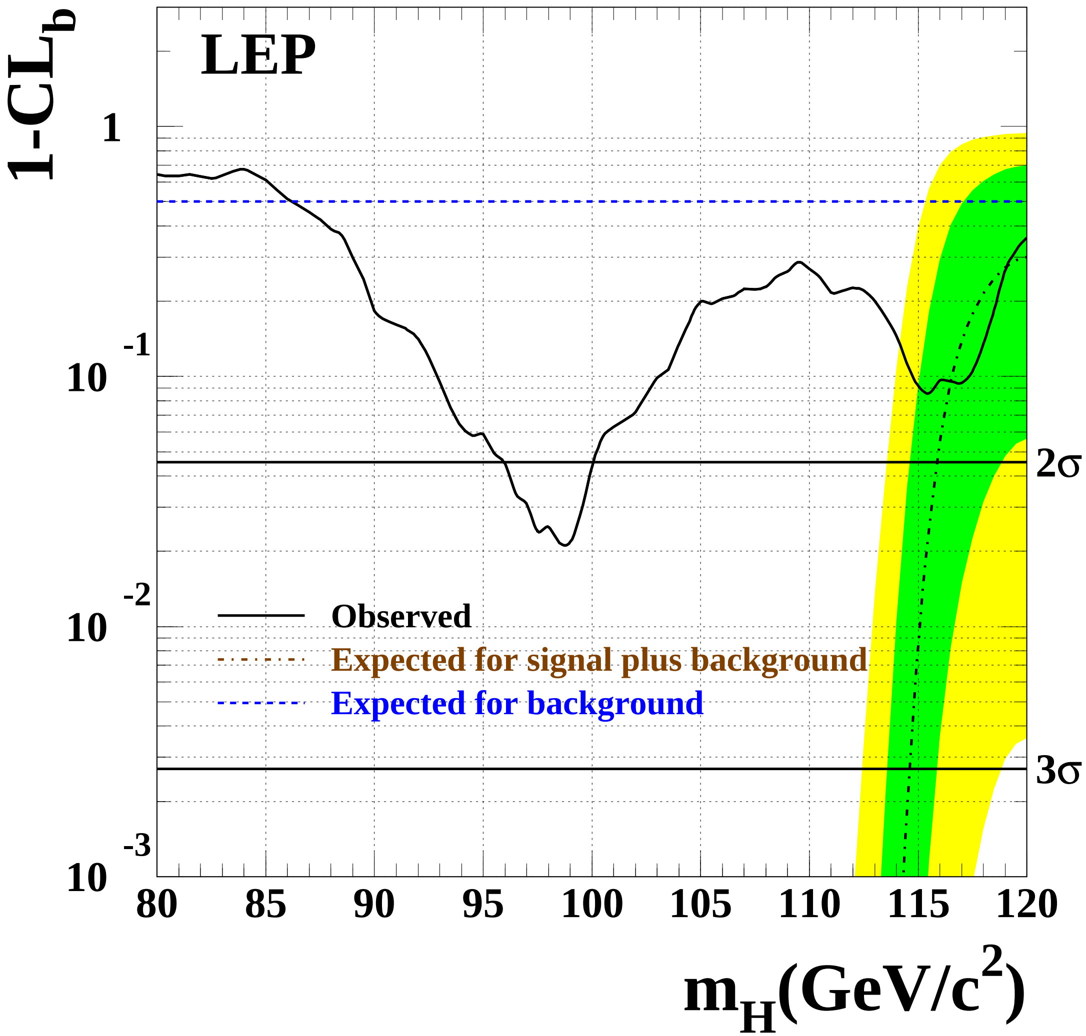


Maybe Higgs is at ~ 100 GeV

Search for the SM Higgs at LEP

LHWG-2003-011



Search for the SM Higgs at LEP

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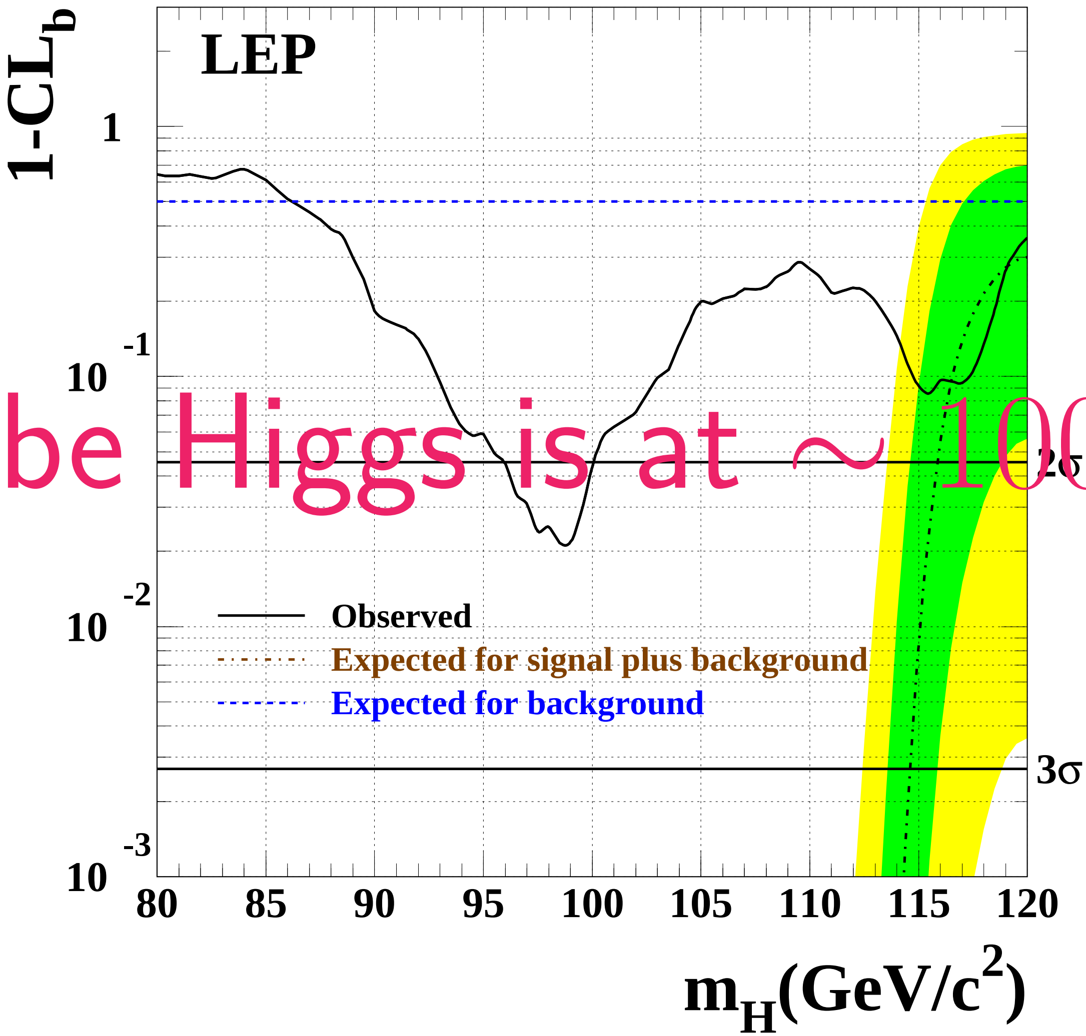
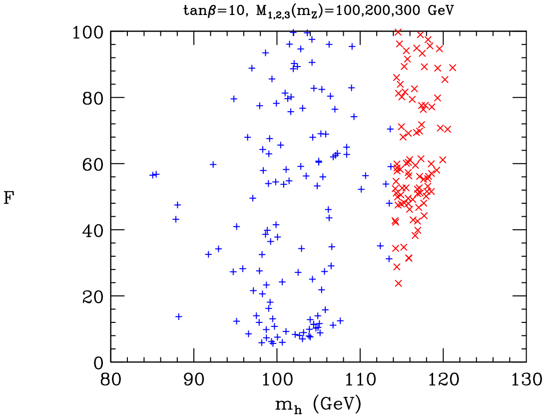


Maybe Higgs is at ~ 100 GeV

Explaining $m_h \sim 100$ GeV excess

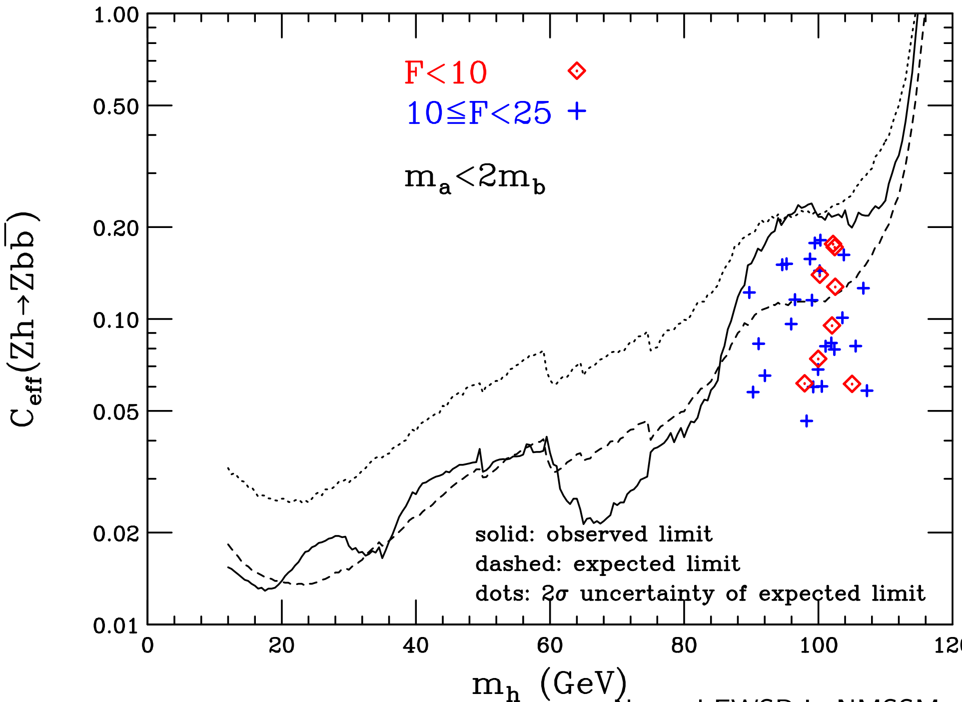
m_{h_1}/m_{a_1} (GeV)	Branching Ratios $h_1 \to b\bar{b}$	$h_1 \to a_1 a_1$	$a_1 \to \tau^+\tau^-$	n_{obs}/n_{exp} units of 1σ	$s95$	N_{SD}^{LHC}
98.0/2.6	0.062	0.926	0.000	2.25/1.72	2.79	1.2
100.0/9.3	0.075	0.910	0.852	1.98/1.88	2.40	1.5
100.2/3.1	0.141	0.832	0.000	2.26/2.78	1.31	2.5
102.0/7.3	0.095	0.887	0.923	1.44/2.08	1.58	1.6
102.2/3.6	0.177	0.789	0.814	1.80/3.12	1.03	3.3
102.4/9.0	0.173	0.793	0.875	1.79/3.03	1.07	3.6
102.5/5.4	0.128	0.848	0.938	1.64/2.46	1.24	2.4
105.0/5.3	0.062	0.926	0.938	1.11/1.52	2.74	1.2



$$n_{obs} = (1 - CL_b)_{observed}$$
$$n_{exp} = (1 - CL_b)_{expected}$$

thanks to P. Bechtle, LHWG

$$C_{eff}^{2b} = [g^2_{ZZh}/g^2_{ZZh_{SM}}]B(h \to b\bar{b})$$



Is light CP-odd Higgs natural?

V_{NMSSM} has $U(1)_R$ symmetry in the limit $A_\lambda, A_\kappa \to 0$

B. A. Dobrescu and K. T. Matchev, hep-ph/0008192

Superpotential is $U(1)_R$ invariant for $R_S = 1/2\ R_{H_u H_d}$:

$$W \ = \ W_{MSSM} + \lambda\, \widehat{S}\widehat{H}_u\widehat{H}_d + \frac{\kappa}{3}\ \widehat{S}^3$$

$U(1)_R$ spontaneously broken by v_u, v_d, $s \longrightarrow$ NG boson!

A_λ, A_κ explicitely break $U(1)_R$:

$$\mathcal{L}^{SSB} \ = \ \mathcal{L}^{SSB}_{MSSM} + \lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3 + m_S^2 S S^*$$

$$m_{a_1} \ \propto \ A_\kappa, \ \ A_\lambda$$

$U(1)_R$ also broken by gaugino masses (effect at 1-loop level)

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$$m_{a_1}^2 \simeq 3s \left(\kappa A_\kappa \sin^2\theta_A + \frac{3\lambda A_\lambda \cos^2\theta_A}{2\sin 2\beta} \right)$$

$$a_1 \equiv \cos\theta_A \, a_{MSSM} + \sin\theta_A \, a_S \qquad \cos\theta_A \simeq \frac{2v}{s\tan\beta}$$

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RG running:

A_κ , $A_\lambda \simeq 0$ at M_{GUT}

$$dA_\lambda/dt = \left(-6A_t\lambda_t^2 + 8\lambda^2 A_\lambda - 4\kappa^2 A_\kappa - 6g_2^2 M_2 - (6/5)g_1^2 M_1\right)/(16\pi^2)$$

$$dA_\kappa/dt = 12\left(-\lambda^2 A_\lambda + \kappa^2 A_\kappa\right)/(16\pi^2)$$

$A_\kappa \ll A_\lambda \simeq O(M_2)$ at M_Z

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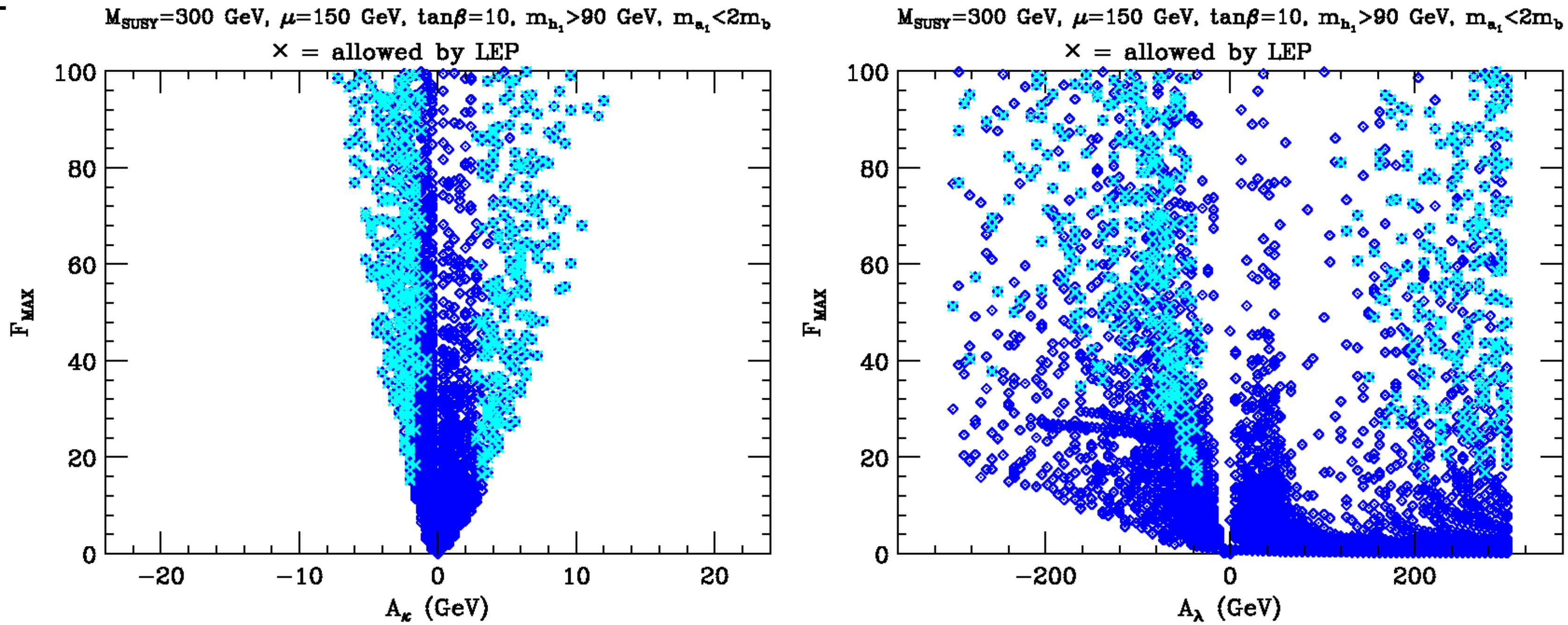
$$a_1 \equiv \cos\theta_A\, a_{MSSM} + \sin\theta_A\, a_S \qquad \cos\theta_A \simeq \frac{2v}{s\tan\beta}$$

A_κ and A_λ terms comparable for: $\cos\theta_A \ll 1$, equivalent to $a_1 \simeq a_s$

$m_{a_1} < m_{h_1}/2$, mostly singlet, is natural!

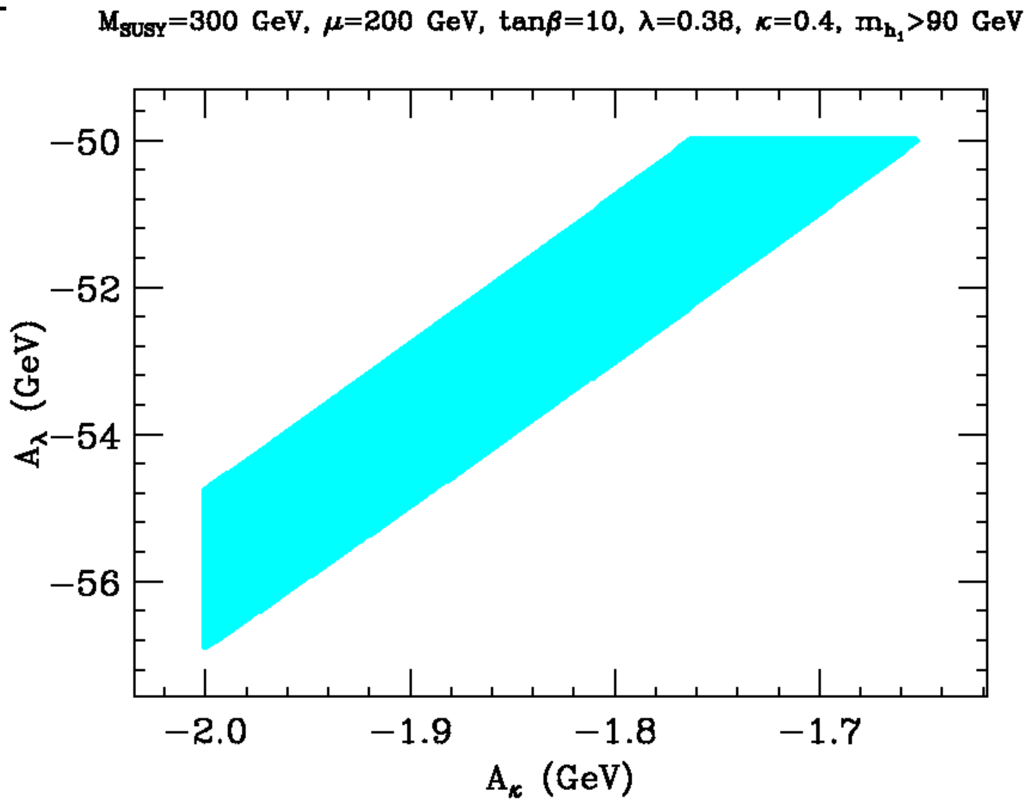
Is light CP-odd Higgs natural?



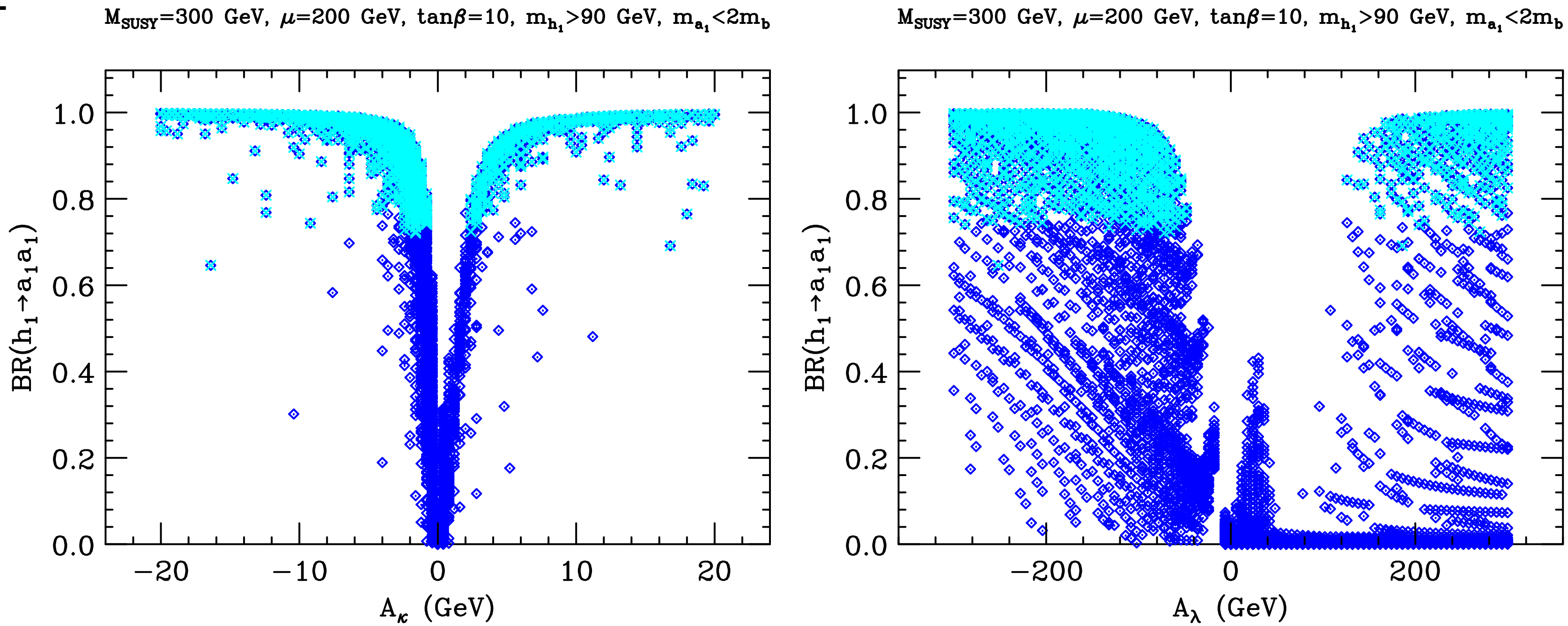
$$F_{MAX} = \max\left\{\left|\frac{A_\lambda}{m_a^2}\frac{dm_a^2}{dA_\lambda}\right|, \left|\frac{A_\kappa}{m_a^2}\frac{dm_a^2}{dA_\kappa}\right|\right\}$$

5 - 10 % tuning of A_κ to A_λ is required for $m_a < 2m_b$!

Is light CP-odd Higgs natural?



$Br(h \to aa)$ vs. A_κ and A_λ



haa coupling:

$$\supset c_\lambda A_\lambda + c_\kappa A_\kappa$$

for $|A_\kappa| \gtrsim$ few GeV, $h \to aa$ always dominates

no additional constraints from $Br(h \to aa)$

Conclusions

- Higgs $\lesssim 100$ GeV
  - wanted by SUSY/natural EWSB
  - preferred by precision EW data
  - "indicated" by LEP data
  - possible and natural in NMSSM!

$h \to aa \to \tau^+\tau^-\tau^+\tau^-$, $B(h \to aa) \sim 0.9$

$h \to b\bar{b}$, $B(h \to b\bar{b}) \sim 0.1$

can fully explain $\sim 2\sigma$ excess

Conclusions

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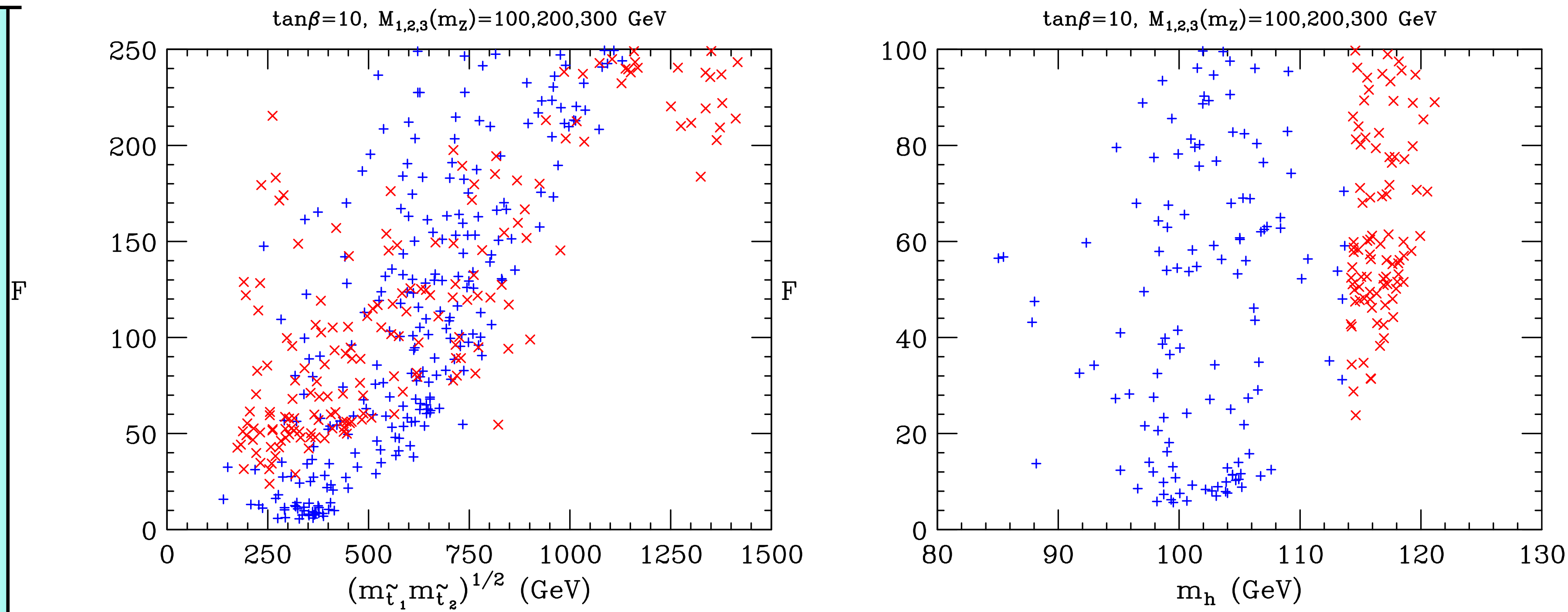
can fully explain $\sim 2\sigma$ excess

- important to study Higgs to Higgs decays at LEP, Tevatron and LHC
- similar results to be expected in many SUSY models with more complicated Higgs sector than that of CP conserving MSSM

Fine Tuning in NMSSM, $\tan\beta = 10$



+ escapes LEP because $h \to aa$

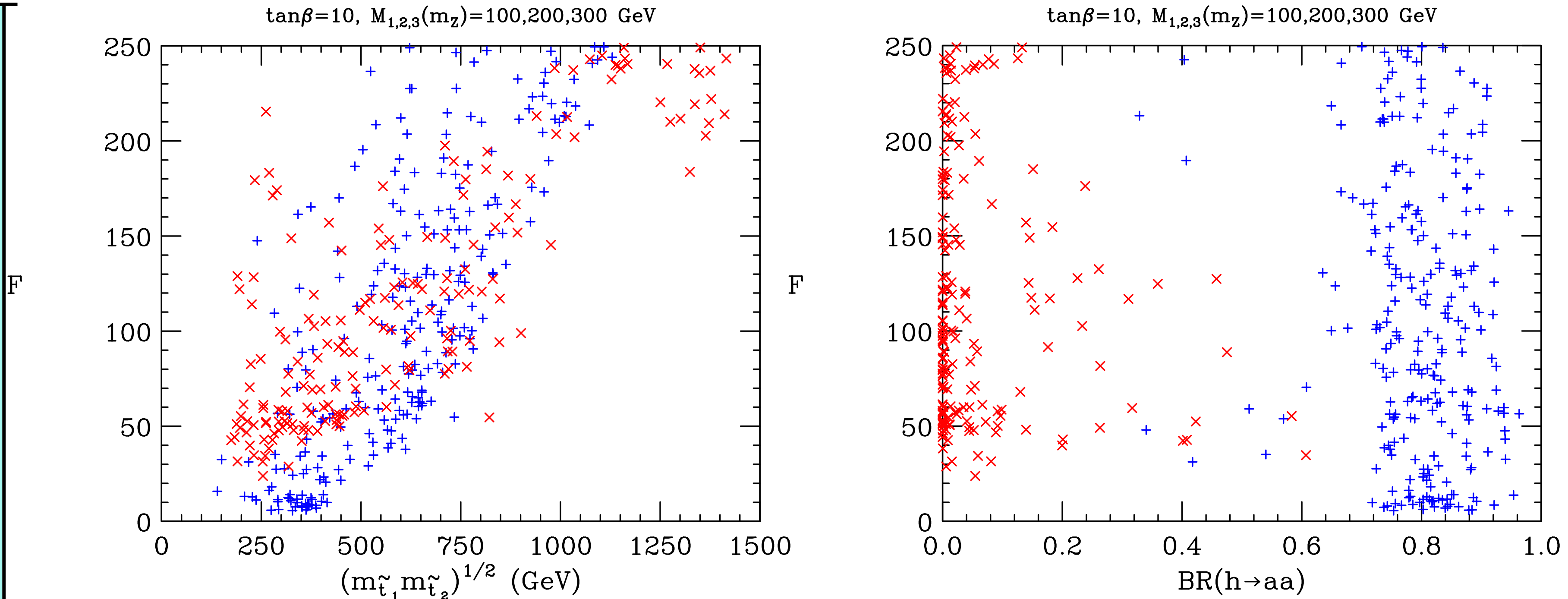
× escapes LEP because $m_h > 115$ GeV

Fine tuning measure:

$$F = \max_p F_p = \max_p \left| \frac{p}{m_Z} \frac{dm_Z}{dp} \right|$$

$$p \in \{M_i(0), i = 1, 2, 3; m_s^2(0), s = Q, u, d, L, e, H_u, H_d, S; A_t(0), A_\lambda(0), A_\kappa(0)\}$$

Fine Tuning in NMSSM, $\tan\beta = 10$



$+$ ($m_{h_1} < 115$ GeV) $\quad h_1 \to a_1 a_1$ dominates

$\times$ ($m_{h_1} > 115$ GeV) $\quad h_1 \to b\bar{b}$ dominates

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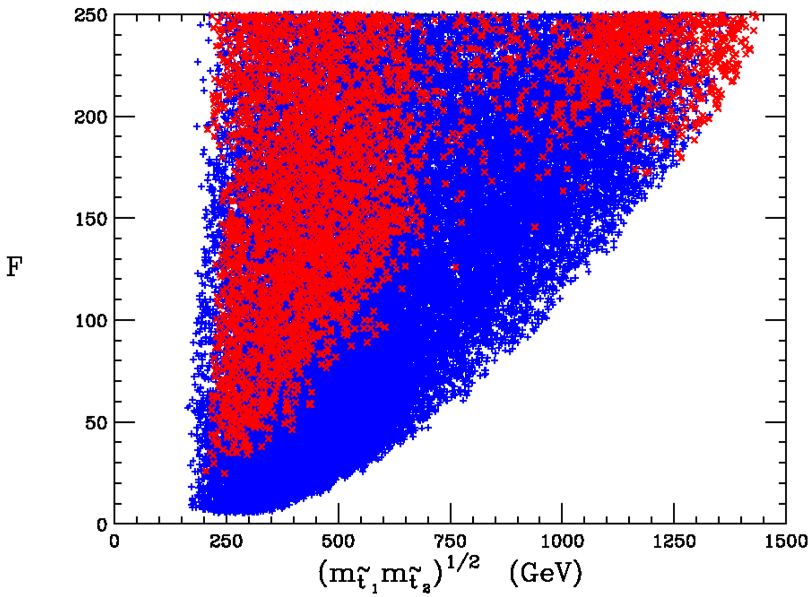
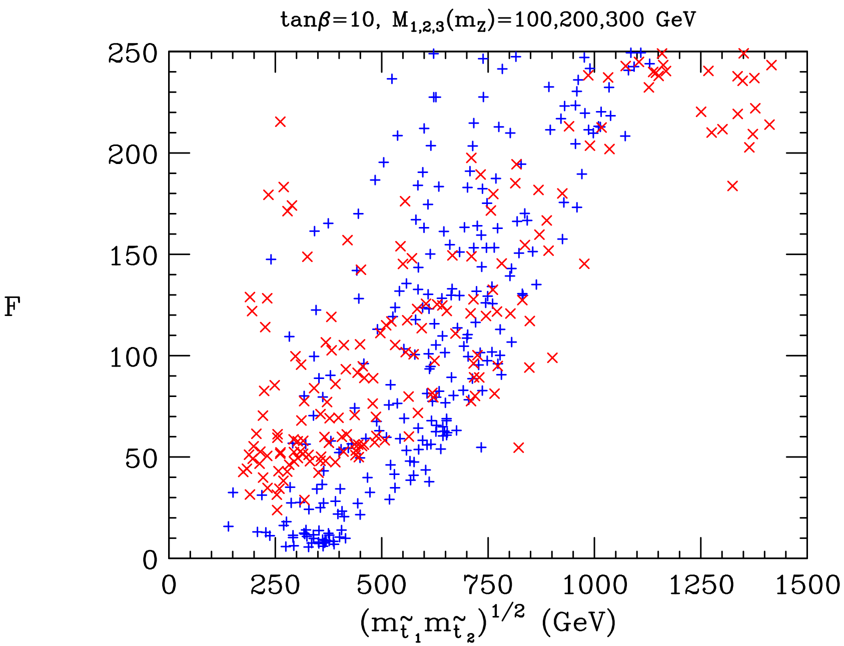
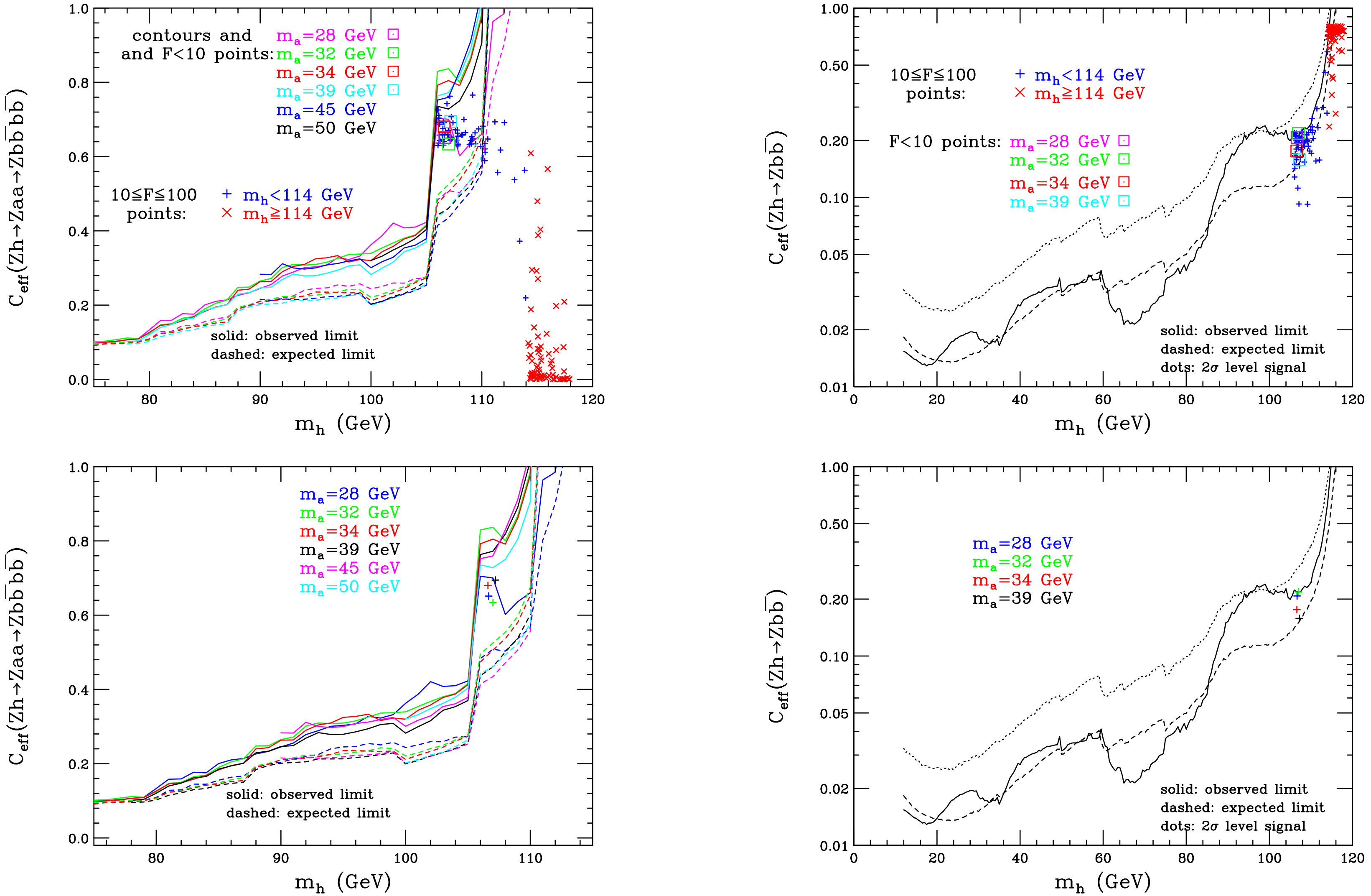
Comparing MSSM and NMSSM

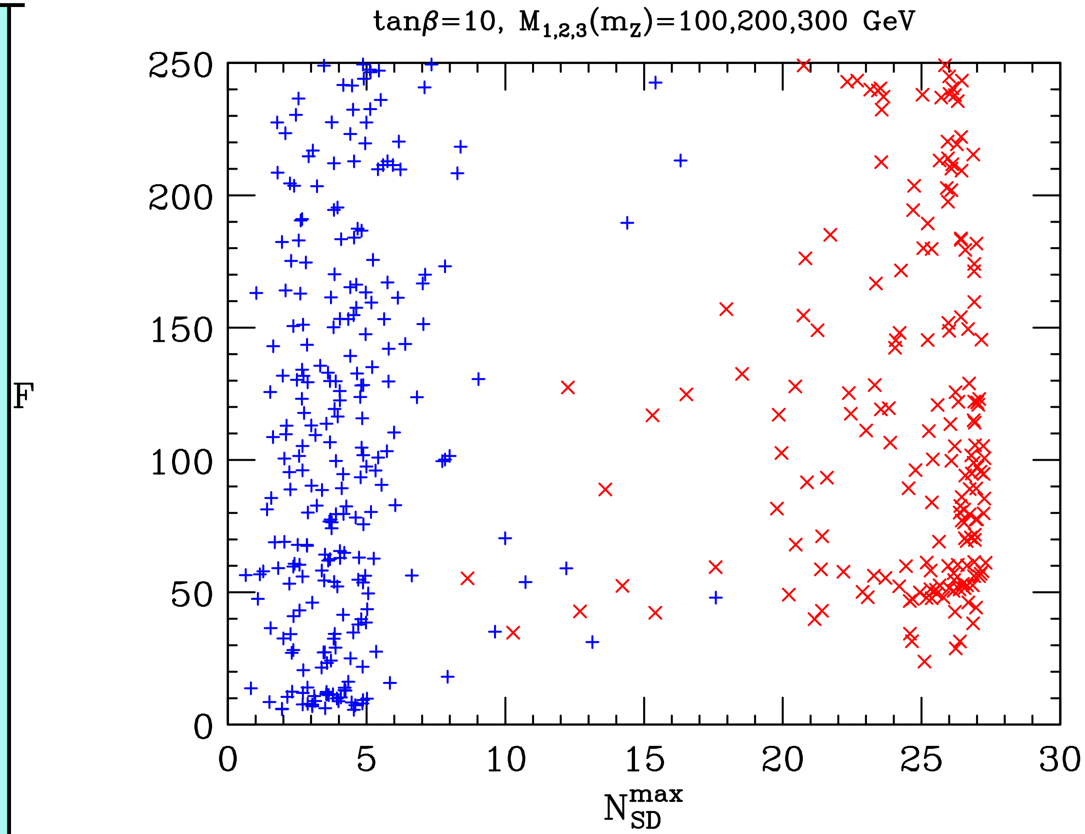




Explaining LEP excess ($m_a > 2m_b$)



LHC Discovery Potential



Standard decay modes:

$gg \to h/a \to \gamma\gamma$

associated Wh/a or $t\bar{t}h/a$ prod.

with $\gamma\gamma l^{\pm}$ in the final state

$t\bar{t}h/a$ prod. with $h/a \to b\bar{b}$

$b\bar{b}h/a$ prod. with $h/a \to \tau^+\tau^-$

$gg \to h \to ZZ^{(*)} \to$ 4 leptons

$gg \to h \to WW^{(*)} \to l^+l^-\nu\bar{\nu}$

$WW \to h \to \tau^+\tau^-$

$WW \to h \to WW^{(*)}$

$WW \to h \to invisible$

for an integrated luminosity: $L = 300 fb^{-1}$

Search for the SM Higgs at LEP

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