Motivation and Evidence for the $h \longrightarrow aa$ NMSSM Higgs Scenario

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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 CP-conserving MSSM into an awkward corner of parameter space characterized by very high fine-tuning. Further, electroweak baryogenesis is only possible if one of the stop masses is $\lesssim m_t$, and LEP limits on the light Higgs then imply that the heavier stop must be *very* heavy. Some relaxation of these problems is possible by allowing large CP violation in the Higgs sector.

  Still, at a more fundamental level, a satisfactory explanation of the μ term in the MSSM superpotential, $\mu \widehat{H}_u \widehat{H}_d$,[1] remains elusive. For successful phenomenology μ can neither be zero nor can it be $\mathcal{O}(M_\mathrm{P})$ (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_SUSY that would have been observed at LEP. It cannot be $\mathcal{O}(M_\mathrm{P})$ 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

[1] Hatted (unhatted) capital letters denote superfields (scalar superfield components).

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** $\sim 1~\mathrm{TeV}$**. As we shall discuss, this can be guaranteed by appropriate discrete symmetries, which simultaneously remove the potential problems associated with cosmological domain walls.**
- **However,** $\lambda\widehat{S}\widehat{H_u}\widehat{H_d}$ **cannot be the end. In particular, without further additions, the superpotential of the model would be:**

$$W_\lambda = \widehat{Q}\widehat{H_u}\mathrm{h_u}\widehat{U}^C + \widehat{H_d}\widehat{Q}\mathrm{h_d}\widehat{D}^C + \widehat{H_d}\widehat{L}\mathrm{h_e}\widehat{E}^C + \lambda\widehat{S}\widehat{H_u}\widehat{H_d}\,, \qquad (1)$$

The superpotential presented in Eq. (1), and its derived Lagrangian, contain an extra global U(1) Peccei-Quinn (PQ) Symmetry. Assigning PQ charges, Q^{PQ}**, according to**

$$\widehat{Q}:-1, \widehat{U}^C:0, \widehat{D}^C:0, \widehat{L}:-1, \widehat{E}^C:0, \widehat{H_u}:1, \widehat{H_d}:1, \widehat{S}:-2, \qquad (2)$$

the model is invariant under the global $U(1)$ transformation $\widehat{\Psi}_i \to e^{iQ_i^{PQ}\theta}\widehat{\Psi}_i$, where

$$\widehat{\Psi}_i \in \{\widehat{Q},\ \widehat{U}^C,\ \widehat{D}^C,\ \widehat{L},\ \widehat{E}^C,\ \widehat{H}_u,\ \widehat{H}_d,\ \widehat{S}\}. \quad (3)$$

The PQ symmetry will spontaneously break when the Higgs scalars gain vevs, and a pseudo[2]-Nambu-Goldstone boson, known as the PQ axion (it is actually one of the pseudoscalar Higgs bosons), will be generated. For values of $\lambda \sim \mathcal{O}(1)$, this axion would have been detected in experiment and this model ruled out. There are three ways that this model can be saved.

– One can decouple the axion using very small λ. But, why should λ be really tiny.
– Promote the PQ symmetry to a local symmetry so that axion will be absorbed in the process of giving the new Z' mass.
– Explicitly break the PQ symmetry.
  It is this latter route that the NMSSM follows.
  To implement the explicit PQ symmetry breaking, we note that the new

[2] The axion is only a "pseudo"-Nambu-Goldstone boson since the PQ symmetry is explicitly broken by the QCD triangle anomaly. The axion then acquires a small mass from its mixing with the pion.

superfield $\widehat{S}$ has no gauge couplings but has a PQ charge.
Then, one can naively introduce any term of the form $\widehat{S}^n$ with $n \in \mathbb{Z}$ into the superpotential in order to break the PQ symmetry.
However, since the superpotential is of dimension 3, any power with $n \neq 3$ will require a dimensionful coefficient naturally of the GUT or Planck scale, naively making the term either negligible (for $n > 3$) or unacceptably large (for $n < 3$).

- 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 $\frac{1}{3}\kappa A_\kappa S^3$ is allowed in addition to $\lambda A_\lambda S H_u H_d$.

- **However,** the $\mathbb{Z}_3$ symmetry which we enforced on the model to ensure no more dimensionful couplings cannot be completely unbroken. If it were, a "domain wall problem" would arise.

In particular, if $\mathbb{Z}_3$ symmetry is exact, observables are unchanged when we (globally) transform all the fields according to $\Psi \to e^{i2\pi/3}\Psi$.

Therefore the model will have three separate but degenerate vacua, and which one of these ends up being the "true" vacuum is a random decision taken at the time of electroweak symmetry breaking.

However, one expects that causally disconnected regions of space would not necessarily choose the same vacuum, and our observable universe should consist of different domains with different ground states, separated by domain walls.

Such domain wall structures create unacceptably large anisotropies in the cosmic microwave background.

Historically, it was always assumed that the $\mathbb{Z}_3$ symmetry could be broken by an appropriate type of unification with gravity at the Planck scale.

In particular, non-renormalizable operators will generally be introduced into the superpotential and Kähler potential which break $\mathbb{Z}_3$ and lead to a preference for one particular vacuum, thereby solving the problem.

But, these same operators may give rise at the loop level to quadratically divergent tadpole contributions in the Lagrangian, of the form (Nilles, Lahanas, Ellwanger, Bagger, Jain, Abel, Kolda, etal)

$$\mathcal{L}_{\rm soft} \supset t_S S \sim \frac{1}{(16\pi^2)^n} M_{\rm P} M_{\rm SUSY}^2 S , \quad (4)$$

where n is the number of loops.

Clearly, this tadpole breaks the $\mathbb{Z}_3$ symmetry as desired.

But, if $n < 5$, t_S is several orders of magnitude larger than the soft-SUSY breaking scale $M_{\rm SUSY}$, leading to an unacceptably large would-be μ-term of order $\frac{1}{(16\pi^2)^n} M_{\rm P}$.

For example, if the tadpole were generated at the one-loop level, the effective μ-term would be huge of order 10^{16}–10^{17} GeV close to the GUT scale, whereas μ should be of order of the electroweak scale to realize a natural Higgs mechanism.

Hence, it was argued by Abel etal that the NMSSM is either ruled out cosmologically or suffers from a naturalness problem related to the destabilization of the gauge hierarchy.

However, there is a simple escape. (Panagiotakopoulos and Tamvakis)

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.

To avoid destabilization while curing the domain wall problem, this symmetry has to be extended to the non-renormalizable part of the superpotential and to the Kähler potential.

As happens to all R-symmetries, the Z_2^R symmetry is broken by the soft-SUSY breaking terms, giving rise to harmless tadpoles of order $\frac{1}{(16\pi^2)^n} M_{\rm SUSY}^3$, with $2 \leq n \leq 4$.

Although these terms are phenomenologically irrelevant, they are entirely sufficient to break the global Z_3 symmetry and make the domain walls collapse.

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 $80~\mathrm{GeV}$. 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) ($\Rightarrow \widetilde{\chi}^0_{1,2,3,4,5}$), 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

$$\lambda\ \widehat{S}\widehat{H_u}\widehat{H_d} + \frac{\kappa}{3}\ \widehat{S}^3 \tag{5}$$

depending on two dimensionless couplings λ, κ beyond the MSSM. The associated trilinear soft terms are

$$\lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3\,. \tag{6}$$

The final two input parameters are

$$\tan\beta = h_u/h_d\,, \quad \mu_{\rm eff} = \lambda s\,, \tag{7}$$

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_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

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

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 Dermisek and I employ is

$$F = \mathrm{Max}_p F_p \equiv \mathrm{Max}_p \left| \frac{d \log m_Z}{d \log p} \right| , \tag{9}$$

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.

- How do we get small fine-tuning?

1. F is minimum for $m_{h_1} \sim 100 \div 104~\mathrm{GeV}$ (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 $\sqrt{m_{\widetilde{t}_1} m_{\widetilde{t}_2}} \sim 350~\mathrm{GeV}$ level.
2. $m_{h_1} \sim 100~\mathrm{GeV}$ is only LEP-allowed if $h_1 \to a_1 a_1$ hides the h_1.
3. We are happy with a light a_1 since it is associated with the $\kappa A_\kappa, \lambda A_\lambda \to 0$ limit of the soft-SUSY-breaking potential.

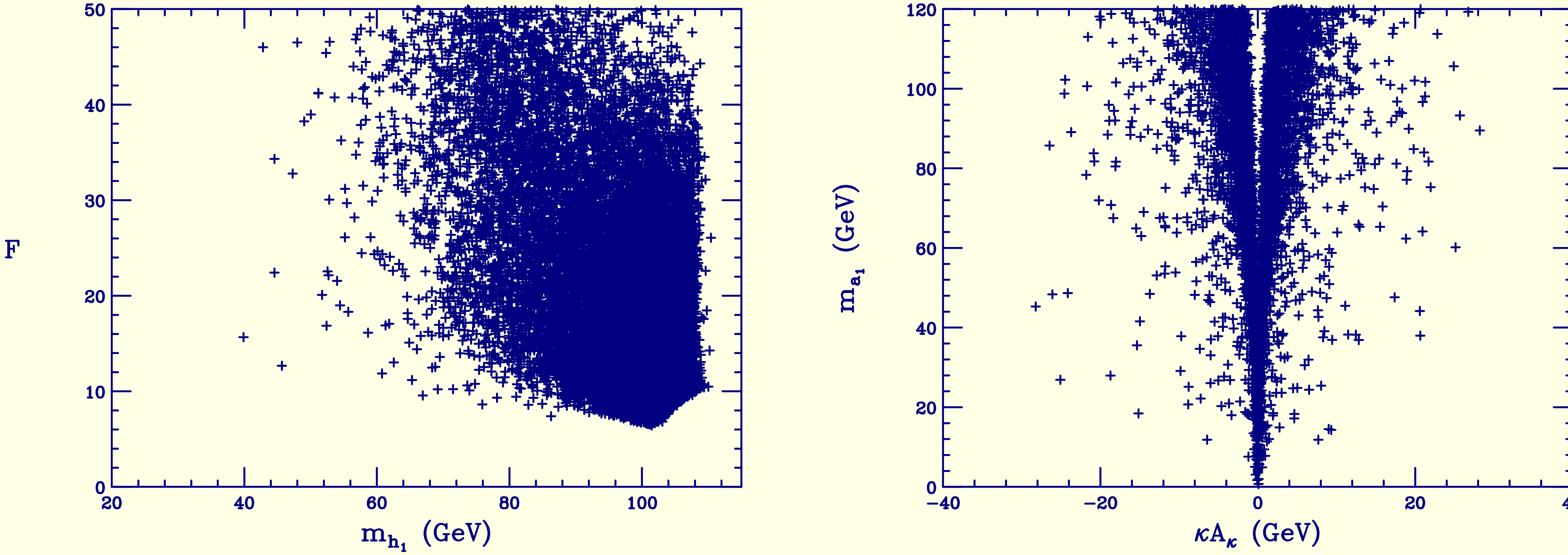
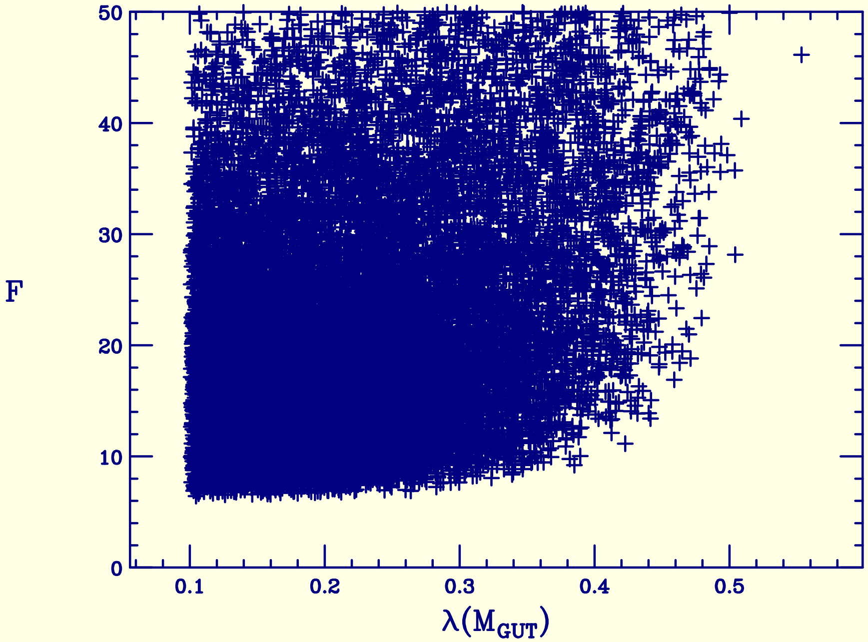


Figure 1: F vs. m_{h_1} (left) and m_{a_1} vs. κA_κ (right).

- **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 κA_κ and λA_λ terms in the soft-SUSY-breaking potential. (We ignore the small contributions from anomalies.) Thus, m_{a_1} is expected to vanish as κA_κ and λA_λ vanish.**

  In practice, it is mainly κA_κ that is important here — the λA_λ impact on m_{a_1} is small when the a_1 is largely singlet, the case of interest here.



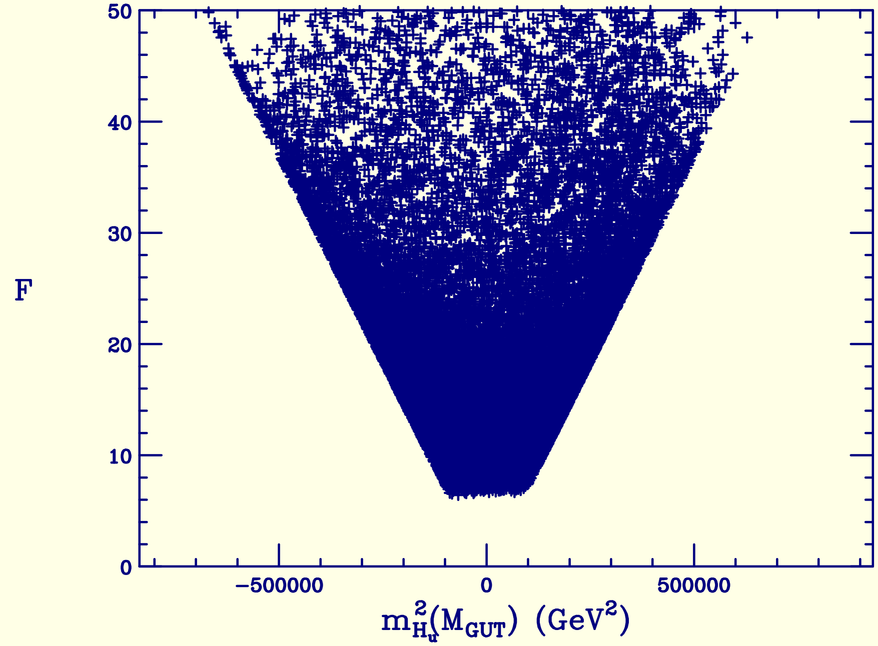


Figure 2: F vs. λ_{GUT} (left) and F vs. $(m_{H_u}^2)_{GUT}$ (right).

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

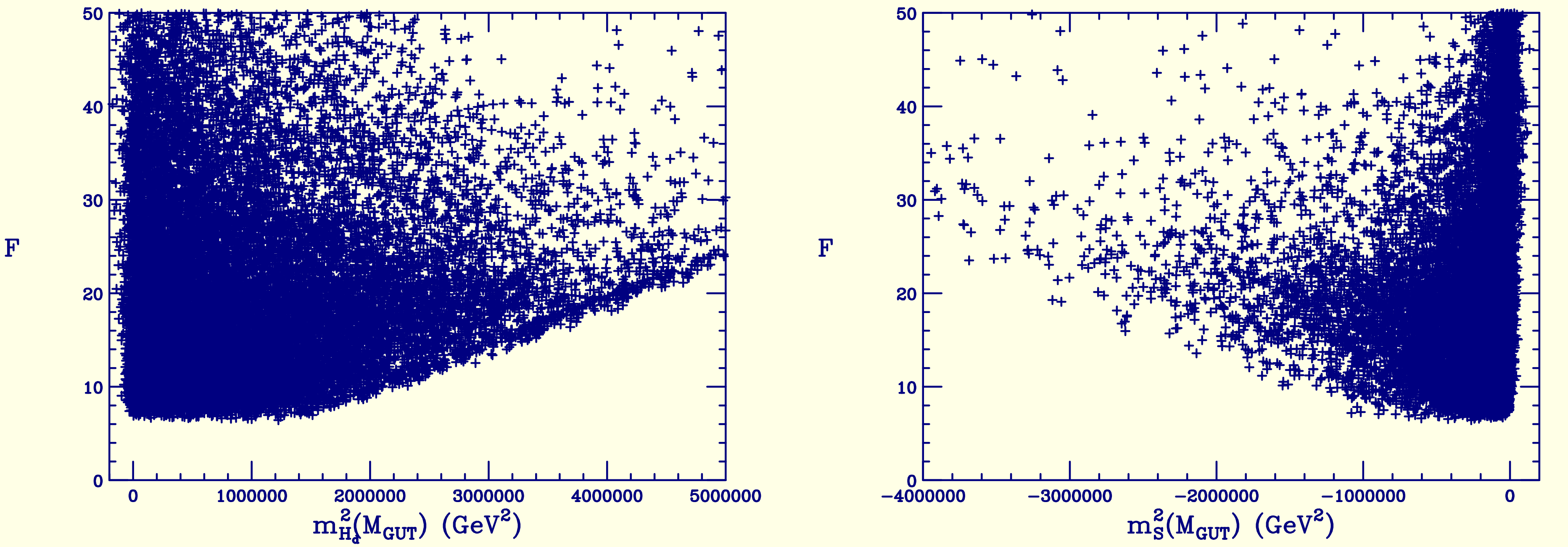


Figure 3: F vs. $(m^2_{H_d})_{GUT}$ (left) and F vs. $(m^2_S)_{GUT}$ (right).

- Small $m^2_{H_d}(M_U)$ and $m^2_S(M_U)$ are also preferred as shown in Fig. 3.
- There is no discernible dependence of F on κA_κ within the range of κA_κ that gives a light a_1.

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 $m_{h_1} \sim 100~\mathrm{GeV}$ (and is SM-like) and yet the h_1 escapes LEP limits due to the presence of $h_1 \to a_1 a_1$ 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 $M_{1,2,3} = 100, 200, 300~\mathrm{GeV}$.

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

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

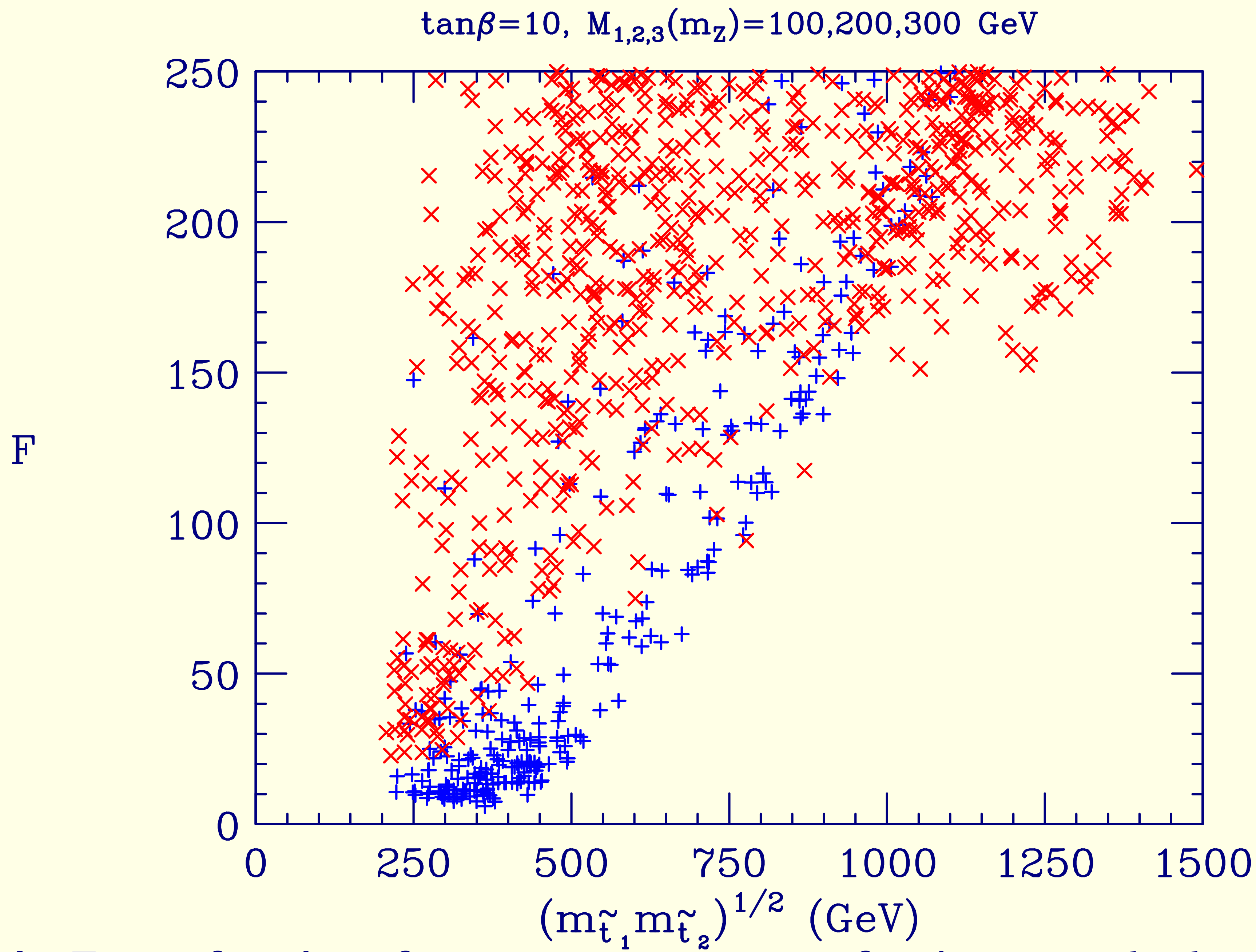


Figure 4: ***F*** **as a function of root mean stop mass after latest** *single-channel* **LEP limits.**

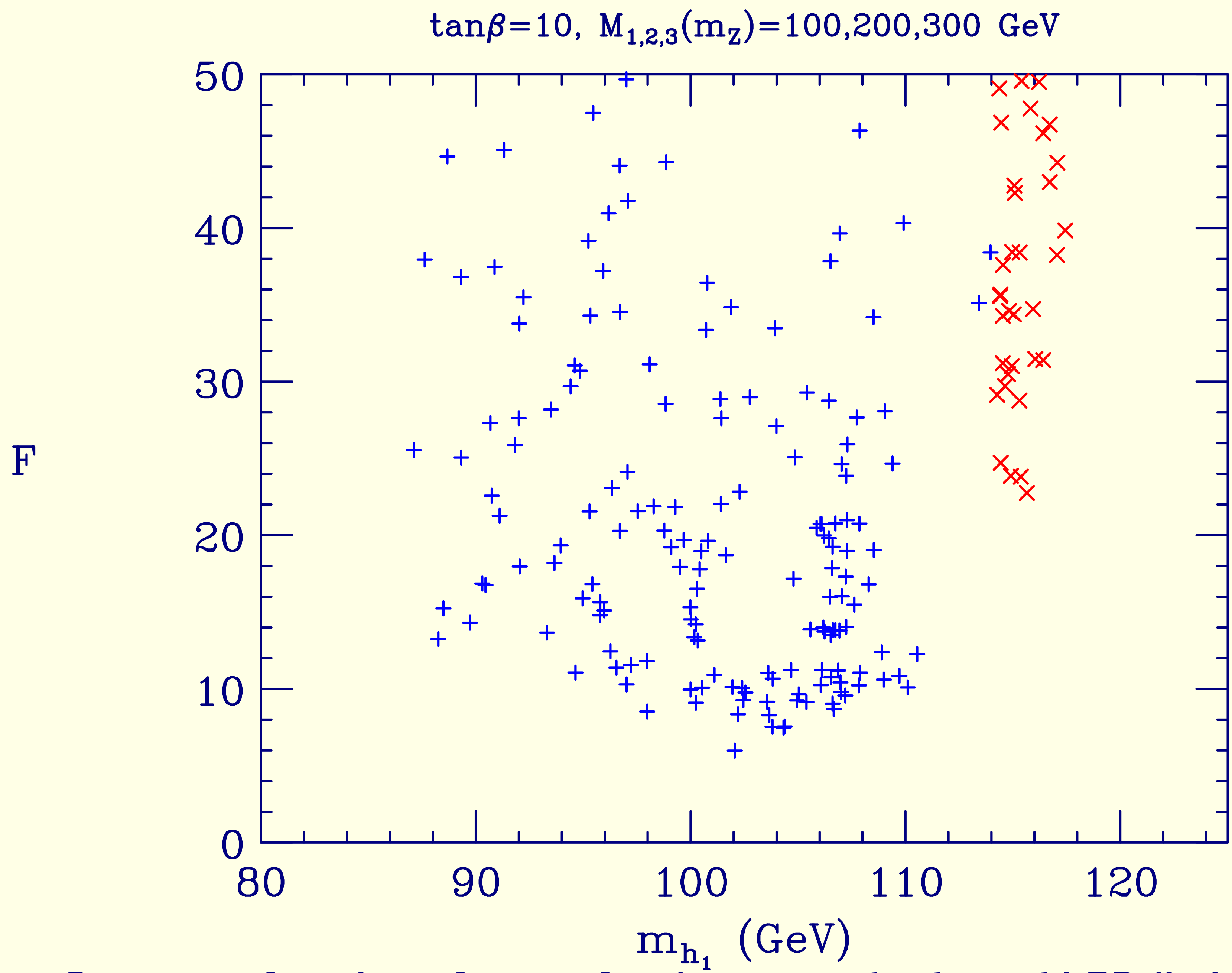


Figure 5: F **as a function of** m_{h_1} **after latest** *single-channel* **LEP limits.**

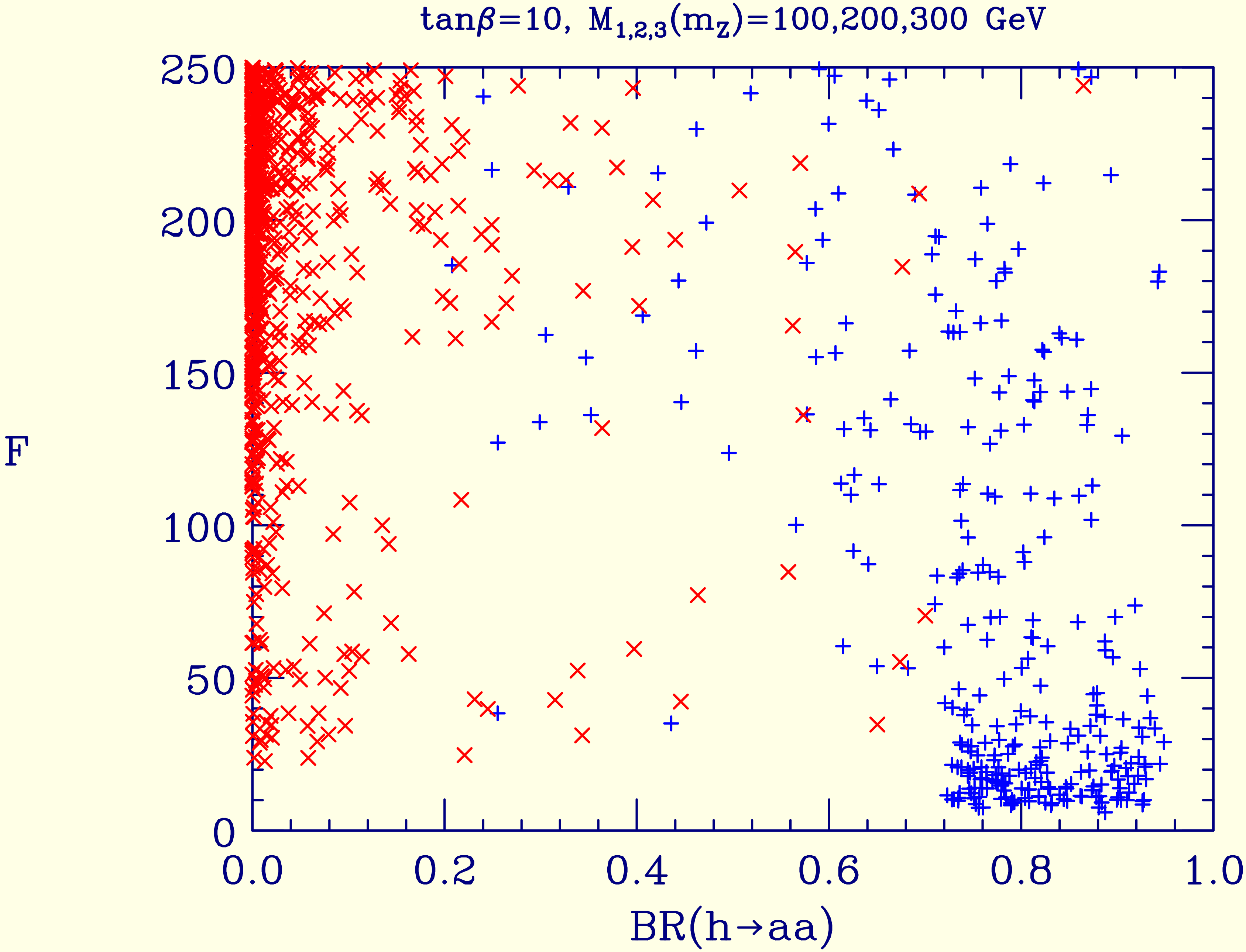


Figure 6: F as a function of $B(h_1 \to a_1 a_1)$ after latest *single-channel* LEP limits. Note that $h_1 \to a_1 a_1$ can be dominant even when m_{h_1} is large enough that the decay is not needed to escape LEP limits.

- **It is interesting to compare the new LEP limits for $Zh \to Zaa \to Z4b$ production to the old limits: Fig. 7.**

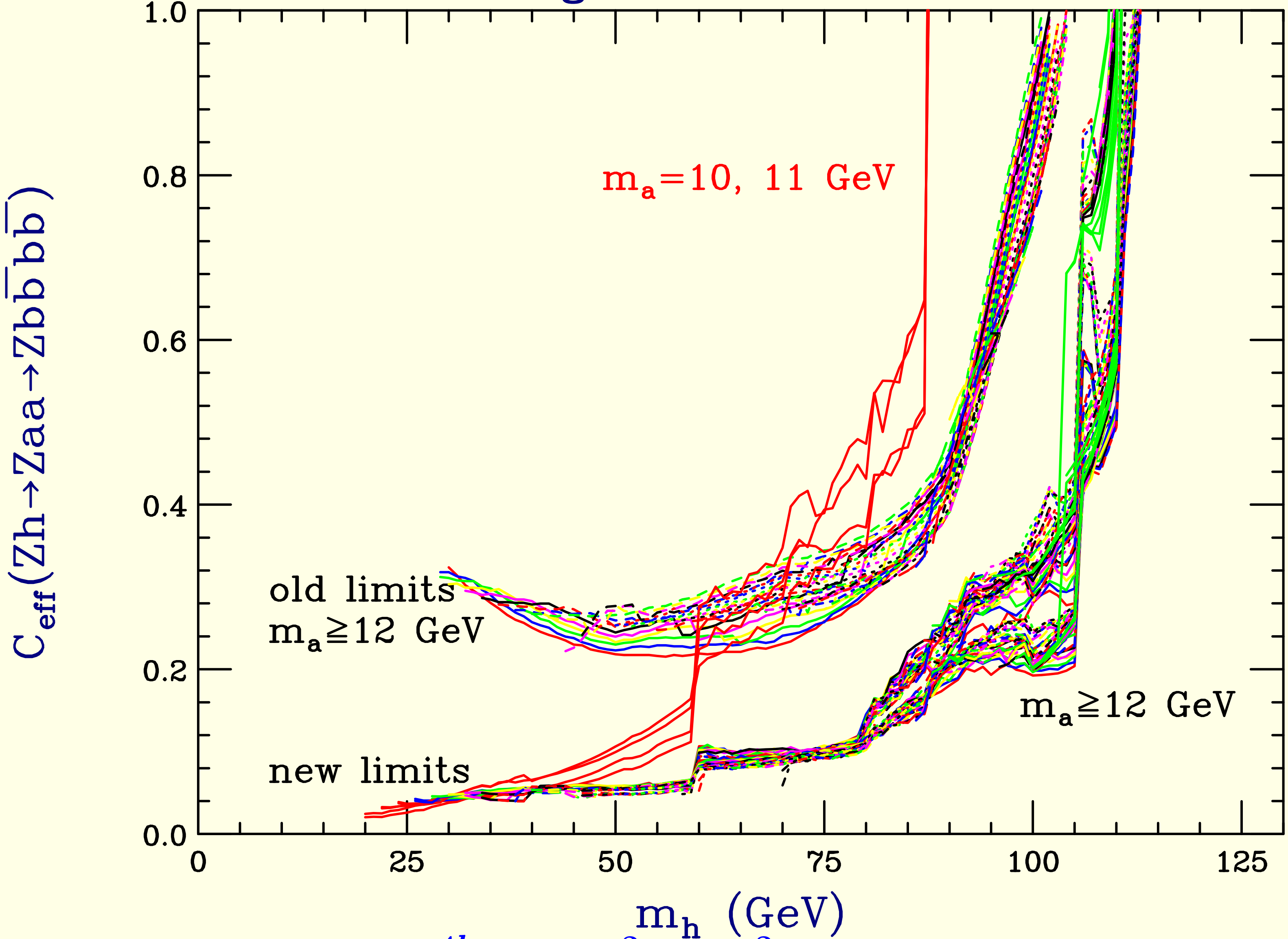


Figure 7: LEP limits on $C_{eff}^{4b} = [g_{ZZh}^2/g_{ZZh_{SM}}^2]B(h \to aa)[B(a \to b\bar{b})]^2$, old and new. New are stronger but small F still possible.

- **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. 8 is the relevant plot.**

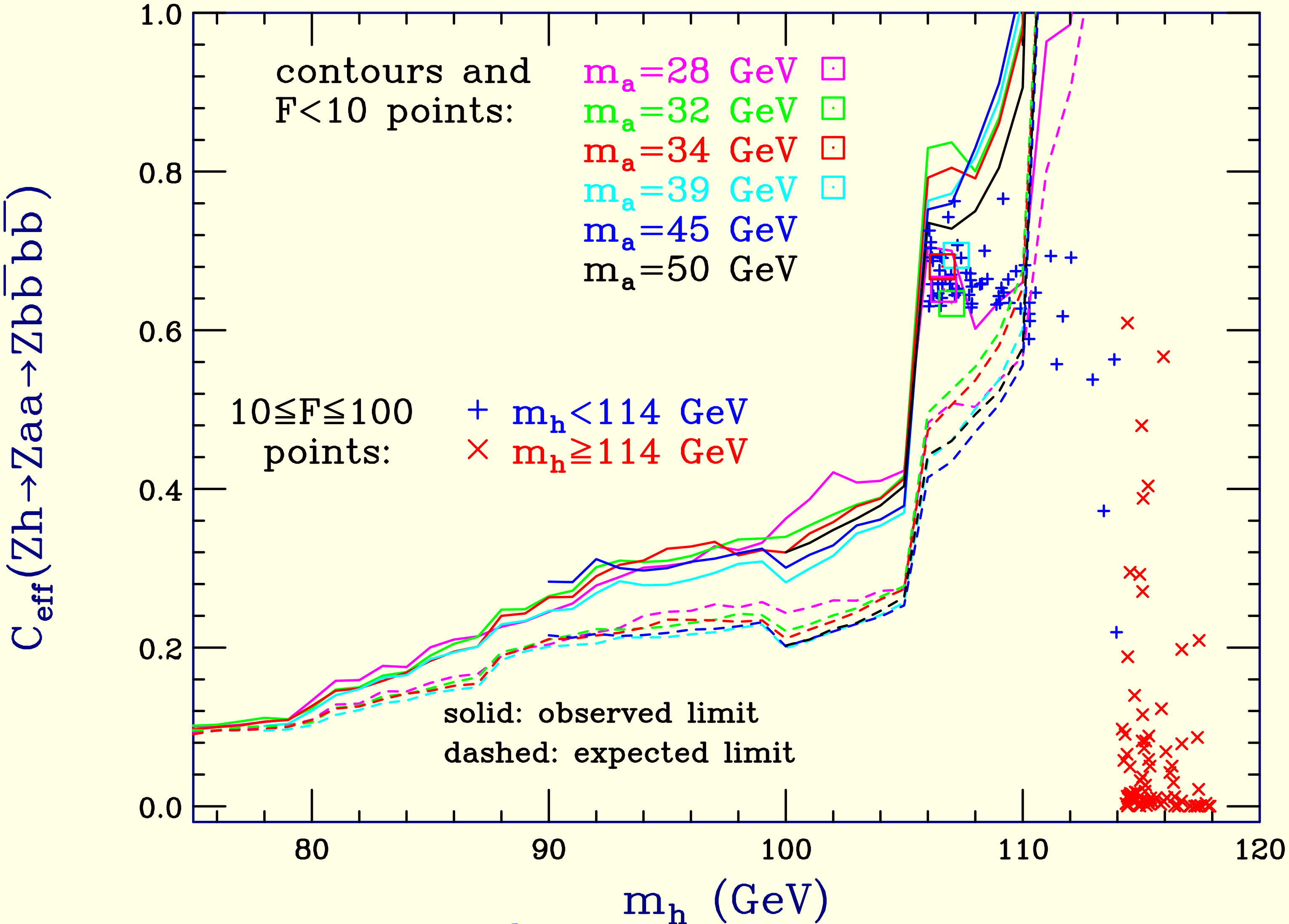


Figure 8: New LEP limits on C_{eff}^{4b} and low-F points. Note the $m_{a_1} \sim 25-40$ points between expected and observed limits.

- 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. 9.

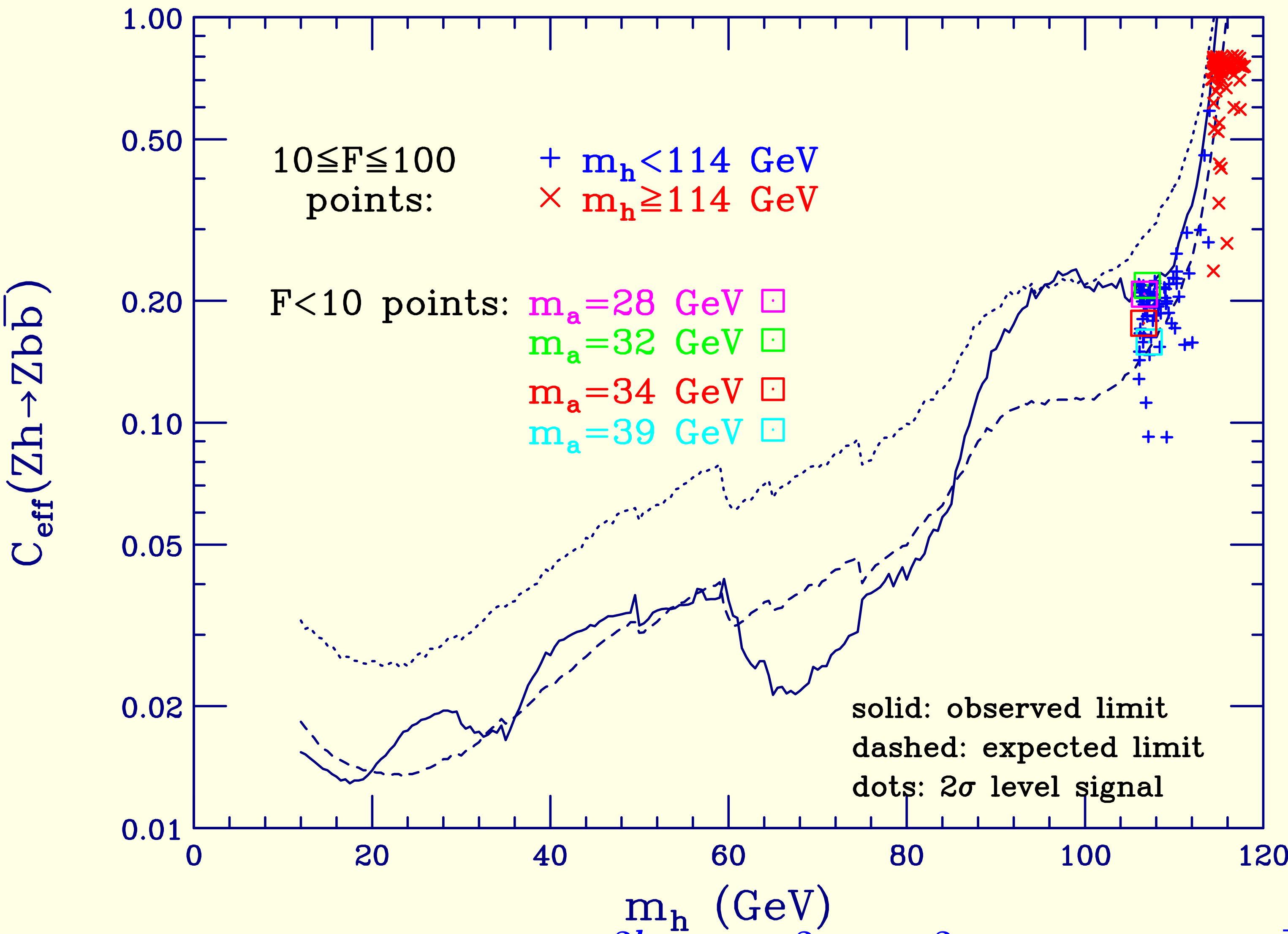


Figure 9: Observed LEP limits on $C_{eff}^{2b} = [g_{ZZh}^2/g_{ZZh_{\rm SM}}^2]B(h \to b\bar{b})$ for the low-F points with $m_{a_1} > 2m_b$.

- The observed 95% CL limit on C_{eff}^{2b} is shown in Fig. 9. Our points fit right below the observed limit but above the expected limits shown in Fig. 8. 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 $m_{h_1} \lesssim 108 \div 110~\mathrm{GeV}$ 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 $87~\mathrm{GeV}$ —- 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 Υ, ... 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 $\kappa A_\kappa \to 0$.

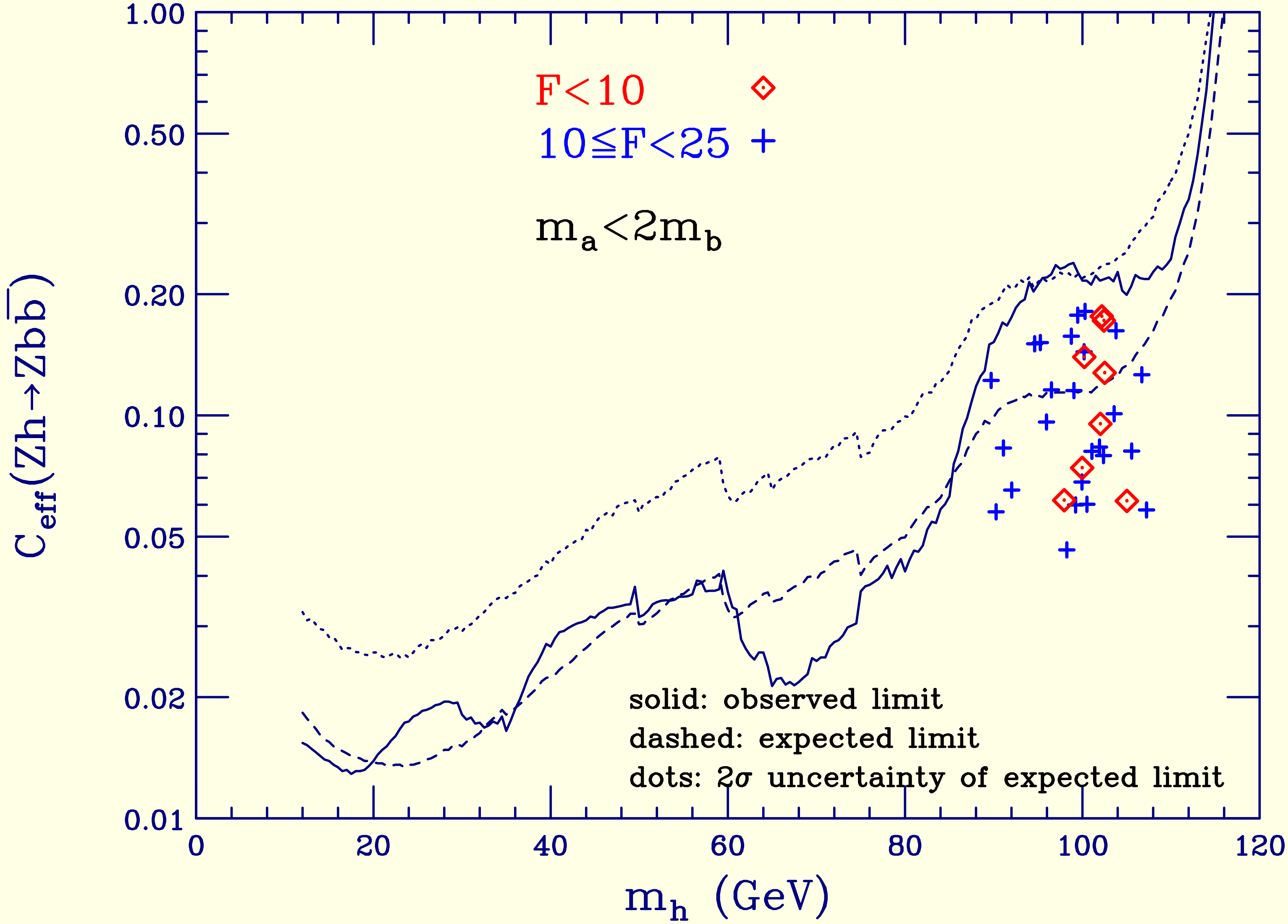


Figure 10: Observed LEP limits on C^{2b}_{eff} for the low-F points with $m_{a_1} < 2m_b$.

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. (Recall: the smaller $1-CL_b$ the less consistent is the data with expected background only.)

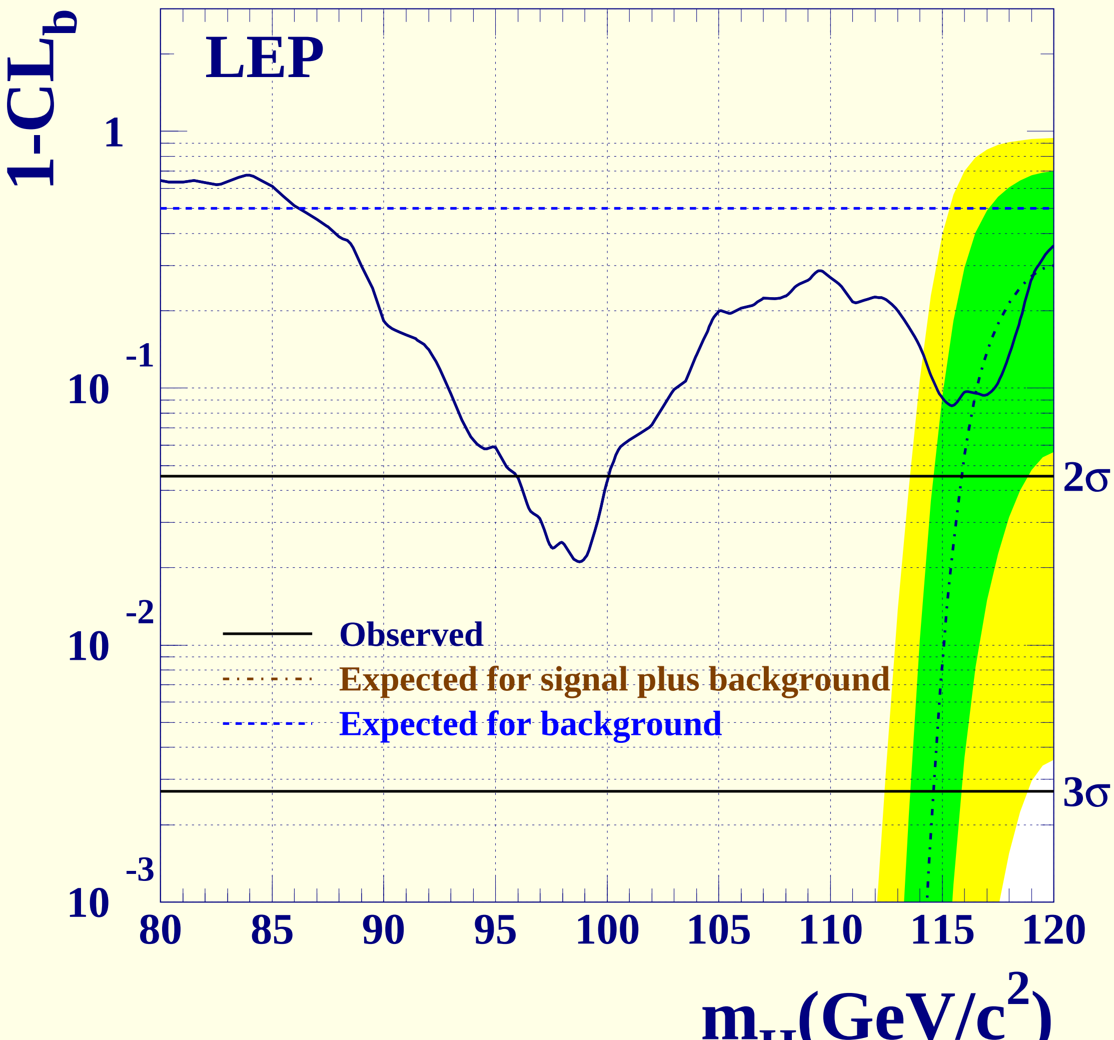


Figure 11: Plot of $1 - CL_b$ for the $Zb\bar{b}$ final state.

- 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 $h_1 \to b\bar{b}$	$h_1 \to a_1 a_1$	$a_1 \to \tau\overline{\tau}$	$n_{\rm obs}/n_{\rm exp}$ 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 $\tan\beta = 10$, $M_{1,2,3}(m_Z) = 100, 200, 300~\mathrm{GeV}$ NMSSM scan. N_{SD}^{LHC} is the statistical significance of the best "standard" LHC Higgs detection channel for integrated luminosity of $L = 300~\mathrm{fb}^{-1}$.

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 $m_{h_1} \lesssim 100~\mathrm{GeV}$ 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.

- **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 $\kappa A_\kappa, \lambda A_\lambda \to 0$ 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, $\lambda(m_Z) \sim 0.15 \div 0.25$, $\kappa(m_Z) \sim 0.15 \div 0.3$, $|A_\kappa(m_Z)| < 4~\mathrm{GeV}$ 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 small κA_κ.

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

Perhaps it is useful to remind ourselves of the standard LHC cross sections.

1. In particular, WW fusion at $m_{h_1} = 100~\mathrm{GeV}$ yields $\sigma \sim 5~\mathrm{pb}$, equivalent to about 1.5×10^5 Higgs produced for $L = 30~\mathrm{fb}^{-1}$ of integrated luminosity (the first few years of LHC operation). Multiplying by $B(h_1 \to a_1 a_1)[B(a_1 \to \tau^+\tau^-)]^2 \sim 0.85(0.93)^2 \sim 0.65$ yields 10^5 events in the 4τ channel.
   This means it may be realistic to consider $WW \to h_1 \to a_1 a_1 \to 4\tau$ in the particularly clean final state where each τ decays to $\mu + \nu\overline{\nu}$.
   I have started to work with Markus Schumacher on this mode.

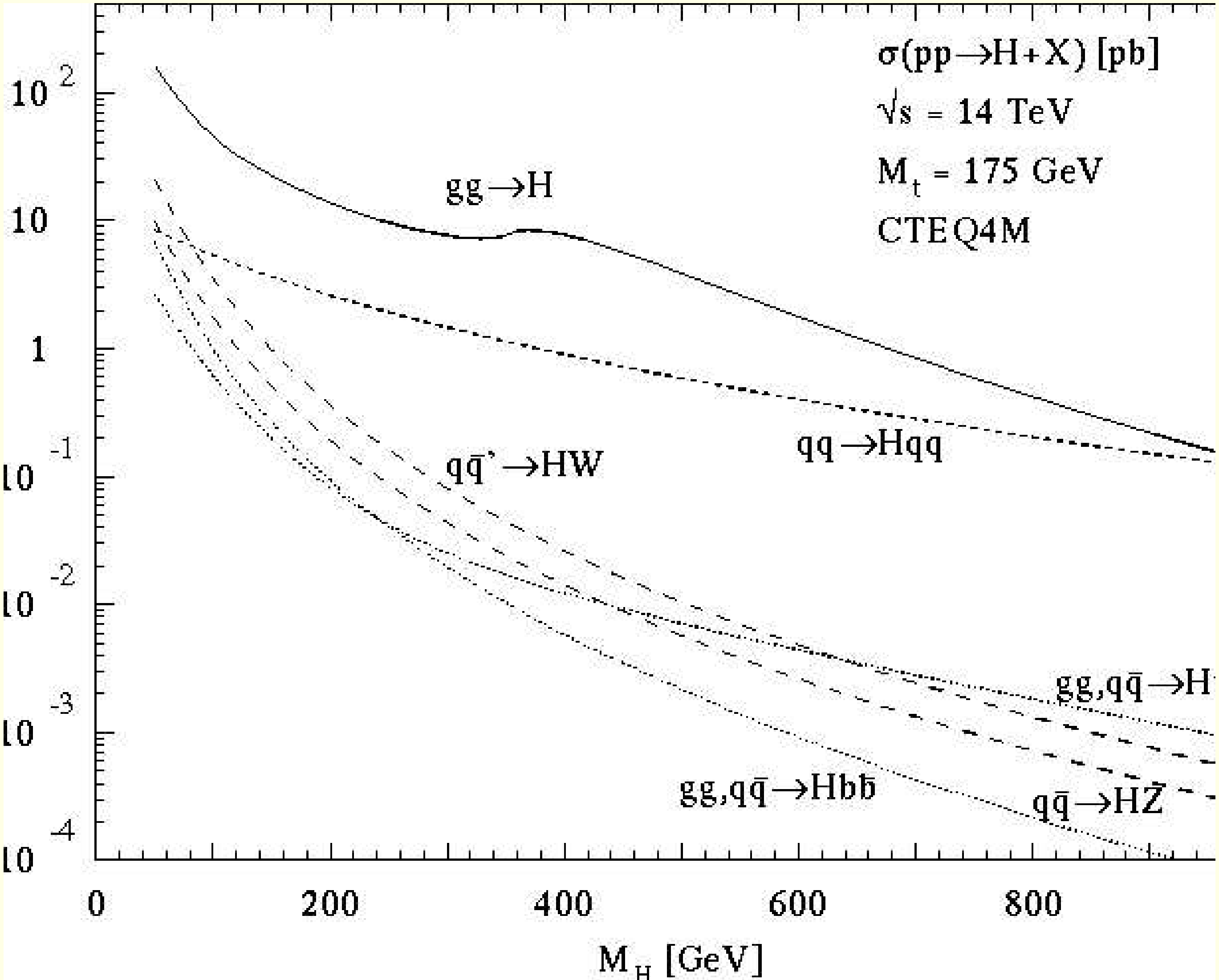


Figure 12: The standard Higgs production cross sections at the LHC.

– The events must be triggered at level 1 by one or two μ's from one of the τ's. This is not all that inefficient: e.g. $B(4\tau \to 2$ or more $\mu' s) \sim 15\%$ $\Rightarrow$ roughly 15000 events , but the spectrum must be examined.
– The triggered events of interest can be further isolated by demanding the forward jets expected in WW fusion.
– The 4τ mode might in the end actually be fairly background free?
– There would be some ability to reconstruct m_{h_1} using the fact that the two τ's and, in particular, the two μ tracks from one light a_1 are quite collinear and so you could do the usual collinear mass reconstruction game of treating the two μ pairs as two objects with collinear visible momentum and missing momentum.

Let me now show some actual first results for $m_{h_1} = 100~\mathrm{GeV}$ and $m_{a_1} = 8~\mathrm{GeV}$. First, consider what we get before tagging the quark jets left behind by the fusing W's.

– We require at least three muons within $|\eta| < 2.5$ with the following p_T cuts:
three muons with $p_T > 7~\mathrm{GeV}$ and one with $p_T > 20~\mathrm{GeV}$ or two with $p_T > 10~\mathrm{GeV}$
then, 927 out of 5000 generated Higgs events are retained, i.e. an efficiency of nearly 20%.
(Requiring four detectable muons kills the signal almost completely.)

- The angles between the taus and muons from the decay of the a_1 are small, which is good for ...
- the reconstructed mass of the h_1 in the acollinear approximation. The RMS of the mass distribution is ~ 11 GeV.
- Note, we need at least three muons otherwise we cannot suppress the Zjj with $Z \to \tau^+\tau^-$ background.

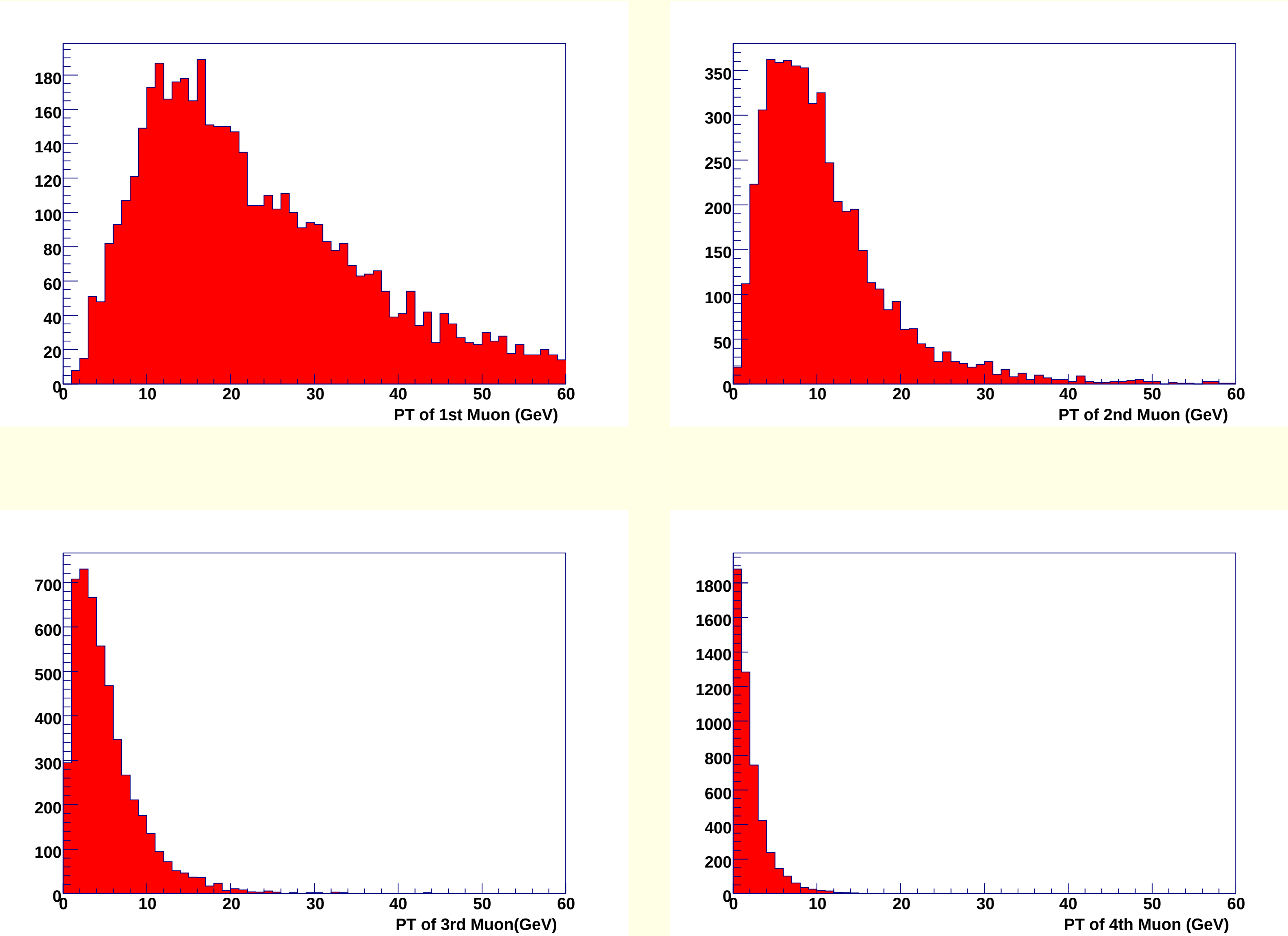


Figure 13: p_T's of the 4 μ's, ordered.

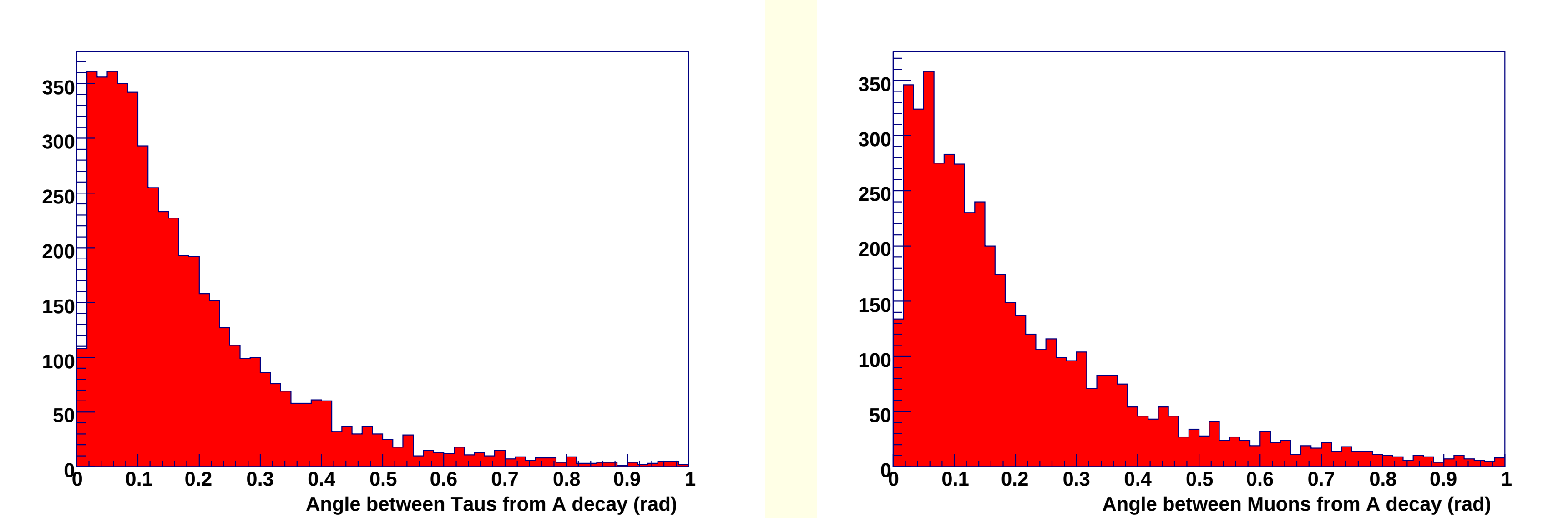


Figure 14: Angles between τ's and μ's from one a_1 decay.

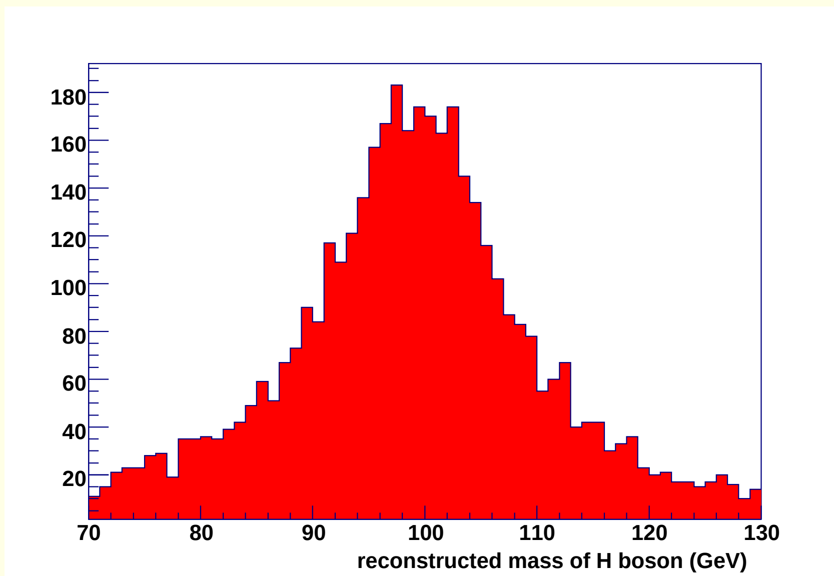


Figure 15: Reconstructed m_{h_1} using collinear approximation and the three most energetic μs.

Next, we used the fast simulation of the ATLAS detector and applied some basic VBF cuts (we demanded two tagging jets with cuts on their rapidity difference, $m_{jet\ jet}$, etc.), but did not yet apply a central jet veto.

Including lepton acceptance and p_T cuts as well as trigger requirements $\Rightarrow 3\%$ efficiency, including branching ratios, and a mass resolution of $17~\mathrm{GeV}$.

This is not bad given that:

- We are probably close to eliminating backgrounds (calculations of these are still needed).
- The starting cross section is quite large

2. Another mode is $t\bar{t}h_1 \to t\bar{t}a_1a_1 \to t\bar{t}\tau^+\tau^-\tau^+\tau^-$.
   - 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 τ's and mass reconstruction as above.
3. Third, 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 $h_1 \to a_1a_1 \to 4\tau$ 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 papers by 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.

4. Last, but definitely not least, diffractive production $pp \to pph_1 \to ppX$. 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.
   – At low-$\mathcal{L}$, suppose we accumulate $L = 30$ fb^{-1}, $\Rightarrow 30 \div 90$ events before acceptance and tagging.

   A study (JFG, Khoze, de Roeck, Ryskin, ...) for the $h_1 \to a_1a_1 \to 4\tau$ 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 τ's.
A di-muon trigger might be the best.
Using $B(4\tau \to 2 \text{ or more } \mu's) \sim 0.15$. $\Rightarrow$ acceptance $\times B = 0.06$.
Then, μ spectra must be taken into account $\Rightarrow$ another 50% cut (at most optimistic, requires MC).
Overlapping τ's give overlapping μ's so some reduction here might occur?
– **Net result** ($L = 30 \text{ fb}^{-1}$): $events \lesssim 90 \times 0.06 \times 0.5 \lesssim 3$.
$\Rightarrow$ must do at high luminosity in presence of overlapping events.

- At the Tevatron it is possible that Zh_1 and Wh_1 production, with $h_1 \to a_1a_1 \to 4\tau$, 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.

  Event rates at least as bad as for diffractive.

- **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).

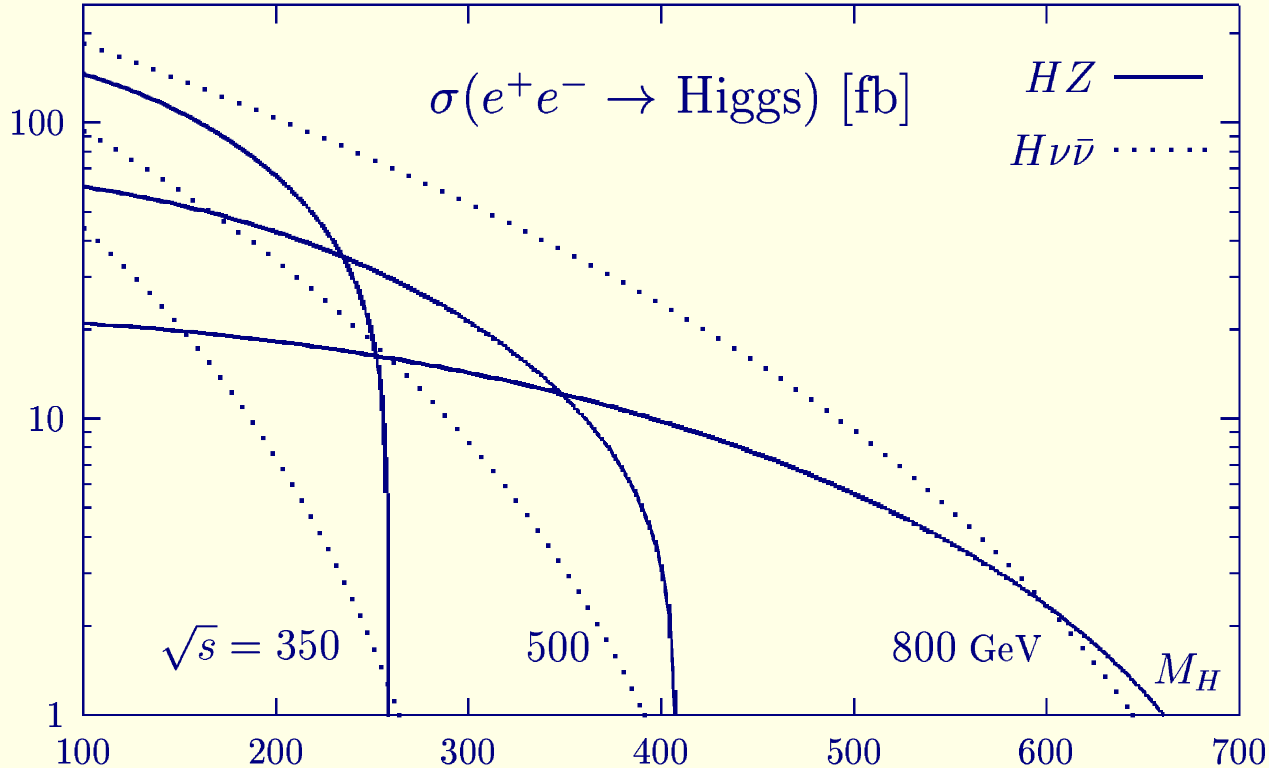


Figure 16: Cross sections at the ILC.

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 3×10^4 Higgs bosons in the Zh_1 mode.

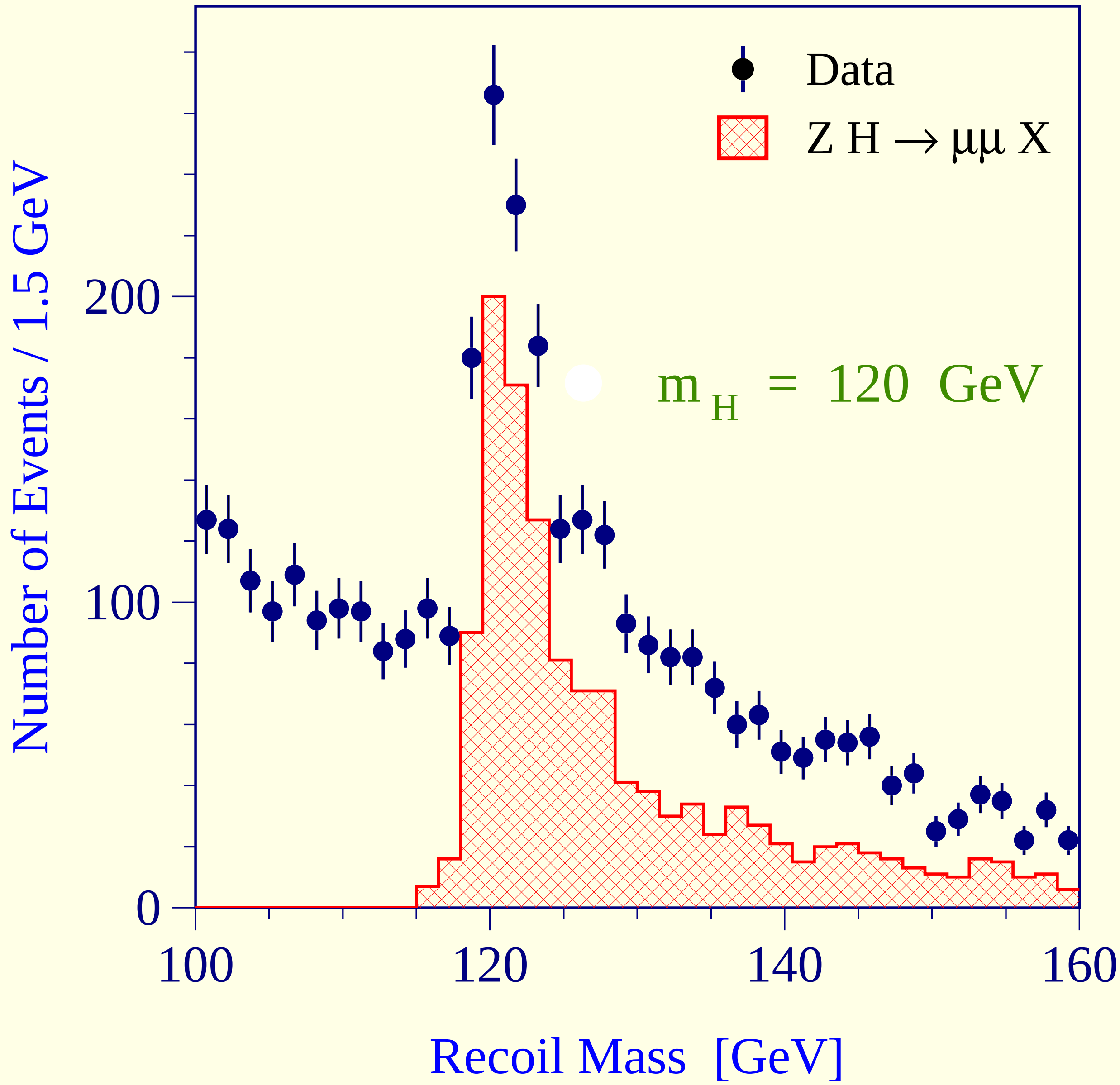


Figure 17: Decay-mode-independent Higgs M_X peak in the $Zh \to \mu^+\mu^- X$ mode for $L = 500~\mathrm{fb}^{-1}$ at $\sqrt{s} = 350~\mathrm{GeV}$, taking $m_h = 120~\mathrm{GeV}$..

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

- Although the $h \to b\bar{b}$ and $h \to \tau^+\tau^-$ rates are $1/10$ of the normal, the number of Higgs produced will be such that you can certainly see $Zh \to Zb\bar{b}$ and $Zh \to Z\tau^+\tau^-$ 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 $B(h_1 \to a_1 a_1)$, which is probably the only way to directly measure the crucial λ 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	$\delta\mathrm{BR}/\mathrm{BR}$	$\delta g/g$
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 [BR($h \to X\overline{X}$)] and couplings [g_{hXX}], for various choices of final state $X\overline{X}$, assuming $m_h = 120$ GeV at the LC. In all but four cases, the results shown are based on 500 fb^{-1} of data at $\sqrt{s} = 500$ GeV. Results for $h\gamma\gamma$, $ht\bar{t}$, $h\mu\mu$ and hhh are based on 1 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 $B(h_1 \to$ SM particles $\sim 0.1 \times$ usual), most errors above must be multiplied by $\sim \sqrt{10}$.

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

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

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

  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 $h_1 \to a_1a_1 \to \tau^+\tau^- jj$ ($j = c, g$), thereby getting still more cross checks.**

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

- **At a $\gamma\gamma$ collider, the $\gamma\gamma \to h_1 \to 4\tau$ 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 $e^+e^- \to Za_1a_1$, 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 $400~\mathrm{GeV}$ in mass, and essentially inaccessible at both the LHC and all but a $\gtrsim 1~\mathrm{TeV}$ 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 $m_{h_1} > 114~\mathrm{GeV}$ (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 $m_{h_1} \gtrsim 108 \div 110$ 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. $t\bar{t}h_1 \to t\bar{t}a_1 a_1 \to t\bar{t}4b$.
   This I imagine will be viable. In the LEP-like procedure the two b's from one τ 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 $\widetilde{\chi}_2^0 \to h_1 \widetilde{\chi}_1^0$.
   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.

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 $pp \to pph_1$ 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?
   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 $h_1 \to a_1 a_1 \to 4b$ 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 $h \to aa$ 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. $\Rightarrow$ $m_{a_1} > 2m_b$ 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 $\widetilde{\chi}_1^0$ 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 $\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \rightarrow a_1 \rightarrow X$ 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 $m_h \sim 100~\mathrm{GeV}$ 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 $m_h \gtrsim 110~\mathrm{GeV}$.

- 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 appears to be a very attractive possibility, but rates are small

  Maybe $WW \to h_1 \to a_1 a_1 \to 4\mu$ will be the best?

- 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 all but the most basic detection of a few Higgs events and for checking the dark matter abundance if a light $\widetilde{\chi}_1^0$ with $2m_{\widetilde{\chi}_1^0} \sim m_{a_1}$ 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 $WW \to WW$ might in the worst of cases, $a_1 \to jj$, be our only hint, other than precision EW, that there is a light Higgs.