Avoiding Fine-Tuning in the NMSSM: Theoretical and Experimental Implications

Jack Gunion
Davis Institute for High Energy Physics, U.C. Davis

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Outline

- Brief Review of the NMSSM
- NMHDECAY
- Brief Review of Fine-Tuning and Little Hierarchy Problems in the MSSM
- Evasion of Fine-Tuning and Little Hierarchy Problems In the NMSSM and Implications

Collaborators:

- NMHDECAY: U. Ellwanger and C. Hugonie
- Fine-Tuning: R. Dermisek

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The NMSSM

- The Next to Minimal Supersymmetric Standard Model (NMSSM [1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 12, 13]) provides a very elegant solution to the μ problem of the MSSM via the introduction of a singlet superfield $\widehat{S}$.

  For the simplest possible scale invariant form of the superpotential, the scalar component of $\widehat{S}$ acquires naturally a vacuum expectation value of the order of the SUSY breaking scale, giving rise to a value of μ of order the electroweak scale.

- The NMSSM is actually the simplest supersymmetric extension of the standard model in which the electroweak scale originates from the SUSY breaking scale only.

- The NMSSM preserves all the successes of the MSSM (gauge coupling unification, RGE EWSB, dark matter, . . .).

Hence, the phenomenology of the NMSSM deserves to be studied at least as fully and precisely as that of the MSSM.

Its particle content differs from the MSSM by the addition of one CP-even and one CP-odd state in the neutral Higgs sector (assuming CP conservation), and one additional neutralino. Thus, the physics of the Higgs bosons – masses, couplings and branching ratios [1, 7, 8, 9, 10, 11, 12, 13] can differ significantly from the MSSM.

I will be following the conventions of Ellwanger, Hugonie, JFG [14]. The NMSSM parameters are as follows.

a) Apart from the usual quark and lepton Yukawa couplings, the scale invariant superpotential is

$$\lambda\ \widehat{S}\widehat{H_u}\widehat{H_d} + \frac{\kappa}{3}\ \widehat{S}^3 \tag{1}$$

depending on two dimensionless couplings λ, κ beyond the MSSM. (Hatted capital letters denote superfields, and unhatted capital letters will denote their scalar components).

b) The associated trilinear soft terms are

$$\lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3\,. \tag{2}$$

c) The final two input parameters (at tree-level) are

$$\tan\beta = \langle H_u \rangle / \langle H_d \rangle \ , \ \mu_{\rm eff} = \lambda \langle S \rangle \ . \quad (3)$$

These, along with M_Z, can be viewed as determining the three SUSY breaking masses squared for H_u, H_d and S through the three minimization equations of the scalar potential.

Thus, as compared to three independent parameters in the Higgs sector of the MSSM (often chosen as μ, $\tan\beta$ and M_A, before m_Z is input), the Higgs sector of the NMSSM is described by the six parameters

$$\lambda \ , \ \kappa \ , \ A_\lambda \ , \ A_\kappa, \ \tan\beta \ , \ \mu_{\rm eff} \ . \quad (4)$$

We will choose sign conventions for the fields such that λ and $\tan\beta$ are positive, while κ, A_λ, A_κ and $\mu_{\rm eff}$ should be allowed to have either sign.

In addition, values for the gaugino masses and of the soft terms related to the squarks and sleptons that contribute to the radiative corrections in the Higgs sector and to the Higgs decay widths must be input.

NMHDECAY

We (Ellwanger, Hugonie, JFG [14]) have developed the NMSSM analogue of HDECAY. The program, and associated data files, can be downloaded at:

`http://www.th.u-psud.fr/NMHDECAY/nmhdecay.html`

`http://higgs.ucdavis.edu/nmhdecay/nmhdecay.html`

The web pages provide a simplified description of the program and instructions on how to use it. The program will be updated to include additional features and refinements in subsequent versions. We welcome comments with regard to improvements that users would find helpful.

NMHDECAY performs the following tasks:

1. It checks whether the running Yukawa couplings encounter a Landau singularity below the GUT scale.

2. NMHDECAY checks whether the physical minimum (with all vevs non-zero) of the scalar potential is deeper than the local unphysical minima with vanishing $\langle H_u \rangle$ or $\langle H_d \rangle$.

3. It computes the masses and couplings of all physical states in the Higgs, chargino and neutralino sectors and checks that all Higgs and squark masses-squared are positive. **1. through 3. define a "physically acceptable" parameter set.**

4. It computes the branching ratios into two particle final states (including charginos and neutralinos and other Higgs bosons — decays to squarks and sleptons will be implemented in a new release) of all Higgs particles.

5. It checks whether the Higgs masses and couplings violate any bounds from negative Higgs searches at LEP, including many quite unconventional channels that are relevant for the NMSSM Higgs sector. (The $ZH \to Zaa \to Zb\bar{b}b\bar{b}$ channel has been slightly updated by LEP — see talk by A. Sopczak; we will update this as soon as tabular data is provided.)

   It also checks the bound on the invisible Z width (possibly violated for light neutralinos). In addition, NMHDECAY checks the bounds on the lightest chargino and on neutralino pair production.

The most important LEP information for the low fine-tuning NMSSM cases are the ZH with $H \to hadrons$ (not necessarily two jets), ZH with $H \to hh \to b\bar{b}b\bar{b}$, and ZH with $H \to hh \to \tau^+\tau^-\tau^+\tau^-$ limits. I show the relevant plots (before above-mentioned update) below. The point is that the bounds are weaker than for ZH with $H \to b\bar{b}$.

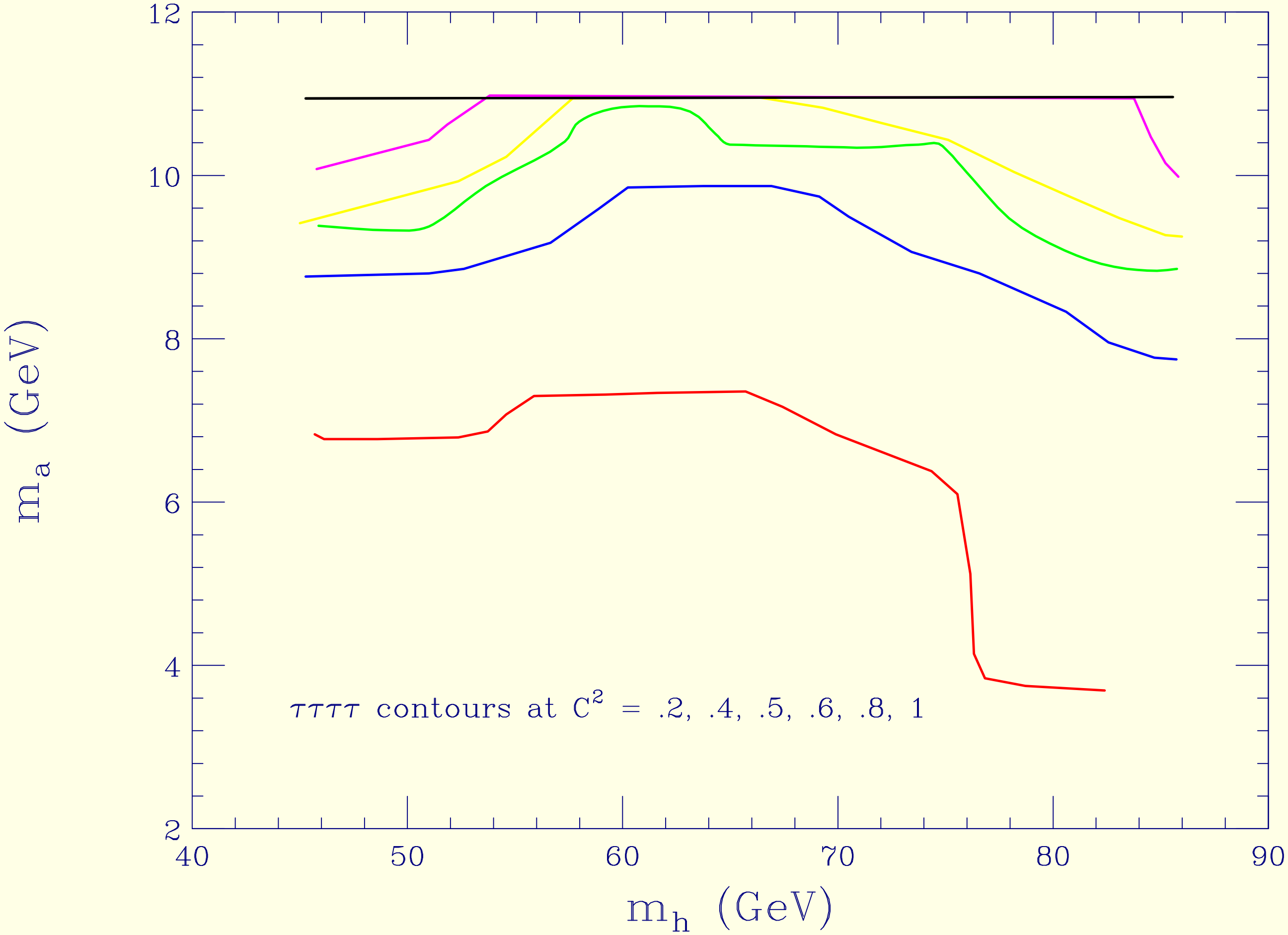

Figure 1: Contours of limits on $C^2 = [g^2_{Zh}/[g^2_{Zh}]_{SM}] \times BR(h \to aa) \times [BR(a \to \tau^+\tau^-)]^2$ at $C^2 = 0.2$, 0.4, 0.5, 0.6, 0.8 and 1 (red, blue, green, yellow, magenta, and black, respectively). For example, if $C^2 > 0.2$, then the region below the $C^2 = 0.2$ contour is excluded at 95% CL. Note how limits run out for $m_h \gtrsim 86$ GeV.

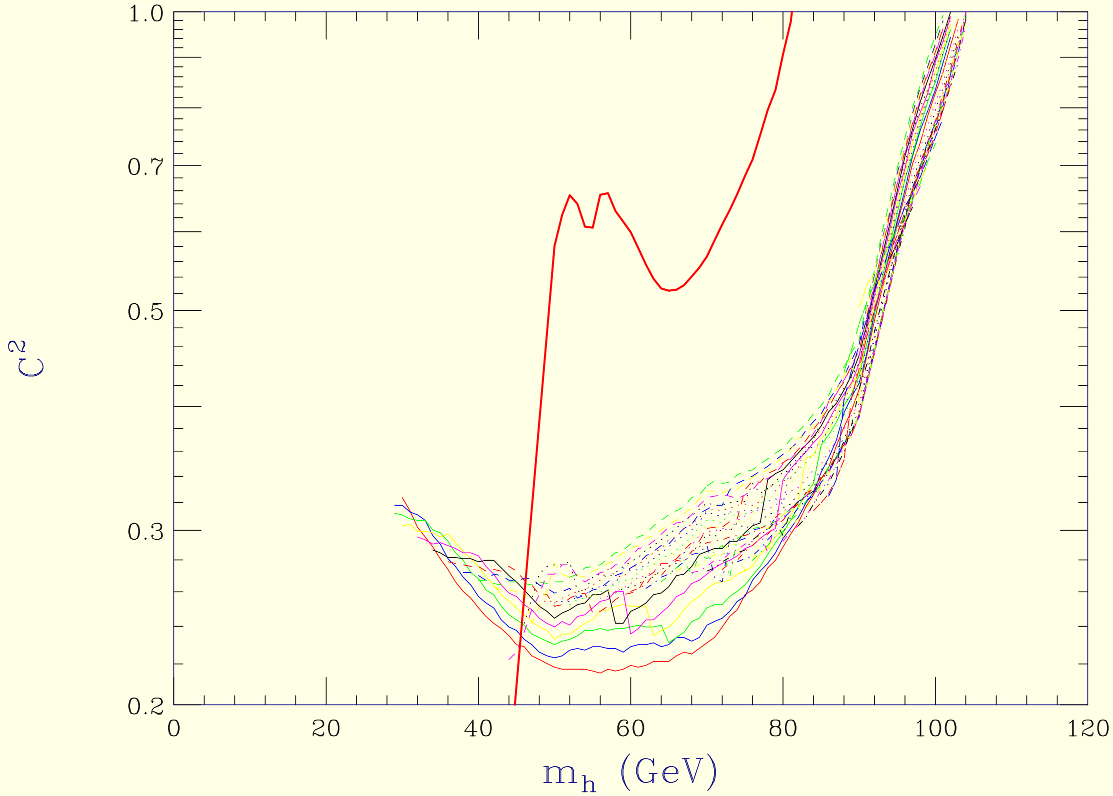

Figure 2: Plot of the 95% CL limits on $C^2 = [g^2_{Zh}/[g^2_{Zh}]_{SM}] \times BR(h \to aa) \times [BR(a \to b\bar{b})]^2$. The different curves are for different m_a values: solid lines are for 12, 13, 14, 15, 16 and 17 GeV in order of red, blue, green, yellow, magenta, black; dotted lines are for 18, 19, 20, 21, 22 and 23 in same color order; dotted lines are for 24, 25, 26, 27, 28 and 29 in same color order; dotdash lines are for 30, 31, 32, 33, 34, and 35 in same color order; long-dash lines are for 36, 37, 38, 39, 40 and 41 in same color order; and dot-dot-dash lines are for 42, 43, 44, 45 46 and 47 in same color order. The thick solid red line is the limit for an arbitrary hadronic final state.

Summary: by processing a possible NMSSM parameter choice through NMHDECAY, we can be certain of the associated Higgs phenomenology and of the fact that the parameter choice does not violate LEP and other experimental limits.

A trivial note:

Consider the simplified case of $BR(h \to b\bar{b}) = x$ and $BR(h \to aa) = (1-x)$. Suppose we have two 95% CL bounds of $x < a$ and $(1-x) < b$ with both $a < 1$ and $b < 1$. If we saturate both bounds, then $x = a/(a+b)$. Thus, when we are close to a ruled out scenario, we will typically have b significantly smaller than a and the way to avoid exclusion will then be to have $BR(h \to b\bar{b})$ near zero, but not exactly zero.

The MSSM Fine-Tuning Problem

w. Radovan Dermisek [30]

I will present very briefly some MSSM results for fine tuning that will allow an apples-to-apples comparison with the NMSSM. For the MSSM and NMSSM, I will be employing $M_{1,2,3} = 100, 200, 300~\mathrm{GeV}$. Fine tuning is fairly sensitive to M_3 and the value chosen is at the current borderline of Tevatron exclusion. Fine tuning gets worse with increasing M_3. It will also be convenient to present results at fixed $\tan\beta$.

The basic fine-tuning measure is

$$F = \mathrm{Max_a} \left| \frac{d \log m_Z}{d \log a} \right| \tag{5}$$

where the parameters a are the GUT scale soft-SUSY-breaking parameters and the μ parameter. I will give more detail about the procedure for computing F in the MSSM and NMSSM shortly.

The results presented will be after scanning over a very broad range in the soft SUSY breaking masses squared (we are mainly sensitive to the stop left and right squared masses) and over a range of A_t (see below).

We also scan over $|\mu| \geq 100$ GeV (which avoids bounds from LEP on the $\widetilde{\chi}_1^{\pm}$ mass),

In the MSSM case, we scan over $m_A \geq 120$ GeV, for which LEP requires $m_h \geq 114$ GeV.

Our MSSM results are summarized by two graphs (we take $\tan\beta = 10$). One is for scans with $|A_t| < 0.5$ TeV and the second is for scans over the much broader range $|A_t| < 4$ TeV.

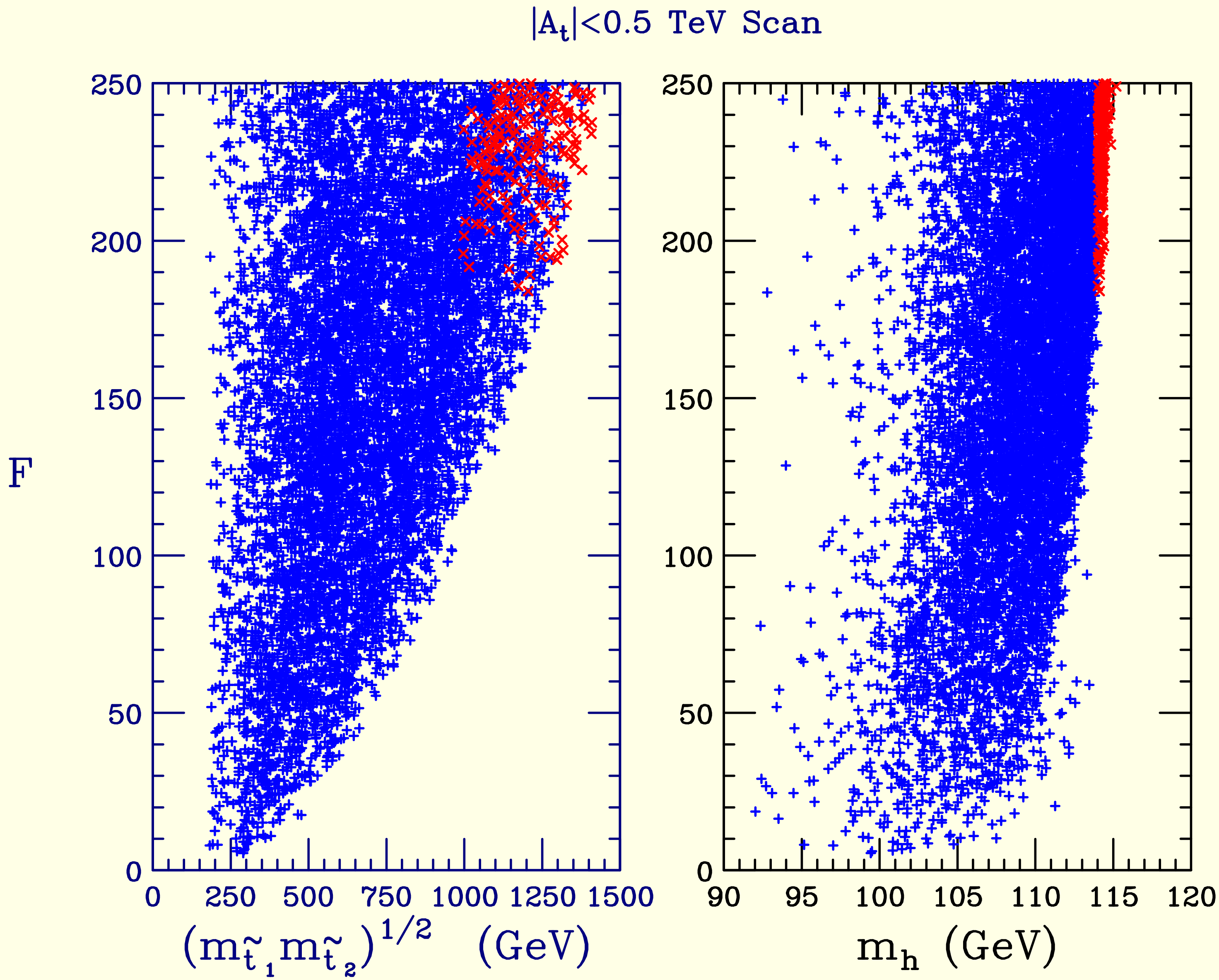

Figure 3: The $|A_t| < 500$ GeV results. x$= m_h \geq 114$ GeV. $+= m_h < 114$ GeV.

For moderate $|A_t|$, $m_h \geq 114$ GeV requires large $\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ and the minimum value of F consistent with this LEP bound is about 180.

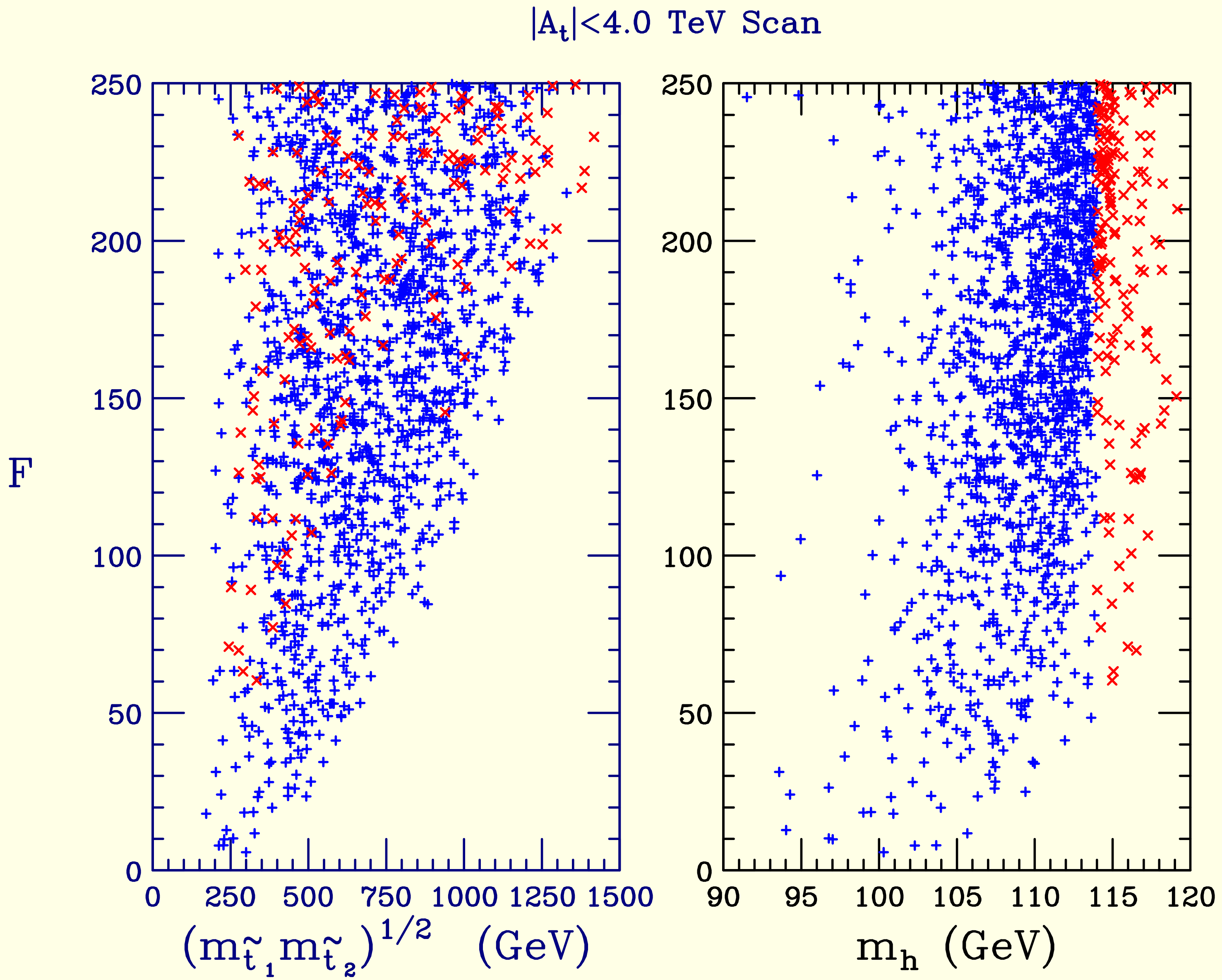

Figure 4: The $|A_t| < 4\ \mathrm{TeV}$ results.

You can reduce fine-tuning to a level of $F \sim 50$ if you allow for very large A_t, which gives large Higgs mass at lower $\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$.

The NMSSM Solution to the Fine-Tuning and Little Hierarchy Problems

w. Radovan Dermisek [30]

Fine tuning in the NMSSM was examined by Bastero-Gil, Hugonie, King, Roy and Vempati [2]. Some amelioration with respect to the MSSM was found. Their approach was to maximize the quartic coupling λ (which is not fixed by gauge couplings in the NMSSM) so as to get a lightest Higgs that is above the LEP bound. The λ values needed are very close to the bound at which the model becomes non-perturbative during evolution.

We claim that the fine tuning measure can be reduced to even lower levels, in fact to non-fine-tuned levels, without requiring λ to be large. Indeed, modest values of λ will be preferred.

To explore fine tuning, we proceed as follows.

- We choose a value of $\tan\beta$ and take $M_{1,2,3} = 100, 200, 300~\mathrm{GeV}$.

- We choose random m_Z-scale values for λ, κ and $\tan\beta$ and for the soft-SUSY-breaking parameters A_λ, A_κ, $A_t = A_b$, M_1, M_2, M_3, m_Q^2, m_U^2, m_D^2, m_L^2, and m_E^2, all of which enter into the evolution equations.

- We process each such choice through NMHDECAY to check that the scenario satisfies all theoretical and available experimental constraints.

- For accepted cases, we then evolve to determine the GUT-scale values of all the above parameters.

- The fine-tuning derivative for each parameter is determined by:
  - shifting the GUT-scale value for that parameter by a small amount,
  - evolving all parameters back down to m_Z,
  - redetermining the potential minimum, which gives new values for the Higgs vevs, h'_u and h'_d,
  - and finally computing a new value for m_Z^2 using $m_Z'^2 = \overline{g}^{\,2}(h_u'^2 + h_d'^2)$.

Results for $\tan\beta = 10$ and $M_{1,2,3}(m_Z) = 100, 200, 300~\mathrm{GeV}$ appear in Fig. 5.

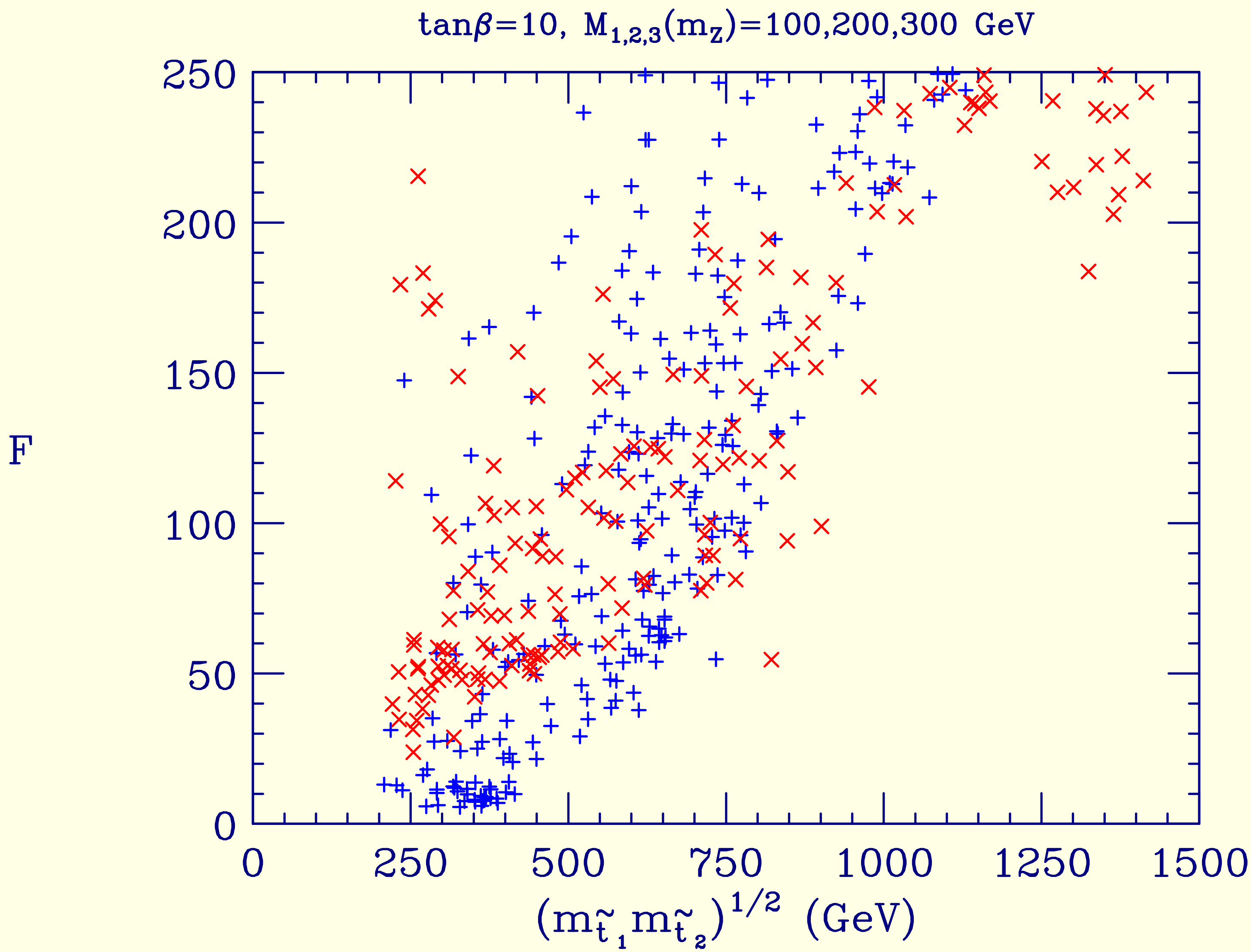

Figure 5: For the NMSSM, we plot the fine-tuning measure F vs. $\sqrt{m_{\widetilde{t}_1} m_{\widetilde{t}_2}}$ for NMHDECAY-accepted scenarios with $\tan\beta = 10$ and $M_{1,2,3}(m_Z) = 100, 200, 300$ GeV. Points marked by '+' ('×') escape LEP exclusion primarily due to dominance of $h_1 \to a_1 a_1$ decays (due to $m_{h_1} > 114$ GeV).

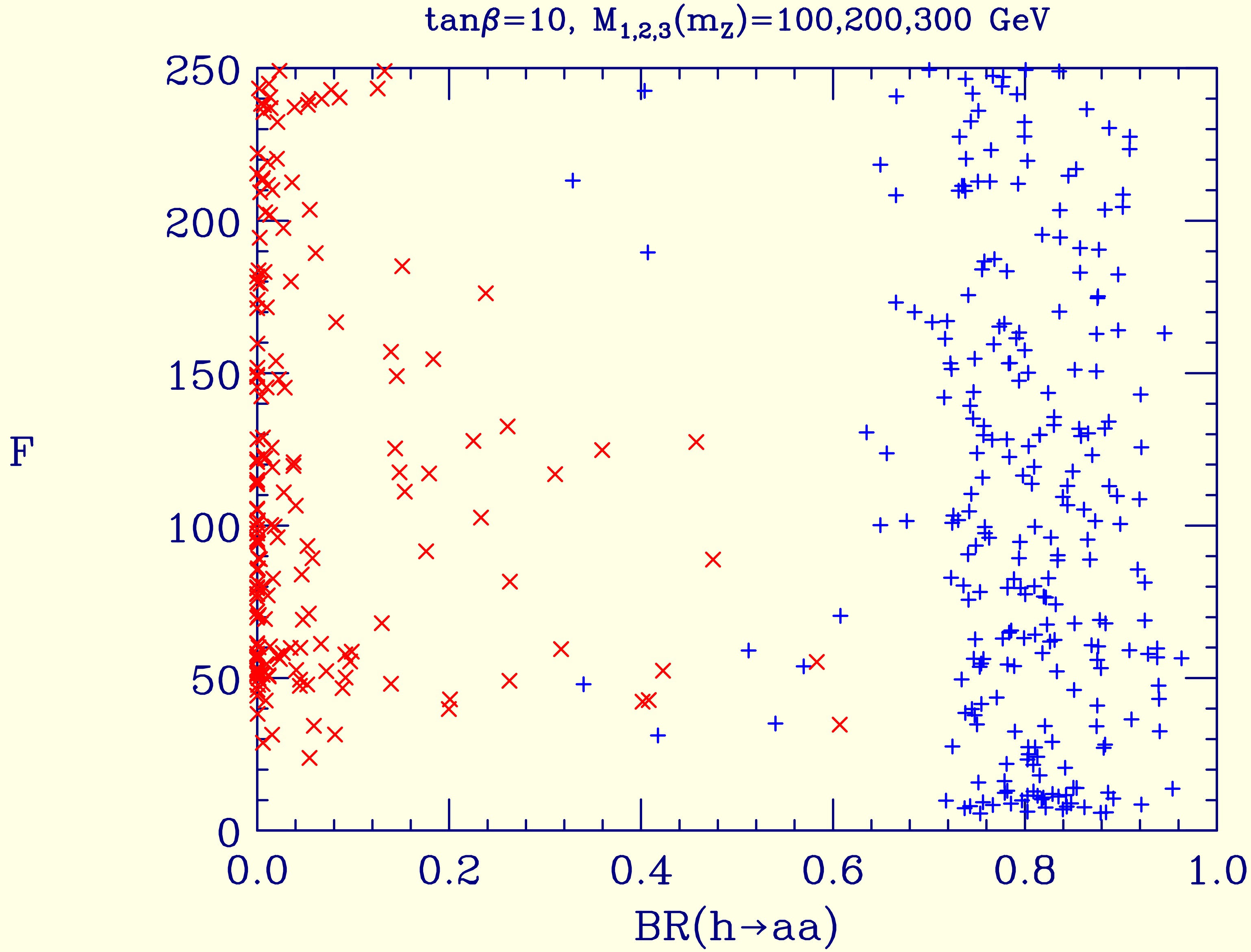

Figure 6: For the NMSSM, we plot the fine-tuning measure F vs. $BR(h_1 \to a_1 a_1)$ for NMHDECAY-accepted scenarios with $\tan\beta = 10$ and $M_{1,2,3}(m_Z) = 100, 200, 300$ GeV. Point notation as in Fig. 5.

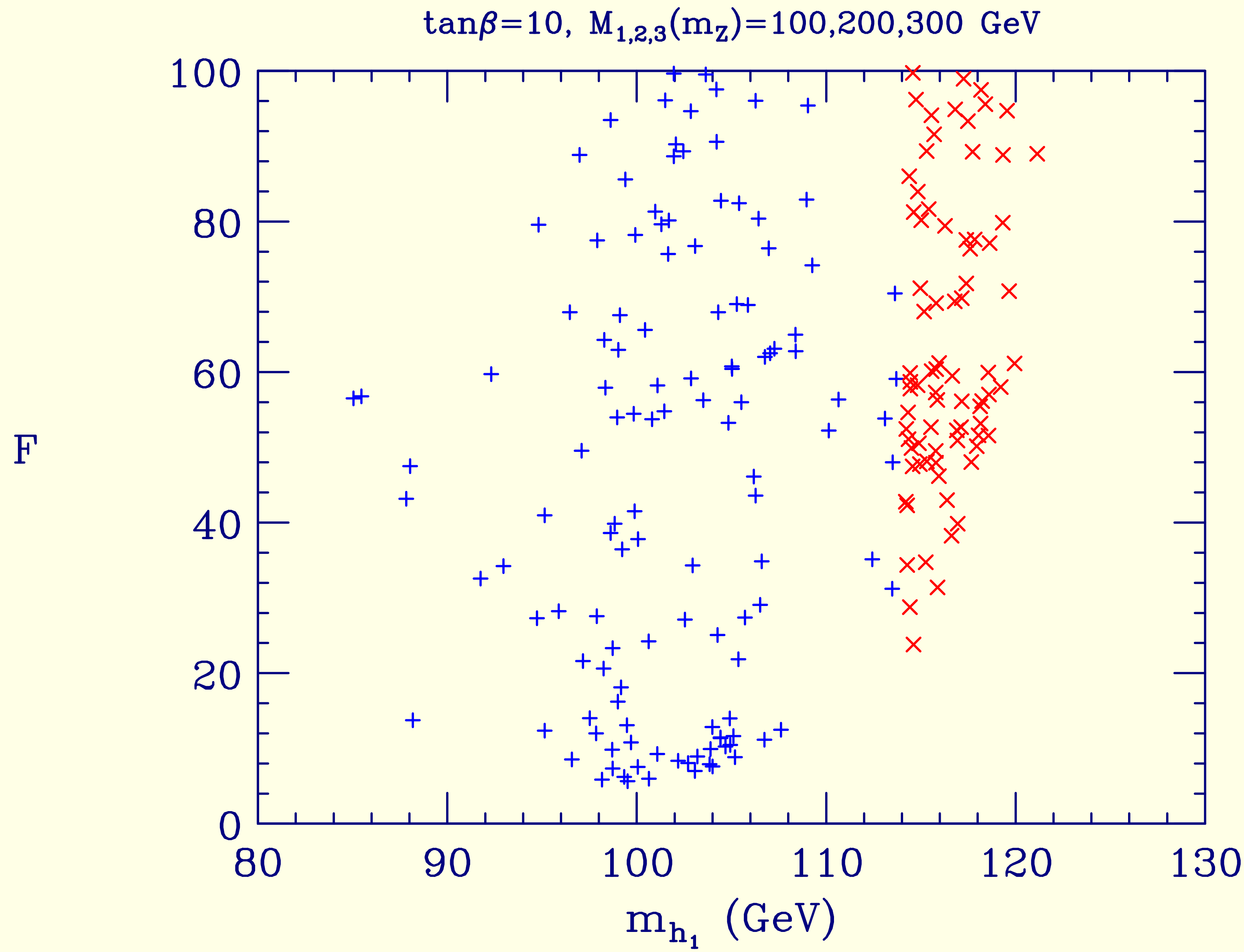

Figure 7: For the NMSSM, we plot the fine-tuning measure F vs. m_{h_1} for NMHDECAY-accepted scenarios with $\tan\beta = 10$ and $M_{1,2,3}(m_Z) = 100, 200, 300$ GeV. Point notation as in Fig. 5.

- We see that F as small as $F \sim 5.5$ can be achieved for $\sqrt{m_{\widetilde{t}_1} m_{\widetilde{t}_2}} \sim 250 \div 400~\mathrm{GeV}$.

- In the figure, the $+$ points have $m_{h_1} < 114~\mathrm{GeV}$ and escape LEP exclusion by virtue of the dominance of $h_1 \to a_1 a_1$ decays, a channel to which LEP is less sensitive as compared to the traditional $h_1 \to b\bar{b}$ decays.

- Points marked by $\times$ have $m_{h_1} > 114~\mathrm{GeV}$ and will escape LEP exclusion regardless of the dominant decay mode.

  For most of these latter points $h_1 \to b\bar{b}$ decays are dominant, even if somewhat suppressed; $h_1 \to a_1 a_1$ decays dominate for a few.

- For both classes of points, the h_1 has fairly SM-like couplings.

- The minimum F increases rapidly with m_{h_1} as seen in Fig. 7.

  The lowest F values are only achieved for $m_{h_1} \lesssim 105$.

  However, even for $m_{h_1} \geq 114~\mathrm{GeV}$, the lowest F value of $F \sim 24$ is far below that attainable for $m_h \geq 114~\mathrm{GeV}$ in the MSSM unless one employs very large A parameters. We have restricted our scan to $|A_t| < 500~\mathrm{GeV}$.

In the region of parameter space where we get small F, there is a cancellation between two terms appearing in the derivatives of m_Z^2 with respect to the crucial GUT parameters. This is related to the fact that m_Z^2 is given by a quadratic equation in terms of the NMSSM parameters as opposed to the usual MSSM linear equation.

In more detail, we have

$$\frac{1}{2} m_Z^2 = -\mu_{\text{eff}}^2 + \frac{m_{H_d}^2 - \tan^2\beta m_{H_u}^2}{\tan^2\beta - 1}\,. \qquad (6)$$

However, μ_{eff} is not a fundamental parameter in this case, whereas in the MSSM case the same formula applies with $\mu_{\text{eff}} \to \mu$, where μ is a fundamental (but purely adhoc) parameter. From the potential

minimization conditions a 2nd equation involving $\mu_{\rm eff}$ is obtained:

$$\kappa\lambda\left(\frac{1}{\tan\beta}m_{H_d}^2 - m_{H_u}^2\tan\beta\right) - \lambda^2\left(m_{H_d}^2 - m_{H_u}^2\right)$$
$$= \frac{1}{2}m_Z^2\frac{\tan^2\beta - 1}{\tan^2\beta + 1}\left[\kappa\lambda\left(\frac{1}{\tan\beta} + \tan\beta\right) - 2\lambda^2 + \frac{2}{g^2}\lambda^4\right]$$
$$+\mu_{eff}A_\lambda\lambda^2\left(\frac{1}{\tan\beta} - \tan\beta\right) \quad (7)$$

Solving for $\mu_{\rm eff}^2$ and substituting into the MSSM-like equation gives a quadratic equation for m_Z^2. Defining

$$a = -\frac{1}{2}\frac{\tan^2\beta - 1}{\tan^2\beta + 1}\left[\kappa\lambda\left(\frac{1}{\tan\beta} + \tan\beta\right) - 2\lambda^2 + \frac{2}{g^2}\lambda^4\right] \quad (8)$$

$$b = \frac{1}{\tan\beta}k\lambda\left(m_{Hd}^2 - m_{Hu}^2\tan^2\beta\right) - \lambda^2\left(m_{Hd}^2 - m_{Hu}^2\right) \quad (9)$$

$$c = A_\lambda\lambda^2\left(\frac{1}{\tan\beta} - \tan\beta\right) \quad (10)$$

we have

$$AM_Z^4 + BM_Z^2 + C = 0, \tag{11}$$

where

$$A = a^2 \tag{12}$$

$$B = 2ab + c^2/2 \tag{13}$$

$$C = b^2 + c^2 \frac{m_{Hd}^2 - m_{Hu}^2 \tan^2\beta}{1 - \tan^2\beta}. \tag{14}$$

Only one of the two solutions

$$m_Z^2 = \frac{1}{2A}\left(-B \pm \sqrt{B^2 - 4AC}\right) \tag{15}$$

applies for any given set of parameter choices. For small F cases, m_Z^2 is obtained by cancellation of the two terms and there is also a corresponding cancellation of derivatives of the two terms with respect to the important GUT parameters.

- Similar results are obtained at other $\tan\beta$ values.

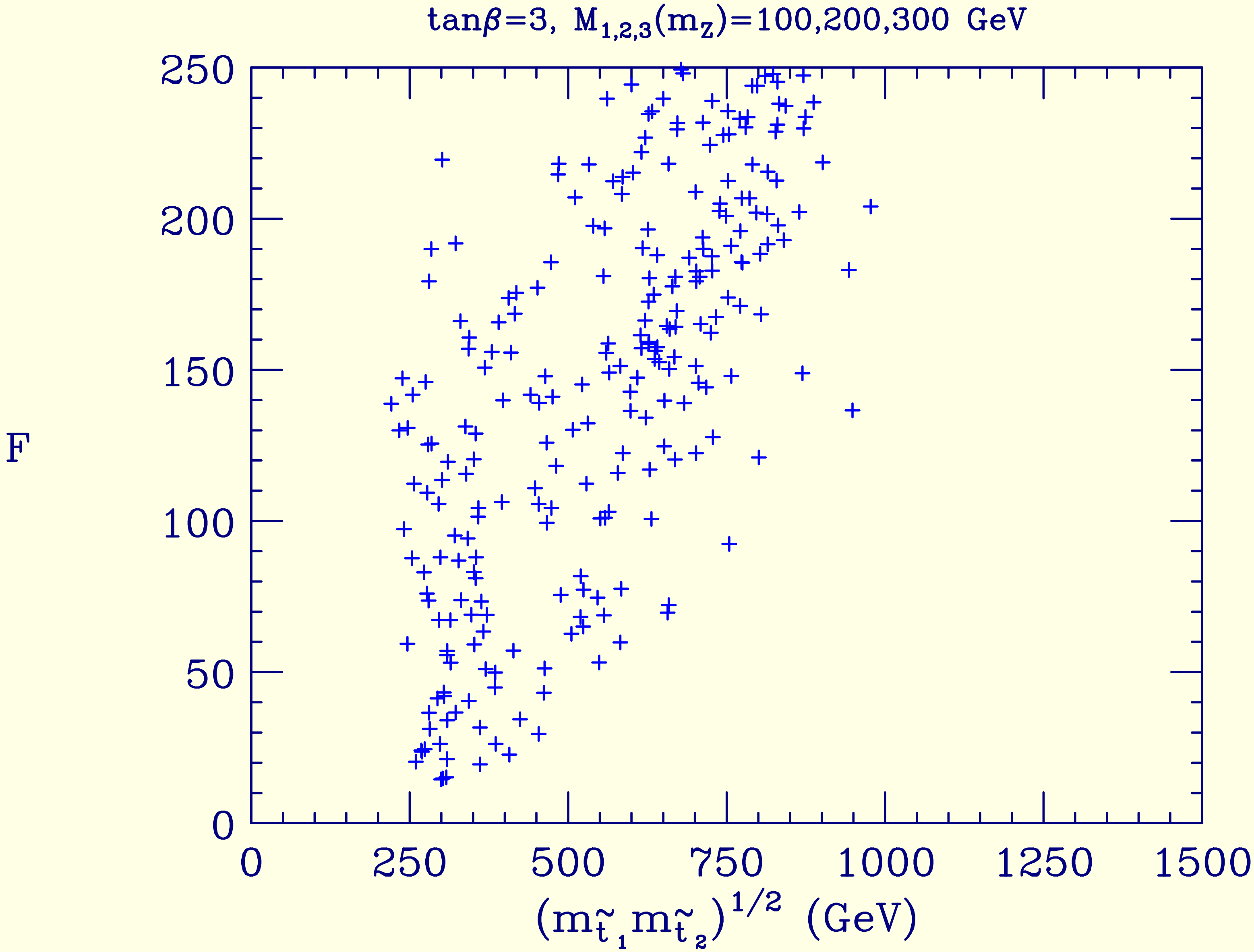

Figure 8: We plot the fine-tuning measure F vs. $\sqrt{m_{\widetilde{t}_1} m_{\widetilde{t}_2}}$ for NMHDECAY-accepted scenarios with $\tan\beta = 3$ and $M_{1,2,3}(m_Z) = 100, 200, 300~\mathrm{GeV}$. There are no points with $m_{h_1} \geq 114~\mathrm{GeV}$. (We scan over only $|A_t| \leq 500~\mathrm{GeV}$.)

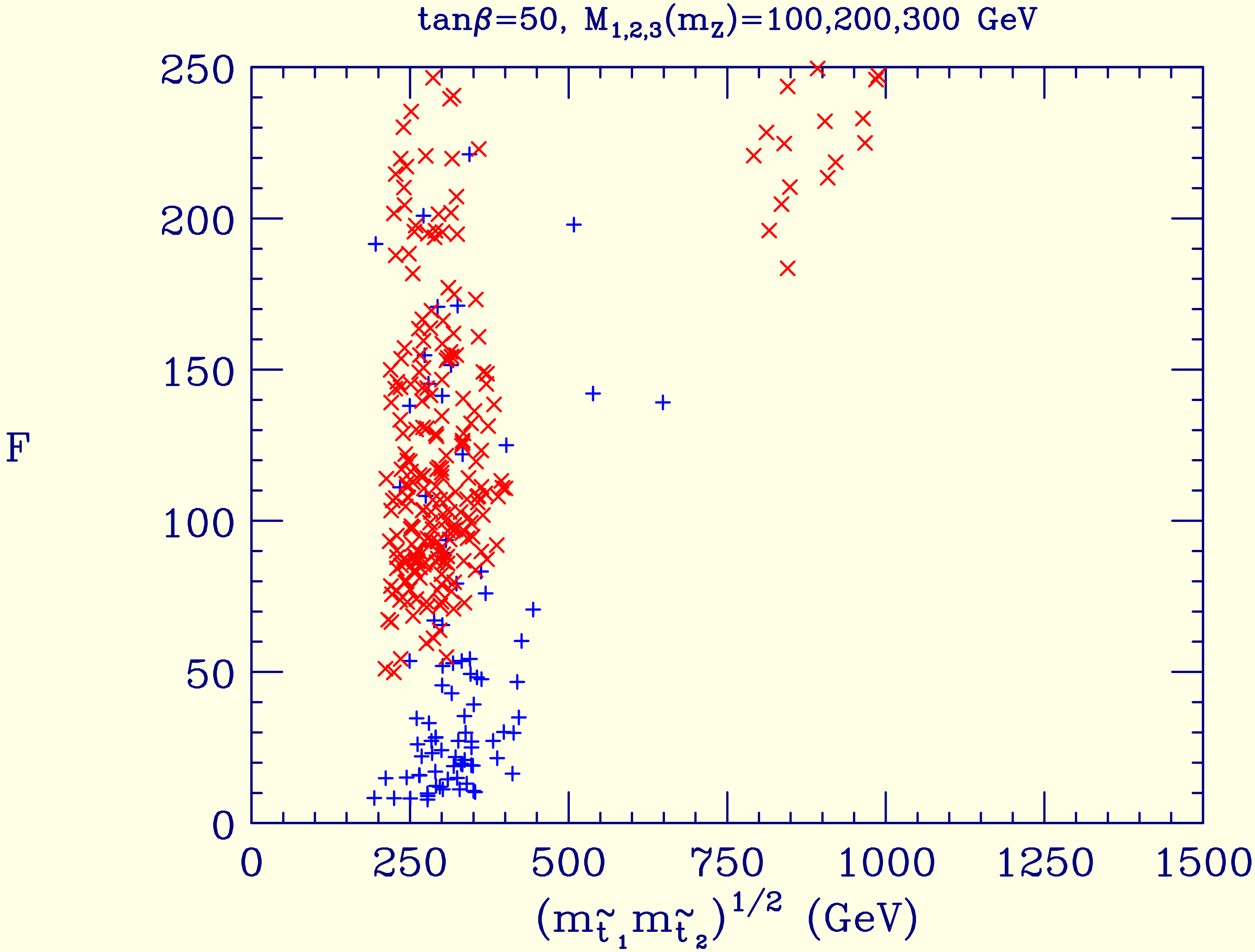

Figure 9: For the NMSSM, we plot the fine-tuning measure F vs. $\sqrt{m_{\widetilde{t}_1} m_{\widetilde{t}_2}}$ for NMHDECAY-accepted scenarios with $\tan\beta = 50$ and $M_{1,2,3}(m_Z) = 100, 200, 300$ GeV. $m_{h_1} \geq 114$ GeV can be achieved for low $\sqrt{m_{\widetilde{t}_1} m_{\widetilde{t}_2}}$, but leads to somewhat increased F. (We scan over only $|A_t| \leq 500$ GeV.)

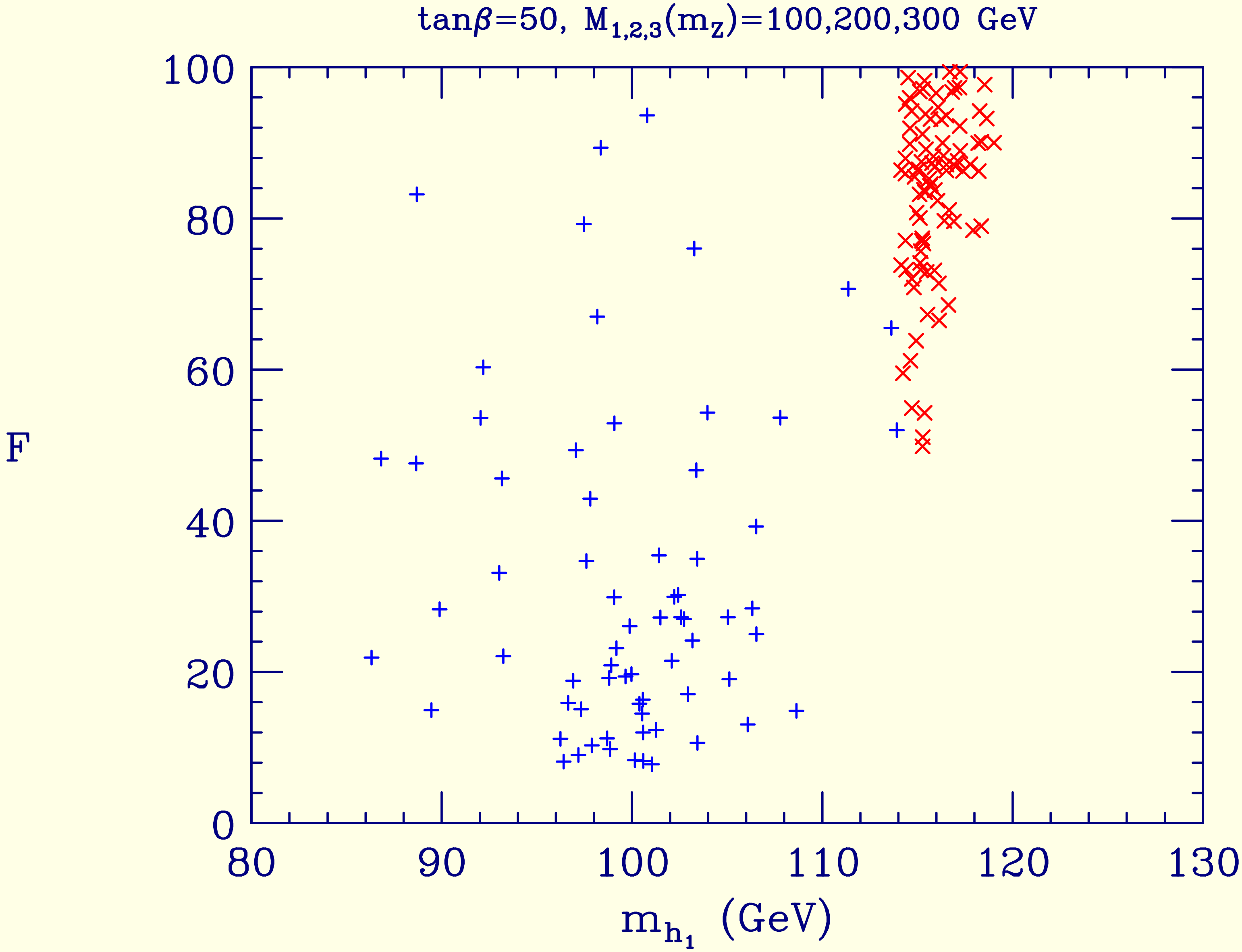

Figure 10: For the NMSSM, we plot the fine-tuning measure F vs. m_{h_1} for NMHDECAY-accepted scenarios with $\tan\beta = 50$ and $M_{1,2,3}(m_Z) = 100, 200, 300~\mathrm{GeV}$. $m_{h_1} \geq 114~\mathrm{GeV}$ can be achieved for low $\sqrt{m_{\widetilde{t}_1} m_{\widetilde{t}_2}}$, but leads to somewhat increased F. (We scan over only $|A_t| \leq 500~\mathrm{GeV}$.)

- Results in the NMSSM for $\tan\beta = 3$ are plotted in Fig. 8 for $M_{1,2,3}(m_Z) = 100, 200, 300~\mathrm{GeV}$ and scanning as in the $\tan\beta = 10$ case.

  We see that $F \sim 15$ is achievable for $\sqrt{m_{\widetilde{t}_1} m_{\widetilde{t}_2}} \sim 300~\mathrm{GeV}$. No points with $m_{h_1} > 114~\mathrm{GeV}$ were found.

  All the plotted points escape LEP limits because of the dominance of the $h_1 \to a_1 a_1$ decay.

- Results in the NMSSM for $\tan\beta = 50$ are plotted in Fig. 9 for $M_{1,2,3}(m_Z) = 100, 200, 300~\mathrm{GeV}$ and scanning as in the $\tan\beta = 10$ case.

  We see that $F \sim 8$ is achievable for $\sqrt{m_{\widetilde{t}_1} m_{\widetilde{t}_2}} \sim 250~\mathrm{GeV}$. The $m_{h_1} \leq 114~\mathrm{GeV}$ points (which includes all those with very low F) escape LEP limits because of the dominance of the $h_1 \to a_1 a_1$ decay.

You will notice that the preferred m_{h_1} value of $\sim 100~\mathrm{GeV}$ is exactly what is needed for a Higgs bosons with SM coupling to WW, ZZ to give good precision EW agreement.

What kind of GUT scale boundary conditions yield low F?

$\tan\beta = 10$ Example

- **Scale m_Z parameter values:**

  $\lambda \in [0.1, 0.3]$; $\kappa \in [0.1, 0.3]$; $|A_\kappa| \in [2, 4]$ GeV; $|A_\lambda| \in [100, 200]$ GeV; $|\mu_{\rm eff}| \in [100, 300]$ GeV (100 GeV was the lowest value we allowed); $m_{\widetilde t_1} \in [200, 400]$ GeV; $m_{\widetilde t_2} \in [200, 500]$ GeV; $A_t \in [-100, -200]$ GeV; soft-SUSY-breaking masses — $m_Q, m_u, m_d \in [200, 400]$ GeV; $m^2_{H_u} \in [0, -(250 \text{ GeV})^2]$, $m^2_{H_d} \in [0, (200 \text{ GeV})^2]$, $m^2_S \in [0, -(200 \text{ GeV})^2]$

- **GUT scale parameters for very lowest F.**

  $\lambda \in [0.15, 0.2]$; $\kappa \in [0.2, 0.3]$

  $A_\kappa \sim -10$ GeV; $A_\lambda \sim 90$ GeV; $A_t \sim 600$ GeV

  $m^2_{H_u}, m^2_{H_d}, m^2_S \sim 0$

  $|m^2_Q| \lesssim (250 \text{ GeV})^2$; $|m^2_u| \lesssim (350 \text{ GeV})^2$; $|m^2_d| \lesssim (250 \text{ GeV})^2$.

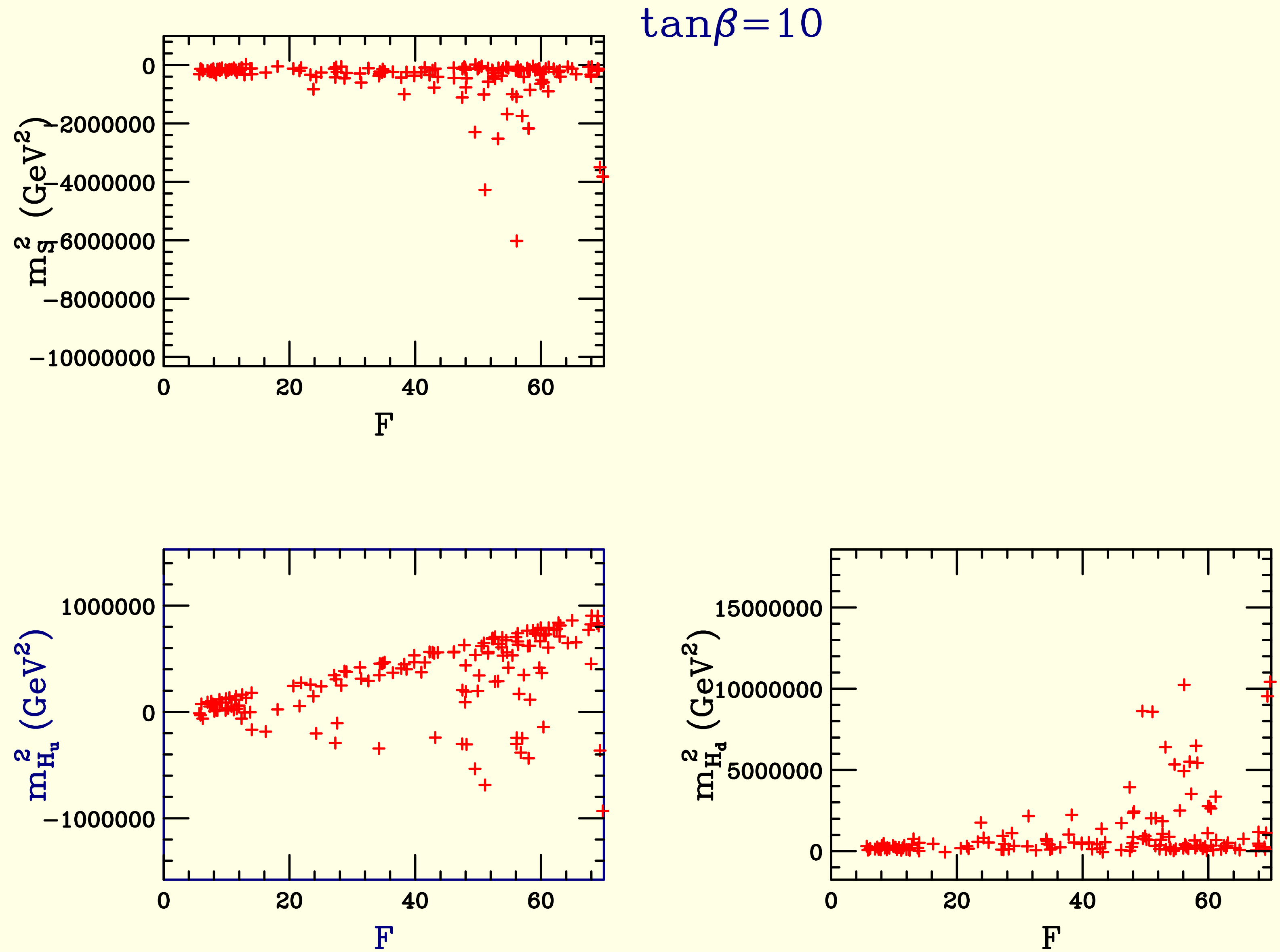

Figure 11: Plots of GUT-scale soft-SUSY-masses squared for the Higgs showing convergence to no-scale limit for smallest F values.

LHC Higgs Physics

- We have supplemented NMHDECAY with a program (not publicly available, at least yet) which evaluates the prospects for LHC Higgs discovery for any given choice of parameters.

- It is absolute crucial to include Higgs-to-Higgs decays in assessing these prospects.

  The importance of such decays was first realized at Snowmass 1996 (JFG, Haber, Moroi [19]) and was later elaborated on in papers by Dobrescu, Landsberg, and Matchev [25]. Detailed NMSSM scenarios were first studied in several papers by Ellwanger, Hugonie and JFG [26, 27]. A recent paper updating these earlier discussions is [28].

- In the absence of Higgs-to-Higgs decays, the LHC is guaranteed to find at least one of the NMSSM Higgs bosons at 5σ in at least one of the "standard" SM/MSSM channels:

  1) $gg \to h/a \to \gamma\gamma$;

2) associated Wh/a or $t\bar{t}h/a$ production with $\gamma\gamma\ell^{\pm}$ in the final state;
3) associated $t\bar{t}h/a$ production with $h/a \to b\bar{b}$;
4) associated $b\bar{b}h/a$ production with $h/a \to \tau^+\tau^-$;
5) $gg \to h \to ZZ^{(*)} \to$ 4 leptons;
6) $gg \to h \to WW^{(*)} \to \ell^+\ell^-\nu\bar{\nu}$;
7) $WW \to h \to \tau^+\tau^-$;
8) $WW \to h \to WW^{(*)}$.
9) $WW \to h \to invisible$.

We also input the ATLAS result (Assamagan:2004gv) that $t \to H^+ b$ will be detected for $m_{H^\pm} \lesssim 155\ \mathrm{GeV}$. This is our final "standard" detection mode.

- Overall, we have a quite robust LHC no-lose Higgs detection theorem for NMSSM parameters such that LEP constraints are passed and Higgs-to-Higgs decays are not allowed, but only so long as $L \geq 100\mathrm{fb}^{-1}$ and channel efficiencies are as simulated.

- However, if $h \to aa, \ldots$ decays are allowed, NMSSM parameter points can be found such that none of the above "standard" detection modes will give an observable signal.

The best detection mode we (JFG, Ellwanger, Hugonie, Moretti [27]) have been able to think of is $WW \to h \to aa \to jj\tau^+\tau^-$. However, even after a long series of cuts, it is far from clear that the signal in the reconstructed $M_{jj\tau^+\tau^-}$ mass distribution, which resides in the $[50, 120]$ GeV mass zone, will emerge above the very large $t\bar{t}$ background.

Some ATLAS people (Zerwas, Baffioni) are pursuing this question.

I have started discussing with V. Khoze the possibility of using the double diffractive approach to isolate the $h \to aa \to b\bar{b}\tau^+\tau^-$ final state.

- Even if no Higgs boson is observed, the LHC will at least be able to check whether or not $WW \to WW$ is perturbative.

  It will take quite a lot of luminosity to verify the perturbative level, but if verified we will at least know that there is something responsible that the LHC has missed.

  If $WW \to WW$ is perturbative, then

  1. Must go back and search very carefully for some signal such as the $h \to aa$ signal, etc. that was missed.
  2. The ILC might be absolutely essential for Higgs detection in the end!!!

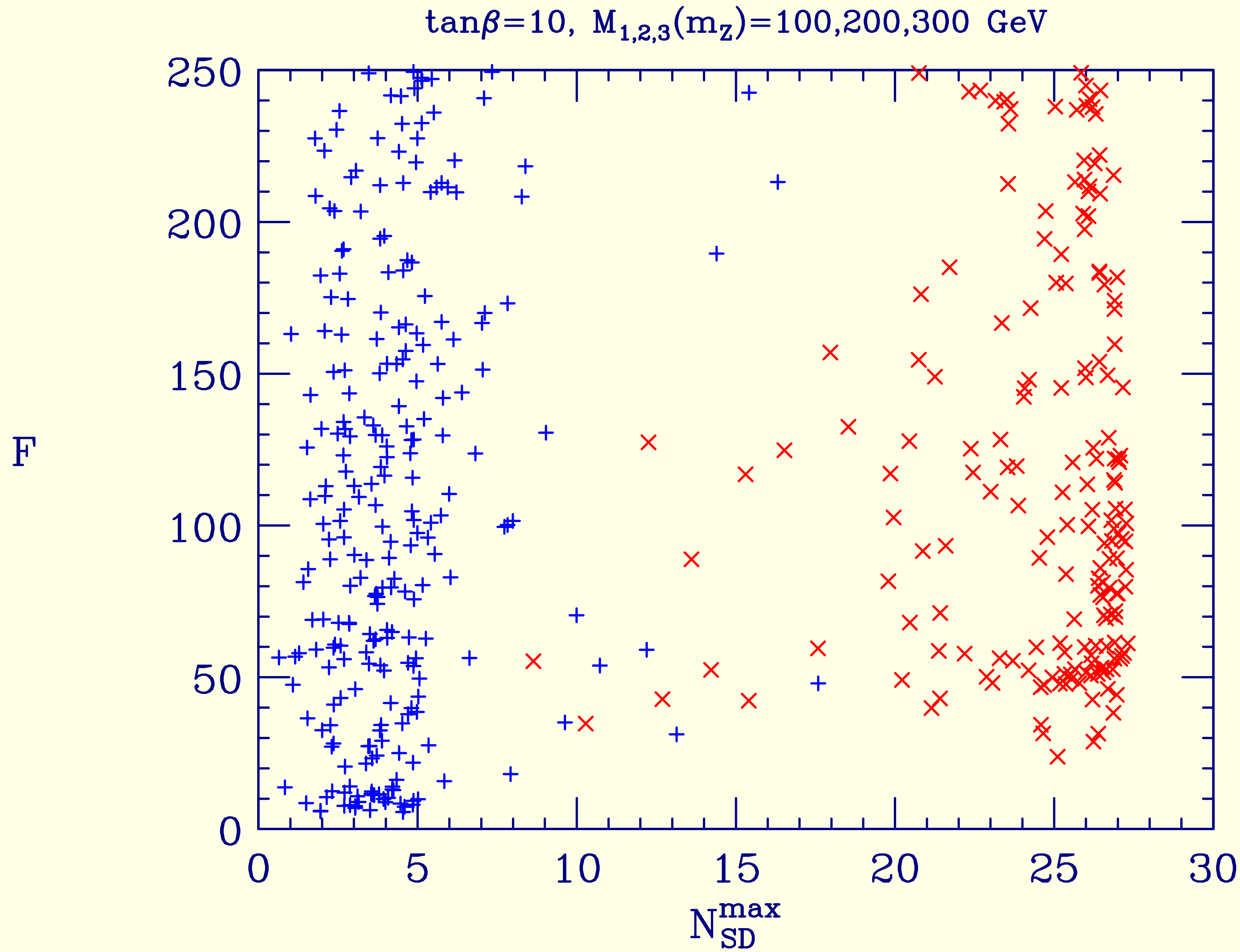

Figure 12: Plot of maximum "standard" channel statistical significance as a function of F — $\tan\beta = 10$.

- **In an overall scan, it is only for a very small percentage of the parameter points that the LHC signals fall below the observable level, assuming $L = 300\mathrm{fb}^{-1}$ of integrated luminosity.**

  Such points always have a SM-like Higgs decaying to two lighter Higgs.

However, Fig. 12 shows that small fine-tuning implies that the LHC will absolutely have to search for the $h_1 \to a_1 a_1$ decays for moderate $\tan\beta$.

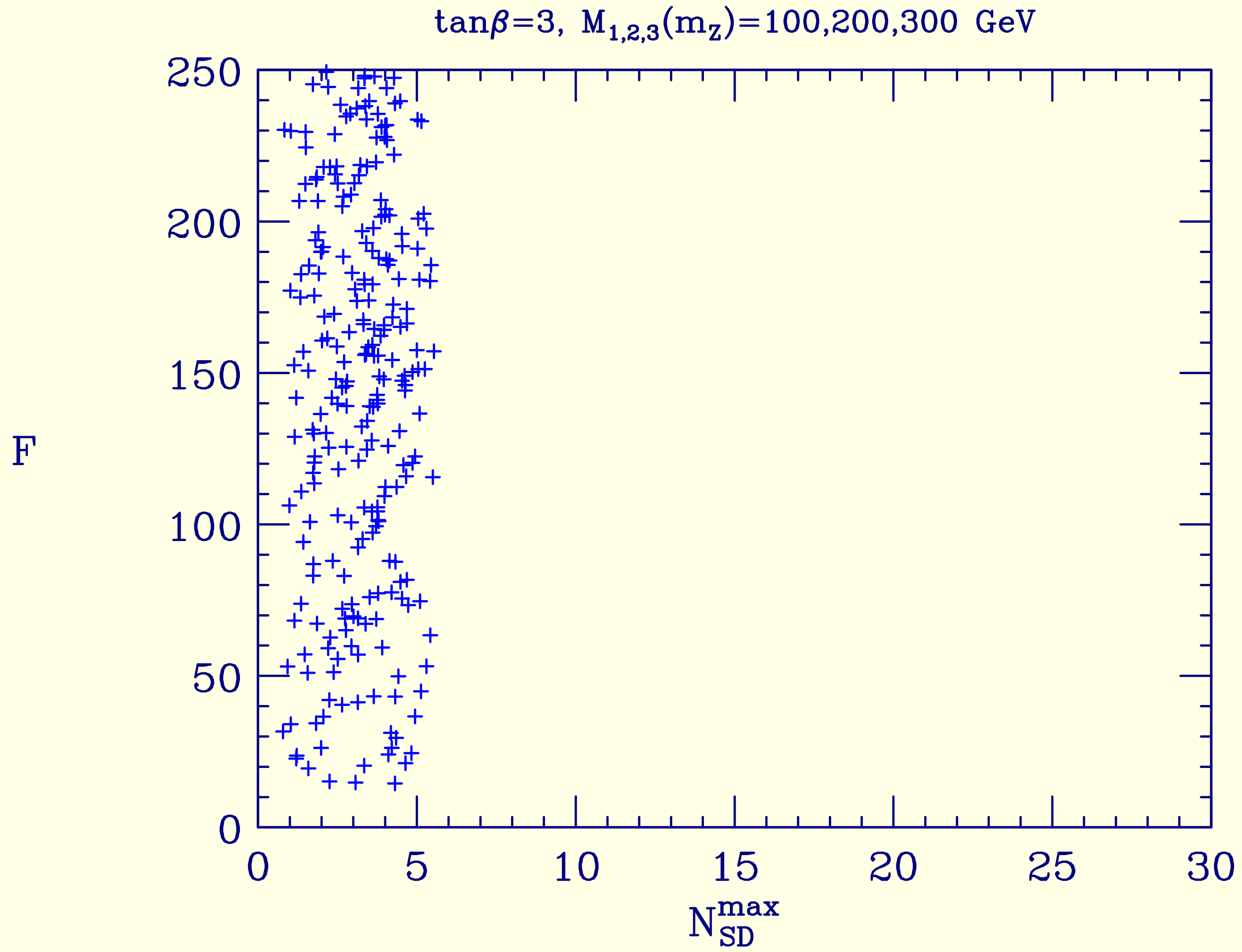

Figure 13: Plot of maximum "standard" channel statistical significance as a function of F — $\tan\beta = 3$.

All scenarios (with $|A_t| < 500~\mathrm{GeV}$) are of this type at $\tan\beta = 3$ as seen in Fig. 13.

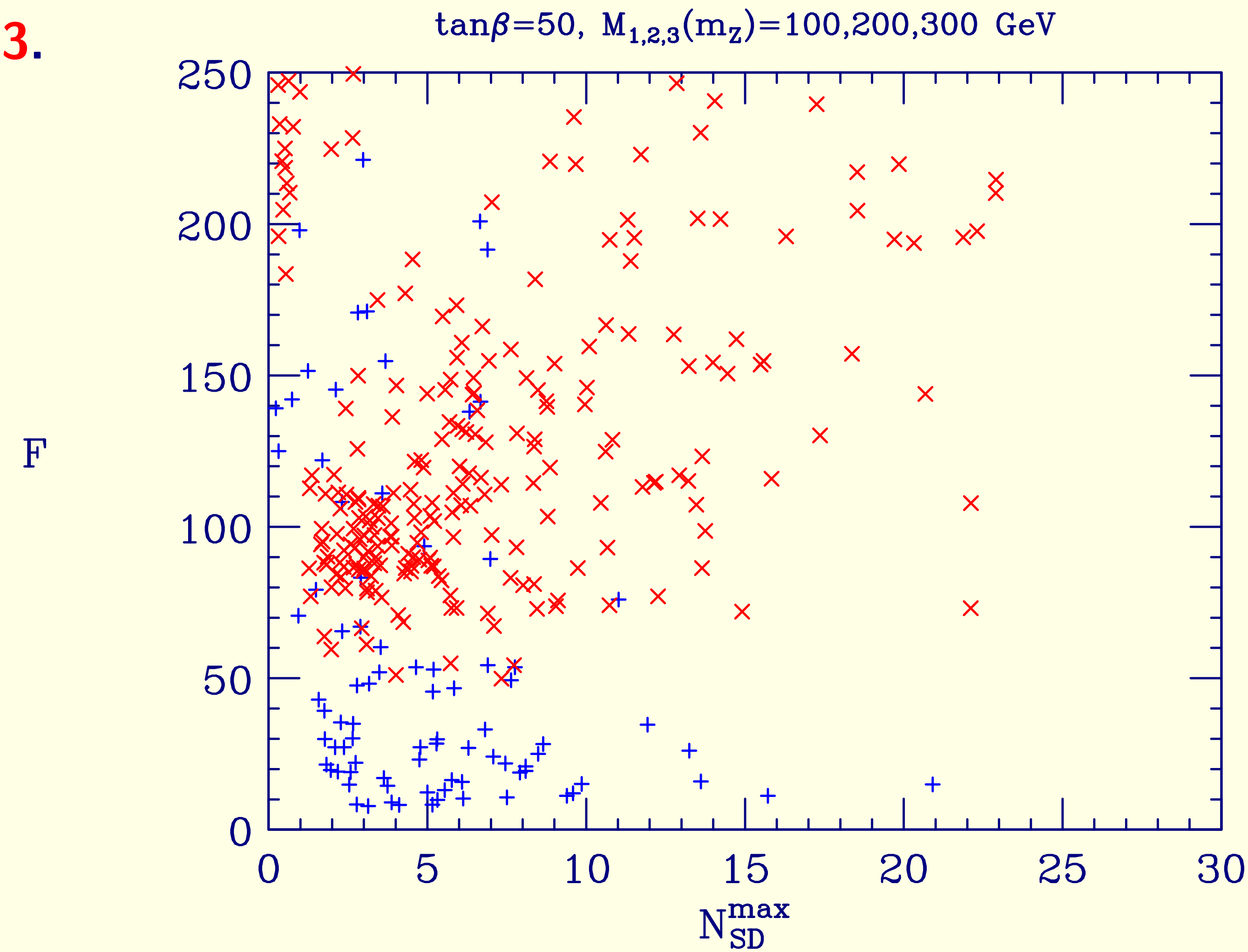

Figure 14: Plot of maximum "standard" channel statistical significance as a function of F — $\tan\beta = 50$.

This is relaxed a bit at high $\tan\beta$ as shown in Fig. 14. However, you should also note how easy it is for $m_{h_1} \geq 114$ GeV cases to fall in the danger zone.

Difficult scenarios at the ILC and γC

- For low-F scenarios, we always find that h_1 has reasonable WW, ZZ coupling and mass $\sim 100~\mathrm{GeV}$.

  Discovery of the h_1 will be very straightforward via $e^+e^- \to Zh_1$ using the $e^+e^- \to ZX$ reconstructed M_X technique which is independent of the "unexpected" complexity of the h_1 decay to a_1a_1.

  This will immediately provide a direct measurement of the ZZh_1 coupling with very small error.

  Then, look for different final states and check for Higgs-like coupling of the a_1 to various final state fermions.

- At the γC, detecting the process $\gamma\gamma \to h_1 \to a_1a_1 \to b\bar{b}b\bar{b}$ or $b\bar{b}\tau^+\tau^-$ is extremely easy. Huge signal over background is obtained (JFG, Szleper [29]).

Conclusions

- Supersymmetric Higgs Hunters may want to start hoping that fine-tuning is an irrelevant consideration.
- If low fine-tuning is imposed for an acceptable model, we should expect:
  - a $m_{h_1} \sim 100~\mathrm{GeV}$ Higgs decaying via $h_1 \to a_1 a_1$.

    Higgs detection will be quite challenging at a hadron collider.
    Higgs detection at the ILC is easy using the missing mass $e^+e^- \to ZX$ method of looking for a peak in M_X.
    Higgs detection in $\gamma\gamma \to h_1 \to a_1 a_1$ will be easy.
  - The very smallest F values are attained when:
    * h_2 and h_3 have "moderate" mass, i.e. in the $300~\mathrm{GeV}$ to $700~\mathrm{GeV}$ mass range;
    * the a_1 mass is typically in the $5~\mathrm{GeV}$ to $20~\mathrm{GeV}$ range (but with a few exceptions) and the a_1 is always mainly singlet.
    * the stops and other squarks are light;
    * the gluino, and, by implication assuming conventional mass orderings, the wino and bino all have modest mass;
    * the LSP is largely bino — the singlino is heavy since s is large.

- **Detailed studies of the $WW \to h_1 \to a_1 a_1$ channel by the experimental groups at both the Tevatron and the LHC should receive significant priority.**

- **It is likely that other models in which the MSSM μ parameter is generated using additional scalar fields can achieve small fine-tuning in a manner similar to the NMSSM.**

- **In general, very natural solutions to the fine-tuning and little hierarchy problems are possible in relatively simple extensions of the MSSM.**

  One does not have to employ more radical approaches or give up on small fine-tuning!

  Further, small fine-tuning probably requires a light SUSY spectrum in all such models and SUSY should be easily explored at both the LHC (and very possibly the Tevatron) and the ILC and $\gamma\gamma$ colliders.

  Only Higgs detection at the LHC will be a real challenge.

  Ability to check perturbativity of $WW \to WW$ at the LHC might prove to be very crucial to make sure that there really is a light Higgs accompanying light SUSY.