LEP and NMSSM Motivations for the Dominance of $h \to aa \to 4\tau$ Decays and LHC/ILC Implications

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Outline

1. **Brief Review of NMSSM**

2. **Higgs in the NMSSM, new 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 μ term in the MSSM superpotential, $\mu\widehat{H}_u\widehat{H}_d$, remains elusive. For successful phenomenology μ can neither be zero nor can it be $\mathcal{O}(M_{\rm P})$ (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 $m_W^2/m_{\rm SUSY}$ that would have been observed at LEP. It cannot be $\mathcal{O}(M_{\rm P})$ 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 μ parameter is then automatically generated by $\langle S\rangle$ leading

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 $\sim 1~\mathrm{TeV}$. 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 κ dimensionless is allowed.

  The same applies to the soft SUSY breaking terms. Only $\kappa A_\kappa S^3$ 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.

Again 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 among other things imply a rather light charged Higgs boson. In fact, it might be the lightest of the Higgs boson with mass as low as $80~\mathrm{GeV}$. Tevatron top-decay results will soon greatly limit such a possibility and either prove the correctness of this model or very strongly constrain it.

– **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) ($\Rightarrow \widetilde{\chi}^0_{1,2,3,4,5}$), 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

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

depending on two dimensionless couplings λ, κ beyond the MSSM. [Hatted (unhatted) capital letters denote superfields (scalar superfield components).] The associated trilinear soft terms are

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

The final two input parameters are

$$\tan\beta = h_u/h_d\,, \quad \mu_{\rm eff} = \lambda s\,, \tag{3}$$

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 $m^2_{H_u}$, $m^2_{H_d}$ and m^2_S) 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 $m^2_{H_u}$, $m^2_{H_d}$ and m^2_S, along with A_λ and A_κ determine the EWSB vevs, λ and κ being dimensionless.)

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

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

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 $h \to aa$ 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. $h \to \gamma\gamma$, $t\bar{t}h, a \to t\bar{t}b\bar{b}$, $t\bar{t}h, a \to t\bar{t}\gamma\gamma$, $b\bar{b}h, a \to b\bar{b}\tau^+\tau^-$, $WW \to h \to \tau^+\tau^-$, 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 $h \to aa, \ldots$ 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

$$F = \mathrm{Max}_p F_p \equiv \mathrm{Max}_p \left| \frac{d \log m_Z}{d \log p} \right| , \tag{5}$$

where the parameters p comprise the GUT-scale values of λ, κ, A_λ, A_κ, and the usual soft-SUSY-breaking gaugino, squark, slepton, . . . masses.

- A light a_1 is also associated with NMSSM parameter choices that approach an attractive symmetry limit of the theory.

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

- Dermisek and I have shown that fine-tuning is absent in the NMSSM for precisely those parameter choices for which $h_1 \to a_1 a_1$ decays are present.

  In particular, the weaker LEP limits on such decays in the Zh production state allow a smaller value of m_h, which already goes a long way towards giving small fine-tuning.

  In addition, the NMSSM gives a natural algebraic reduction of fine-tuning when the lightest CP-odd Higgs boson has modest mass.

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

  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 $m_{h_1} < 114~\mathrm{GeV}$ and the $\times$ points have $m_{h_1} \geq 114~\mathrm{GeV}$.

  For $m_{h_1} < 114~\mathrm{GeV}$, one can achieve very low F values.

  Lowest F is achieved when the h_1 has very SM-like couplings to gauge bosons and fermions and when $m_{h_1} \sim 100~\mathrm{GeV}$, which is, of course, exactly the value preferred by precision electroweak constraints.

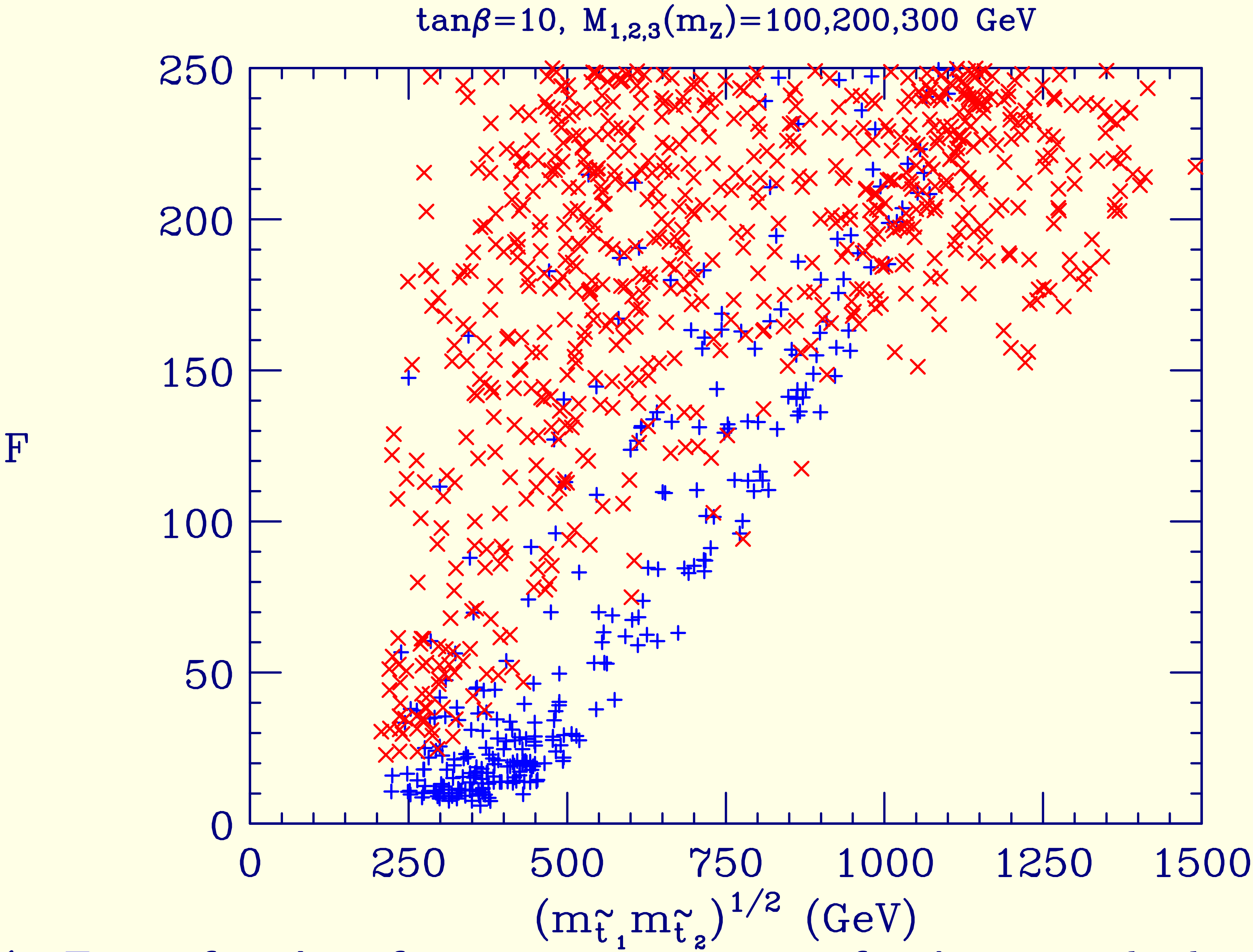

Figure 1: F **as a function of root mean stop mass after latest** *single-channel* **LEP limits.**

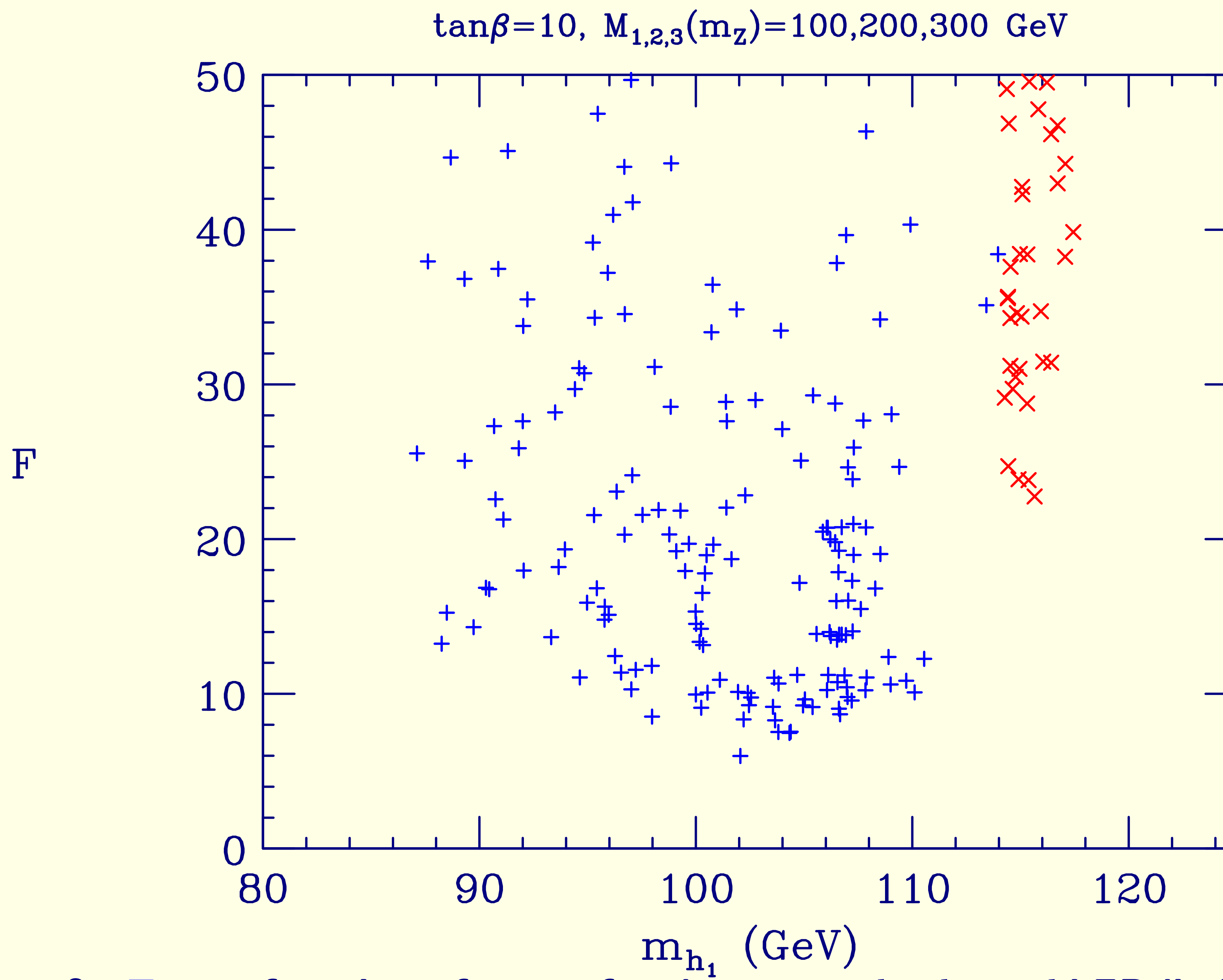

Figure 2: F **as a function of** m_{h_1} **after latest** *single-channel* **LEP limits.**

- **It is interesting to compare the new LEP limits for $Zh \to Zaa \to Z4b$ production to the old limits: Fig. 3.**

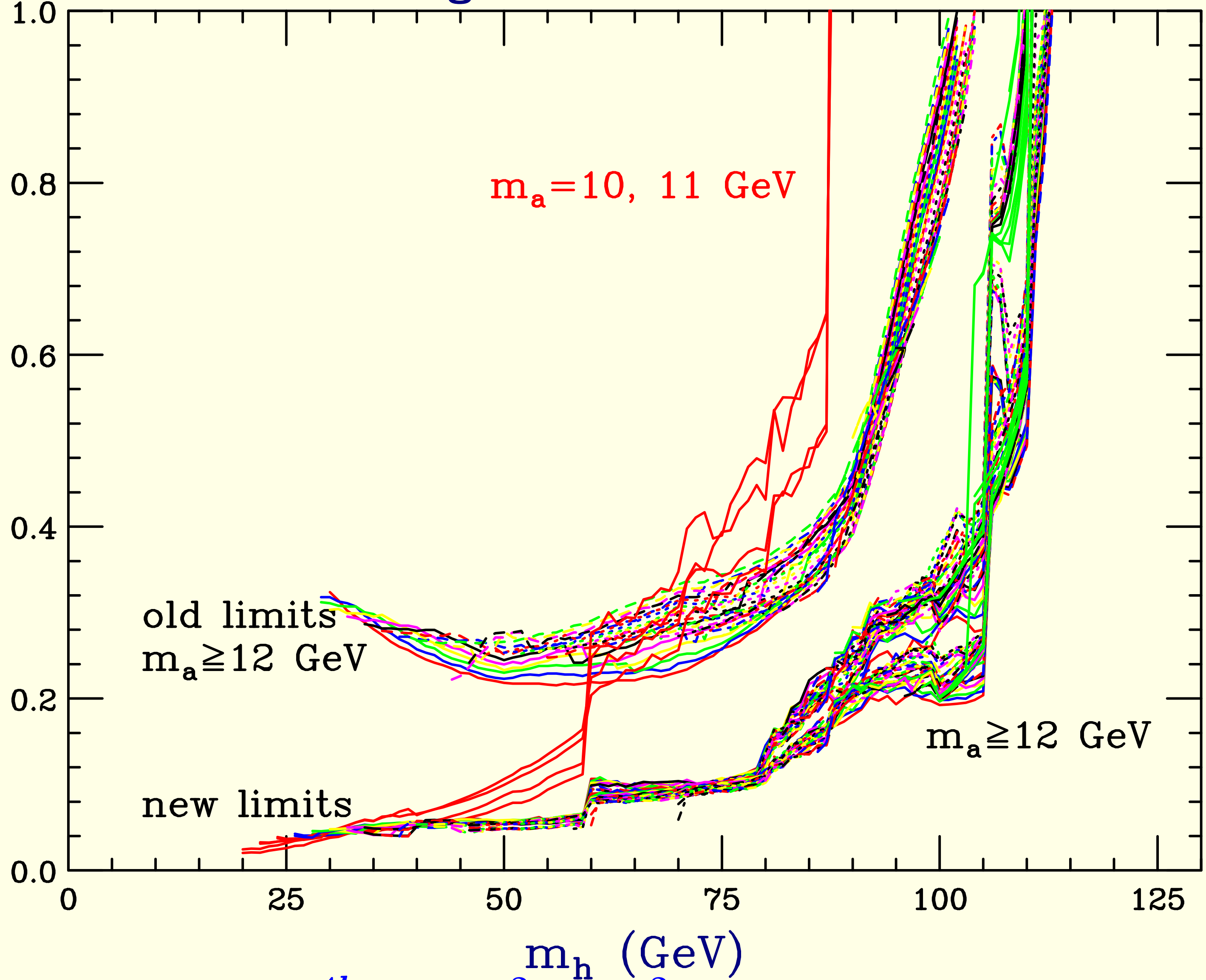

Figure 3: LEP limits on $C^{4b}_{eff} = [g^2_{ZZh}/g^2_{ZZh_{\rm SM}}]B(h \to aa)[B(a \to b\bar{b})]^2$, old and new. New are stronger but small F still possible.

- **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. 4 is the relevant plot.**

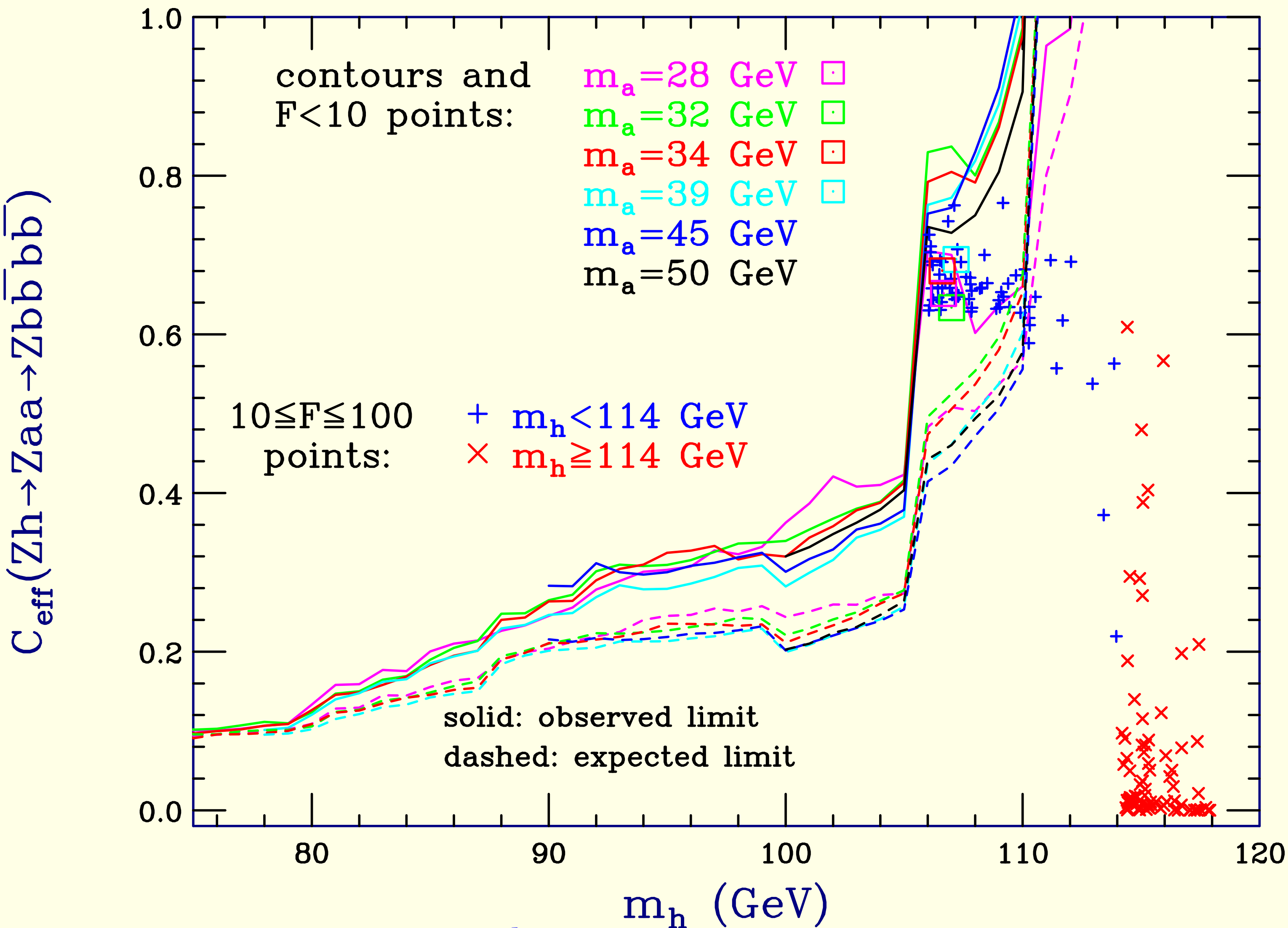

Figure 4: New LEP limits on C_{eff}^{4b} and low-F points. Note the $m_{a_1} \sim 25-40$ points between expected and observed limits.

- 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. 5.

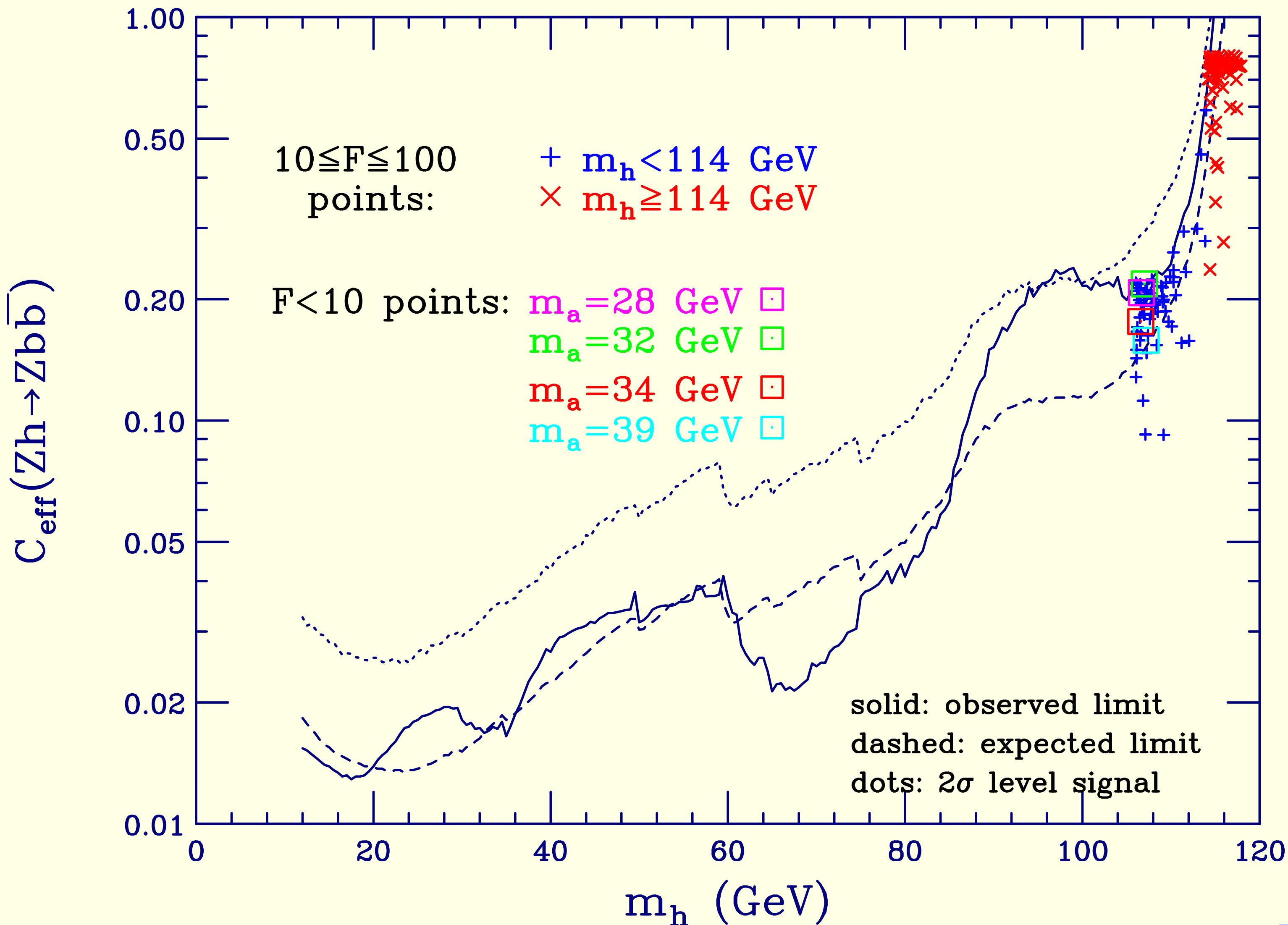

Figure 5: Observed LEP limits on $C_{eff}^{2b} = [g_{ZZh}^2/g_{ZZh_{\rm SM}}^2]B(h \to b\bar{b})$ for the low-F points with $m_{a_1} > 2m_b$.

- **The observed 95% CL limit is shown in Fig. 5. Our points fit right below the observed limit but above the expected limits shown in Fig. 4. 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 $h \to 4b$ or $h \to 2b$ 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 $Z \to jets$, 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 $h_1 \to b\bar{b}$ direct decay branching ratio and you can change the $h_1 \to a_1 a_1 \to 4b$ branching ratio, but roughly speaking $B(h_1 \to b's) \gtrsim 0.85$ (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 this is unlikely to ever be analyzed, but I am pushing.)

– Note: Such a light to very light a_1 is not excluded by Υ, ... precision decay measurements since the a_1 turns out to be very singlet like for all the low-F scenarios.

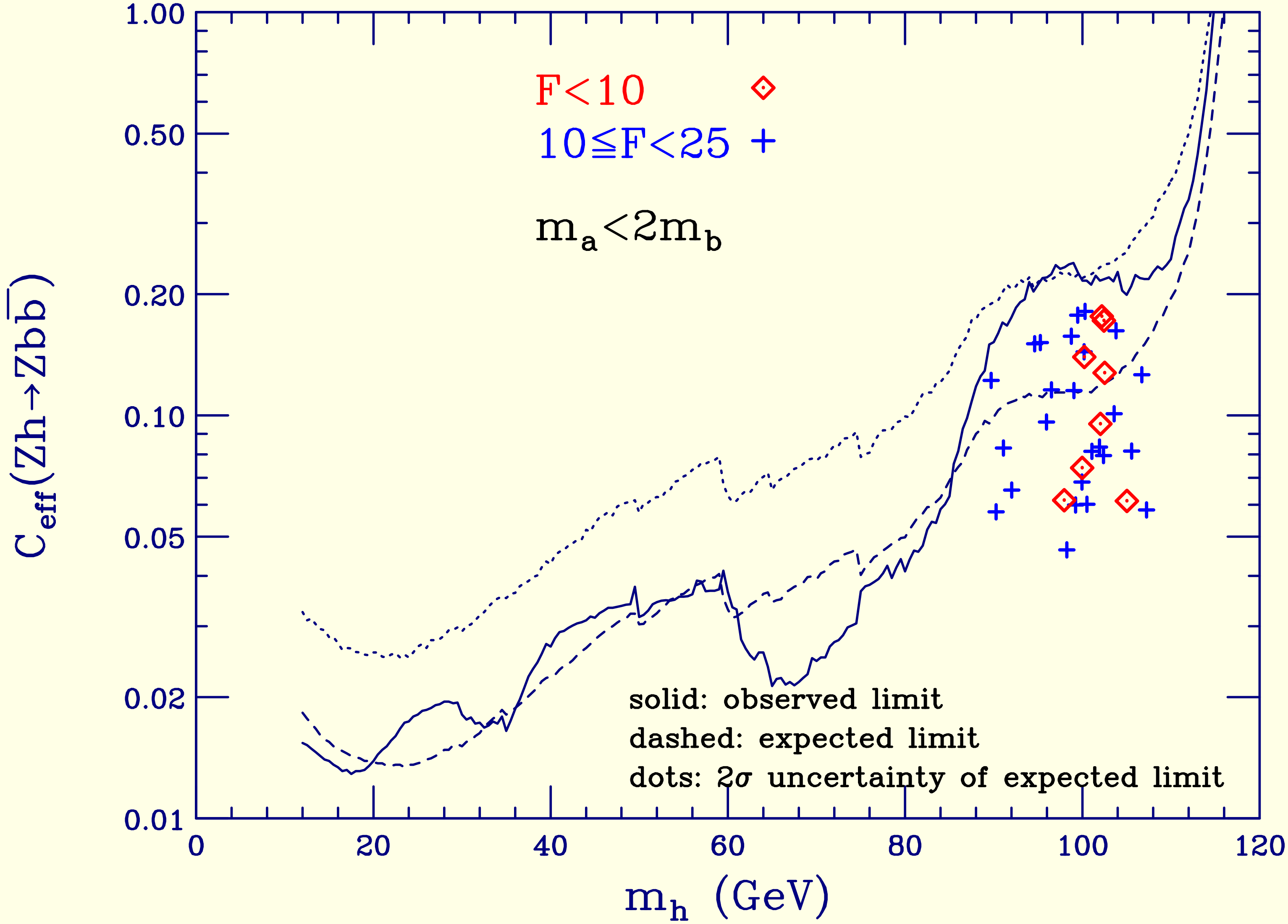

Figure 6: Observed LEP limits on C^{2b}_{eff} for the low-F points with $m_{a_1} < 2m_b$.

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.

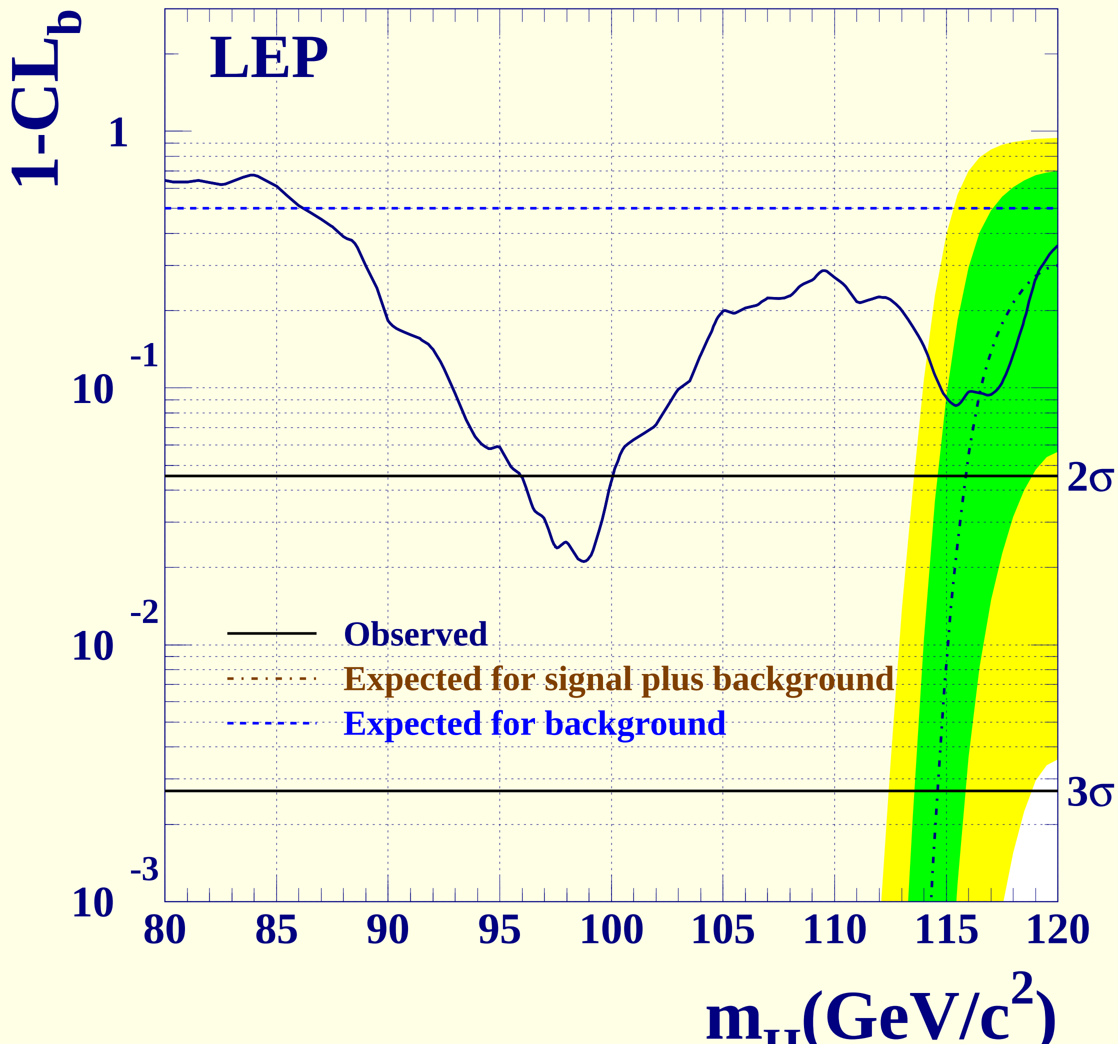

Figure 7: Plot of $1 - CL_b$ for the $Zb\bar{b}$ final state.

- The observed vs. expected discrepancy yields bad consistency with pure background and a preferred h mass (assuming reduced $B(h \to b\bar{b})$) 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, $n_{\rm obs}$ ($n_{\rm exp}$) 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 $(1 - CL_b)_{\rm observed}$ and $(1 - CL_b)_{\rm expected}$ using the usual tables: e.g. $(1 - CL_b) = 0.32$, 0.045, 0.0027 correspond to 1σ, 2σ, 3σ 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 $h_1 \to b\bar{b}$	$h_1 \to a_1 a_1$	$a_1 \to \tau\bar{\tau}$	$n_{\rm obs}/n_{\rm exp}$ units of 1σ	$s95$	N_{SD}^{LHC}
98.0/2.6	0.062	0.926	0.000	2.25/1.72	2.79	1.2
100.0/9.3	0.075	0.910	0.852	1.98/1.88	2.40	1.5
100.2/3.1	0.141	0.832	0.000	2.26/2.78	1.31	2.5
102.0/7.3	0.095	0.887	0.923	1.44/2.08	1.58	1.6
102.2/3.6	0.177	0.789	0.814	1.80/3.12	1.03	3.3
102.4/9.0	0.173	0.793	0.875	1.79/3.03	1.07	3.6
102.5/5.4	0.128	0.848	0.938	1.64/2.46	1.24	2.4
105.0/5.3	0.062	0.926	0.938	1.11/1.52	2.74	1.2

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 $\tan\beta = 10$, $M_{1,2,3}(m_Z) = 100, 200, 300~{\rm GeV}$ NMSSM scan. N_{SD}^{LHC} is the statistical significance of the best "standard" LHC Higgs detection channel for integrated luminosity of $L = 300~{\rm fb}^{-1}$.

Comments

– If $n_{\rm exp}$ is larger than $n_{\rm obs}$ then the excess predicted by the signal plus background Monte Carlo is larger than the excess actually observed and vice versa.

– The points with $m_{h_1} \lesssim 100~{\rm GeV}$ have the largest $n_{\rm obs}$.

- Point 2 gives the best consistency between $n_{\rm obs}$ and $n_{\rm exp}$, 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 1σ) 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 $Zh \to Z + b$'s excess of the sort seen.

- So, is there any other reason to take a light a_1 seriously? The answer is **YES**.

  A light a_1 is natural in the NMSSM in the $\kappa A_\kappa, \lambda A_\lambda \to 0$ limit.

This can be understood as a consequence of a global $U(1)_R$ symmetry of the scalar potential (in the limit $\kappa A_\kappa, \lambda A_\lambda \to 0$) which is spontaneously broken by the vevs, resulting in a Nambu-Goldstone boson in the spectrum (Dobrescu, Matchev), which is the a_1.

This symmetry is explicitly broken by the trilinear soft terms so that for small $\kappa A_\kappa, \lambda A_\lambda$ the lightest CP odd Higgs boson is naturally much lighter than other Higgs bosons.

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

The effect of λA_λ on m_{a_1} is further suppressed when the a_1 is largely singlet in nature, as is the case for low-F scenarios.

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_κ receives only a small correction from the running (such corrections being one loop suppressed compared to those for A_λ).

Finally, we note that the above $\lambda(m_Z)$ values are such that λ will remain perturbative when evolved up to the unification scale, implying that the resulting unification-scale λ 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 $h \to aa$ 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 $h_1 \to a_1 a_1$ 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 $h_1 \to \gamma\gamma$, $Wh_1 + t\bar{t}h_1 \to \gamma\gamma\ell^{\pm}X$, $t\bar{t}h_1/a_1 \to t\bar{t}b\bar{b}$, $b\bar{b}h_1/a_1 \to b\bar{b}\tau^+\tau^-$ and $WW \to h_1 \to \tau^+\tau^-$.

  Even after $L = 300~\mathrm{fb}^{-1}$ of accumulated luminosity, the typical maximal signal strength is at best 3.5σ. For the eight points of Table 1, this largest signal derives from the $Wh_1 + t\bar{t}h_1 \to \gamma\gamma\ell^\pm X$ channel.

There is a clear need to develop detection modes sensitive to the $h_1 \to a_1 a_1 \to \tau^+\tau^-\tau^+\tau^-$ and (unfortunately) $4j$ decay channels.

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

Hadron Colliders

1. One detection mode that can be considered is $WW \to h_1 \to a_1 a_1 \to 4\tau$.
2. Second, recall that the $\widetilde{\chi}_2^0 \to h_1 \widetilde{\chi}_1^0$ channel provides a signal in the MSSM when $h_1 \to b\bar{b}$ decays are dominant.
   It has not been studied for $h_1 \to a_1 a_1 \to 4\tau$ decays.
   If a light $\widetilde{\chi}_1^0$ provides the dark matter of the universe (as possible because of the $\widetilde{\chi}_1^0 \widetilde{\chi}_1^0 \to a_1 \to X$ annihilation channels for a light a_1, see JFG, McElrath, Hooper and Belanger et al, and references therein), the $m_{\widetilde{\chi}_2^0} - m_{\widetilde{\chi}_1^0}$ mass difference might be large enough to allow such decays.
3. Last, but definitely not least, diffractive production (look around you for people who have studied this) $pp \to pph_1 \to ppX$, where the mass M_X can be reconstructed with roughly a $1-2~\mathrm{GeV}$ resolution, can potentially reveal a Higgs peak, independent of the decay of the Higgs.

A study (JFG, Khoze, de Roeck, Ryskin, ...) is underway to see if this discovery mode works for the $h_1 \to a_1 a_1 \to 4\tau$ decay mode as well as it appears to work for the simpler SM $h_{\rm SM} \to b\bar{b}$ case.

The main issue may be whether events can be triggered.

- Recall that currently (i.e. without a major expenditure on extra time delays in the level 1 pipeline), 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 (which, by the way, is produced with close to SM rate since this rate relies on the unaltered ggh_1 coupling strength).
- Thus, one has to trigger on the decay products of the τ's. In a conversation last night, we decided that a di-muon trigger might not have too bad an efficiency.

  First, although the μ decay products of the τ's are soft, triggering is possible down to transverse momentum of just $3~{\rm GeV}$.

  Second, the branching ratio for getting two μ's from four τ's is also not bad.

  However, one must keep in mind that the event will have two pairs of overlapping τ's. Perhaps this reduces the efficiency for isolating the μ's from two τ's from the same a_1?

- At the Tevatron it is possible that Zh_1 and Wh_1 production, with $h_1 \to a_1 a_1 \to 4\tau$, will provide the most favorable channels.

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

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

- Perhaps one could also consider $gg \to h_1 \to a_1 a_1 \to 4\tau$ 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 $h_1 \to 4\tau$.

  However, rates imply that the h_1 signal could only be seen if Tevatron running is extended until $L > 20~\mathrm{fb}^{-1}$ (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 $WW \to WW$ 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 $Zh \to \ell^+\ell^- X$ reconstructed M_X approach (which allows Higgs discovery independent of the Higgs decay mode). Direct detection in the $Zh \to Z4\tau$ mode will also be possible. At a $\gamma\gamma$ collider, the $\gamma\gamma \to h \to 4\tau$ signal will be easily seen (Gunion, Szleper).

- 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.

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

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 $h \to aa$ 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 $h_2 \to h_1 h_1$ decays with $m_{h_1} > 2m_b$ most typical. These scenarios escape LEP constraints not because $h_1 \to \tau^+\tau^-$, but rather because the ZZh_2 coupling is sufficiently suppressed for consistency of the model with the net $Z + b$'s event rate.

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

  Indeed, scenarios with $m_{h_1} > 114~\mathrm{GeV}$ (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 $m_{h_1} \gtrsim 108 \div 110~\mathrm{GeV}$ 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 $h_1 \to 4b$ being the largest when $m_{a_1} > 2m_b$.

- At the LHC, the modes that seem to hold some promise are:
  1. $WW \to h_1 \to a_1 a_1 \to b\bar{b}\tau^+\tau^-$.
     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. Gluino cascades containing $\widetilde{\chi}_2^0 \to h_1 \widetilde{\chi}_1^0$.
     It is known that the h_1 can be discovered in such cascades if the production rate for gluinos is large and $h_1 \to b\bar{b}$ is the primary decay. The case of $h_1 \to 4b$ will be harder since the jets are softer, but maybe some signal will survive.
  3. Doubly diffractive $pp \to pph_1$ followed by $h_1 \to a_1 a_1 \to 4b$ or $2b2\tau$.
     Would triggering on the $4b$ final state be possible using the muonic decays of the b's?

- 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 $h_1 \to a_1 a_1 \to 4b$ or $2b2\tau$. There is a study underway. Rates are low.

New Dark Matter Scenarios

with McElrath and Hooper

- **The typical low-F scenario has a light a_1 and a $\widetilde{\chi}_1^0$ that is mainly bino.**

- **The mass of the $\widetilde{\chi}_1^0$ can be easily adjusted by varying the bino SUSY breaking mass M_1 (with negligible effect on the fine-tuning measure).**

  $\Rightarrow$ new dark matter scenarios with a very light $\widetilde{\chi}_1^0$ that achieves an appropriate dark matter density based on $\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to a_1 \to X$ annihilation in the early universe.

  $\Rightarrow$ increased need for ILC measurements to verify $\widetilde{\chi}_1^0$ and a_1 properties with sufficient accuracy to check that it all works.

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 $h \to aa \to 4\tau$ or $4j$ (requiring $m_a < 2m_b$) leaving an appropriately reduced rate for $h \to b\bar{b}$.

  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 $h \to b\bar{b}$ at a reduced rate and $h \to aa \to b\bar{b}b\bar{b}$ 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 $h \to aa \to 4\tau$ 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 $h \to 4j$ 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 $h_1 \to a_1 a_1$ (or $h_2 \to h_1 h_1$) 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 AT THE LHC APPEARS TO BE THE IDEAL, AND PERHAPS ONLY, POSSIBILITY.

- **The naturally associated dark matter scenario would have an unexpectedly light $\widetilde{\chi}_1^0$. 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 this.