The NMSSM Higgs Sector

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Outline

- Why the NMSSM?
- Brief Review of the NMSSM
- NMHDECAY
- NMSSM Higgs at the LHC
- NMSSM Higgs at the ILC and γC
- Evasion of Fine-Tuning and Little Hierarchy Problems In the NMSSM and Implications

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Motivations for the NMSSM

SM problems:

- **No explanation for the huge hierarchy of $m_{h_{\rm SM}} \ll M_{\rm P}$, as required for perturbativity of $W_L W_L \to W_L W_L$, ... If the scale of new physics is Λ, then**

$$\delta m_h^2\Big|_{top} \sim -\frac{N_c |\lambda_t|^2}{8\pi^2}\Lambda^2 \tag{1}$$

  and in the absence of new physics communicating to the Higgs sector before $M_{\rm P}$, $\Lambda \sim M_{\rm P}$ leads to huge fine-tuning.

- **No explanation for negative m^2 in Higgs potential needed for EWSB.**

- **Gauge coupling unification does not take place.**

MSSM successes:

- **Gauge coupling unification works very well (though not perfectly).**

- **Evolution from GUT scale to m_Z can naturally produce $m^2_{H_u} < 0$ and, hence, EWSB.**

- **Dark matter.**

- **Low-Scale ($\lesssim$ TeV) Supersymmetry could in principle solve the naturalness / hierarchy problem.**

BUT **there are significant problems for the MSSM**

MSSM problems:

- **The CP-conserving MSSM is being pushed into parameter regions characterized by substantial fine tuning and a "little" hierarchy problem (i.e. large stop masses) in order to have a heavy enough Higgs boson for consistency with LEP limits.**

- **A strong phase transition for baryogenesis is hard to arrange when the Higgs is heavy and the stops are heavy.**

- **No really attractive explanation for the μ parameter has emerged.**

- **One can marginally escape all but the last of these problems if significant Higgs sector CP violation is introduced through SUSY loops.**

What are the alternatives to the MSSM?:

- **We can ignore the naturalness and hierarchy issues and accept the huge fine-tuning of "Split Supersymmetry" (Arkani-Hamed etal).**

- **We can "temporarily" solve the hierarchy problem up to $\mathbf{\Lambda \sim 10}$ TeV using Little Higgs models (Arkani-Hamed etal).**
  - **After $\mathbf{\Lambda \sim 10}$ TeV new strong interactions must enter.**
  - **Is there really consistency with precision electroweak?**
  - **A recent paper (Casas etal) argues that fine tuning in the little Higgs models is comparable to that of the SM and larger than in the MSSM.**

- **Large Extra Dimensions? (Dimopoulos, ...)**

  This remains a possibility, but could we really be so "lucky" (or unlucky, given that all physics would end at a scale of order a TeV).

- **Higgsless Models? (Terning etal)**

– Not only do we need extra dimensions, RS warping, and so forth, but we also need special ($v \to \infty$) boundary conditions on the TeV brane.
– Lots of special arrangements regarding fermions are needed for consistency with precision electroweak.

- The NMSSM?

  – We will show that the CP-conserving NMSSM can solve all these problems.
  Indeed, the NMSSM can have a very low-level of fine-tuning, small little hierarchy, good electroweak baryogenesis,...
  Thus, is it not time to adopt the NMSSM as the baseline supersymmetric model?
  – The NMSSM phenomenology is considerably richer than that of the MSSM in many important ways.
  – The NMSSM is the simplest of a class of models that emerge from string theory with extra singlet super fields. For example, there are models with extra superfields that are singlets under the SM groups, but charged under a new $U(1)'$. One such model was studied by McElrath, Han, Langacker, ...
  – The focus here is on Higgs physics.
  The NMSSM Higgs sector, even assuming no CP violation in the Higgs

sector as we do, is a big step up in the complexity of the possibilities and analyzes that will be required to zero in on the model and determine all its parameters.

If string theory is any guide, nature is likely to be overly generous when it comes to the Higgs sector.

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

$$\lambda \ \widehat{S}\widehat{H}_u\widehat{H}_d + \frac{\kappa}{3} \ \widehat{S}^3 \tag{2}$$

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

The μ term of the MSSM arises from

$$\lambda\widehat{S}\widehat{H}_u\widehat{H}_d \to \lambda\langle S\rangle\widehat{H}_u\widehat{H}_d \equiv \mu_{\rm eff}\widehat{H}_u\widehat{H}_d\,. \tag{3}$$

b) The associated trilinear soft terms are

$$\lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3 \,. \tag{4}$$

In the MSSM language,

$$\lambda A_\lambda S H_u H_d \to \lambda A_\lambda \langle S \rangle H_u H_d \equiv B_\mu \mu_{\rm eff} H_u H_d \,. \tag{5}$$

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

$$\tan\beta = \langle H_u \rangle / \langle H_d \rangle \,, \; \mu_{\rm eff} = \lambda \langle S \rangle \,. \tag{6}$$

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 as defined in the soft-SUSY-breaking potential components

$$m_{H_u}^2 H_u^2 + m_{H_d}^2 H_d^2 + m_S^2 S^2 \,. \tag{7}$$

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

$$\lambda\ ,\ \kappa\ ,\ A_\lambda\ ,\ A_\kappa,\ \tan\beta\ ,\ \mu_{\rm eff}\ . \tag{8}$$

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.

NB: A possible cosmological domain wall problem [4] can be avoided by introducing suitable non-renormalizable operators [5] that do not generate dangerously large singlet tadpole diagrams [6]. Basically, our point of view is that the NMSSM should be viewed as an effective theory that works up to some very high scale of order M_U. The problems above can be resolved by new physics associated with the GUT to String scale physics.

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 is being regularly updated to include additional features and refinements. 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, neutralinos, other Higgs bosons and squarks and sleptons, the latter implemented in the latest 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 SUSY 2005 talk by A. Sopczak; we will update this as soon as tabular data is provided.)

6. NMHDECAY 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 Higgs Phenomenology

- The additional CP-even and CP-odd Higgs bosons (we will assume that the Higgs sector is CP-conserving) are contained in the real and imaginary parts of the complex singlet scalar field S.

  These seemingly simple additions open up a vast range of new Higgs phenomenology as compared to the MSSM.

- The 3 CP-even fields mix to form h_1, h_2, h_3 and the 2 CP-odd fields mix to form a_1, a_2. (The third CP-odd field is absorbed in giving mass to the Z as usual.)

  One should keep in mind that it is often the case that one of the lightest two CP-even Higgs bosons, will have a large singlet component. Similarly, the a_1, can easily have a large singlet component. Such Higgs bosons may not be easy to make or detect

- Although there is no time to discuss here, the singlet neutralino also opens up a whole new domain of SUSY phenomenology and Dark Matter phenomenology.

- We shall zero in on the most difficult of the possibilities, which also turns out to be highly motivated from the point of view of fine-tuning.

  This is the case in which the h_1 is fairly SM-like but decays via $h_1 \to a_1 a_1$ where the a_1 has a significant, perhaps dominant, singlet component.

  Thus, I want to spend a few moments discussing what kind of limits we have on such a scenario coming from LEP data.

- 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 $H \to b\bar{b}$.

  To the best of our ability we have incorporated all the LEP limits into NMHDECAY. By processing a possible NMSSM parameter choice through NMHDECAY, we can be relatively certain of the associated Higgs phenomenology and of the fact that the parameter choice does not violate LEP and other experimental limits.

  In looking at LEP plots, keep in mind that a typical point of interest with $m_{a_1} \geq 2m_b$ has $B(h_1 \to a_1 a_1)[B(a_1 \to b\bar{b})]^2 \sim 0.55 - 0.65$. For

$m_{a_1} < 2m_b$, **one typically has** $B(h_1 \to a_1 a_1)[B(a_1 \to \tau^+\tau^-)]^2 \sim 0.7$**.** **And in both cases** $g^2_{ZZh_1} < g^2_{ZZh_{\rm SM}}$ **by perhaps** $5 - 10\%$**.**

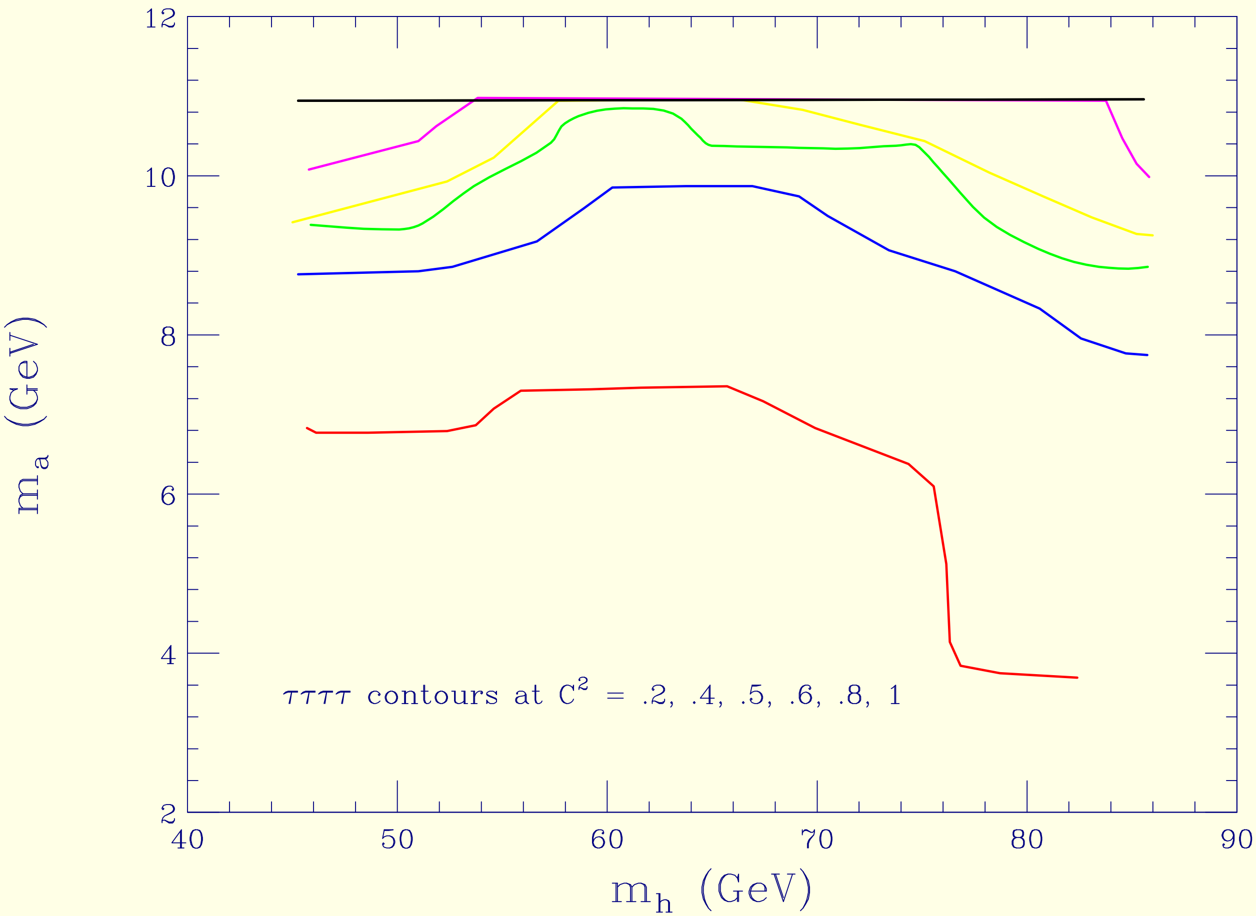


Figure 1: **Contours of limits on** $C^2 = [g^2_{ZZh}/[g^2_{ZZh}]_{SM}] \times BR(h \to aa) \times [BR(a \to \tau^+\tau^-)]^2$ **at** $C^2 = 0.2$, 0.4, 0.5, 0.6, 0.8 **and** 1 **(red, blue, green, yellow, magenta, and black, respectively). For example, if** $C^2 > 0.2$**, then the region below the**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

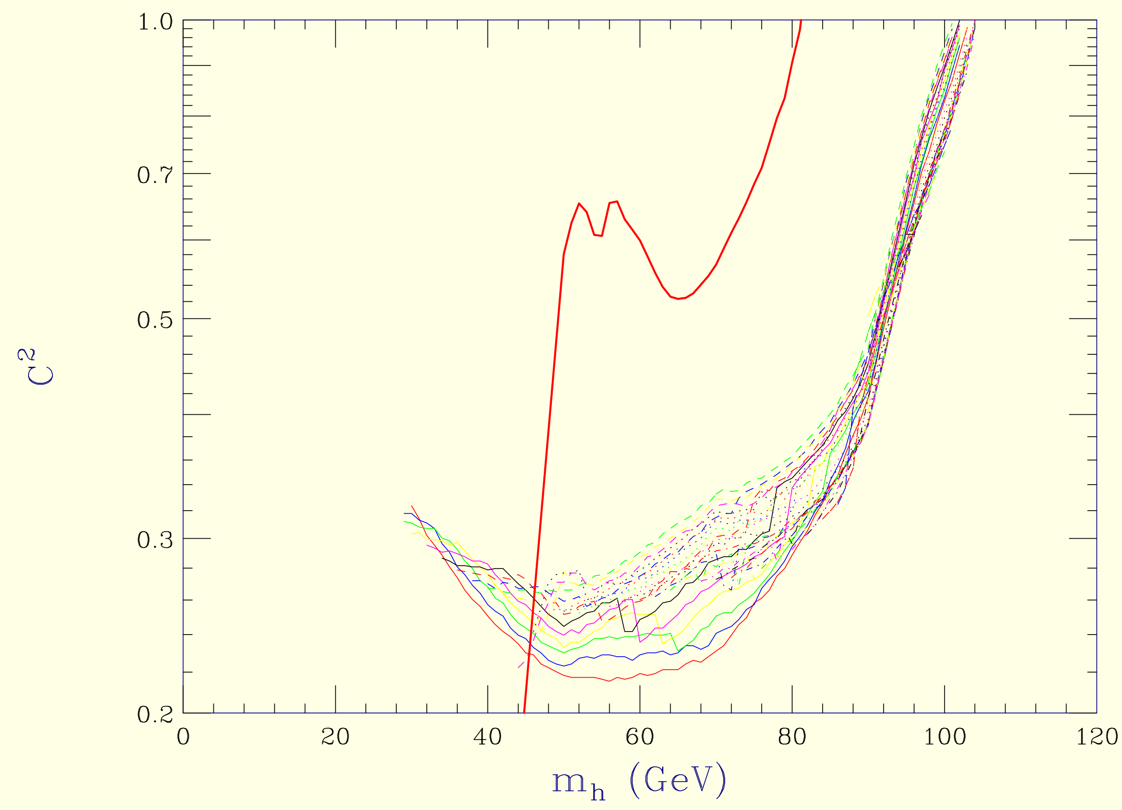


Figure 2: OPAL plot of the 95% CL limits on $C^2 = [g^2_{ZZh}/[g^2_{ZZh}]_{SM}] \times BR(h \to aa) \times [BR(a \to b\bar{b})]^2$. The different curves are for different m_a values: solid lines are for 12, 13, 14, 15, 16 and 17 GeV in order of red, blue, green, yellow, magenta, black; dotted lines are 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.

$S_{95} = \sigma_{max}/\sigma_{ref}$ Limits $H_2Z \to H_1H_1Z$

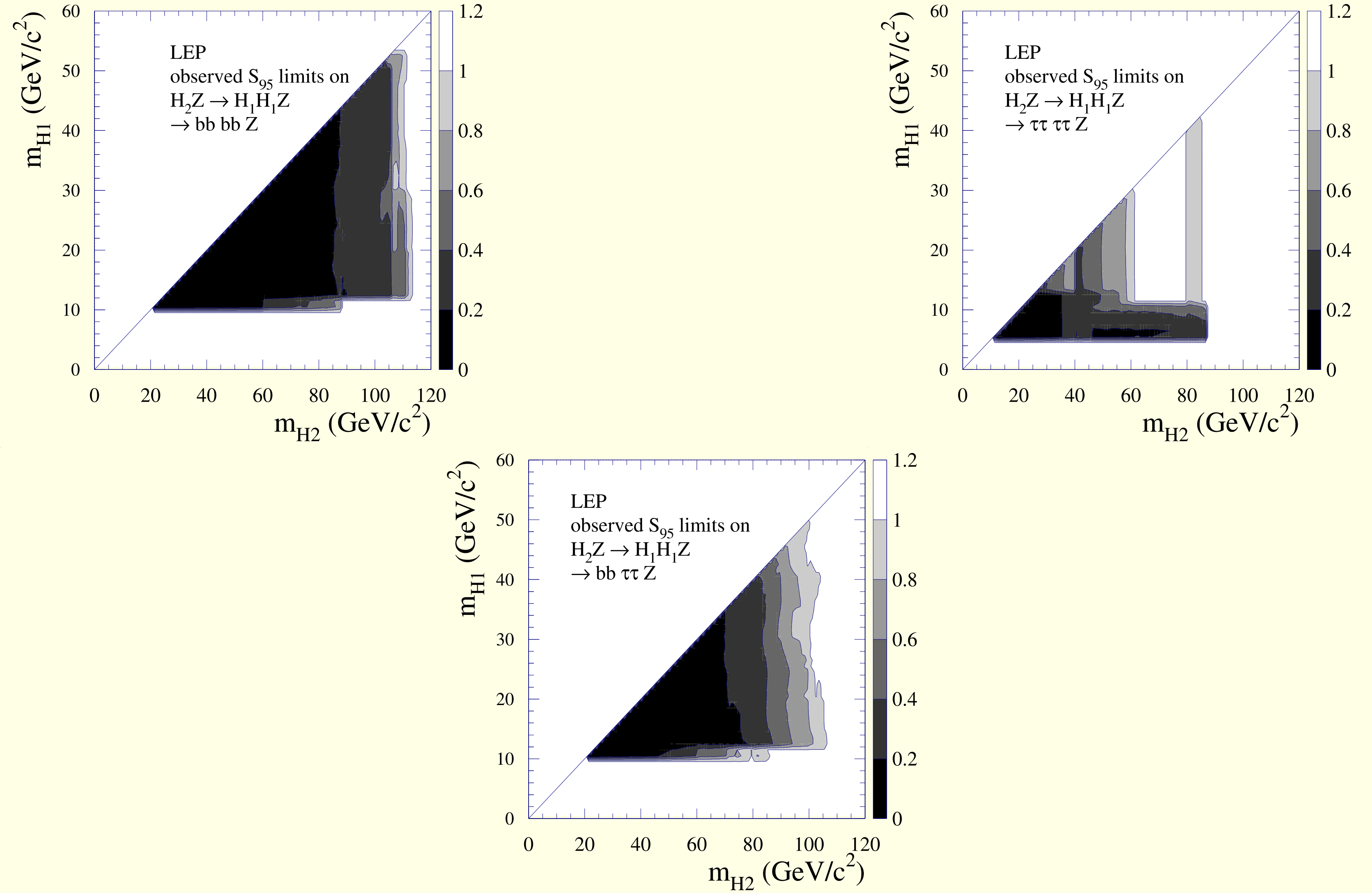


Figure 3: Plot of the 95% CL limits on $C^2 = [g^2_{ZZh}/[g^2_{ZZh}]_{SM}] \times BR(h \to aa) \times [BR(a \to b\bar{b})]^2$, LEP Higgs WG.

- It should be noted that a light a_1 is a natural result in the limit where the NMSSM acquires one of two new symmetries [25]. Either will protect the mass of a light a_1 against significant radiative corrections.

  1. There is a $U(1)_{PQ}$ symmetry if $\kappa \to 0$ (and, hence, $\kappa A_\kappa \to 0$).
  2. There is a $U(1)_R$ symmetry in the $A_\kappa, A_\lambda \to 0$ limit.

  The $h_1 \to a_1 a_1$ scenarios are frequently ones that approach these symmetry limits.

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.

By and large, these modes work very well for the NMSSM. In a very large scan over parameter space we found only 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,

$$\lambda = 0.0163; \quad \kappa = -0.0034; \quad \tan\beta = 5.7;$$
$$\mu_{\rm eff} = -284 \text{ GeV}; \quad A_\lambda = -70 \text{ GeV}; \quad A_\kappa = -54 \text{ GeV}, \qquad (9)$$

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

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
$B(h_i\ or\ a_i \to b\bar{b})$	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, $R_i = g_{h_iVV}/g_{h_{SM}VV}$, $t_i = g_{h_it\bar{t}}/g_{h_{SM}t\bar{t}}$, $b_i = g_{h_ib\bar{b}}/g_{h_{SM}b\bar{b}}$, $g_i = g_{h_igg}/g_{h_{SM}gg}$ 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 $t\bar{t}$ and $b\bar{b}$ normalized relative to the scalar $t\bar{t}$ and $b\bar{b}$ SM Higgs couplings and g'_i and γ'_i are the a_igg and $a_i\gamma\gamma$ $\epsilon \times \epsilon'$ couplings relative to the $\epsilon \cdot \epsilon'$ coupling of the SM Higgs.

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 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]) had been able to think of was $WW \to h \to aa \to jj\tau^+\tau^-$. 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 that may or may not have a tail extending down into this low mass region

(after cuts).

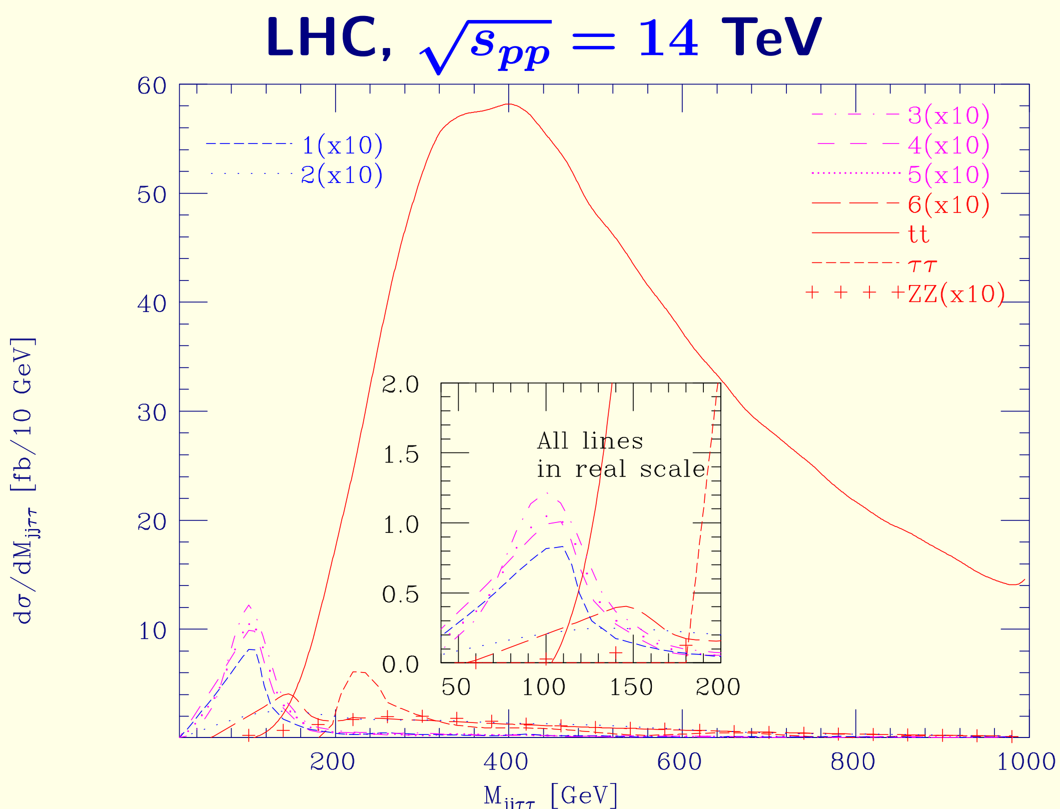


Figure 4: *Reconstructed mass of the $jj\tau^+\tau^-$ system for signals and backgrounds before b-tagging. No K factors are included.*

Some ATLAS people (D. Zerwas, ...) are pursuing this question. There appear to be differences between the simulations we performed (which would lead to a visible signal) and those performed by Zerwas and collaborators. They have a higher jet multiplicity that renders our cuts too inefficient.

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

  The proponents of this approach argue that the mass resolution for the reconstructed h mass (using tagged protons in forward and backward direction) will be of order $1-2~\mathrm{GeV}$ and that backgrounds will be quite small. If this is the case, the h will stick up as a peak in the reconstructed mass distribution independently of how it decays.

  The main issue appears to be whether or not the event can be triggered. The b's are somewhat soft as are the leptons, ... from the τ's. A Monte Carlo must be run to see what happens.'

- A final possibility is to look for the h_1 in the cascade decays of the gluinos, assuming $\widetilde{\chi}_2^0 \to h_1 \widetilde{\chi}_1^0$ is an alllowed 2-body decay.

  This has shown promise in LHC studies when $h_1 \to b\overline{b}$. These analyzes need to be repeated for the $h_1 \to a_1 a_1 \to 4b$ or $2b2\tau$ modes.

- 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 must go back and search very carefully for some signal such as the $h \to aa$ signal, etc. that was missed.

Or, go the ILC.

- It should be admitted that the fraction of parameter space for which $h_1 \to a_1 a_1$ must be detected is small in a generic sense.

  However, we have found (and I briefly review this at the end) that requiring low fine-tuning for the model zeroes in on precisely the part of parameter space for which we must face this scenario.

NMSSM Higgs at the ILC

- The considerable flexibility in the Higgs couplings and the more complicated nature of the Higgs potential both imply that the ILC is likely to be absolutely crucial to performing a sufficient number of precision measurements that the Higgs parameters and couplings can all be accurately determined.

  For example, it is very easy to find parameter choices such that the $h_{1,2,3}$ share the WW/ZZ coupling strength squared, implying weak LHC signals for each. The ILC will have no trouble seeing all three and measuring their masses and basic couplings with substantial precision.

- Of course, if nature chooses a difficult $h_1 \to a_1 a_1$ point, whether or not the LHC sees a signal, only the ILC will fully confirm that the signal is truly that of a Higgs boson.

- 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 $a_1 a_1$.

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

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

In addition, to fully determine the model parameters, it will be crucial that the ILC be able to measure $B(h_1 \rightarrow a_1 a_1)$ with precision (independent of the a_1 decay modes). The strategy for doing so has not yet been worked out. In particular, since the a_1 is fairly singlet-like, it will not be easily produced on its own at the ILC. This is something that definitely requires further study.

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.**

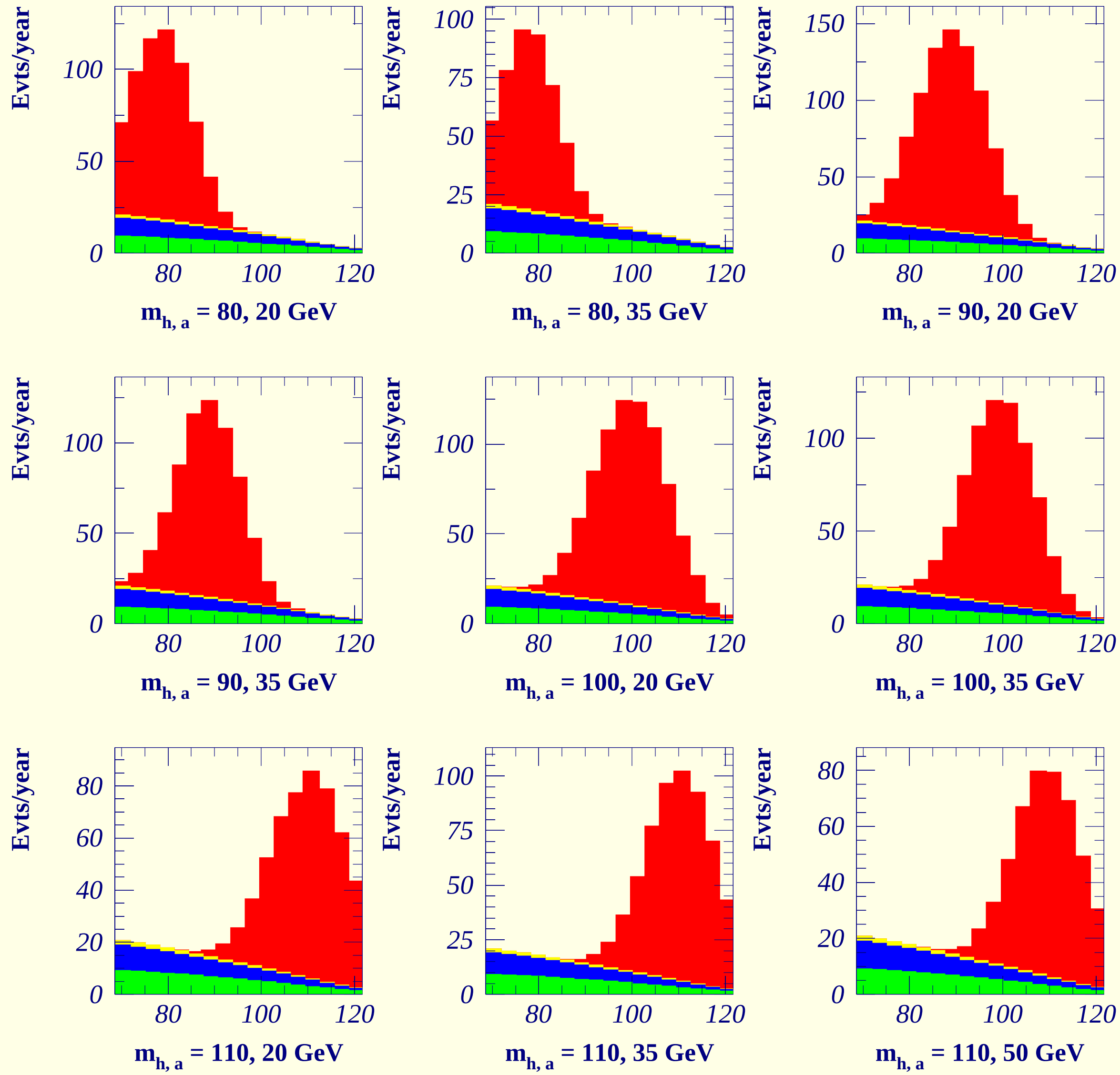
- **The hard-core simulation work has been performed by Michal Szleper.**

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.**

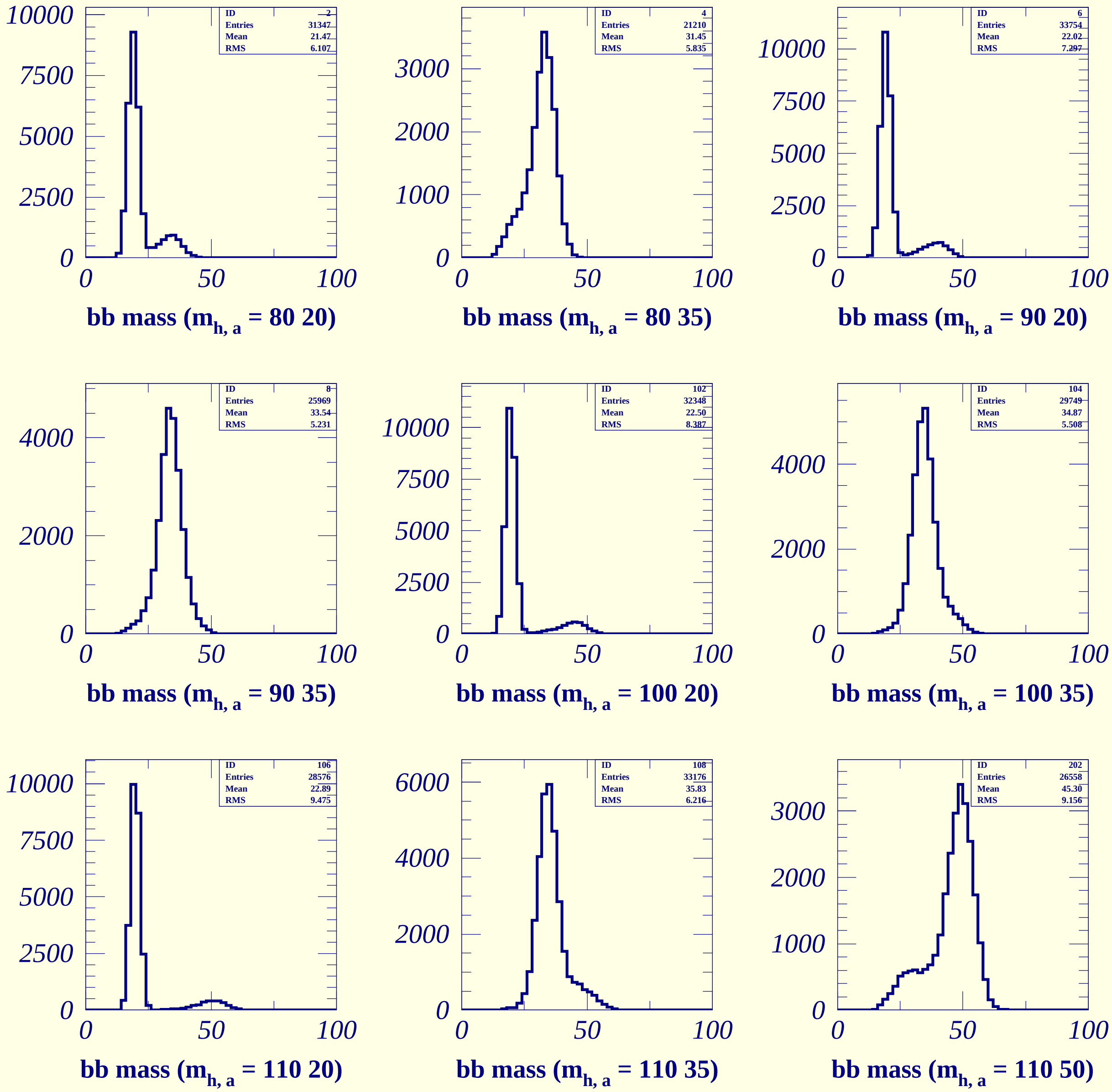
- **Excellent determination of m_a is possible — see 2nd figure.**

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



How well can we determine the a mass?

RECONSTRUCTED bb MASSES



The 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

$$F = \mathrm{Max_a} \left| \frac{d \log m_Z}{d \log a} \right| \tag{10}$$

where the parameters a are the GUT scale soft-SUSY-breaking parameters and the μ parameter. I do not have time to give details about the procedure for computing F in the MSSM.

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.

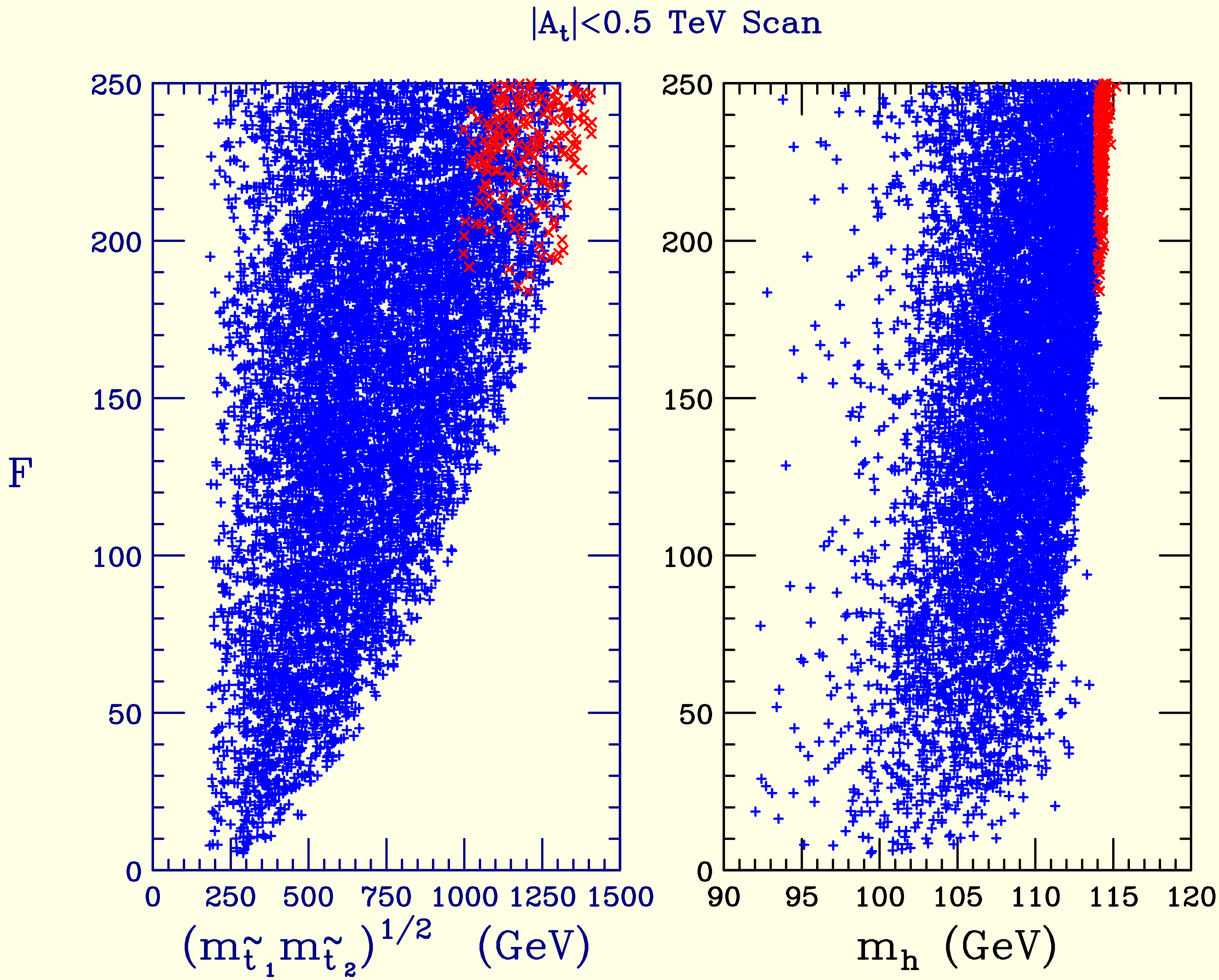


Figure 5: **The** $|A_t| < 500$ GeV **results.** $\times = m_h \geq 114$ GeV. $+ = m_h < 114$ GeV.

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.

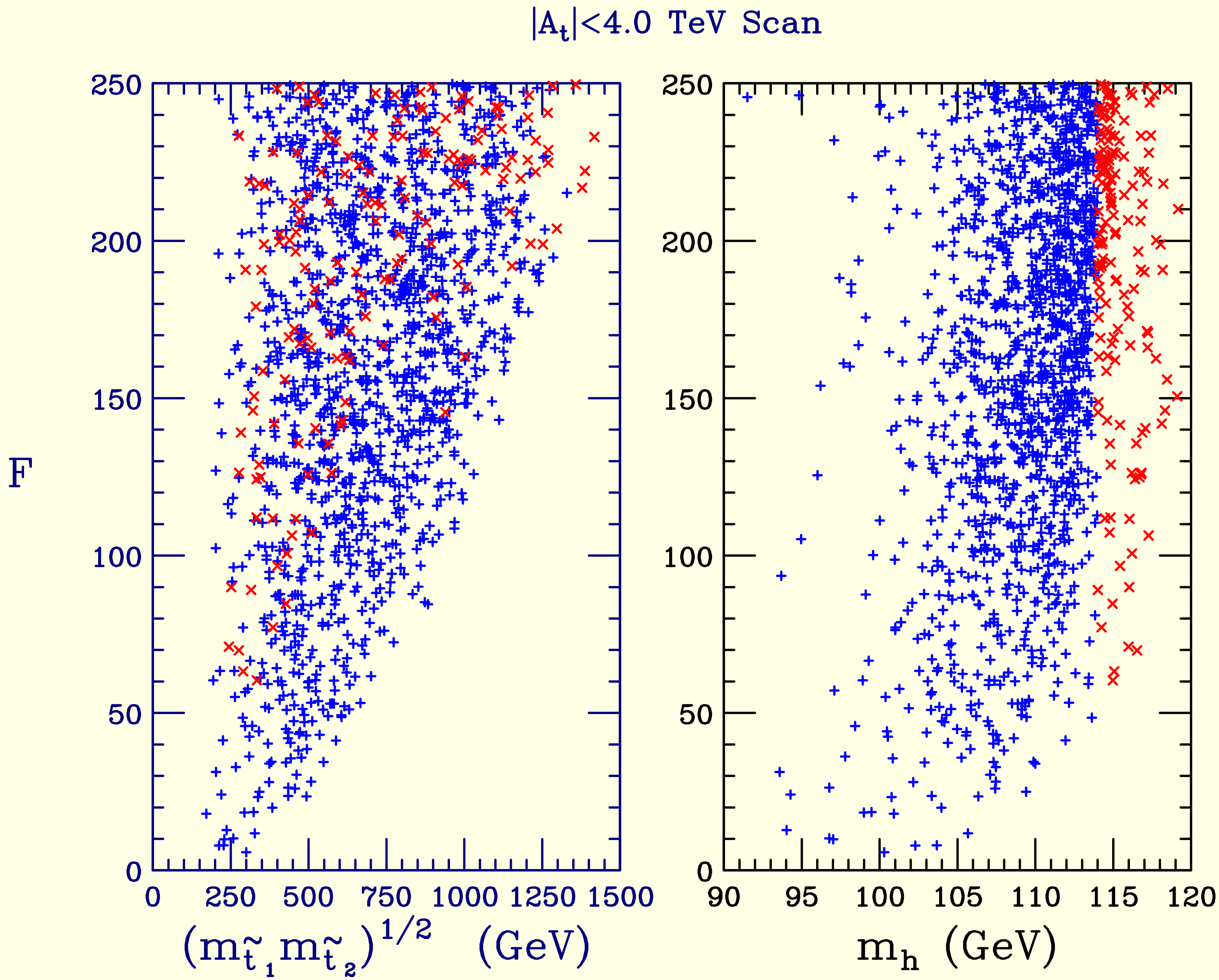


Figure 6: **The $|A_t| < 4$ TeV results.**

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 $\sqrt{m_{\widetilde{t}_1} m_{\widetilde{t}_2}}$.

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 $m'^2_Z = \overline{g}^{\,2}(h'^2_u + h'^2_d)$.**

Results for $\tan\beta = 10$ and $M_{1,2,3}(m_Z) = 100, 200, 300$ GeV appear in Fig. 7. Similar results are obtained at other $\tan\beta$ values.

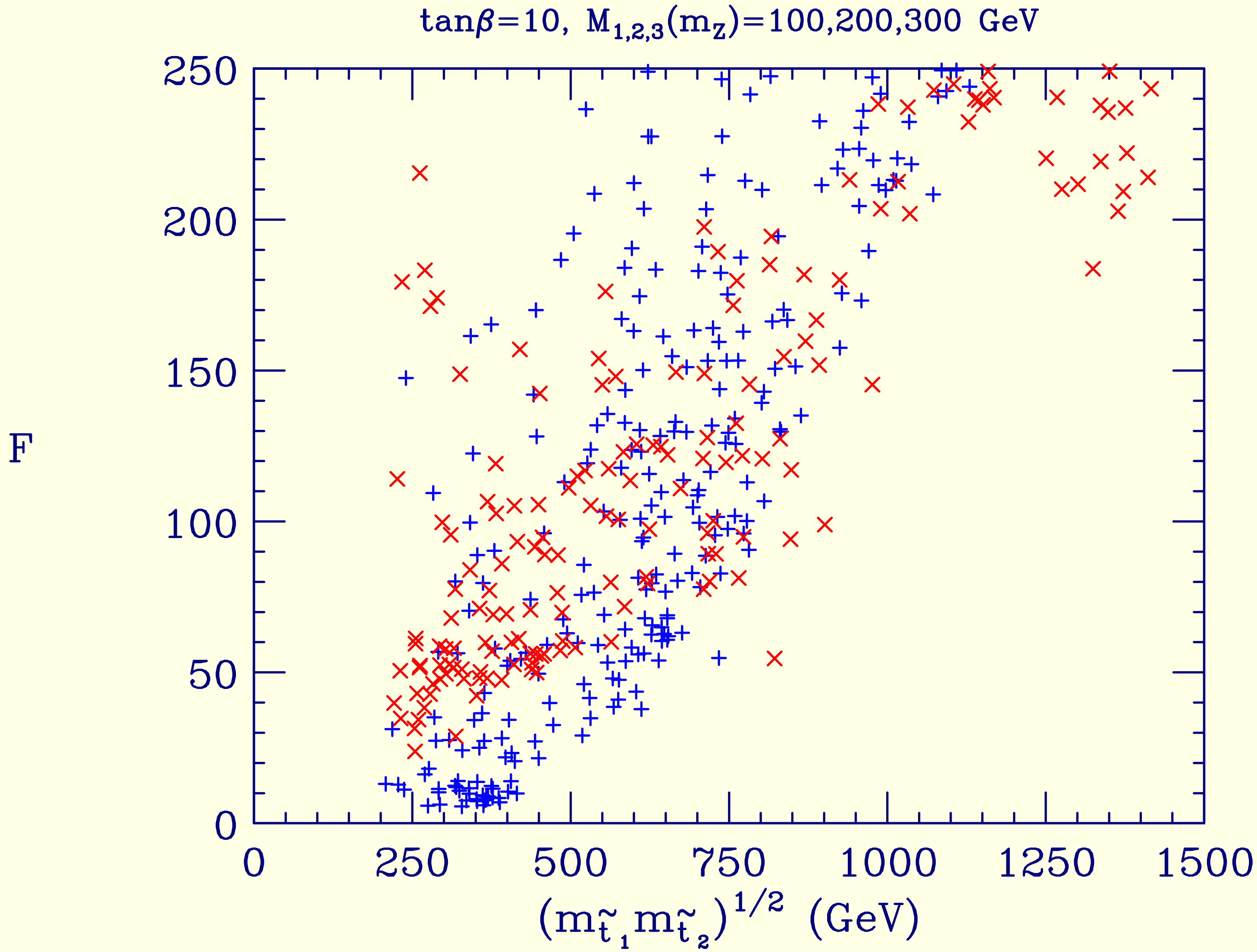


Figure 7: For the NMSSM, we plot the fine-tuning measure F vs. $\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ for NMHDECAY-accepted scenarios with $\tan\beta = 10$ and $M_{1,2,3}(m_Z) = 100, 200, 300$ GeV. Points marked by '+' ('×') escape LEP exclusion primarily due to dominance of $h_1 \to a_1 a_1$ decays (due to $m_{h_1} > 114$ GeV).

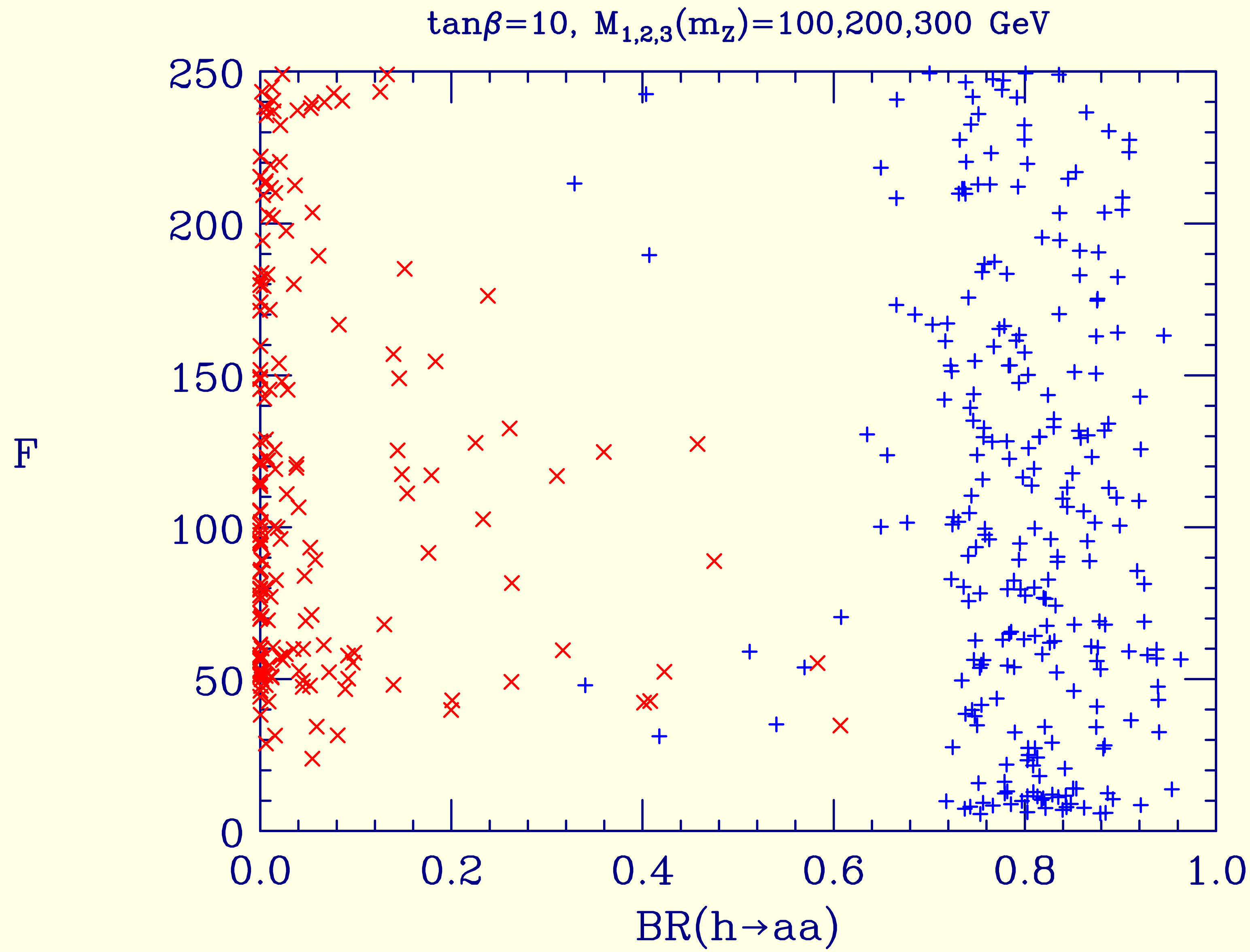


Figure 8: For the NMSSM, we plot the fine-tuning measure F vs. $BR(h_1 \to a_1 a_1)$ for NMHDECAY-accepted scenarios with $\tan\beta = 10$ and $M_{1,2,3}(m_Z) = 100, 200, 300$ GeV. Point notation as in Fig. 7.

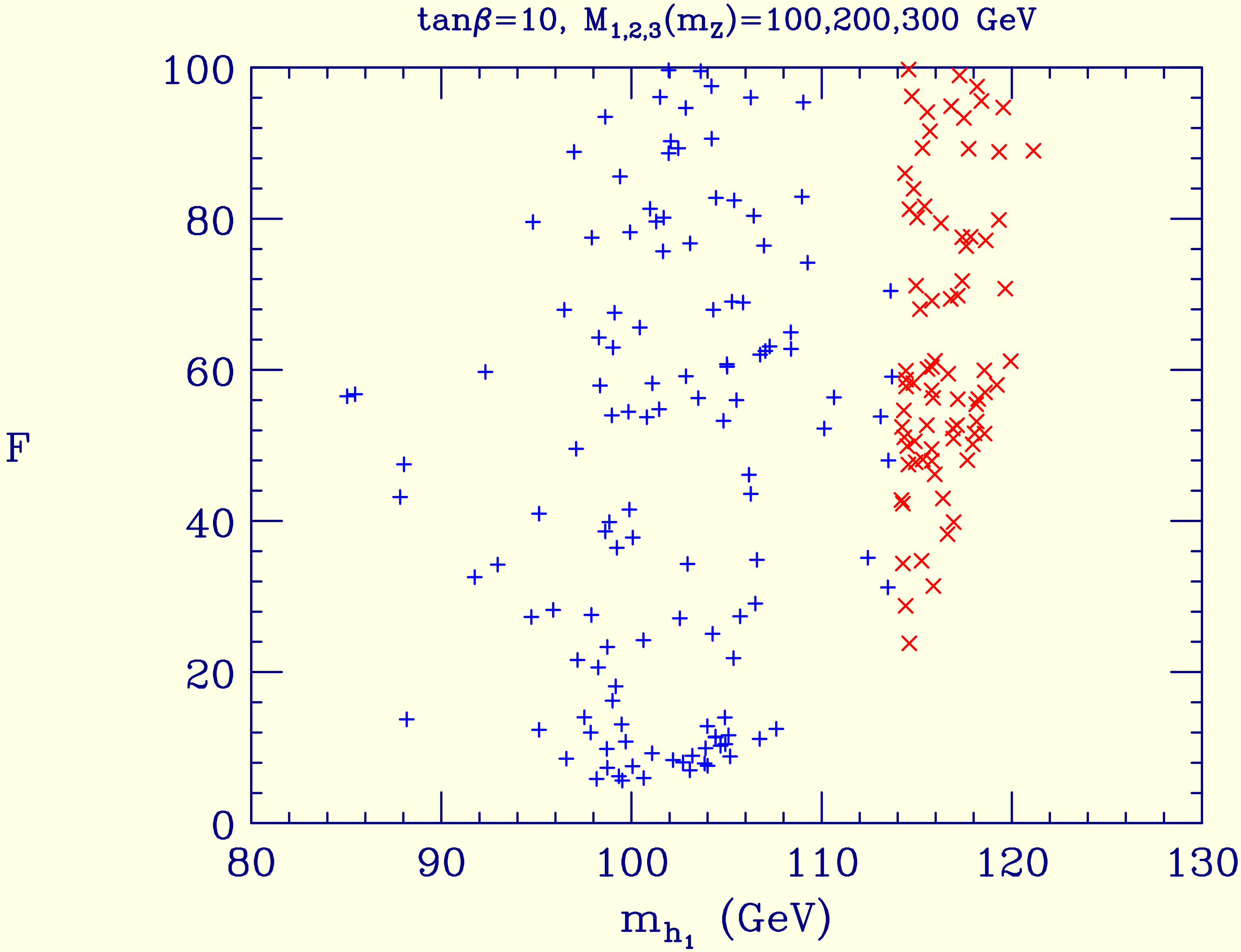


Figure 9: For the NMSSM, we plot the fine-tuning measure F vs. m_{h_1} for NMHDECAY-accepted scenarios with $\tan\beta = 10$ and $M_{1,2,3}(m_Z) = 100, 200, 300$ GeV. Point notation as in Fig. 7.

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

- In the figure, the $+$ points have $m_{h_1} < 114 \text{ GeV}$ 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 $m_{h_1} > 114 \text{ GeV}$ 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. 9.

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

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

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

LHC Implications

- **These are presented in Fig. 10.**

  Fig. 10 shows that small fine-tuning implies that the LHC will absolutely have to search for the $h_1 \rightarrow a_1 a_1$ decays for moderate $\tan\beta$.

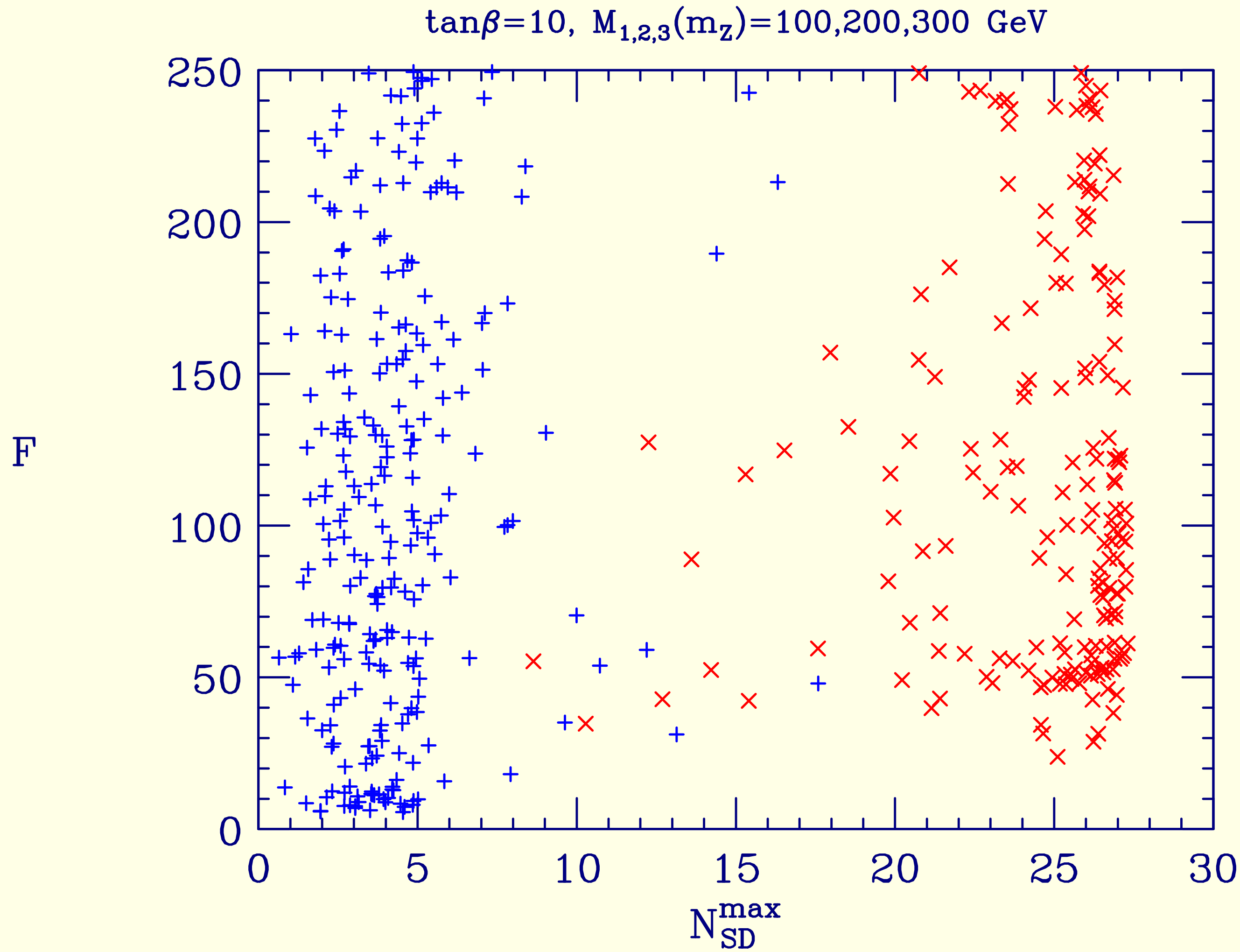


Figure 10: Plot of maximum "standard" channel statistical significance as a function of F — $\tan\beta = 10$.

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 $m_{h_1} \sim 100$ 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 GeV to 700 GeV mass range;
    * the a_1 mass is typically in the 5 GeV to 20 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.