LHC/ILC Complementarity for NMSSM Higgs Bosons

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Outline

- Brief Review of the NMSSM
- NMHDECAY
- NMSSM LHC Higgs Phenomenology: Is there a no-lose theorem?
- Brief Review of Fine-Tuning and Little Hierarchy Problems and Proposed Solutions
- Evasion of Fine-Tuning and Little Hierarchy Problems In the NMSSM and Phenomenological Implications: back to $h \to aa$.

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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

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

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

$$\lambda \ , \ \kappa \ , \ A_\lambda \ , \ A_\kappa , \ \tan\beta \ , \ \mu_{\rm eff} \ . \tag{4}$$

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. We provide two forms of the NMHDECAY program:

- NMHDECAY_SLHA.f — for study of one parameter point in the SLHA conventions for particle labeling etc. familiar to experimentalists;
- NMHDECAY_SCAN.f — designed for general phenomenological work including scanning over ranges of NMSSM parameters.

The programs, and associated data files, can be downloaded from the two web pages:

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

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

The web pages provide simplified descriptions of the programs and instructions on how to use them. The programs 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.

   A warning is produced if this happens.

2. Finally, 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 $\langle H_d \rangle$.

   If this is not the case, a warning is produced.

3. It computes the masses and couplings of all physical states in the Higgs, chargino and neutralino sectors.

   Error messages are produced if a Higgs or squark mass squared is negative.

4. It computes the branching ratios into two particle final states (including charginos and neutralinos — decays to squarks and sleptons will be implemented in a later 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.**

   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.

   Corresponding warnings are produced in case any of these phenomenological constraints are violated.

If 1) through 3) are ok, this defines a physically acceptable parameter set.

Thus, 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.

LHC Implications: I

We begin by summarizing the results of [28], which focuses on the no-lose theorem issues rather than on fine-tuning.

- A critical issue is whether or not Higgs-to-Higgs decays are present

  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].

  Scans discussed in this section will be for randomly chosen parameter values in the following ranges:

$$10^{-4} \leq \lambda \leq 0.75; \quad -0.65 \leq \kappa \leq 0.65; \quad 1.6 \leq \tan\beta \leq 54$$
$$-1 \text{ TeV} \leq \mu_{\rm eff}, A_\lambda, A_\kappa \leq +1 \text{ TeV}\,. \tag{5}$$

  We also take $M_1 = 500$ GeV, $M_2 = 1$ TeV and $M_3 = 3$ TeV.

Thus, the lightest neutralino can only be significantly lighter than $500~\mathrm{GeV}$ if it is mainly singlino or (when μ_{eff} is relatively small) higgsino.

For the chosen $M_{1,2,3}$ values, LHC detection of the gauginos will be quite difficult and decay of Higgs bosons to gauginos, including the invisible $\widetilde{\chi}_1^0\widetilde{\chi}_1^0$ channel, will in most cases be negligible.

We also choose $m_Q = m_U = m_D = m_L = m_E \equiv m_{\mathrm{SUSY}} = 1$ TeV for the soft-SUSY-breaking masses for all generations. This means that squarks and sleptons will be at the edge of the LHC discovery reach.

In other words, we choose parameters so that Higgs boson detection might be the only new physics signal within reach of the LHC.

However, the Higgs phenomenology does not depend much on this unless the soft-masses are below 400 to $500~\mathrm{GeV}$.

No Higgs-to-Higgs Decays No Lose Theorem

We first scanned over NMSSM parameter choices for which Higgs-to-Higgs decays are not allowed, searching for cases in which the SM/MSSM "standard modes" have the weakest signals. The standard modes for neutral Higgs detection in question are:

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) $WW \to h \to invisible$**.**

Of course, there is also the possibility of seeing the charged Higgs boson in $t \to H^+b$ **decays. The discovery contours displayed in Fig. 1 imply that** $m_{H^{\pm}} \lesssim 155~\mathrm{GeV}$ **(**$\Rightarrow m_A \lesssim 135~\mathrm{GeV}$**) will allow such detection.**

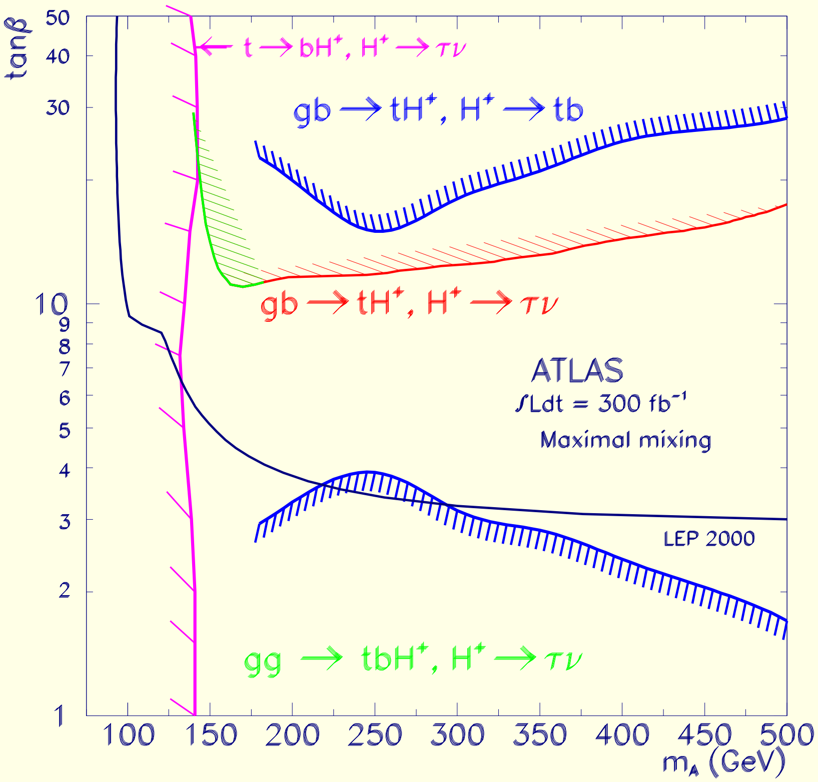

Figure 1: We display the contours for 5σ charged Higgs detection from (Assamagan:2004gv). The purple contour is the relevant one.

Charged Higgs detection and neutral Higgs detection in the standard modes 1) – 9) are complementary: the smaller the lower limit on $m_{H^\pm}$ for which we assume good significance for $t \to H^\pm b$ detection, the smaller can be the minimum $N_{SD} = S/\sqrt{B}$ for neutral Higgs detection.

This is revealed in a large scan in which we found 2455 physically acceptable points that:

- passed all LEP limits,
- had no Higgs-to-Higgs decays,
- had $m_{H^\pm} \geq 155~\mathrm{GeV}$,
- and had $< 10\sigma$ signals for all Higgs in modes 1) – 9) at the LHC assuming $L = 300\mathrm{fb}^{-1}$.

All points with no-Higgs-to-Higgs decays had at least one $\geq 5\sigma$ significance channel:

$\Rightarrow$ no-lose theorem.

Statistics on the important channels for these 2455 points are summarized in table 1. Note the importance of the channels 3), 4) and 7) for these most difficult cases.

Channel with highest $S/\sqrt{B}$	1	2	3	4	5	6	7	8	9
No. of points	0	0	343	132	0	1	1979	0	0

Table 1: Most important channel for detecting the 2455 no-Higgs-to-Higgs-decays points that were most difficult for LHC detection.

- The point yielding the very lowest LHC statistical significance had the following parameters,

$$\lambda = 0.0163; \quad \kappa = -0.0034; \quad \tan\beta = 5.7;$$
$$\mu_{\rm eff} = -284 \text{ GeV}; \quad A_\lambda = -70 \text{ GeV}; \quad A_\kappa = -54 \text{ GeV}, \tag{6}$$

which yielded $m_{H^\pm} \sim 155$ GeV and neutral Higgs boson properties as given in table 2.

The most visible processes for this point had $N_{SD} = S/\sqrt{B} > 6$. These were the $WW \to h_2 \to \tau^+\tau^-$, $WW \to h_3 \to \tau^+\tau^-$ and $t\bar{t}h_2 \to t\bar{t}b\bar{b}$ channels.

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

Higgs	h_1	h_2	h_3	a_1	a_2
Mass (GeV)	99	114	145	98	134
R_i	0.49	0.72	-0.48	—	—
t_i or t_i'	0.46	0.65	-0.64	-0.01	0.18
b_i or b_i'	1.71	3.23	4.49	0.36	5.59
g_i or g_i'	0.41	0.56	0.79	0.02	0.14
γ_i or γ_i'	0.51	0.75	0.43	0.01	0.10
$B(h_i\ or\ a_i \to b\overline{b})$	0.91	0.90	0.88	0.92	0.91
$B(h_i\ or\ a_i \to \tau^+\tau^-)$	0.08	0.08	0.09	0.08	0.09
Chan. 1) $S/\sqrt{B}$	0.00	0.22	0.20	0.00	0.00
Chan. 2) $S/\sqrt{B}$	0.42	0.80	0.15	0.42	0.00
Chan. 3) $S/\sqrt{B}$	3.52	6.25	5.39	3.52	5.39
Chan. 4) $S/\sqrt{B}$	0.73	1.26	3.86	1.26	3.86
Chan. 5) $S/\sqrt{B}$	0.00	0.15	1.00	—	—
Chan. 6) $S/\sqrt{B}$	0.00	0.00	0.80	—	—
Chan. 7) $S/\sqrt{B}$	0.00	6.70	6.54	—	—
Chan. 8) $S/\sqrt{B}$	0.00	0.20	0.25	—	—
All-channel $S/\sqrt{B}$	3.61	9.29	9.41	3.76	6.63

Table 2: Properties of the neutral NMSSM Higgs bosons for the most difficult no-Higgs-to-Higgs-decays LHC point. In the table, $R_i = g_{h_i VV}/g_{h_{SM} VV}$, $t_i = g_{h_i t\overline{t}}/g_{h_{SM} t\overline{t}}$, $b_i = g_{h_i b\overline{b}}/g_{h_{SM} b\overline{b}}$, $g_i = g_{h_i gg}/g_{h_{SM} gg}$ and $\gamma_i = g_{h_i \gamma\gamma}/g_{h_{SM}\gamma\gamma}$ for $m_{h_{SM}} = m_{h_i}$. Similarly, t_i' and b_i' are the $i\gamma_5$ couplings of a_i to $t\overline{t}$ and $b\overline{b}$ normalized relative to the scalar $t\overline{t}$ and $b\overline{b}$ SM Higgs couplings and g_i' and γ_i' are the $a_i gg$ and $a_i\gamma\gamma$ $\epsilon \times \epsilon'$ couplings relative to the $\epsilon \cdot \epsilon'$ coupling of the SM Higgs.

Higgs-to-Higgs Decays Allowed

- **We performed a scan of NMSSM parameter space requiring that** *at least one* **of the following decay modes be kinematically allowed for some h and or a:**

$$i)\ h \rightarrow h'h'\ ,\quad ii)\ h \rightarrow aa\ ,\quad iii)\ h \rightarrow h^{\pm}h^{\mp}\ ,\quad iv)\ h \rightarrow aZ\ ,$$
$$v)\ h \rightarrow h^{\pm}W^{\mp}\ ,\quad vi)\ a' \rightarrow ha\ ,\quad vii)\ a \rightarrow hZ\ ,\quad viii)\ a \rightarrow h^{\pm}W^{\mp}\ . \tag{7}$$

- **For most of these points it turns out that 5σ discovery of a neutral Higgs boson in at least one of the modes 1) – 9) is still possible.**

  The number of parameter space points for which one or more of the decays $i) - viii)$ is allowed, but 5σ discovery of a neutral Higgs boson in modes 1) – 9) is not possible, represents less than 1% of the physically acceptable points; in our scan we have found 3480 such points.

  In one sense, this small percentage is encouraging in that it implies that

the standard LHC detection modes 1) – 9) suffice for most of randomly chosen parameter points.

However, it should be noted that the fraction of points for which modes 1) – 9) suffice will decrease rapidly as the assumed LHC integrated luminosity is reduced.

The parameters associated with these points for which all NMSSM Higgs bosons escape LEP detection and LHC detection in modes 1) – 9) occur throughout the broad range defined in eq. (5).

The scenarios associated with these points have some generic properties of considerable interest that make them worthy of further study.

1. First, for all these 3480 points, the h_3 and a_2 are so heavy that they will only be detectable if a super high energy LC is eventually built so that $e^+e^- \to Z \to h_3 a_2$ is possible, implying that LHC Higgs detection must rely on the lighter h_1, h_2 and a_1 states.
2. The NMSSM parameter choices for which the latter cannot be detected at the LHC in the standard modes are such that there is a light, fairly SM-like CP-even Higgs boson (h_1 or h_2) that decays mainly to two lighter CP-odd or CP-even Higgs bosons ($h_{1,2} \to a_1 a_1$ or $h_2 \to h_1 h_1$).

We will denote the parent SM-like CP-even Higgs boson by h_H and the daughter Higgs boson that appears in the pair decay by h_L.

For most such cases, h_L is actually the lightest CP-odd scalar a_1 and h_H is the lightest or 2nd lightest CP-even scalar, h_1 or h_2.

3. In general, the h_L decays to $b\bar{b}$ and $\tau^+\tau^-$ (if $m_{h_L} > 2m_b$) or to jj and $\tau^+\tau^-$ (if $2m_\tau < m_{h_L} < 2m_b$) or, as unfortunately still possible, to jj if $m_{h_L} < 2m_\tau$.
   In the first two cases, a possibly viable LHC signal then comes [26, 27, 28] from $WW \rightarrow h_H \rightarrow h_L h_L \rightarrow jj\tau^+\tau^-$ in the form of a bump in the $M_{jj\tau^+\tau^-}$ reconstructed mass distribution, computed by looking at the $\tau \rightarrow \ell\nu\overline{\nu}$ decays and projecting $\not{p}_T$ onto ℓ directions.

- Out of the above 3480 points, we have selected eight benchmark points, the properties of which are displayed in tables 3 and 4, that illustrate the cases where LHC detection of the NMSSM Higgs bosons in the standard modes 1) – 9) would not be possible.

  The first five are such that the $WW \rightarrow h_H \rightarrow h_L h_L \rightarrow jj\tau^+\tau^-$ detection mode might be effective.

  Points 6, 7 and 8 are chosen to illustrate cases where the h_L appearing in the final state does not decay to either $b\bar{b}$ or $\tau^+\tau^-$, implying that the $WW \to h_H \to h_L h_L \to jj\tau^+\tau^-$ potential detection mode would not be useful.

We now discuss in more detail the characteristics of these eight benchmark points.

- **Points 1, 2 and 3** are designed to illustrate $h_1 \to a_1 a_1$ decay cases for a selection of possible h_1 and a_1 masses.

  For point 1, m_{a_1} is below the $b\bar{b}$ threshold so that the main a_1 decay is to $\tau^+\tau^-$ or jj.

  For points 2 and 3, $a_1 \to b\bar{b}$ and $a_1 \to \tau^+\tau^-$ decays will be dominant and in the usual ratio.
- **Point 4** is such that the h_1 and h_2 (with masses $m_{h_1} = 97~\mathrm{GeV}$ and $m_{h_2} = 150~\mathrm{GeV}$) share the WW/ZZ coupling strength squared and both decay to $a_1 a_1$.

  The a_1 decays to $b\bar{b}$ and $\tau^+\tau^-$ in the usual ratio.
- **Point 5** illustrates a case in which it is the h_2 that is SM-like and it decays to $h_1 h_1$.

  The $h_1 \to b\bar{b}$ and $h_1 \to \tau^+\tau^-$ decays are the dominant ones and are in the usual ratio.

Although m_{h_1} is rather small in this case, it would not have been seen at LEP due to its singlet nature.

Nonetheless, $BR(h_2 \to h_1 h_1)$ is large due to the new trilinear NMSSM couplings.

- For **point 6**, the h_1 is SM-like and decays via $h_1 \to a_1 a_1$, but $a_1 \to \gamma\gamma$ is dominant due to the singlet nature of a_1.

  The 4γ final state would provide a highly distinctive signal that should be easily seen at the LHC [25].
- **Point 7** illustrates a case in which the h_2 is SM-like and decays via $h_2 \to h_1 h_1$.

  The new feature compared to point 5 is that the h_1 has reduced coupling to $b\bar{b}$ and $\tau^+\tau^-$ due to the fact that parameters are such that h_1 is almost entirely H_u in nature. [1]

  Obviously, the $WW \to h_2 \to jj\tau^+\tau^-$ mode would not be relevant for this type of scenario.

  We do not think that the resulting $h_2 \to 4j$ signal could be isolated from backgrounds.
- **Point 8** illustrates a case in which the h_1 is SM-like and decays via

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[1] A continuum of points of this type was discussed in ref. [14].

$h_1 \to a_1 a_1$.

It differs from earlier such points in that the a_1 is extremely light and decays mainly to jj ($j = s, c, g$).

Like for point 7, the $WW \to h_1 \to jj\tau^+\tau^-$ detection channel would not be relevant.

This a_1 would not have been seen at LEP in the $h_1 a_1$ mode for several reasons (for details see the references and discussions in [14]):

Point Number	1	2	3	4	5
Bare Parameters					
λ	0.22	0.4	0.22	0.67	0.56
κ	-0.1	-0.35	0.59	0.2	0.1
$\tan\beta$	5.	15.	7.8	4.1	2.5
$\mu_{\rm eff}$ (GeV)	$-520.$	$-160.$	530.	$-200.$	$-180.$
A_λ (GeV)	$-580.$	$-580.$	$-920.$	$-600.$	$-440.$
A_κ (GeV)	-2.8	-8.7	-2.1	$-30.$	172.
CP-even Higgs Boson Masses and Couplings					
m_{h_1} (GeV)	90.	100.	119.	97.	40.
R_1	0.99	0.97	-1.00	0.69	0.00
t_1	0.99	0.97	-1.00	0.72	0.05
b_1	1.00	0.90	-1.01	0.31	-0.35
g_1	0.99	0.97	1.00	0.74	0.15
γ_1	0.99	0.99	1.00	0.78	0.11
$B(h_1 \to b\bar{b})$	0.08	0.02	0.01	0.01	0.93
$B(h_1 \to \tau^+\tau^-)$	0.01	0.00	0.00	0.00	0.07
$B(h_1 \to a_1 a_1)$	0.91	0.97	0.99	0.99	0.00
m_{h_2} (GeV)	479.	288.	1431.	150.	125.
R_2	0.16	0.26	0.00	0.72	-1.00
t_2	0.16	0.26	0.13	0.70	-1.00
b_2	0.19	0.57	-7.8	1.10	-1.03
g_2	0.16	0.26	0.12	0.69	0.99
γ_2	0.19	0.24	0.08	0.65	0.99
$B(h_2 \to a_1 a_1)$	0.04	0.44	0.00	0.97	0.00
$B(h_2 \to h_1 h_1)$	0.25	0.21	0.00	0.00	0.92
m_{h_3} (GeV)	952.	1016.	2842.	753.	495.

Point Number	1	2	3	4	5
CP-odd Higgs Boson Masses and Couplings					
m_{a_1} (GeV)	10.	20.	31.	45.	144.
t_1'	-0.01	0.00	-0.01	-0.02	-0.06
b_1'	-0.22	-0.85	-0.53	-0.40	-0.40
g_1'	0.15	0.48	0.19	0.08	0.06
γ_1'	0.12	0.11	0.15	0.49	0.61
$B(a_1 \to b\bar{b})$	0.00	0.94	0.93	0.93	0.85
$B(a_1 \to \tau^+\tau^-)$	0.83	0.06	0.07	0.07	0.08
$B(a_1 \to jj)$	0.17	0.00	0.00	0.00	0.01
m_{a_2} (GeV)	952.	1018.	1434.	750.	495.
Charged Higgs Boson Mass					
$m_{h^\pm}$ (GeV)	954.	1017.	1432.	742.	487.
LSP Mass					
$m_{\widetilde{\chi}_1^0}$	453.	136.	476.	113.	82.
Most Visible of the LHC Processes 1)-9)	2(h_1)	5(h_2)	2(h_1)	5(h_2)	2(h_2)
$N_{SD} = S/\sqrt{B}$ of this process at L =300 fb^{-1}	1.6	0.7	0.3	0.5	2.0

Table 3: Properties of five scenarios for which LHC Higgs detection would only be possible in the $WW \to h_{1,2} \to a_1 a_1 \to jj\tau^+\tau^-$ or $WW \to h_2 \to h_1 h_1 \to jj\tau^+\tau^-$ mode. The quantities R_i, t_i, b_i, g_i, γ_i, t_i', b_i', g_i' and γ_i' were defined in the caption of table 2. Important absolute branching ratios are displayed. Only the masses of the heavy h_3, a_2 and $h^\pm$ are given. The mass of the lightest neutralino (LSP) is also given. The second-to-last row gives the channel and Higgs boson yielding the largest $N_{SD} = S/\sqrt{B}$ in channels 1) – 9). The following row gives the corresponding N_{SD} for $L = 300\mathrm{fb}^{-1}$.

Point Number	**6**	**7**	**8**
Bare Parameters			
λ	0.39	0.5	0.27
κ	0.18	-0.15	0.15
$\tan\beta$	3.5	3.5	2.9
μ_{eff}	$-245.$	$200.$	$-753.$
A_λ	$-230.$	$780.$	$312.$
A_κ	$-5.$	$230.$	8.4
CP-even Higgs Boson Masses and Couplings			
m_{h_1} (GeV)	$94.$	$57.$	$95.$
R_1	0.94	-0.28	1.00
t_1	0.95	-0.30	0.99
b_1	0.89	0.01	1.05
g_1	0.95	0.33	0.99
γ_1	0.96	0.37	1.00
$B(h_1 \to jj)$	0.01	0.93	0.00
$B(h_1 \to a_1 a_1)$	0.94	0.00	1.00
m_{h_2} (GeV)	$239.$	$125.$	$483.$
R_2	0.33	-0.96	-0.01
t_2	0.30	-0.95	-0.36
b_2	0.67	-1.07	2.84
g_2	0.29	0.95	0.37
γ_2	0.30	0.94	0.68
$B(h_2 \to h_1 h_1)$	0.32	0.93	0.01
m_{h_3} (GeV)	$562.$	$731.$	$821.$

Point Number	6	7	8
CP-odd Higgs Boson Masses and Couplings			
m_{a_1} (GeV)	40.	188.	1.
t_1'	0.00	0.04	0.08
b_1'	0.00	0.53	0.62
g_1'	0.00	0.04	0.36
γ_1'	0.47	0.31	0.39
$B(a_1 \to jj)$	0.00	0.00	0.95
$B(a_1 \to \mu\mu)$	0.00	0.00	0.05
$B(a_1 \to \gamma\gamma)$	0.98	0.00	0.00
$B(a_1 \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0)$	0.00	0.99	0.00
m_{a_2} (GeV)	558.	736.	493.
Charged Higgs Boson Mass			
$m_{h^\pm}$ (GeV)	560.	727.	485.
LSP Mass			
$m_{\widetilde{\chi}_1^0}$	211.	81.	500.
Most Visible of the LHC Processes 1)-9)	5(h_2)	2(h_2)	5(h_3)
$N_{SD} = S/\sqrt{B}$ of this process at L =300 fb^{-1}	1.5	1.3	0.1

Table 4: Properties of three representative scenarios for which LHC Higgs detection would not even be possible in the $WW \to h_{1,2} \to a_1 a_1 \to jj\tau^+\tau^-$ or $WW \to h_2 \to h_1 h_1 \to jj\tau^+\tau^-$ modes.

- **The LHC $WW \to h \to aa \to jj\tau^+\tau^-$ mode**

  - In earlier work, we (Ellwanger, Gunion, Hugonie, Moretti) studied 6 (different) points where this would be the only Higgs discovery mode at the LHC.

  - After many cuts, including forward / backward jet tagging and various vetoes, but no b-tagging, we were able to eliminate the potentially serious DY $\tau^+\tau^- + jets$ background, leaving $t\bar{t}$ as the major background.

  - We obtained the signals in the $M_{jj\tau^+\tau^-}$ distribution shown in Fig. 2.

    For all six cases, the Higgs resonance produces a bump at low $M_{jj\tau^+\tau^-}$ with lots of events (for $L = 300~\mathrm{fb}^{-1}$).

    The main issue is whether or not the tail from the $t\bar{t}$ background really cuts off where shown.

    Some ATLAS people (Zerwas, Baffioni) use different cuts and claim not, but they are redoing with cuts closer to the cuts employed for Fig. 2.

LHC, $\sqrt{s_{pp}} = 14$ TeV

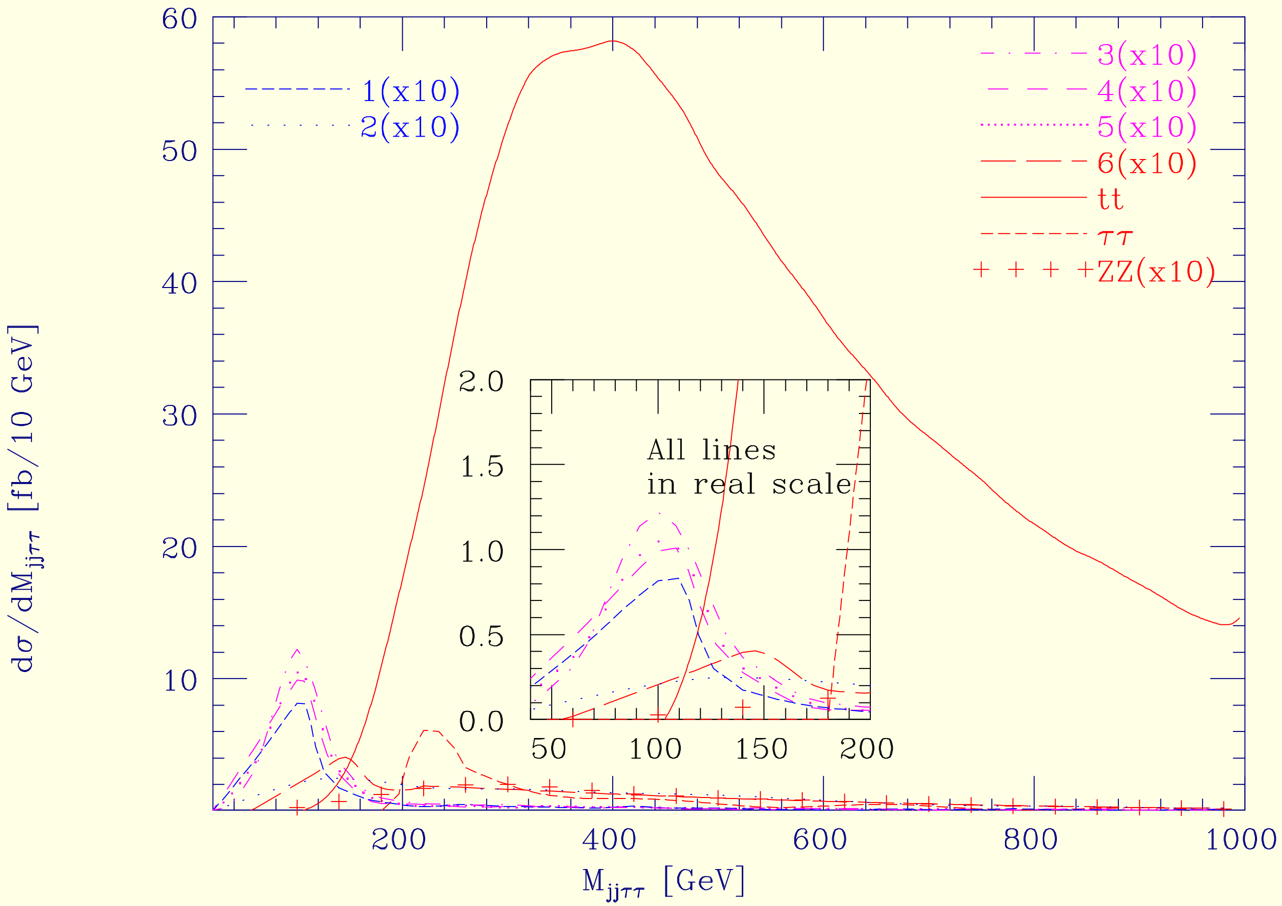


Figure 2: *Reconstructed mass of the $jj\tau^+\tau^-$ system for signals and backgrounds before b-tagging. No K factors are included.*

- **Question:** **Can the Tevatron be sensitive to the Higgs-to-Higgs decay scenarios?**

This will be discussed by Bob McElrath on Friday.

The jury is out, but we (McElrath, Chertok, Conway, JFG, Safanov) have started to look at the $gg \to h_1 \to a_1 a_1 \to 4\tau$ mode assuming $2m_\tau < m_{a_1} < 2m_b$.

The Minimal LHC Role

- **Even if no Higgs boson is observed, we 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 $h_H \to h_L h_L$ signal, etc. that was missed.**
  2. **There is something for a modest energy ILC to see !!!**

Comments

It is tempting to view the points for which the “standard” modes fail and $h_H \to h_L h_L$ detection is needed as a very small subset of the physically acceptable parameter choices and, therefore, highly unlikely to be nature’s choice.

However, it turns out that the fine-tuning and little hierarchy problems of the CP-conserving MSSM are best avoided for just such points (but with lower soft-SUSY-breaking scales than assumed so far.)

We will return to this momentarily, but we first contrast the LHC/Tevatron difficulties with the ILC and a $\gamma\gamma$ collider.

At both machines, detection of $h_H \to h_L h_L$ is quite easy since the h_H is always relatively light and fairly SM-like.

Difficult scenarios at the ILC

- Whether or not we have a good LHC signal if nature chooses a difficult point, ultimately, a means of confirmation and further study will be critical.

  Thus, it is important to summarize the prospects at the LC.

- For difficult scenarios, we always find that either h_1 or h_2 has reasonable WW, ZZ coupling and mass at most $\sim 140~\mathrm{GeV}$ (but possibly much lower).

  Discovery of the h will be very straightforward via $e^+e^- \to Zh$ using the $e^+e^- \to ZX$ reconstructed M_X technique which is independent of the "unexpected" complexity of the h decay to a_1a_1 (or h_1h_1 for $h = h_2$).

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

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

- The LC should find it quite easy to look for even a rather light h decaying to aa in the ZX channel.

The role of a γC

The γC working group has been considering the role that might be played by such a facility in a variety of physics situations. Some references for our work appear below.

References

[1] D. Asner *et al.*, arXiv:hep-ph/0308103.

[2] D. Asner, B. Grzadkowski, J. F. Gunion, H. E. Logan, V. Martin, M. Schmitt and M. M. Velasco, arXiv:hep-ph/0208219.

[3] M. M. Velasco *et al.*, in *Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001)* ed. N. Graf, eConf C010630, E3005 (2001) [arXiv:hep-ex/0111055].

The γC could play a special role for NMSSM parameter cases such that the only LHC signal for Higgs bosons is the $jj\tau^+\tau^-$ low mass bump.

- If the difficult h has already been seen at an LC, the γC will allow for refined measurements, especially of the $\gamma\gamma$ coupling which will not be precisely SM-like.

- But, it is also possible that a CLIC-test module-based low-energy γC could be built before the LC.

- We have studied the potential of such a CLICHE (CLIC Higgs Experiment) in the case of the difficult $h \to aa$ scenarios discussed previously.

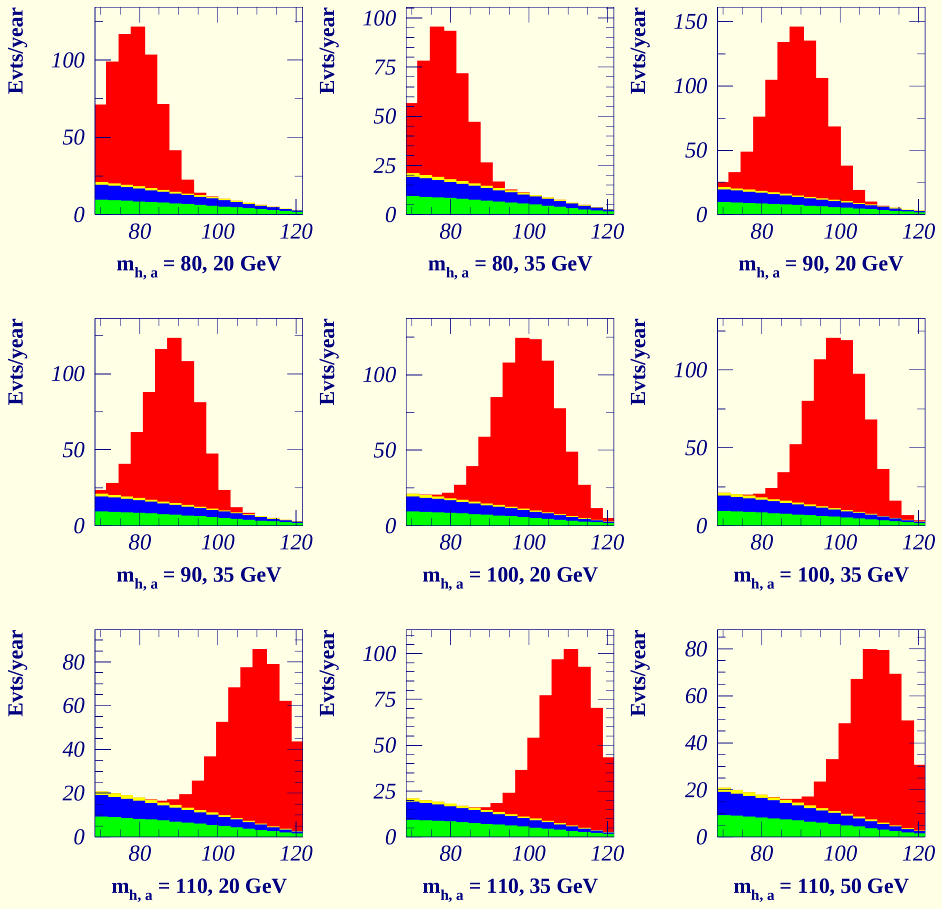
- The hard-core simulation work has been performed by Michal Szleper.

Results for **broad** spectrum, assuming $h \to aa$, with $a \to b\bar{b}$

- Result is excellent signals and small backgrounds in all cases — see 1st figure.

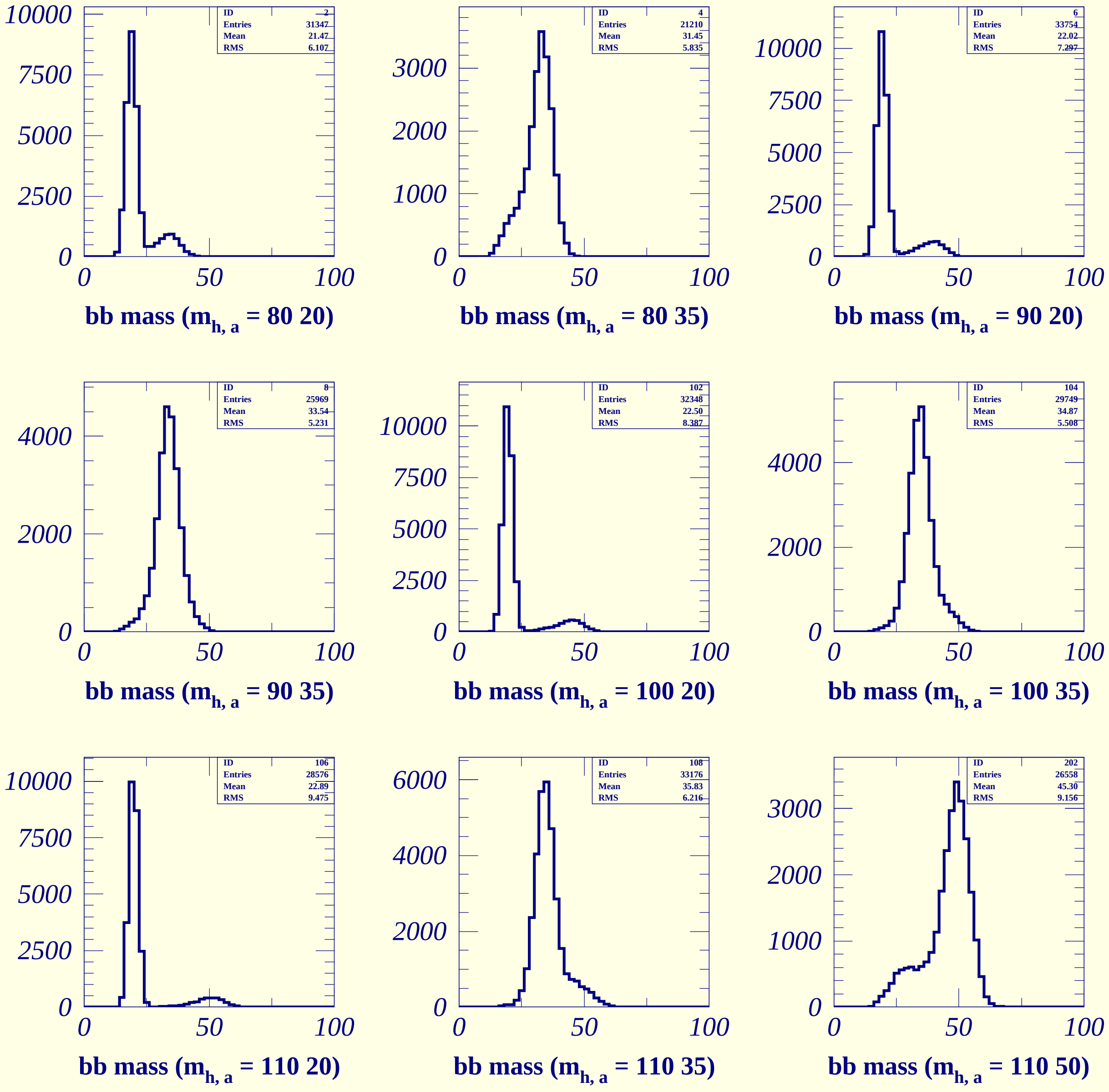
- Excellent determination of m_a is possible — see 2nd figure.

4-JET INV. MASS - SIGNAL on top of BACKGROUND



How well can we determine the a mass?

RECONSTRUCTED bb MASSES



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

w. Radovan Dermisek [30]

The basic fine-tuning measure is

$$F = \mathrm{Max_a} \left| \frac{d \log m_Z}{d \log a} \right| \tag{8}$$

where the parameters a are the GUT scale soft-SUSY-breaking parameters and the μ parameter.

To explore fine tuning, we proceed as follows.

- 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. 3.

- 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 $h_1 \to b\overline{b}$ 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 $h_1 \to b\overline{b}$ decays are dominant, even if somewhat suppressed; $h_1 \to a_1 a_1$ decays dominate for a few.

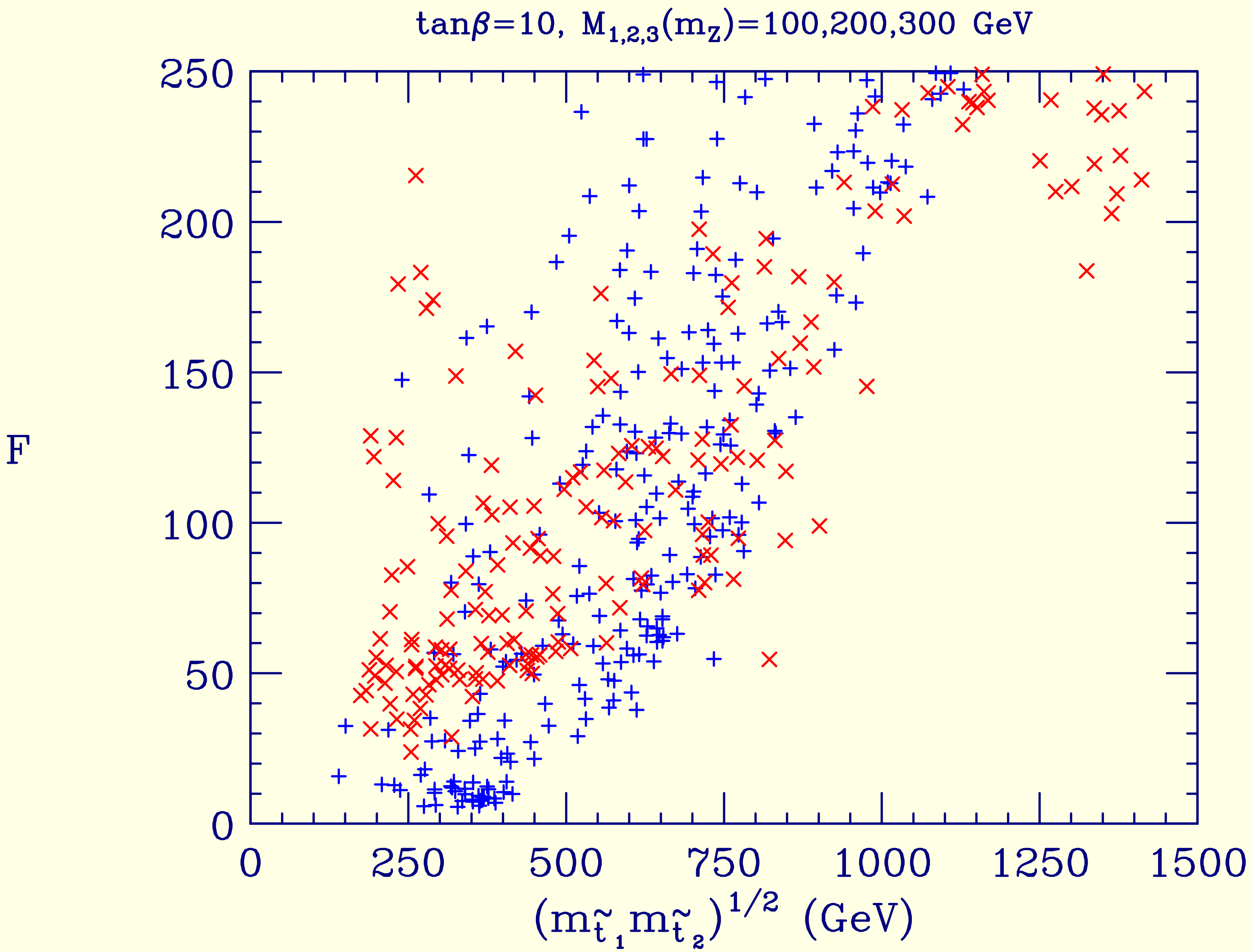


Figure 3: For the NMSSM, we plot the fine-tuning measure F vs. $\sqrt{m_{\tilde t_1} m_{\tilde t_2}}$ for NMHDECAY-accepted scenarios with $\tan\beta = 10$ and $M_{1,2,3}(m_Z) = 100, 200, 300~\mathrm{GeV}$. Points marked by '$+$' ('$\times$') escape LEP exclusion primarily due to dominance of $h_1 \to a_1 a_1$ decays (due to $m_{h_1} > 114~\mathrm{GeV}$).

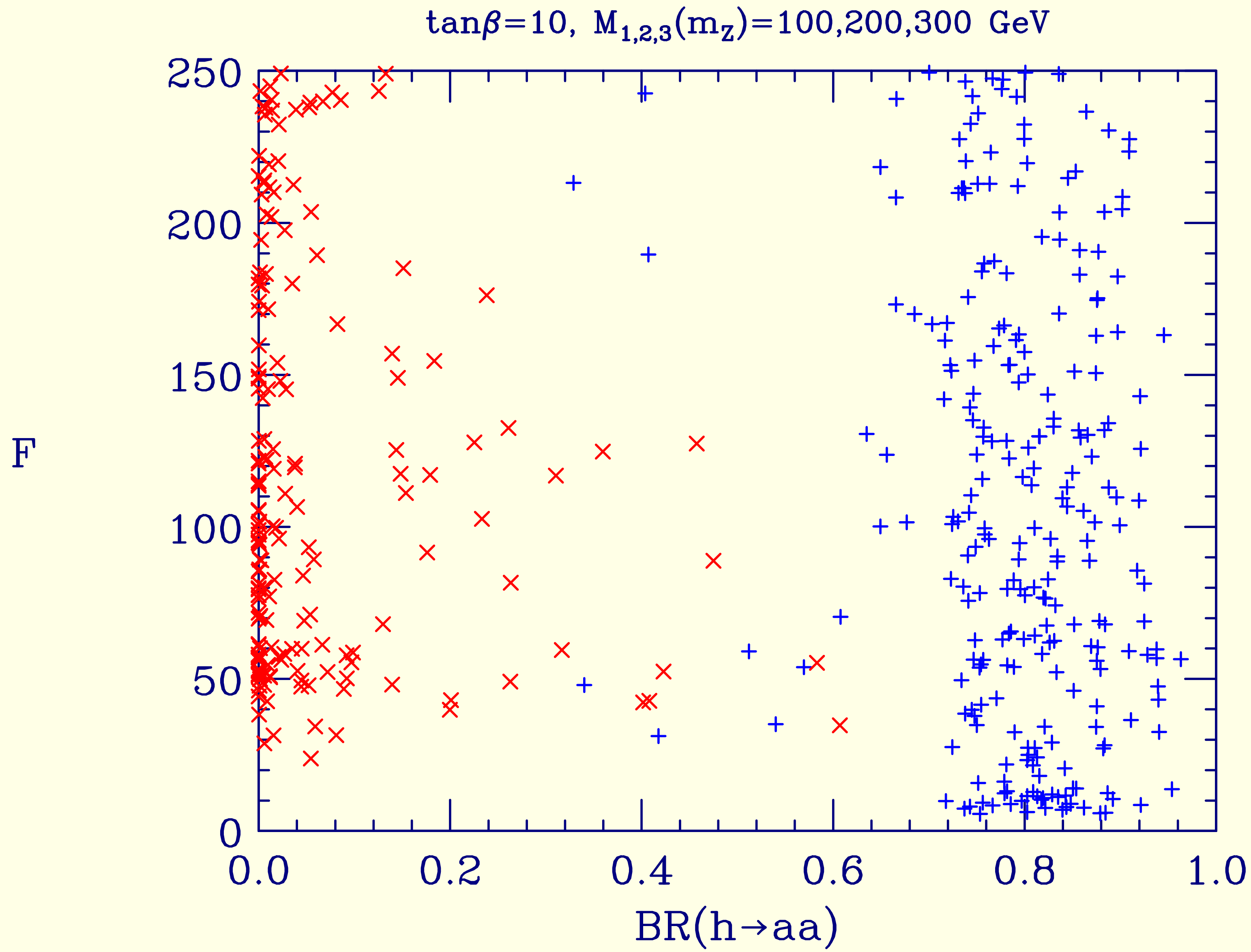


Figure 4: For the NMSSM, we plot the fine-tuning measure F vs. $BR(h_1 \to a_1a_1)$ for NMHDECAY-accepted scenarios with $\tan\beta = 10$ and $M_{1,2,3}(m_Z) = 100, 200, 300$ GeV. Point notation as in Fig. 3.

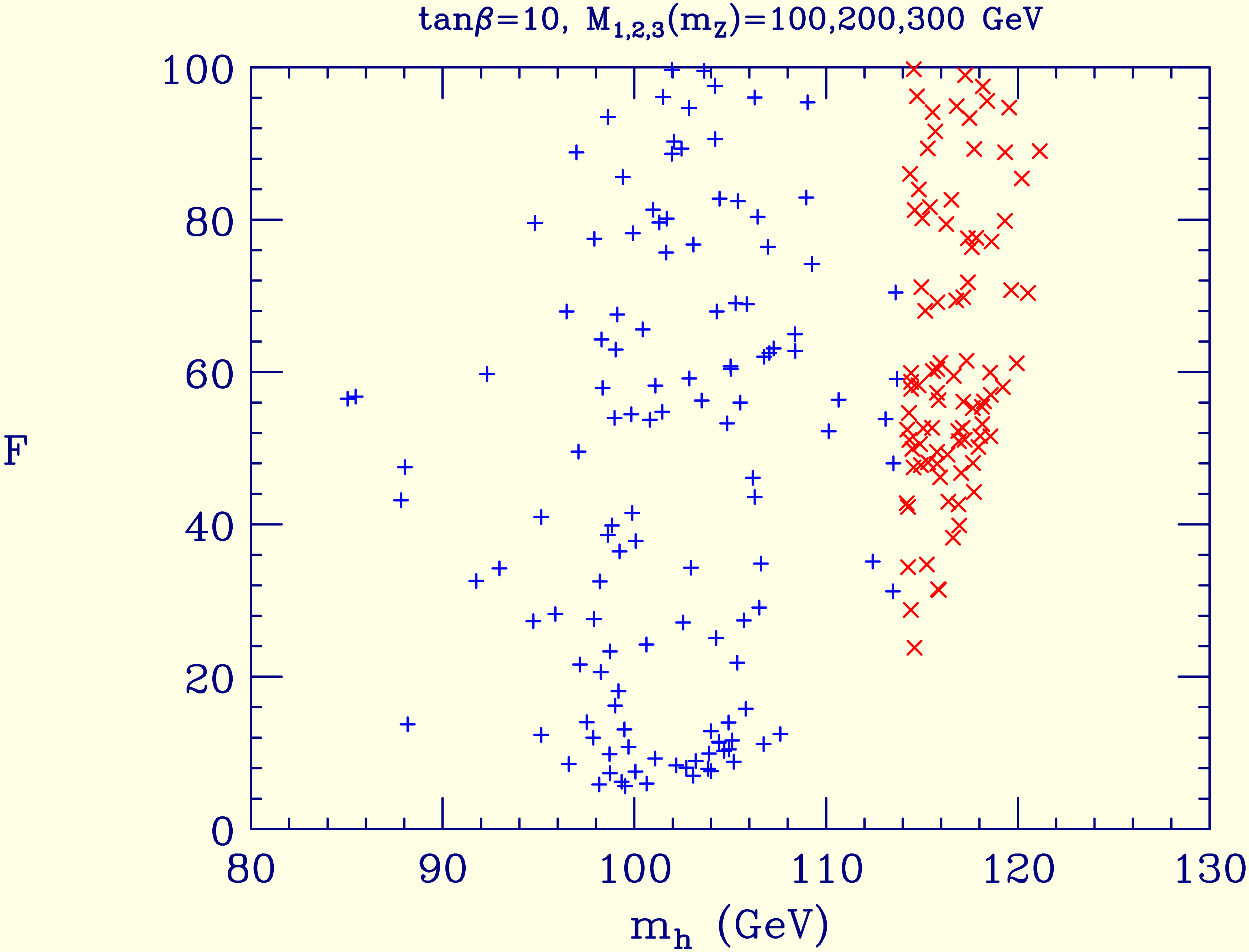


Figure 5: For the NMSSM, we plot the fine-tuning measure F vs. m_{h_1} for NMHDECAY-accepted scenarios with $\tan\beta = 10$ and $M_{1,2,3}(m_Z) = 100, 200, 300~\mathrm{GeV}$. Point notation as in Fig. 3.

Additional Remarks

- 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. 5.

  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.

- For $\tan\beta = 3$, extremely large $\sqrt{m_{\widetilde{t}_1} m_{\widetilde{t}_2}}$ is required for $m_h > 114~\mathrm{GeV}$ in the MSSM, leading to extremely large F.

  Results in the NMSSM for $\tan\beta = 3$ are plotted in Fig. 6 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.

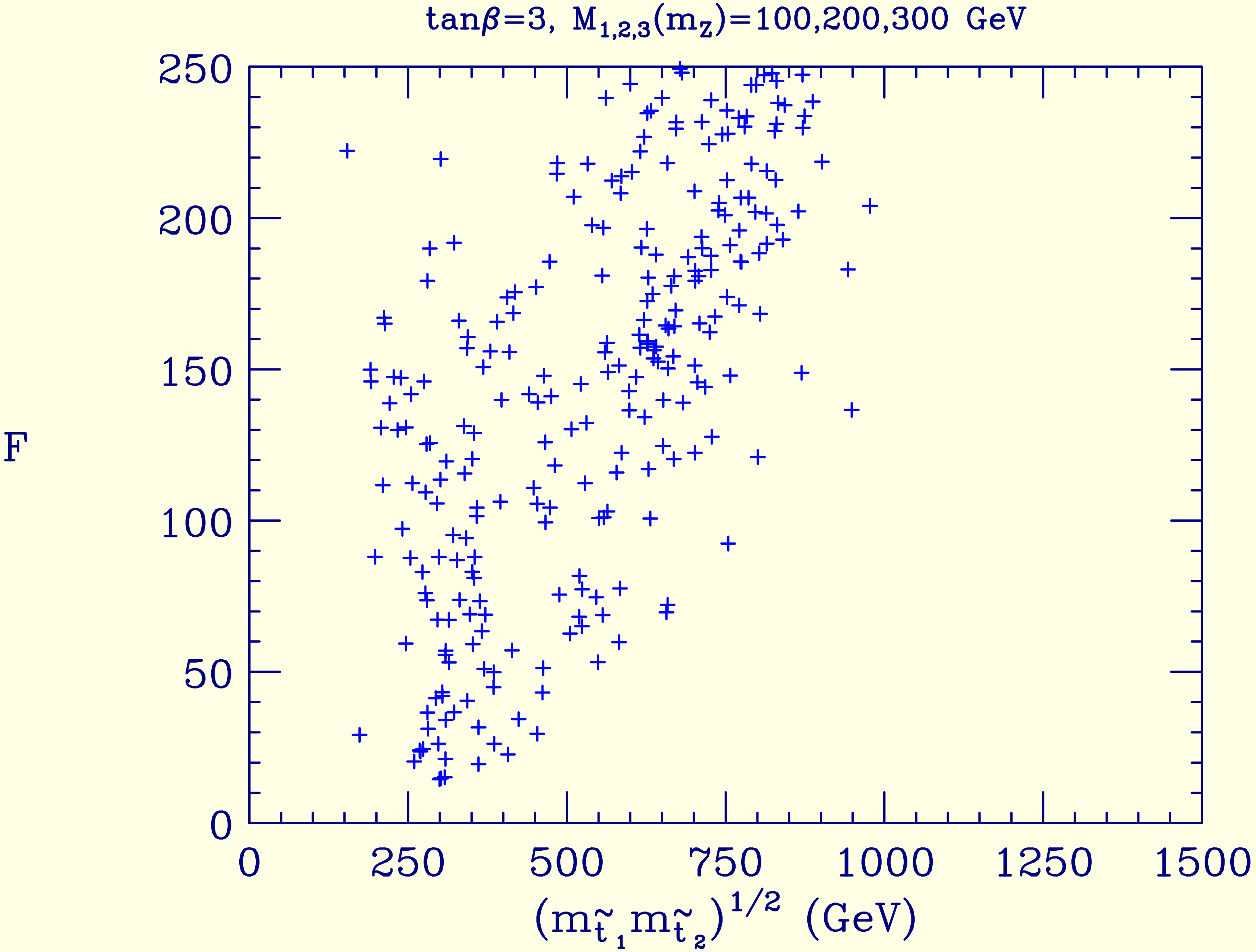


Figure 6: For the NMSSM, we plot the fine-tuning measure F vs. the mass of the lightest stop for NMHDECAY-accepted scenarios with $\tan\beta = 3$ and $M_{1,2,3}(m_Z) = 100, 200, 300$ GeV. There are no points with $m_{h_1} \geq 114$ GeV.

LHC Implications II: Low fine-tuning cases

- A very interesting question is whether or not the Higgs bosons in the low-F cases are observable.
- We have processed the points appearing in the $\tan\beta = 10$ figures through the LHC analysis.

  The result is shown in Fig. 7.
- The very lowest F cases (which have $m_{h_1} < 114~\mathrm{GeV}$) not only escape LEP detection, but also provide very weak signals for LHC Higgs detection in the "standard" modes.

  Sensitivity to the $h_1 \to a_1 a_1$ modes is needed.
- Details are provided for the point with lowest fine-tuning found. We find:

  1. Low mass scales for most SUSY particles.
  2. $m_{h_1} \sim 98~\mathrm{GeV}$, SM-like lightest Higgs.
  3. Standard Higgs signals have tiny N_{SD}.

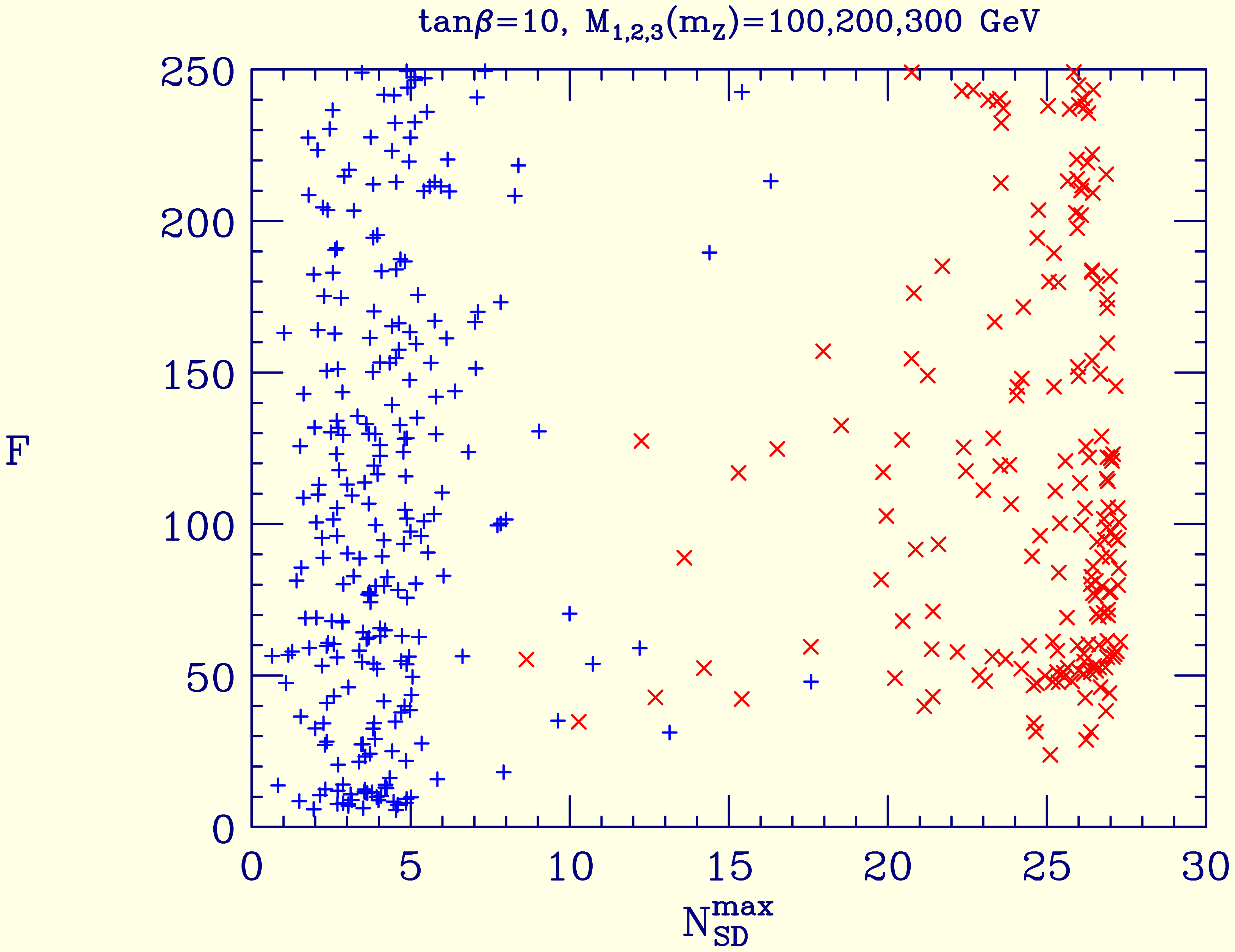


Figure 7: F **vs. maximum statistical significance (**$L = 300\mathrm{fb}^{-1}$**) of "standard" neutral Higgs boson signals:** $\tan\beta = 10$**.**

```
Point     21403

F=  5.84332

lambda=     0.1495
kappa=      0.2593
tan(beta)=   10.00
mu=         134.61
Alambda=   -152.20
Akappa=      -3.18

mQ3=  214.49 mU3=  219.01 mD3=  235.82
Atop= -124.47 Abot= -124.47

M1=  100.00 M2=  200.00

Warning:

 third scalar can decay into squarks

 MAXSIGN,IHMAX,ICHMAX=  1.9475705 1 2

mh1=   98.17
 Components -0.9934 -0.1119  0.0250
 CV=  -0.100E+01
 CU=  -0.998E+00
 CD=  -0.112E+01
 CG=   0.993E+00
```

```
 CGA=  0.103E+01
 BR(h1->gluongluon)=  0.433E-02
 BR(h1->tautau)=      0.919E-02
 BR(h1->mumu)=        0.326E-04
 BR(h1->ss)=          0.600E-04
 BR(h1->cc)=          0.406E-02
 BR(h1->bb)=          0.103E+00
 BR(h1->tt)=          0.000E+00
 BR(h1->WW)=          0.341E-03
 BR(h1->ZZ)=          0.164E-05
 BR(h1->gammagamma)=  0.140E-03
 BR(h1->Zgamma)=      0.218E-05
 BR(h1->Higgses)=     0.879E+00
 BR(h1->sparticles)=  0.000E+00
 Total Width [GeV]=   0.279E-01

 LHC significances
   0.000E+00  0.195E+01  0.192E+01  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00

mh2=  331.11
 Components  0.1098 -0.9912 -0.0743
 CV=   0.106E-01
 CU=   0.110E+00
 CD= -0.996E+01
 CG=   0.165E+00
 CGA=  0.255E+00
 BR(h2->gluongluon)=  0.139E-03
 BR(h2->tautau)=      0.413E-01
 BR(h2->mumu)=        0.146E-03
```

```
 BR(h2->ss)=          0.209E-03
 BR(h2->cc)=          0.229E-04
 BR(h2->bb)=          0.362E+00
 BR(h2->tt)=          0.000E+00
 BR(h2->WW)=          0.569E-03
 BR(h2->ZZ)=          0.258E-03
 BR(h2->gammagamma)=  0.431E-05
 BR(h2->Zgamma)=      0.895E-07
 BR(h2->Higgses)=     0.130E+00
 BR(h2->sparticles)=  0.465E+00
 Total Width [GeV]=   0.165E+01

 LHC Significances
  0.000E+00  0.000E+00  0.000E+00  0.151E+01  0.838E-03  0.738E-03  0.000E+00  0.000E+00  0.125E-03

mh3=  466.78
 Components  0.0331 -0.0710  0.9969
 CV=   0.259E-01
 CU=   0.332E-01
 CD=  -0.714E+00
 CG=   0.340E-01
 CGA=  0.198E+00
 BR(h3->gluongluon)=  0.294E-04
 BR(h3->tautau)=      0.529E-03
 BR(h3->mumu)=        0.187E-05
 BR(h3->ss)=          0.253E-05
 BR(h3->cc)=          0.488E-05
 BR(h3->bb)=          0.444E-02
 BR(h3->tt)=          0.122E-01
```

```
 BR(h3->WW)=          0.200E-01
 BR(h3->ZZ)=          0.952E-02
 BR(h3->gammagamma)=  0.139E-05
 BR(h3->Zgamma)=      0.342E-06
 BR(h3->Higgses)=     0.702E+00
 BR(h3->sparticles)=  0.252E+00
 Total Width [GeV]=   0.932E+00

 LHC Significances
  0.000E+00  0.000E+00  0.000E+00  0.346E-04  0.159E-02  0.122E-02  0.000E+00  0.000E+00  0.000E+00

ma1=   16.79
 Components -0.0144 -0.1435 -0.9895
 CU=  -0.144E-01
 CD=  -0.144E+01
 CG=   0.911E+00
 CGA=  0.825E+00
 BR(a1->gluongluon)=  0.405E-02
 BR(a1->tautau)=      0.550E-01
 BR(a1->mumu)=        0.199E-03
 BR(a1->ss)=          0.564E-03
 BR(a1->cc)=          0.502E-03
 BR(a1->bb)=          0.940E+00
 BR(a1->tt)=          0.000E+00
 BR(a1->gammagamma)=  0.203E-05
 BR(a1->Zgamma)=      0.000E+00
 BR(a1->Higgses)=     0.000E+00
 BR(a1->sparticles)=  0.000E+00
 Total Width [GeV]=   0.129E-02
```

```
 LHC Significances
   0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.000E+00

ma2=  335.07
 Components  0.0985  0.9846 -0.1443
 CU=   0.990E-01
 CD=   0.990E+01
 CG=   0.867E-01
 CGA=   0.230E+00
 BR(a2->gluongluon)=  0.145E-03
 BR(a2->tautau)=      0.307E-01
 BR(a2->mumu)=        0.109E-03
 BR(a2->ss)=          0.155E-03
 BR(a2->cc)=          0.231E-04
 BR(a2->bb)=          0.269E+00
 BR(a2->tt)=          0.000E+00
 BR(a2->gammagamma)=  0.390E-05
 BR(a2->Zgamma)=      0.148E-06
 BR(a2->Higgses)=     0.110E+00
 BR(a2->sparticles)=  0.590E+00
 Total Width [GeV]=   0.221E+01

 LHC Significances
   0.000E+00  0.000E+00  0.000E+00  0.151E+01  0.000E+00  0.000E+00  0.000E+00  0.000E+00  0.125E-03

mhc=  340.15
 Components  0.0995  0.9950
 BR(hc->munu)=       0.155E-03
```

```
 BR(hc->taunu)=      0.438E-01
 BR(hc->su)=         0.104E-04
 BR(hc->bu)=         0.597E-05
 BR(hc->sc)=         0.217E-03
 BR(hc->bc)=         0.597E-03
 BR(hc->bt)=         0.396E+00
 BR(hc->Wh,Wa)=      0.140E+00
 BR(hc->chi+chi0)=   0.419E+00
 Total Width [GeV]=  0.161E+01

mneutralino1=   74.05
 components  0.6868 -0.2647 -0.3594  0.5726  0.0354
mneutralino2=  125.46
 components  0.7040  0.4498  0.3793 -0.3967 -0.0272
mneutralino3= -146.33
 components -0.1144  0.1523  0.7252  0.6609  0.0310
mneutralino4=  245.33
 components -0.1399  0.8393 -0.4482  0.2729  0.0267
mneutralino5=  468.37
 components  0.0021 -0.0055  0.0125 -0.0589  0.9982

mchargino1=  104.58
mchargino2=  245.19

mstop1=  235.42 mstop2=  321.00
msbot1=  220.31 msbot2=  250.50
```

Conclusions

- **The NMSSM is an attractive model, and the $h \to aa$ decay modes have significantly nice features with regard to finetuning.**
- **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 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.**

- The modest mass and typically fairly SM-like couplings of the lightest Higgs boson imply that the Tevatron production rates are significant after accumulating a few fb^{-1}.

  It is not impossible that the backgrounds will be better at the Tevatron than at the LHC.

- Detailed studies 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.

  But, Higgs detection at hadron colliders may be a real challenge.

Ability to check perturbativity of $WW \to WW$ at the LHC might prove to be very crucial.