

# New Developments in the NMSSM

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# Outline

1. Brief review of NMSSM
2. Higgs in the NMSSM, LEP limits and low fine-tuning
3. Implications for future colliders

## Brief NMSSM Review

- The LEP limits on Higgs bosons have pushed the MSSM into an awkward corner of parameter space characterized by very high fine-tuning, lack of electroweak baryogenesis without extreme fine tuning, ....

At a more fundamental level, a satisfactory explanation of the  $\mu$  term in the MSSM superpotential,  $\mu \widehat{H}_u \widehat{H}_d$ ,<sup>1</sup> remains elusive. For successful phenomenology  $\mu$  can neither be zero nor can it be  $\mathcal{O}(M_P)$  (the two natural possibilities). Instead, it must be of order the electroweak or at most the SUSY-breaking scale. (It cannot be zero or there would be a very light chargino of mass  $m_W^2/m_{\text{SUSY}}$  that would have been observed at LEP. It cannot be  $\mathcal{O}(M_P)$  without generating a huge vev for one of the Higgs fields.)

So, what direction should one head in? For me, one substantial motivation is hints from string theory. In particular, it is very clear that extra singlet superfields are common in string models. Let's make use of them and let's do it in the simplest possible way.

The NMSSM introduces just one extra singlet superfield, with superpotential  $\lambda \widehat{S} \widehat{H}_u \widehat{H}_d$ . The  $\mu$  parameter is then automatically generated by  $\langle S \rangle$  leading

<sup>1</sup>Hatted (unhatted) capital letters denote superfields (scalar superfield components).

to  $\mu_{eff} \widehat{H}_u \widehat{H}_d$  with  $\mu_{eff} = \lambda \langle S \rangle$ . The only requirement is that  $\langle S \rangle$  be of order the SUSY-breaking scale at  $\sim 1$  TeV. This can be guaranteed by appropriate discrete symmetries, which simultaneously remove the potential problems associated with cosmological domain walls.

In fact there are two models of particular simplicity: the NMSSM and the MNSSM. I will very briefly describe the differences.

### – The NMSSM

In this model, one demands that the superpotential be invariant under a  $Z_3$  symmetry. Such a symmetry removes all potential superpotential terms that have a dimensionful parameter. For example, linear  $\widehat{S}$  and quadratic  $\widehat{S}^2$  terms are forbidden. Only  $\frac{1}{3} \kappa \widehat{S}^3$  with  $\kappa$  dimensionless is allowed.

The same applies to the soft SUSY breaking terms. Only  $\frac{1}{3} \kappa A_\kappa S^3$  is allowed in addition to  $\lambda A_\lambda S H_u H_d$ .

An additional  $Z_2^R$  symmetry is imposed on all operators to guarantee that the loop-induced tadpole terms that might be present (proportional to  $t_S S$ ) are small enough to be phenomenologically irrelevant as far as TeV scale physics is concerned, but large enough to cure the domain wall problems.

The required symmetries were explored in a series of papers with final

resolution by Panagiotakopoulos and Tamvakis.

– **The MNSSM**

Here, the opposite tack is adopted. The discrete symmetries are chosen so as to forbid the  $\widehat{S}^3$  (and  $\widehat{S}^2$ ) term, allowing only a tadpole like term:  $t_F \widehat{S}$ .

The discrete symmetry setup gives a (multi-)loop-induced soft-SUSY breaking term  $t_S S$  with  $t_S$  being electroweak scale in magnitude.

Then, there is no cosmology problem and  $\langle S \rangle$  is of order the electroweak or SUSY-breaking scale and phenomenology is good.

Again, Panagiotakopoulos and Tamvakis explored the required symmetries and phenomenology has been pursued by them, Dedes, Pilaftsis, ....

The phenomenology of the MNSSM is actually much more restrictive than that of the NMSSM, predicting various Higgs mass-squared sum rules that can be violated in the NMSSM. Also, it is easy to get a rather light charged Higgs boson. In fact, it might be the lightest of the Higgs boson with mass as low as 80 GeV. Tevatron top-decay results will soon greatly limit such a possibility and very strongly constrain the model.

– **The GNMSSM**

This I have defined as a model which no one has explored, in which symmetries are chosen so that both the  $S^3$  terms and the tadpole terms are of appropriate electroweak size to play a substantial phenomenological

role. It would obviously be less constrained than either model.

## Why focus on the NMSSM?

My preference has always been the NMSSM.

- Since the only superpotential terms that are introduced have dimensionless couplings, the scale of the vevs (i.e. the scale of EWSB) is determined by the scale of SUSY-breaking.
- It has a much wider range of phenomenological possibilities than the MNSSM (which is both good and bad).
- It can have minimal fine-tuning and other desirable features. (It is not currently known if the MNSSM can achieve low fine-tuning.)

### ● New Particles

The single extra singlet superfield of the NMSSM contains an extra neutral gaugino (the singlino) ( $\Rightarrow \tilde{\chi}_{1,2,3,4,5}^0$ ), an extra CP-even Higgs boson ( $\Rightarrow h_{1,2,3}$ ) and an extra CP-odd Higgs boson ( $\Rightarrow a_{1,2}$ ).

### ● The parameters of the NMSSM

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

$$\lambda \widehat{S} \widehat{H}_u \widehat{H}_d + \frac{\kappa}{3} \widehat{S}^3 \quad (1)$$

depending on two dimensionless couplings  $\lambda$ ,  $\kappa$  beyond the MSSM. The associated trilinear soft terms are

$$\lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3 . \quad (2)$$

The final two input parameters are

$$\tan \beta = h_u / h_d , \quad \mu_{\text{eff}} = \lambda s , \quad (3)$$

where  $h_u \equiv \langle H_u \rangle$ ,  $h_d \equiv \langle H_d \rangle$  and  $s \equiv \langle S \rangle$ . These, along with  $m_Z$ , can be viewed as determining the three SUSY breaking masses squared for  $H_u$ ,  $H_d$  and  $S$  (denoted  $m_{H_u}^2$ ,  $m_{H_d}^2$  and  $m_S^2$ ) through the three minimization equations of the scalar potential. (From the model building point of view, we emphasize the reverse — i.e. the SUSY-breaking scales  $m_{H_u}^2$ ,  $m_{H_d}^2$  and  $m_S^2$ , along with  $A_\lambda$  and  $A_\kappa$  determine the EWSB vevs,  $\lambda$  and  $\kappa$  being dimensionless.)

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

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

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

Just because of the increased parameter space, the NMSSM is much less constrained than the MSSM, and is not necessarily forced into awkward/fine-tuned corners of parameter space either by LEP limits or by theoretical reasoning. We shall see this in more detail shortly. In my opinion, **the NMSSM should be adopted as the more likely benchmark minimal SUSY model and it should be explored in detail.** There is much to do even after a number of years of working on this.

- To further this study, Ellwanger, Hugonie and I constructed NMHDECAY

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

<http://higgs.ucdavis.edu/nmhdecay/nmhdecay.html>

It computes all aspects of the Higgs sector and checks against many (but, as we shall see, not all) LEP limits and various other constraints.

- We also developed a program to examine the LHC observability of Higgs signals in the NMSSM.



A significant hole in the LHC no-lose theorem emerges: only if we avoid that part of parameter space for which  $h \rightarrow aa$  and similar decays are present is there a guarantee for finding a Higgs boson at the LHC in one of the nine “standard” channels (e.g.  $h \rightarrow \gamma\gamma$ ,  $t\bar{t}h$ ,  $a \rightarrow t\bar{t}b\bar{b}$ ,  $t\bar{t}h$ ,  $a \rightarrow t\bar{t}\gamma\gamma$ ,  $b\bar{b}h$ ,  $a \rightarrow b\bar{b}\tau^+\tau^-$ ,  $WW \rightarrow h \rightarrow \tau^+\tau^-$ , to name the most important ones).

A series of papers (beginning with JFG+Haber+Moroi at Snowmass 1996 and continued by JFG, Ellwanger, Hugonie, Moretti, Miller, .. .) has demonstrated the general nature of this LHC no-lose theorem “hole”, and some discussion will appear later.

- The portion of parameter space with  $h \rightarrow aa, \dots$  is small  $\Rightarrow$  one is tempted to ignore it were it not for the fact that it is where fine-tuning can be absent (small sensitivity to GUT scale SUSY boundary conditions). The canonical measure of fine-tuning that we employ is

$$F = \text{Max}_p F_p \equiv \text{Max}_p \left| \frac{d \log m_Z}{d \log p} \right|, \quad (5)$$

where the parameters  $p$  comprise the GUT-scale values of  $\lambda$ ,  $\kappa$ ,  $A_\lambda$ ,  $A_\kappa$ , and the usual soft-SUSY-breaking gaugino, squark, slepton, . . . masses.

- How do we get small fine-tuning?

1.  $F$  is minimum for  $m_{h_1} \sim 100 \div 102$  GeV (in a totally unconstrained scan of parameter space this is just what one finds). **Neither lower nor higher!** This does not happen for the lowest possible stop masses, but for some reasonable range at  $\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \sim 350$  GeV level.
2.  $m_{h_1} \sim 100$  GeV is only LEP-allowed if  $h_1 \rightarrow a_1 a_1$  hides the  $h_1$ .
3. We are happy with a light  $a_1$  since it is associated with the  $\kappa A_\kappa, \lambda A_\lambda \rightarrow 0$  limit of the soft-SUSY-breaking potential. In fact, it is mainly  $\kappa A_\kappa$  that is important here.

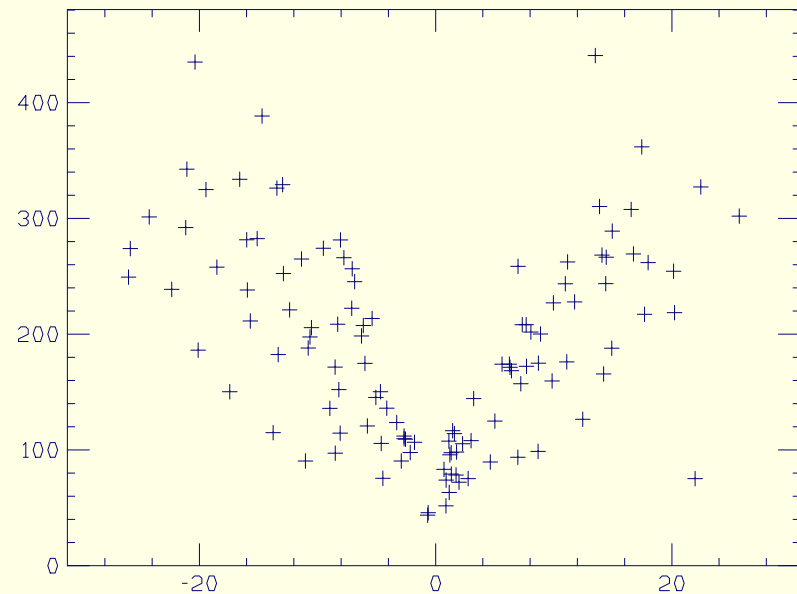
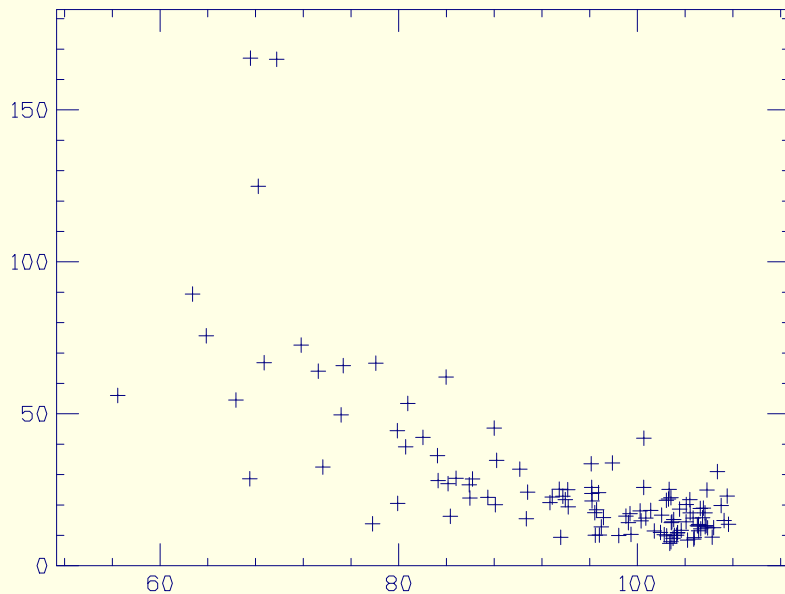


Figure 1:  $F$  vs.  $m_{h_1}$  (left) and  $m_{a_1}$  vs.  $\kappa A_\kappa$  (right).

- In fact, a light  $a_1$  is a pseudo-Nambu-Goldstone boson associated with a  $U(1)_R$  symmetry of the superpotential, whose spontaneous breaking by the vevs of  $H_u$ ,  $H_d$  and  $S$  would yield  $m_{a_1} = 0$  were it not that the  $U(1)_R$  is explicitly broken by the  $\kappa A_\kappa$  and  $\lambda A_\lambda$  terms in the soft-SUSY-breaking potential. (We ignore the small contributions from anomalies.) Thus,  $m_{a_1}$  is expected to vanish as  $\kappa A_\kappa$  and  $\lambda A_\lambda$  vanish.

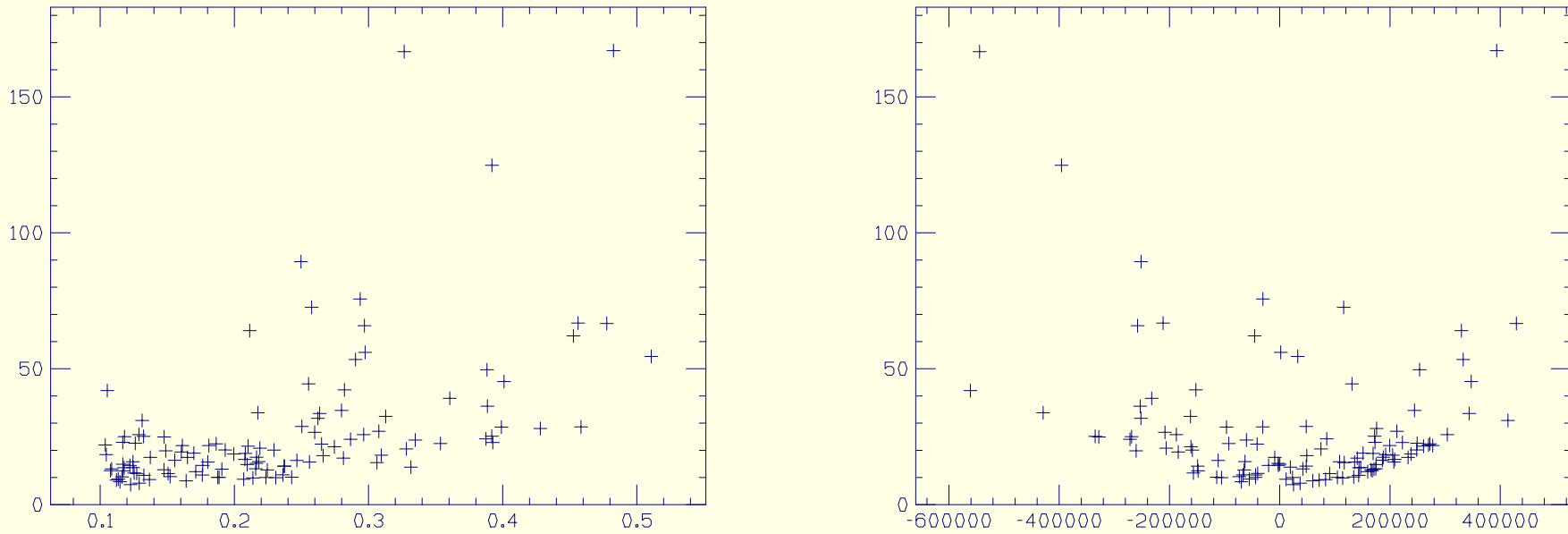


Figure 2:  $F$  vs.  $\lambda_{GUT}$  (left) and  $F$  vs.  $(m^2_{H_u})_{GUT}$  (right).

- Small fine-tuning is also associated with small  $\lambda_{GUT}$  but not small  $\kappa_{GUT}$  ( $\kappa_{GUT}/\lambda_{GUT} \sim 2$  is typical for low- $F$  cases) and small  $(m^2_{H_u})_{GUT}$ .

## Fine-Tuning and new LEP limits (w. Dermisek)

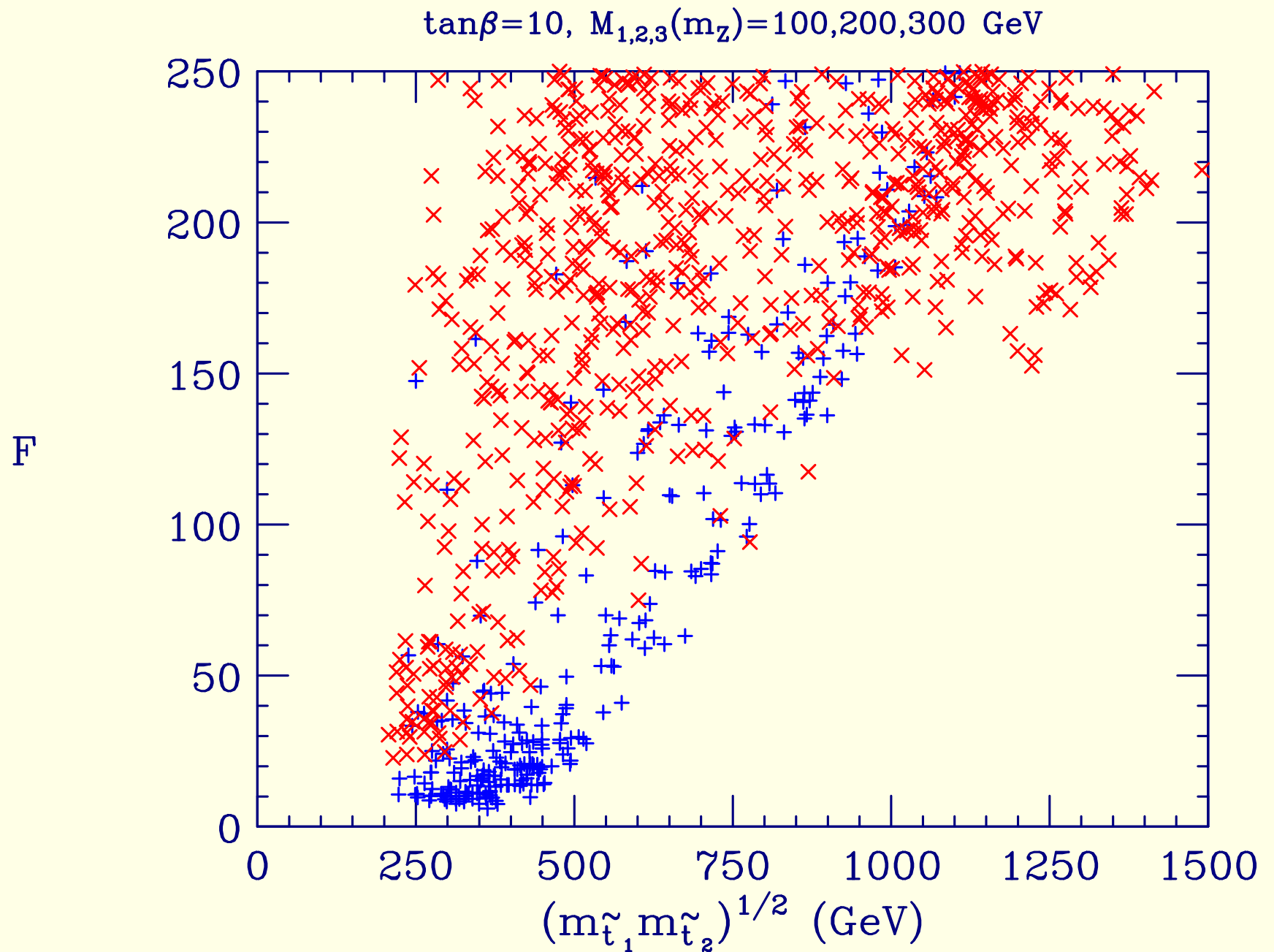
- Thus, Dermisek and I find that fine-tuning is absent in the NMSSM for precisely those parameter choices for which  $m_{h_1} \sim 100$  GeV (and is SM-like) and yet the  $h_1$  escapes LEP limits due to the presence of  $h_1 \rightarrow a_1 a_1$  decays. (There is little improvement in  $F$  per se for smaller  $m_{a_1}$ , but you will see the LEP limits want very small  $m_{a_1}$ .)

We illustrate LEP constrained results for  $\tan\beta = 10$ , and  $M_{1,2,3} = 100, 200, 300$  GeV.

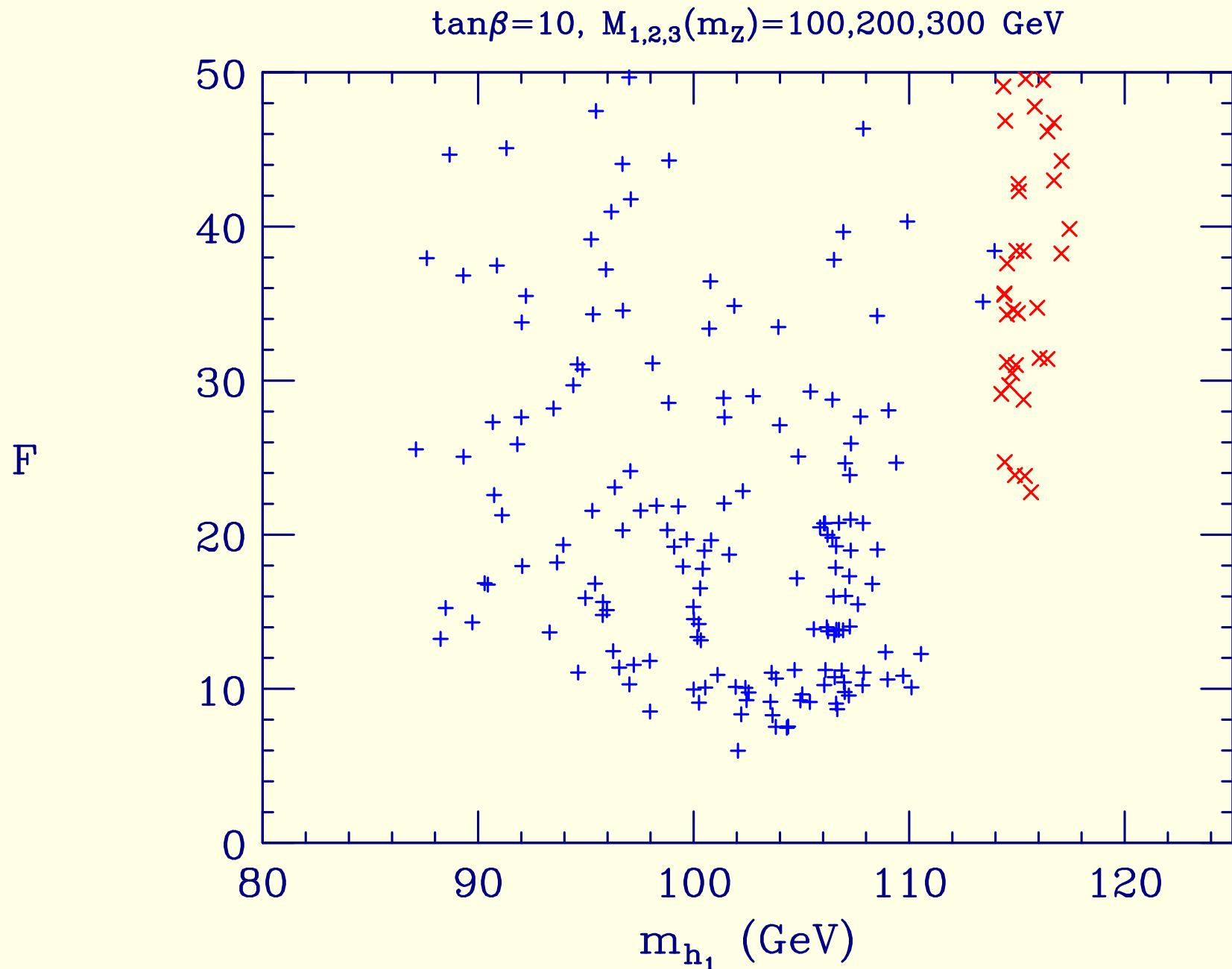
After incorporating the latest LEP **single-channel** limits (to be discussed), we find the results shown in the following figure after doing a large scan. The  $+$  points have  $m_{h_1} < 114$  GeV and the  $\times$  points have  $m_{h_1} \geq 114$  GeV.

For  $m_{h_1} < 114$  GeV, and in particular  $m_{h_1} \sim 100$  GeV, one can achieve very low  $F$  values.

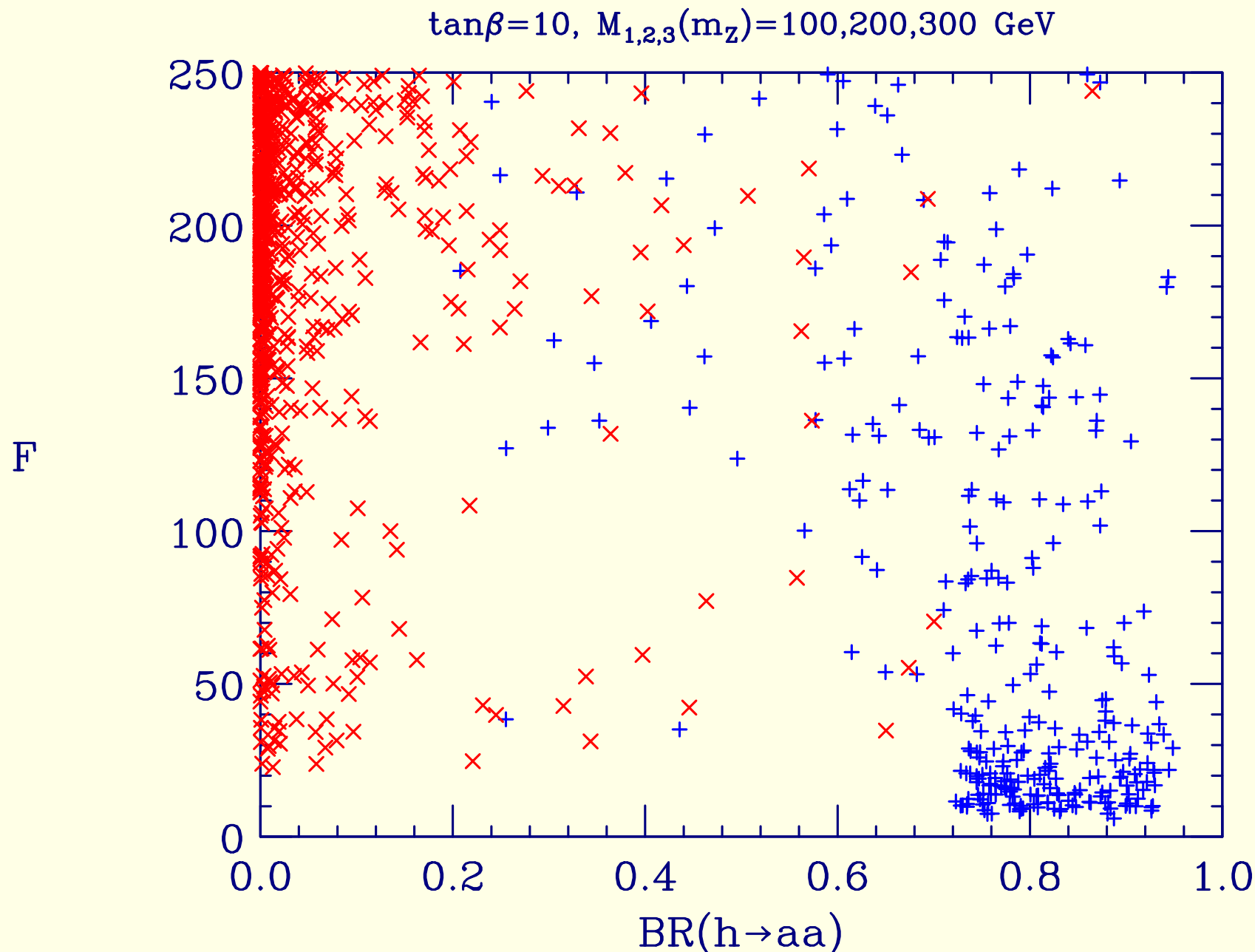
An  $h_1$  with  $m_{h_1} \sim 100$  GeV and SM-like couplings to gauge bosons and fermions is, of course, **exactly the value preferred by precision electroweak constraints.**



**Figure 3:**  $F$  as a function of root mean stop mass after latest *single-channel* LEP limits.



**Figure 4:  $F$  as a function of  $m_{h_1}$  after latest *single-channel* LEP limits.**



**Figure 5:**  $F$  as a function of  $B(h_1 \rightarrow a_1 a_1)$  after latest *single-channel* LEP limits. Note that  $h_1 \rightarrow a_1 a_1$  can be dominant even when  $m_{h_1}$  is large enough that the decay is not needed to escape LEP limits.

- It is interesting to compare the new LEP limits for  $Zh \rightarrow Zaa \rightarrow Z4b$  production to the old limits: Fig. 6.

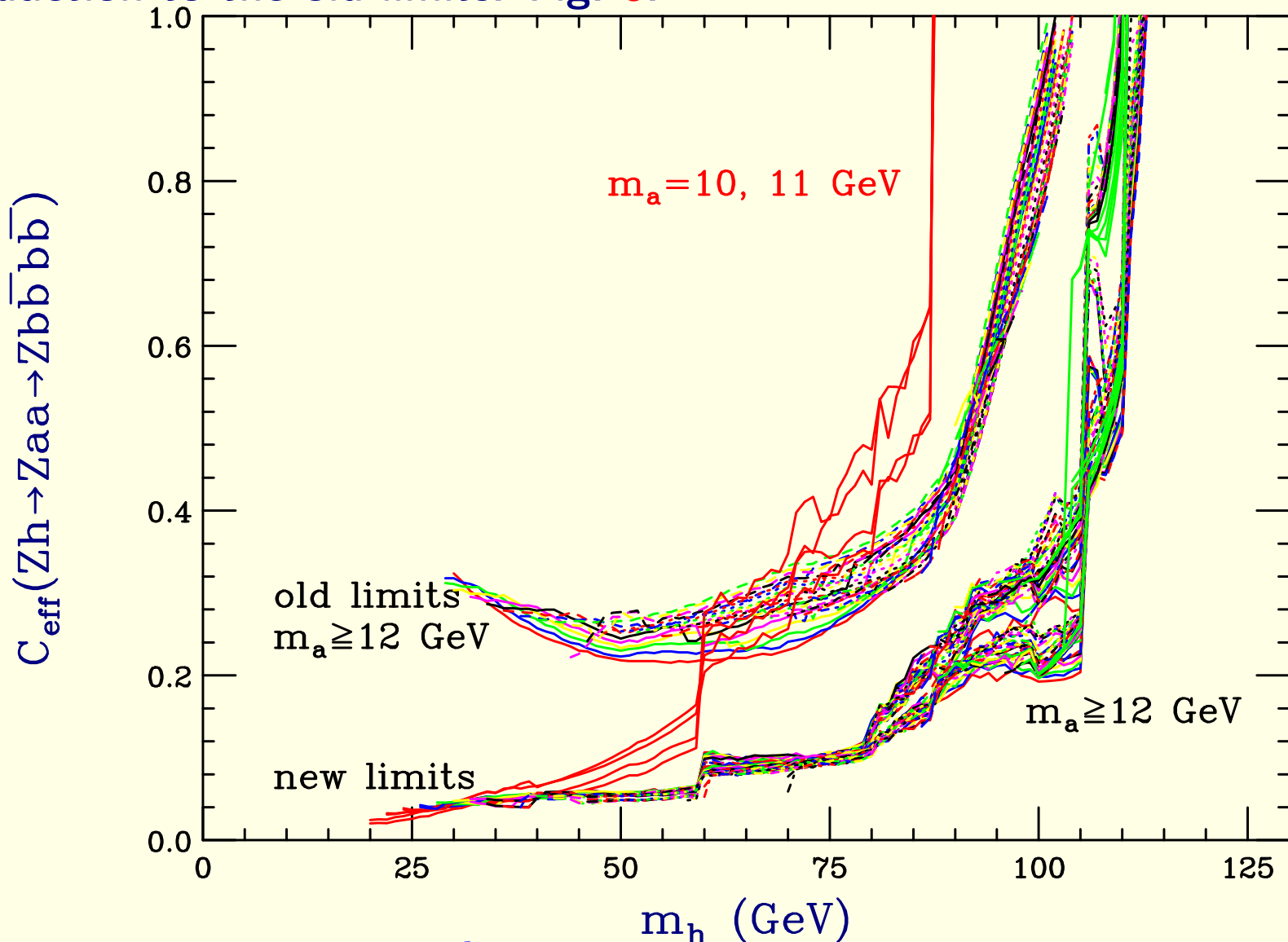


Figure 6: LEP limits on  $C_{eff}^{4b} = [g_{ZZh}^2/g_{ZZh_{SM}}^2]B(h \rightarrow aa)[B(a \rightarrow b\bar{b})]^2$ , old and new. New are stronger but small  $F$  still possible.



- It is particularly interesting to zero-in on the cases with the very lowest fine-tuning values,  $F < 10$ , with  $m_{a_1} > 2m_b$ . Fig. 7 is the relevant plot.

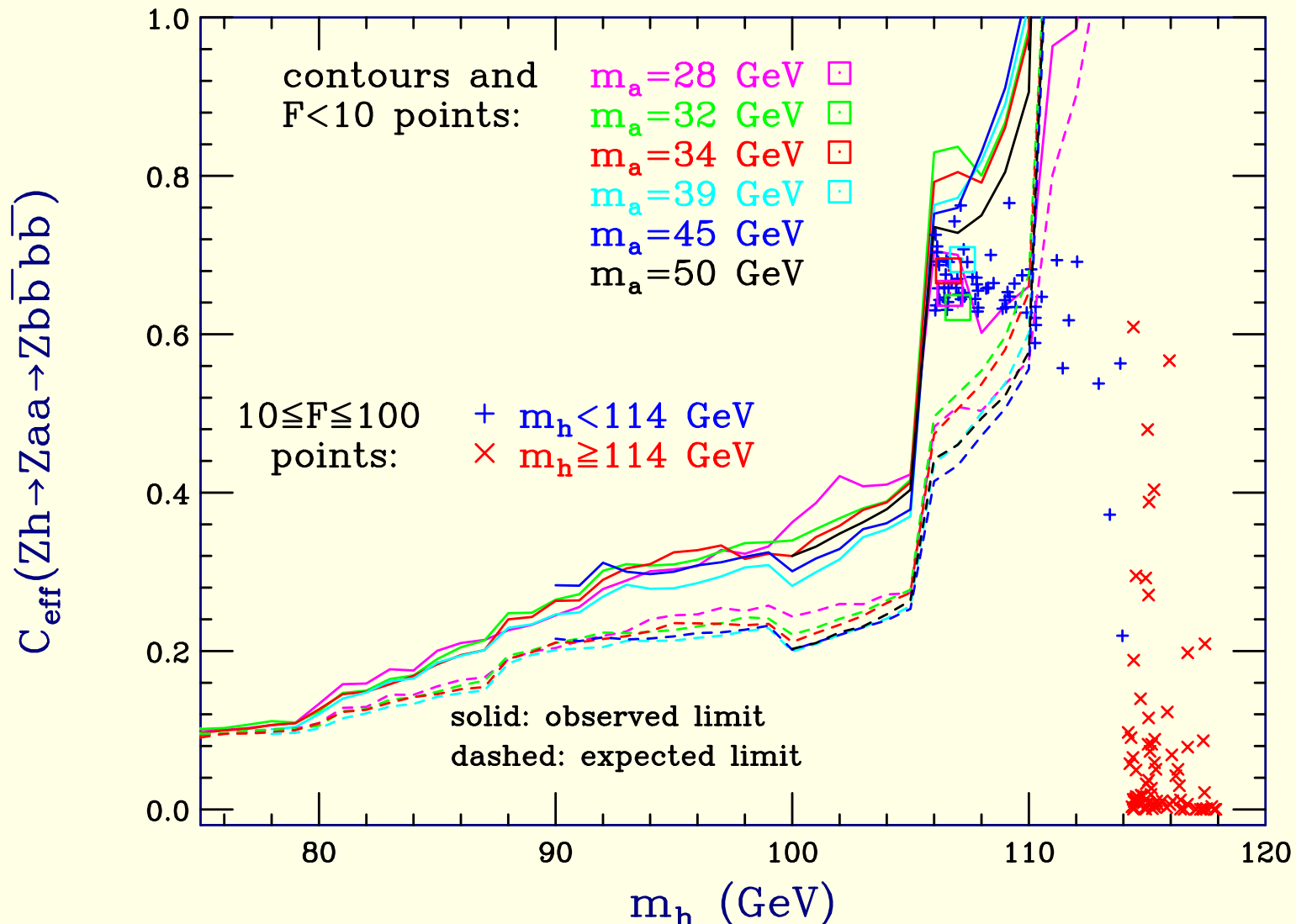


Figure 7: New LEP limits on  $C_{\text{eff}}^{4b}$  and low- $F$  points. Note the  $m_{a_1} \sim 25 - 40$  points between expected and observed limits.

- Of course, we can also look at the  $b\bar{b}$  final state which has some signal in it. The  $F < 10$  points with  $m_{a_1} > 2m_b$  appear in Fig. 8.

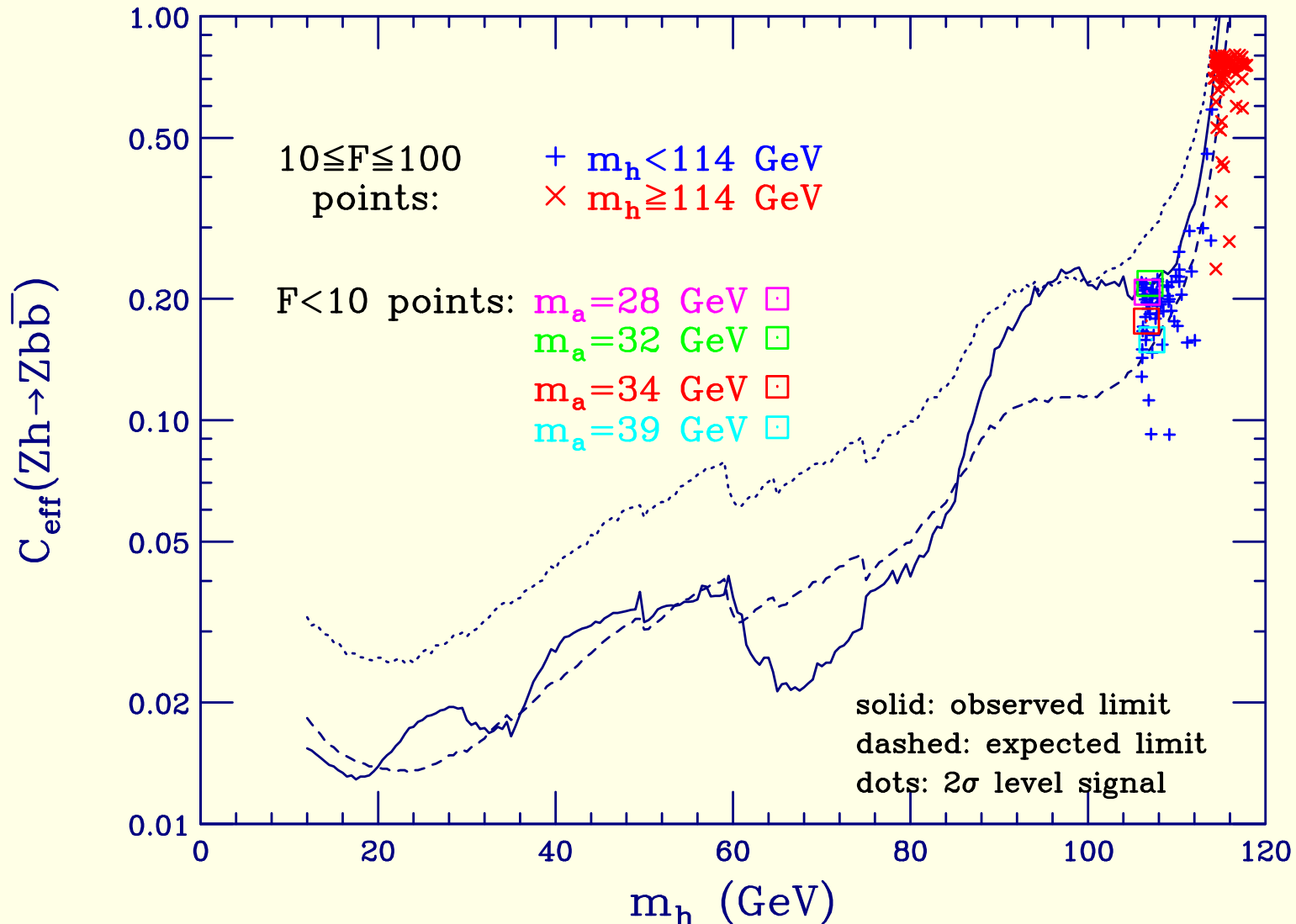


Figure 8: Observed LEP limits on  $C_{eff}^{2b} = [g_{ZZh}^2/g_{ZZh_{SM}}^2]B(h \rightarrow b\bar{b})$  for the low- $F$  points with  $m_{a_1} > 2m_b$ .

- The observed 95% CL limit on  $C_{eff}^{2b}$  is shown in Fig. 8. Our points fit right below the observed limit but above the expected limits shown in Fig. 7. However, these points have problems:

- The  $C_{eff}^{4b}$  limits tend to push one to too high a value of  $m_{h_1}$  to be entirely consistent with the  $C_{eff}^{2b}$  limit event excess region.
- Some of the  $F < 10$  points are really too high for easy consistency with the  $C_{eff}^{4b}$  final states — they push the  $2\sigma \sim 95\%$  CL exclusion limits.
- But, there is an even bigger problem. **The  $Z2b$  and  $Z4b$  channels are not actually independent.**

The limits shown assume that either  $h \rightarrow 4b$  or  $h \rightarrow 2b$  is the only channel contributing to the  $Z + b$ 's final state. We only learned that this was the case after closely consulting with the LEP LHWG people (especially Philip Bechtle who runs the LHWG analysis program). The  $Z2b$  and  $Z4b$  final states begin with the same preselection procedure. For example, for  $Z \rightarrow jets$ , no matter how many jets are actually present, the event is forced into a 4-jet configuration and then analyzed further. There are some discriminating invariants that are employed by some experiments in a neural network framework that separate the  $Z2b$  and  $Z4b$  channels to some extent, **but not completely.**

- Putting the  $F < 10$  scenarios with  $m_{a_1} > 2m_b$  through the full LHWG analysis, one finds that all are excluded at somewhat more than the 99% CL.

In fact, all the  $m_{a_1} > 2m_b$  scenarios with  $m_{h_1} \lesssim 108 \div 110$  GeV are ruled out at a similar level. What is happening is that you can change the  $h_1 \rightarrow b\bar{b}$  direct decay branching ratio and you can change the  $h_1 \rightarrow a_1 a_1 \rightarrow 4b$  branching ratio, but roughly speaking  $B(h_1 \rightarrow b's) \gtrsim 0.85$  (a kind of sum rule). So, if the  $ZZh_1$  coupling is full strength (as is the case in all the scenarios with any kind of reasonable  $F$ ) there is no escape except high enough  $m_{h_1}$ .

- The only way to achieve really low  $F$ , which comes with low  $m_{h_1}$ , and remain consistent with LEP is to have  $m_{a_1} < 2m_b$ . In fact, there are more low- $F$  scenarios of this type than there are ones with  $m_{a_1} > 2m_b$ ! Let us examine the  $F < 10$ ,  $m_{a_1} < 2m_b$  scenarios. The relevant limit from LEP is now only that from the  $Z2b$  channel. (It turns out that LEP has never placed limits on the  $Z4\tau$  channel for  $h$  masses larger than about 87 GeV — I am told, by Bechtle and Schumacher, that this is unlikely to ever be analyzed, but I am pushing.)
- **Note:** Such a light to very light  $a_1$  is not excluded by  $\Upsilon$ , ... precision decay measurements since the  $a_1$  turns out to be very-singlet like for all the low- $F$  scenarios — this is the natural thing for  $\kappa A_\kappa \rightarrow 0$ .

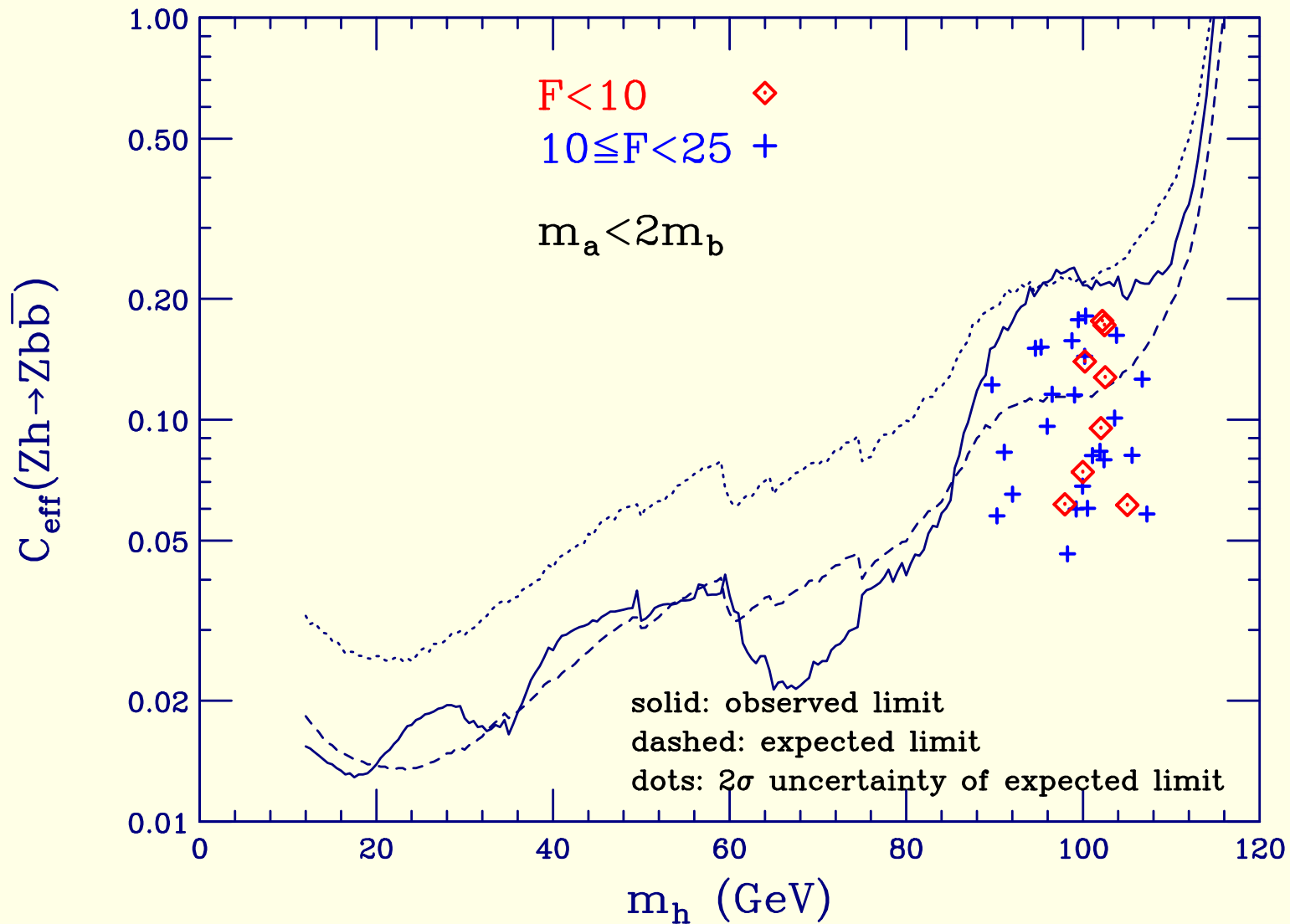


Figure 9: Observed LEP limits on  $C_{eff}^{2b}$  for the low- $F$  points with  $m_{a_1} < 2m_b$ .

So just how consistent are the  $F < 10$  points with the observed event excess. Although it is slightly misleading, a good place to begin is to recall the famous  $1 - CL_b$  plot for the  $Z2b$  channel. (Recall: the smaller  $1 - CL_b$  the less consistent is the data with expected background only.)

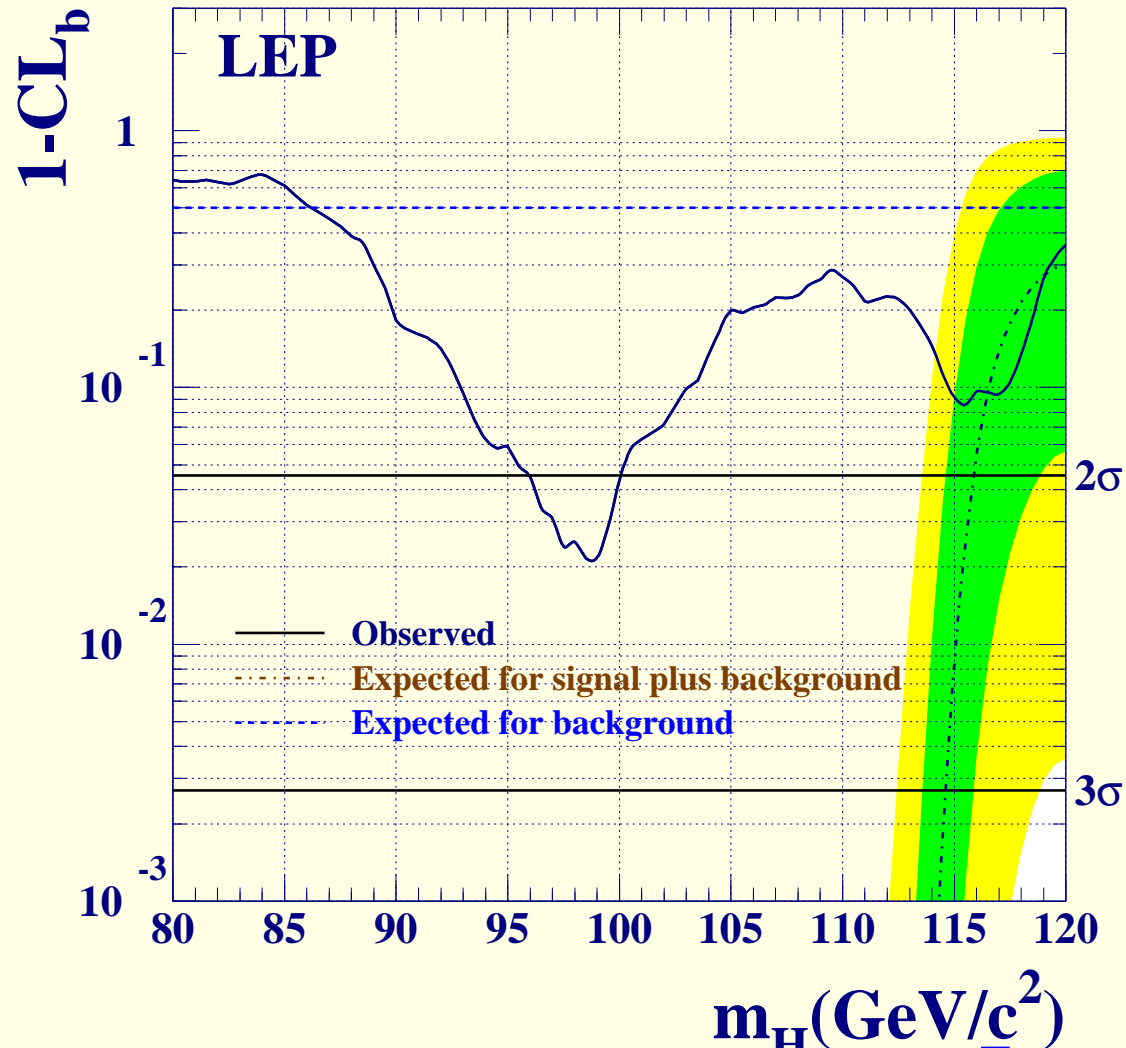


Figure 10: Plot of  $1 - CL_b$  for the  $Zb\bar{b}$  final state.

- The observed vs. expected discrepancy yields bad consistency with pure background and a preferred  $h$  mass (assuming reduced  $B(h \rightarrow b\bar{b})$ ) just a bit below our NMSSM low- $F$  values. This is a good start.

But, to really see how well the  $F < 10$ ,  $m_{a_1} < 2m_b$  points describe the LEP excesses we have to run them through the full LHWG code. There is some information coming from channels other than  $Z2b$  and of course there is variation in the relevant branching ratios.

In Table 1, we give the precise masses and branching ratios of the  $h_1$  and  $a_1$  for all the  $F < 10$  points.

We also give the number of standard deviations,  $n_{\text{obs}}$  ( $n_{\text{exp}}$ ) by which the **observed** rate (**expected** rate obtained for the predicted signal+background) exceeds the predicted background. The numbers are obtained after full processing of all  $Zh$  final states using the preliminary LHWG analysis code (thanks to P. Bechtle). They are derived from  $(1 - CL_b)_{\text{observed}}$  and  $(1 - CL_b)_{\text{expected}}$  using the usual tables: e.g.  $(1 - CL_b) = 0.32, 0.045, 0.0027$  correspond to  $1\sigma, 2\sigma, 3\sigma$  excesses, respectively.

The quantity  $s95$  is the factor by which the signal predicted in a given case would have to be multiplied in order to exceed the 95% CL. All these quantities are obtained by processing each scenario through the full preliminary LHWG confidence level/likelihood analysis.

$m_{h_1}/m_{a_1}$ (GeV)	Branching Ratios			$n_{\text{obs}}/n_{\text{exp}}$ units of $1\sigma$	$s_{95}$	$N_{SD}^{LHC}$
	$h_1 \rightarrow b\bar{b}$	$h_1 \rightarrow a_1 a_1$	$a_1 \rightarrow \tau\bar{\tau}$			
98.0/2.6	0.062	0.926	0.000	2.25/1.72	2.79	1.2
100.0/9.3	0.075	0.910	0.852	1.98/1.88	2.40	1.5
100.2/3.1	0.141	0.832	0.000	2.26/2.78	1.31	2.5
102.0/7.3	0.095	0.887	0.923	1.44/2.08	1.58	1.6
102.2/3.6	0.177	0.789	0.814	1.80/3.12	1.03	3.3
102.4/9.0	0.173	0.793	0.875	1.79/3.03	1.07	3.6
102.5/5.4	0.128	0.848	0.938	1.64/2.46	1.24	2.4
105.0/5.3	0.062	0.926	0.938	1.11/1.52	2.74	1.2

Table 1: Some properties of the  $h_1$  and  $a_1$  for the eight allowed points with  $F < 10$  and  $m_{a_1} < 2m_b$  from our  $\tan\beta = 10$ ,  $M_{1,2,3}(m_Z) = 100, 200, 300$  GeV NMSSM scan.  $N_{SD}^{LHC}$  is the statistical significance of the best “standard” LHC Higgs detection channel for integrated luminosity of  $L = 300 \text{ fb}^{-1}$ .

### Comments

- If  $n_{\text{exp}}$  is larger than  $n_{\text{obs}}$  then the excess predicted by the signal plus background Monte Carlo is larger than the excess actually observed and vice versa.
- The points with  $m_{h_1} \lesssim 100$  GeV have the largest  $n_{\text{obs}}$ .



- Point 2 gives the best consistency between  $n_{\text{obs}}$  and  $n_{\text{exp}}$ , with a predicted excess only slightly smaller than that observed.
- Points 1 and 3 also show substantial consistency.
- For the 4th and 7th points, the predicted excess is only modestly larger (roughly within  $1\sigma$ ) compared to that observed.
- The 5th and 6th points are very close to the 95% CL borderline and have a predicted signal that is significantly larger than the excess observed.
- LEP is not very sensitive to point 8.

Thus, a significant fraction of the  $F < 10$  points are very consistent with the observed event excess.

We wish to emphasize that in our scan there are many, many points that satisfy all constraints and have  $m_{a_1} < 2m_b$ . The remarkable result is that those with  $F < 10$  have a substantial probability that they predict the Higgs boson properties that would imply a LEP  $Zh \rightarrow Z + b$ 's excess of the sort seen.

- Comments on the  $F < 10$ ,  $m_{a_1} < 2m_b$  points

We reiterate that a light  $a_1$  is natural in the NMSSM in the  $\kappa A_\kappa, \lambda A_\lambda \rightarrow 0$  limit since it is the pseudo-Nambu-Goldstone boson associated with the

spontaneously broken (by vevs)  $U(1)_R$  symmetry of the scalar potential.

For the  $F < 10$  scenarios,  $\lambda(m_Z) \sim 0.15 \div 0.25$ ,  $\kappa(m_Z) \sim 0.15 \div 0.3$ ,  $|A_\kappa(m_Z)| < 4$  GeV and  $|A_\lambda(m_Z)| < 200$  GeV, implying small  $\kappa A_\kappa$  and moderate  $\lambda A_\lambda$ .

The effect of  $\lambda A_\lambda$  on  $m_{a_1}$  is further suppressed when the  $a_1$  is largely singlet in nature, as is the case for small  $\kappa A_\kappa$ .

We note that small soft SUSY-breaking trilinear couplings at the unification scale are generic in SUSY breaking scenarios where SUSY breaking is mediated by the gauge sector, as, for instance, in gauge or gaugino mediation.

Although the value  $A_\lambda(m_Z)$  might be sizable due to contributions from gaugino masses after renormalization group running between the unification scale and the weak scale,  $A_\kappa$  receives only a small correction from the running (such corrections being one loop suppressed compared to those for  $A_\lambda$ ).

Finally, we note that the above  $\lambda(m_Z)$  values are such that  $\lambda$  will remain perturbative when evolved up to the unification scale, implying that the resulting unification-scale  $\lambda$  values are natural in the context of model

structures that might yield the NMSSM as an effective theory below the unification scale.

**In short, the light, singlet  $a_1$  scenarios arise in the most natural limit of the NMSSM.**

## Collider Implications

- An important question is the extent to which the type of  $h \rightarrow aa$  Higgs scenario (whether NMSSM or other) described here can be explored at the Tevatron, the LHC and a future  $e^+e^-$  linear collider.

At the first level of thought, the  $h_1 \rightarrow a_1 a_1$  decay mode renders inadequate the usual Higgs search modes that might allow  $h_1$  discovery at the LHC.

Since the other NMSSM Higgs bosons are rather heavy and have couplings to  $b$  quarks that are not greatly enhanced, they too cannot be detected at the LHC. The last column of Table 1 shows the statistical significance of the most significant signal for *any* of the NMSSM Higgs bosons in the “standard” SM/MSSM search channels for the eight  $F < 10$  NMSSM parameter choices.

For the  $h_1$  and  $a_1$ , the most important detection channels are  $h_1 \rightarrow \gamma\gamma$ ,  $Wh_1 + t\bar{t}h_1 \rightarrow \gamma\gamma\ell^\pm X$ ,  $t\bar{t}h_1/a_1 \rightarrow t\bar{t}b\bar{b}$ ,  $b\bar{b}h_1/a_1 \rightarrow b\bar{b}\tau^+\tau^-$  and  $WW \rightarrow h_1 \rightarrow \tau^+\tau^-$ .

Even after  $L = 300 \text{ fb}^{-1}$  of accumulated luminosity, the typical maximal

signal strength is at best  $3.5\sigma$ . For the eight points of Table 1, this largest signal derives from the  $Wh_1 + t\bar{t}h_1 \rightarrow \gamma\gamma\ell^\pm X$  channel.

There is a clear need to develop detection modes sensitive to the  $h_1 \rightarrow a_1a_1 \rightarrow \tau^+\tau^-\tau^+\tau^-$  and (unfortunately)  $4j$  decay channels.

I will focus on  $4\tau$  in my discussion of possibilities below, but keep in mind the  $4j$  case.

## Hadron Colliders

1. One detection mode that can be considered is  $WW \rightarrow h_1 \rightarrow a_1a_1 \rightarrow 4\tau$ .
  - I have started to work with Markus Schumacher on this mode.
  - We know that the cross section is not bad.
  - The events must be triggered at level 1 by one or two  $\mu$ 's from one of the  $\tau$ 's. This is probably not that inefficient: e.g.  $B(4\tau \rightarrow 2 \text{ or more } \mu's) \sim 15\%$ , but spectrum must be examined (for  $2\mu$ 's need each with  $p_T > 15$  GeV. Schumacher is running the MC).
  - The triggered events of interest can be further isolated by demanding the forward jets expected in  $WW$  fusion.
  - The  $4\tau$  mode might in the end actually be fairly background free?
  - One of course has to recognize **overlapping**  $\tau$ 's, which might yield lower efficiency for finding the events of interest.

- Assuming the  $\tau$ 's can be found, there would be some ability to reconstruct  $m_{h_1}$  using the fact that the two  $\tau$ 's from one light  $a_1$  are quite collinear and so you could do the usual collinear mass reconstruction game of treating the two  $\tau$  pairs as two objects with collinear visible momentum and missing momentum.
2. Another mode is  $t\bar{t}h_1 \rightarrow t\bar{t}a_1a_1 \rightarrow t\bar{t}\tau^+\tau^-\tau^+\tau^-$ .
    - Compared to the  $WW$  fusion mode, triggering will be very easy. But, forward jets are absent and, so, cannot be used to help reduce backgrounds.
    - Of course, the cross section is smaller.
    - Overlapping  $\tau$ 's and mass reconstruction as above.
  3. Third, recall that the  $\tilde{\chi}_2^0 \rightarrow h_1\tilde{\chi}_1^0$  channel provides a signal in the MSSM when  $h_1 \rightarrow b\bar{b}$  decays are dominant.
    - It has not been studied for  $h_1 \rightarrow a_1a_1 \rightarrow 4\tau$  decays.
    - If a light  $\tilde{\chi}_1^0$  provides the dark matter of the universe (as possible because of the  $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow a_1 \rightarrow X$  annihilation channels for a light  $a_1$  — see Bob's talk and papers by JFG, McElrath, Hooper and Belanger et al, and references therein), the  $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$  mass difference might be large enough to allow such decays.
  4. Last, but definitely not least, diffractive production  $pp \rightarrow pp h_1 \rightarrow pp X$ . The mass  $M_X$  can be reconstructed with roughly a 1 – 2 GeV resolution,

potentially revealing a Higgs peak, independent of the decay of the Higgs. The news from the Manchester conference is both good and bad.

- The good news is that CDF data appear to confirm that diffractive  $\gamma\gamma$  production takes.
- The bad news is that the rate is not too different from that predicted by the Khoze, Ryskin, ... group, which predicts smallish cross section:  
 $\Rightarrow$  expect  $\sigma \sim 1 \div 3$  fb for  $m_{h_1} \sim 100$  GeV and  $ggh_1$ =SM-like.
- Since can only do this at low- $\mathcal{L}$ .  $L = 30$  fb $^{-1}$   $\Rightarrow$   $30 \div 90$  events before acceptance and tagging.

A study (JFG, Khoze, de Roeck, Ryskin, ...) for the  $h_1 \rightarrow a_1 a_1 \rightarrow 4\tau$  decay mode is underway.

- Only  $420+420$  proton detector option has decent acceptance ( $\sim 40\%$ ).
- Currently (i.e. without a major expenditure on extra time delays in the level 1 pipeline), for  $420 + 420$  one cannot use the distant proton detectors to trigger and still be able to have other information for the event retained.
- Thus, triggering would have to employ the decay products of the centrally produced Higgs.
- Thus, one has to trigger on the decay products of the  $\tau$ 's.

A di-muon trigger might be the best.

Using  $B(4\tau \rightarrow 2 \text{ or more } \mu's) \sim 0.15$ .  $\Rightarrow$  acceptance  $\times B = 0.06$ .

Then,  $\mu$  spectra must be taken into account  $\Rightarrow$  another 50% cut (at most optimistic, requires MC).

Overlapping  $\tau$ 's give overlapping  $\mu$ 's so some reduction here might occur?

– **Net result:**  $events \lesssim 90 \times 0.06 \times 0.5 \lesssim 3$ .

$\Rightarrow$  will need to return to this if we find that  $WW \rightarrow WW$  is perturbative, but no Higgs is detected.

- At the Tevatron it is possible that  $Zh_1$  and  $Wh_1$  production, with  $h_1 \rightarrow a_1a_1 \rightarrow 4\tau$ , will provide the most favorable channels.

If backgrounds are small, one must simply accumulate enough events.

However, efficiencies for triggering on and isolating the  $4\tau$  final state will not be large.

Event rates at least as bad as for diffractive.

- Perhaps one could also consider  $gg \rightarrow h_1 \rightarrow a_1a_1 \rightarrow 4\tau$  which would have substantially larger rate.

Studies are needed.



- If supersymmetry is detected at the Tevatron, but no Higgs is seen, and if LHC discovery of the  $h_1$  remains uncertain, the question will arise of whether Tevatron running should be extended so as to allow eventual discovery of  $h_1 \rightarrow 4\tau$ .

However, rates imply that the  $h_1$  signal could only be seen if Tevatron running is extended until  $L > 20 \text{ fb}^{-1}$  (maybe more) has been accumulated.

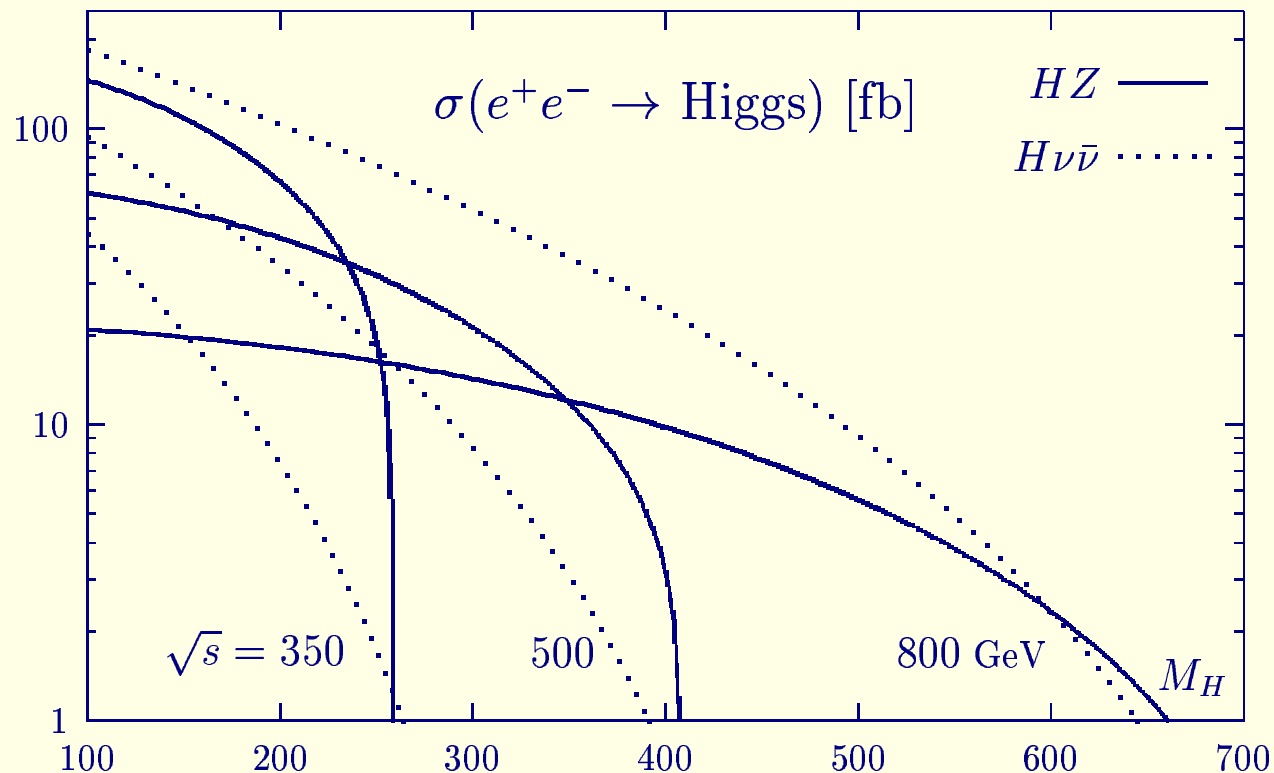
And, there is the risk that  $m_{a_1} < 2m_\tau$ , in which case Tevatron backgrounds in the above modes would be impossibly large.

- Of course, even if the LHC is unable to see any of the NMSSM Higgs bosons, it *would* observe numerous supersymmetry signals and *would confirm that  $WW \rightarrow WW$  scattering is perturbative*, implying that something like a light Higgs boson must be present.

## Lepton Colliders

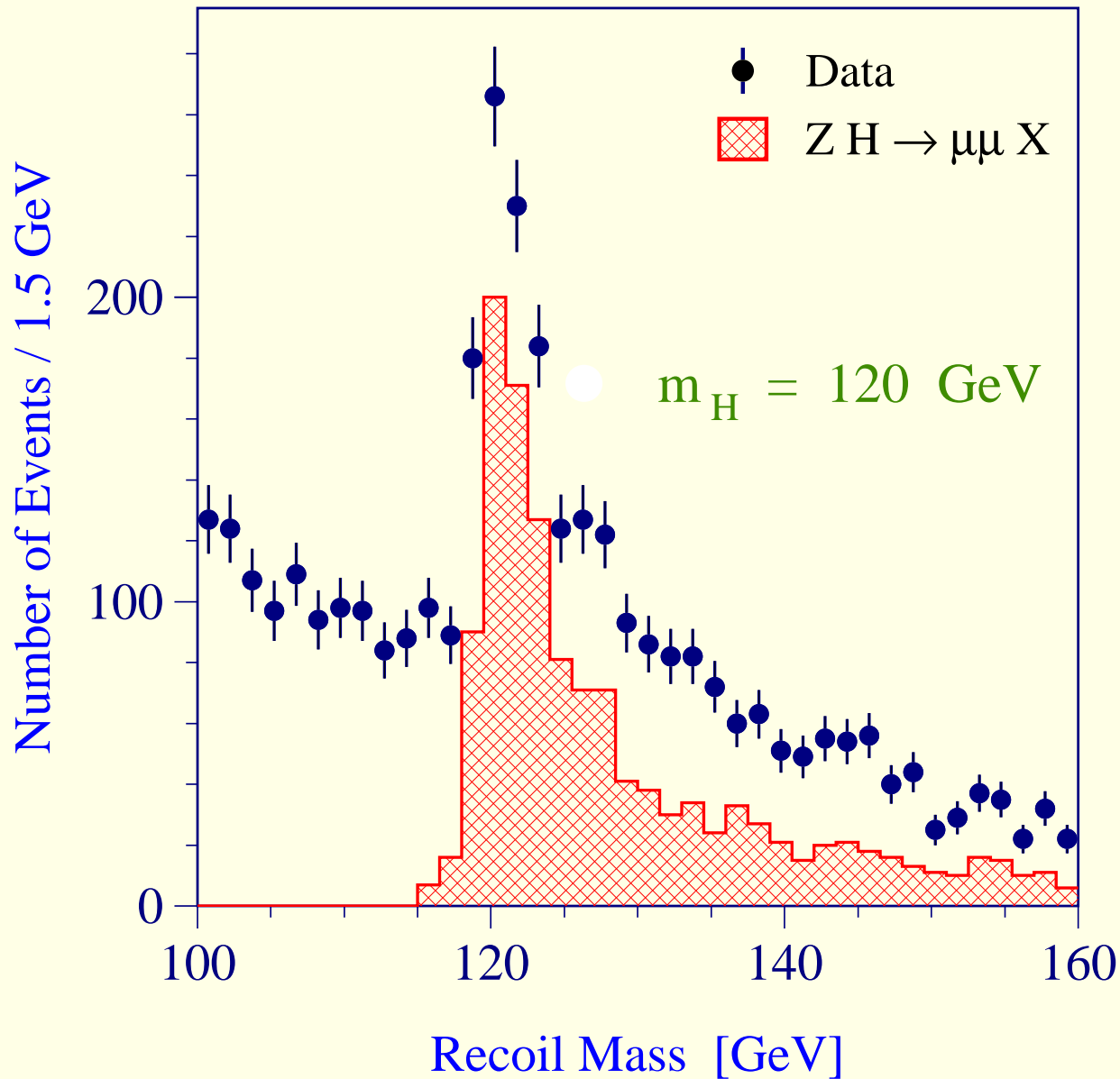
- Of course, discovery of the  $h_1$  will be straightforward at an  $e^+e^-$  linear collider via the inclusive  $Zh \rightarrow \ell^+\ell^-X$  reconstructed  $M_X$  approach (which allows Higgs discovery independent of the Higgs decay mode).

I show a few standard plots.



**Figure 11: Cross sections at the ILC.**

With integrated luminosity of  $L = 300 \text{ fb}^{-1}$  say, as you all know we get a large number of Higgs production events before efficiencies. For example at  $\sqrt{s} = 350 \text{ GeV}$  and  $m_{h_1} = 100 \text{ GeV}$  we produce more than  $3 \times 10^4$  Higgs bosons in the  $Zh_1$  mode.



**Figure 12: Decay-mode-independent Higgs  $M_X$  peak in the  $Zh \rightarrow \mu^+\mu^-X$  mode for  $L = 500 \text{ fb}^{-1}$  at  $\sqrt{s} = 350 \text{ GeV}$ , taking  $m_h = 120 \text{ GeV}$ .**

There are lots of events in just the  $\mu^+\mu^-$  channel (which however you may want to restrict to since it has the best mass resolution).

- Although the  $h \rightarrow b\bar{b}$  and  $h \rightarrow \tau^+\tau^-$  rates are 1/10 of the normal, the number of Higgs produced will be such that you can certainly see  $Zh \rightarrow Zb\bar{b}$  and  $Zh \rightarrow Z\tau^+\tau^-$  in a variety of  $Z$  decay modes.

This is quite important, as it will allow you to subtract these modes off and get a determination of  $B(h_1 \rightarrow a_1 a_1)$ , which is probably the only way to directly measure the crucial  $\lambda$  coupling.

Of course, the errors for branching ratios to all the usual channels will be statistically increased by a factor of roughly  $\sqrt{10}$  due to decreased branching ratios of  $h_1$  to  $b\bar{b}$ ,  $\tau^+\tau^-$ , ... (i.e. any usual channel).

I have not thought carefully, but I guess the  $g_{ZZh}$  measurement would not be much affected since (if I am remembering correctly) that was without using a given final state (otherwise it can't be better than the square root of the error for  $hbb$ ).

The standard SM table appears below.

Higgs coupling	$\delta\text{BR}/\text{BR}$	$\delta g/g$
$hWW$	5.1%	1.2%
$hZZ$	—	1.2%
$htt$	—	2.2%
$hbb$	2.4%	2.1%
$hcc$	8.3%	3.1%
$h\tau\tau$	5.0%	3.2%
$h\mu\mu$	$\sim 30\%$	$\sim 15\%$
$hgg$	5.5%	
$h\gamma\gamma$	16%	
$hhh$	—	$\sim 20\%$

Table 2: Expected fractional uncertainties for measurements of SM Higgs branching ratios [ $\text{BR}(h \rightarrow X\bar{X})$ ] and couplings [ $g_{hXX}$ ], for various choices of final state  $X\bar{X}$ , assuming  $m_h = 120$  GeV at the LC. In all but four cases, the results shown are based on  $500 \text{ fb}^{-1}$  of data at  $\sqrt{s} = 500$  GeV. Results for  $h\gamma\gamma$ ,  $htt$ ,  $h\mu\mu$  and  $hhh$  are based on  $1 \text{ ab}^{-1}$  of data at  $\sqrt{s} = 500$  GeV (for  $\gamma\gamma$  and  $hh$ ) and  $\sqrt{s} = 800$  GeV (for  $tt$  and  $\mu\mu$ ), respectively. For  $B(h_1 \rightarrow \text{SM particles}) \sim 0.1 \times \text{usual}$ , most errors above must be multiplied by  $\sim \sqrt{10}$ .

- Presumably direct detection in the  $Zh \rightarrow Za_1a_1 \rightarrow Z4\tau$  mode will also be possible although I am unaware of any actual studies.

This would give a direct measurement of  $B(h_1 \rightarrow a_1a_1 \rightarrow \tau^+\tau^-\tau^+\tau^-)$ .  
Error?

- Coupled with the indirect measurement of  $B(h_1 \rightarrow a_1a_1)$  from subtracting the direct  $b\bar{b}$  and  $\tau^+\tau^-$  modes would give a measurement of  $B(a_1 \rightarrow \tau^+\tau^-)$ .

This would allow a first unfolding of information about the  $a_1$  itself.

Of course, the above assumes we have accounted for all modes.

- Maybe, given the large event rate, one could even get a handle on modes such as  $h_1 \rightarrow a_1a_1 \rightarrow \tau^+\tau^-jj$  ( $j = c, g$ ), thereby getting still more cross checks.

This latter will not have high accuracy if  $B(a_1 \rightarrow \tau^+\tau^-) > 0.9$  as is the model prediction. But, certainly it should be checked against the  $B(a_1 \rightarrow \tau^+\tau^-)$  value obtained, as outlined above, if at all possible.

- At a  $\gamma\gamma$  collider, the  $\gamma\gamma \rightarrow h_1 \rightarrow 4\tau$  signal will be easily seen (Gunion, Szleper).

This could help provide still more information about the  $h$ .

- In contrast, since (as already noted) the  $a_1$  in these low- $F$  NMSSM scenarios is fairly singlet in nature, its *direct* (i.e. not in  $h_1$  decays) detection will be very challenging even at the ILC.

We plan to look at such reactions as  $e^+e^- \rightarrow Za_1a_1$ , the cross section for which would be large if the  $a_1$  had no singlet part, but is suppressed by  $\cos^2 \theta_{a_1}$ , where  $\cos \theta_{a_1}$  is the  $A_{MSSM}$  fraction, which is small.

- Further, the low- $F$  points are all such that the other Higgs bosons are fairly heavy, typically above 400 GeV in mass, and essentially inaccessible at both the LHC and all but a  $\gtrsim 1$  TeV ILC.

A few notes on  $m_{a_1} > 2m_b$ .

- We should perhaps also not take describing the LEP excess and achieving extremely low fine tuning overly seriously.

Indeed, scenarios with  $m_{h_1} > 114$  GeV (automatically out of the reach of LEP) begin at a still modest (relative to the MSSM)  $F \gtrsim 25$ .

In fact, one can probably push down to as low as  $m_{h_1} \gtrsim 108 \div 110$  GeV when  $m_{a_1} > 2m_b$ .

$\Rightarrow$  must be on the lookout for the  $4b$  and  $2b2\tau$  final states from  $h_1$  decay, with  $h_1 \rightarrow 4b$  being the largest when  $m_{a_1} > 2m_b$ .

• At the LHC, the modes that seem to hold some promise are:

1.  $WW \rightarrow h_1 \rightarrow a_1 a_1 \rightarrow b\bar{b}\tau^+\tau^-$ .

Our (JFG, Ellwanger, Hugonie, Moretti) work suggested some hope. Experimentalists (esp. D. Zerwas) are working on a fully realistic evaluation but are not that optimistic.

2.  $t\bar{t}h_1 \rightarrow t\bar{t}a_1 a_1 \rightarrow t\bar{t}4b$ .

This I imagine will be viable. In the LEP-like procedure the two  $b$ 's from one  $\tau$  would probably be treated as one. Analysis is needed.

Albert de Roeck tells me that the SM analogue of  $t\bar{t}2b$  is very much on the edge (as opposed to earlier claims of robustness).

3. Gluino cascades containing  $\tilde{\chi}_2^0 \rightarrow h_1 \tilde{\chi}_1^0$ .

It is known that the  $h_1$  can be discovered in such cascades if the production rate for gluinos is large and  $h_1 \rightarrow b\bar{b}$  is the primary decay. The case of  $h_1 \rightarrow 4b$  will be harder since the jets are softer, but maybe some signal will survive.



Indeed, to some approximation (depending on  $m_{a_1}$ ) the  $4b$  state could be analyzed (a la LEP analogy) as though it was a  $2b$  final state and such analysis would pick up a significant part of the  $2b + 2b$  final state when the  $b$ 's from one  $a_1$  were fairly collinear.

4. Doubly diffractive  $pp \rightarrow pp h_1$  followed by  $h_1 \rightarrow a_1 a_1 \rightarrow 4b$  or  $2b2\tau$ .  
Would triggering on the  $4b$  final state be possible using the muonic decays of the  $b$ 's?

These modes are also under consideration by JFG, Khoze, ....

- At the Tevatron, perhaps the lack of overlapping events and lower background rates might allow some sign of a signal in modes such as  $Wh_1$  and  $Zh_1$  production with  $h_1 \rightarrow a_1 a_1 \rightarrow 4b$  or  $2b2\tau$ . There is a study underway by G. Huang, Tao Han and collaborators.

However, rates are very low and that is even before including reductions from tagging efficiencies and such.

Conway doesn't believe it can work for expected Tevatron  $L$ .

### General Considerations

- We should note that much of the discussion above regarding Higgs discovery is quite generic. Whether the  $a$  is truly the NMSSM CP-odd  $a_1$  or just a

lighter Higgs boson into which the SM-like  $h$  pair-decays, hadron collider detection of the  $h$  in its  $h \rightarrow aa$  decay mode will be very challenging — only an  $e^+e^-$  linear collider can currently guarantee its discovery.

One should note in particular that the CP-violating MSSM CPX and similar scenarios have  $h_2 \rightarrow h_1 h_1$  decays with  $m_{h_1} > 2m_b$  most typical. These scenarios escape LEP constraints not because  $h_1 \rightarrow \tau^+\tau^-$ , but rather because the  $ZZh_2$  coupling is sufficiently suppressed for consistency of the model with the net  $Z + b$ 's event rate.  $\Rightarrow m_{a_1} > 2m_b$  discussion given above, but taking into account reduced  $h_1$  couplings to  $ZZ, WW$ .

# New Dark Matter Scenarios

with McElrath and Hooper

- The typical low- $F$  scenario has a light  $a_1$  and a  $\tilde{\chi}_1^0$  that is mainly bino.
- The mass of the  $\tilde{\chi}_1^0$  can be easily adjusted by varying the bino SUSY breaking mass  $M_1$  (with negligible effect on the fine-tuning measure).
  - ⇒ new dark matter scenarios with a very light  $\tilde{\chi}_1^0$  that achieves an appropriate dark matter density based on  $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow a_1 \rightarrow X$  annihilation in the early universe.
  - ⇒ increased need for ILC measurements to verify  $\tilde{\chi}_1^0$  and  $a_1$  properties with sufficient accuracy to check that it all works.

See following talk by Bob.

## Conclusions

- The prominent LEP event excess in the  $Z + b$ 's channel for reconstructed Higgs mass of  $m_h \sim 100$  GeV is consistent with a scenario in which the  $ZZh$  coupling is SM-like but the  $h$  decays mainly via  $h \rightarrow aa \rightarrow 4\tau$  or  $4j$  (requiring  $m_a < 2m_b$ ) leaving an appropriately reduced rate for  $h \rightarrow b\bar{b}$ .

This value of  $m_h$  for the SM-like  $h$  of these scenarios is very attractive from a precision electroweak point of view.

- In contrast, the  $Z + b$ 's rate predicted if  $h \rightarrow b\bar{b}$  at a reduced rate and  $h \rightarrow aa \rightarrow b\bar{b}b\bar{b}$  makes up most of the rest is ruled out at better than the 95% CL by the preliminary LHWG analysis unless  $m_h \gtrsim 110$  GeV.
- We strongly encourage the LEP groups to push the analysis of the  $Z4\tau$  channel in the hope of either ruling out the  $h \rightarrow aa \rightarrow 4\tau$  scenario, or finding a small excess consistent with it.

Either a positive or negative result would have very important implications for Higgs searches at the Tevatron and LHC.

- Of course, we cannot ignore the possibility that  $m_a < 2m_\tau$  and we must deal with a dominant  $h \rightarrow 4j$  decay mode.
- Highly non-trivial support for this kind of scenario derives from the NMSSM. NMSSM models with the smallest fine-tuning typically predict precisely the above scenario with  $h = h_1$  and  $a = a_1$ .
- We speculate that lowest fine-tuning will be achieved in other supersymmetric models (with a Higgs sector extended beyond the MSSM) for scenarios that have a dominant  $h_1 \rightarrow a_1 a_1$  (or  $h_2 \rightarrow h_1 h_1$ ) decay with  $m_{a_1}$  ( $m_{h_1}$ )  $< 2m_b$ . This is simply because the SM-like  $h_1$  ( $h_2$ ) which is deeply connected to fine-tuning can be lightest in this way.
- We should work hard to see if we can observe or exclude such a Higgs scenario at the Tevatron and eventually the LHC.

The diffractive Higgs production channel appears to be a very attractive possibility, but rates are small

- The naturally associated dark matter scenario would have an unexpectedly light  $\tilde{\chi}_1^0$ . Its properties and those of the  $a_1$  would need to be determined precisely to check consistency of the dark matter relic density with accelerator data.
  - It seems quite certain that ILC precision data will be essential for all but the most basic detection of a few Higgs events and for checking the dark matter abundance if a light  $\tilde{\chi}_1^0$  with  $2m_{\tilde{\chi}_1^0} \sim m_{a_1}$  is found.
  - If  $m_{a_1} < 2m_\tau$ , probably the diffractive channel will be the only game in LHC town. But would we believe a jets only signal, and will it have more background?
- I am guessing we would need to await the ILC.
- At the LHC, perturbative  $WW \rightarrow WW$  might in the worst of cases,  $a_1 \rightarrow jj$ , be our only hint, other than precision EW, that there is a light Higgs.