Why we should believe in the Next-to-Minimal Supersymmetric Model

How to SIMPLY and SIMULTANEOUSLY eliminate fine-tuning, have the preferred precision electroweak Higgs mass of $\sim m_Z$ and explain the biggest LEP event excess.

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ITP, UCSB, April 28, 2006

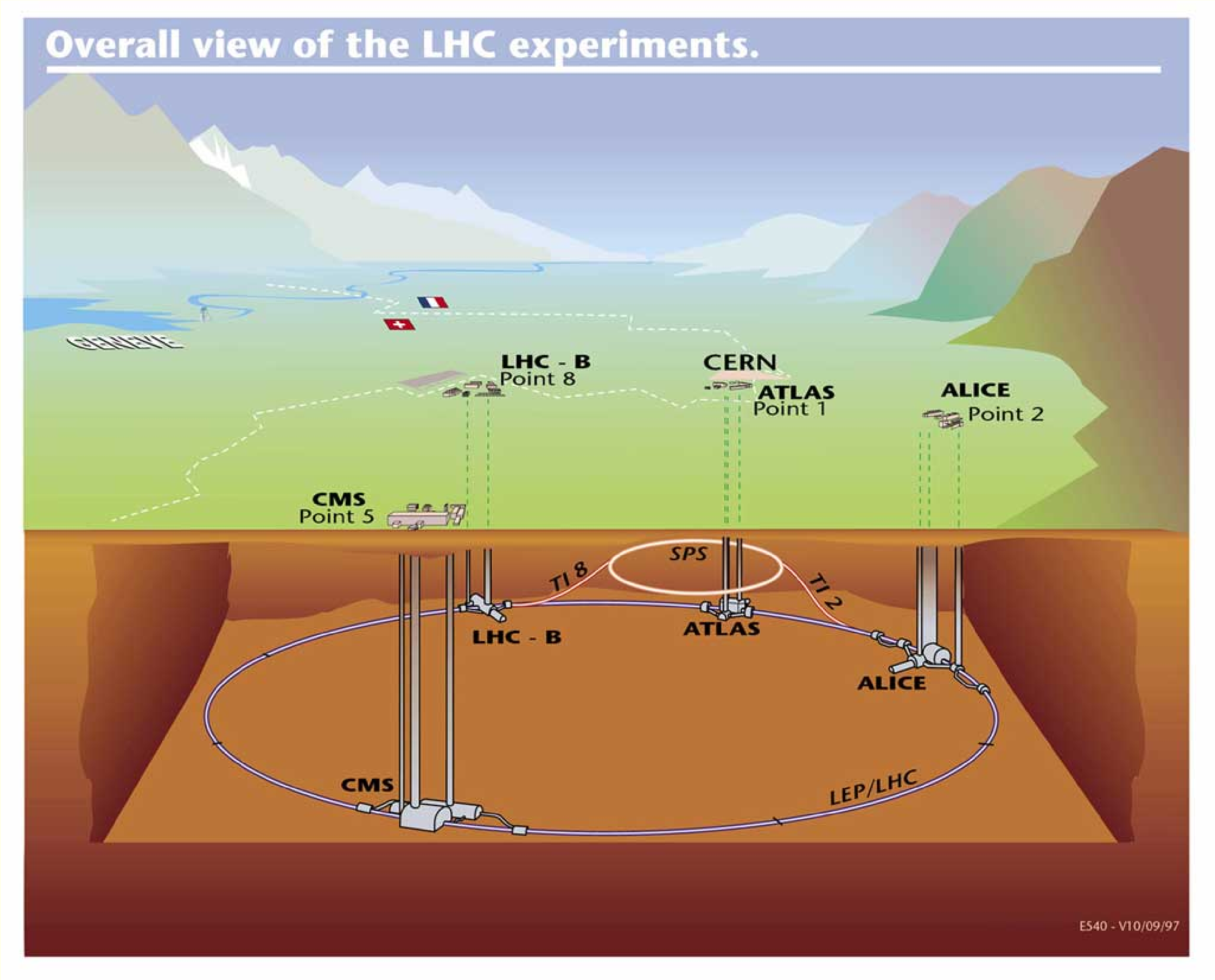
Based largely on:
R. Dermisek and J. Gunion, hep-ph/0510322
R. Dermisek and J. Gunion, hep-ph/0502105
J. Gunion, D. Hooper and B. McElrath, hep-ph/0509024

See also: J. Gunion, D. Miller, A. Pilaftsis, forthcoming CPNSH (CP-violating and Non-Standard Higgses) CERN Yellowbook Report.

Outline

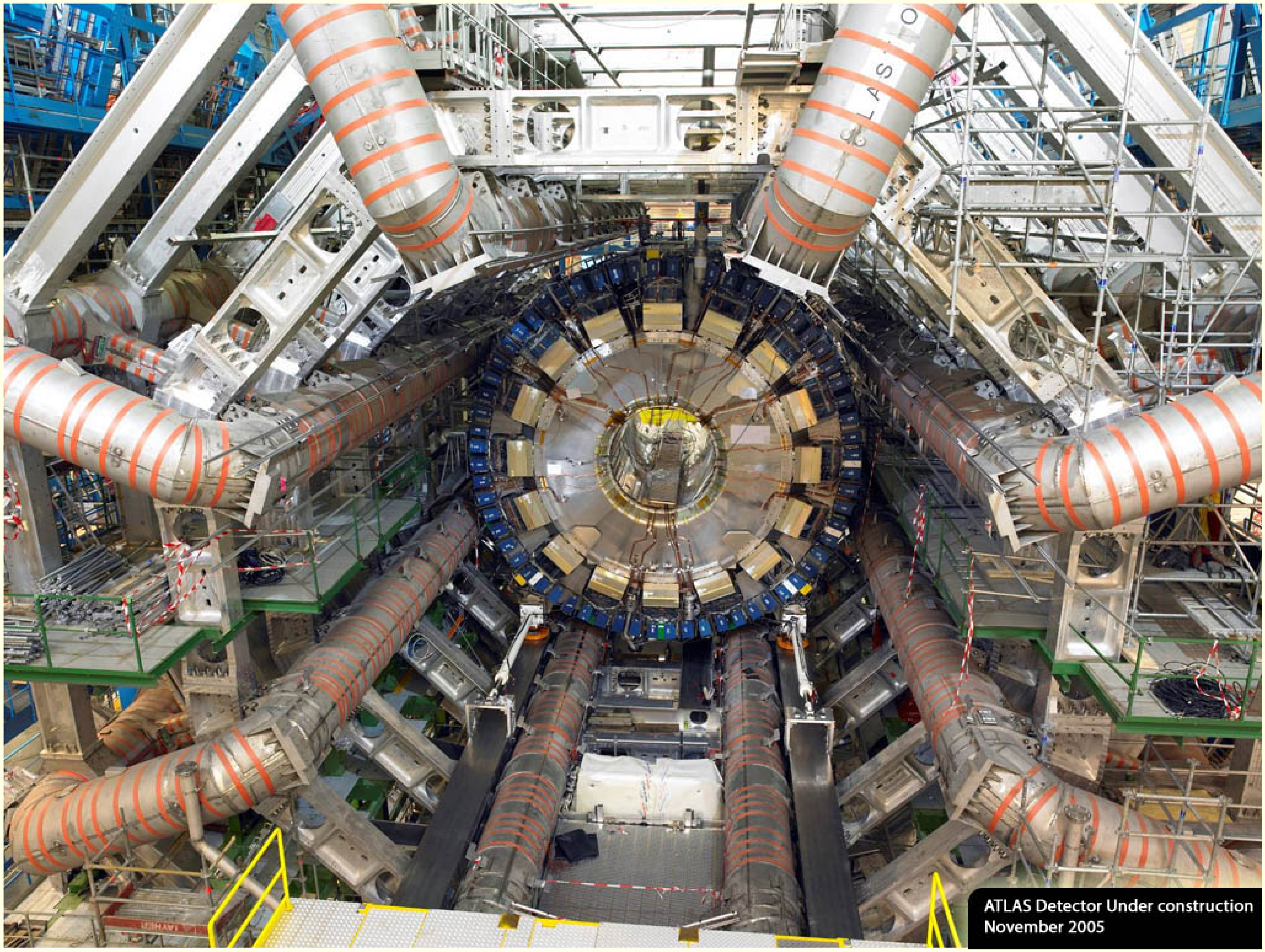
1. Reality is coming.
2. SUSY solves the hierarchy problem.
3. The Minimal SUSY Model (MSSM) is very attractive, but LEP limits on the lightest Higgs imply that it is in a fine-tuned part of parameter space.
4. The Next to Minimal Supersymmetric Model (NMSSM) maintains all the attractive features of the MSSM while avoiding fine tuning.
5. Low-fine-tuning NMSSM models change how to search for the Higgs at the LHC and imply that one should look again at the LEP data for a certain Higgs signal.
6. NMSSM models imply new possibilities for dark matter.
7. NMSSM models allow for adequate electroweak baryogenesis.

Reality is at hand

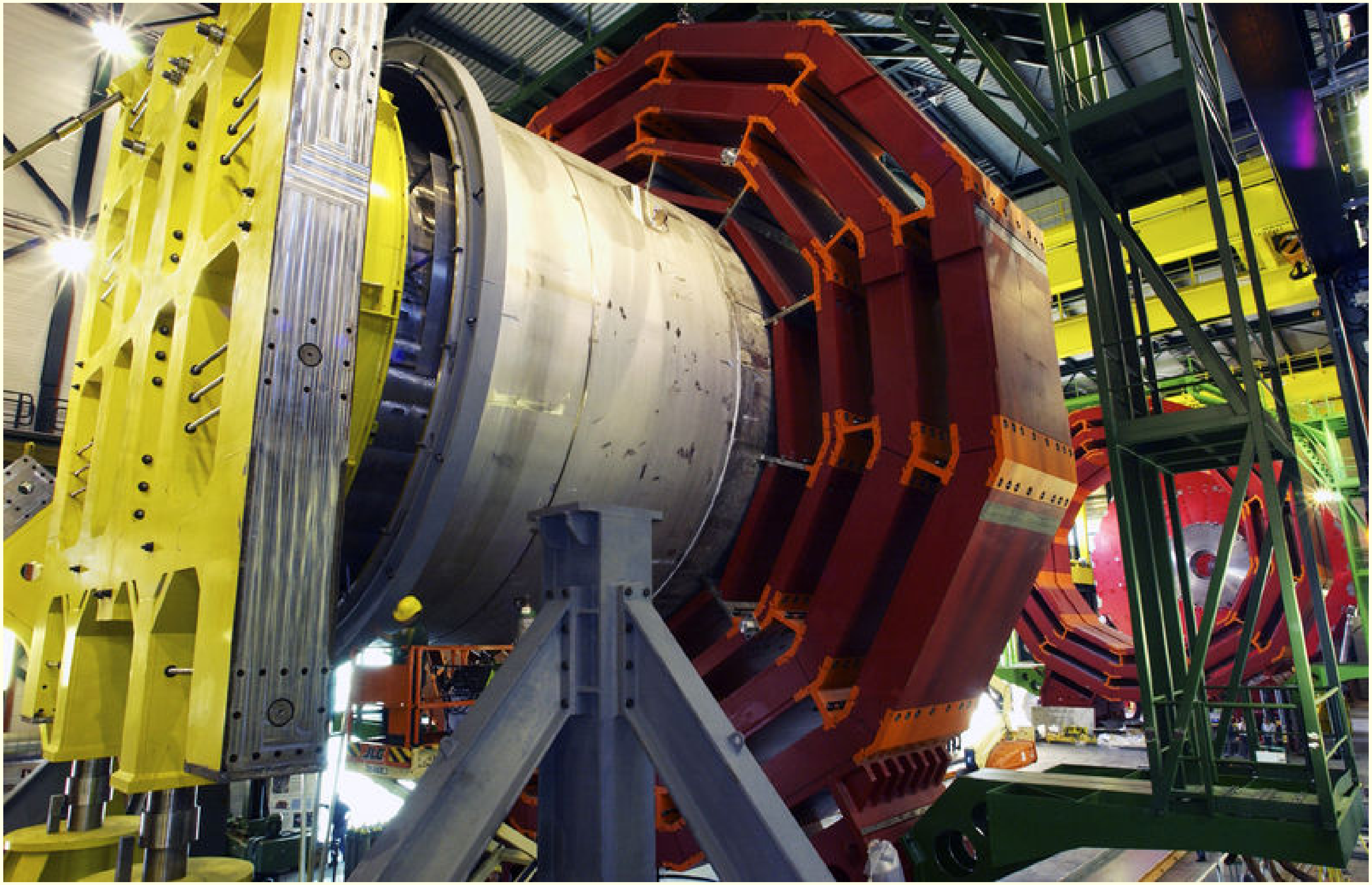


The Tunnel

The Magnets



The ATLAS Detector



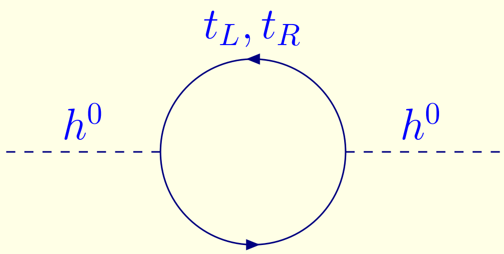
The CMS Detector

So shouldn't we get real!

The Beauty of Supersymmetry

- **SUSY is mathematically intriguing.**
- **SUSY is naturally incorporated in string theory.**
- **Scalar fields have a natural place in SUSY, and so there are candidates for the spin-0 fields needed for electroweak symmetry breaking and Higgs bosons.**
- **If the SUSY breaking scale, $m_{\mathrm{SU}\not{\mathrm{S}}\mathrm{Y}}$, is of order a TeV, $\Rightarrow$ a solution to the naturalness/hierarchy problem. Recall:**

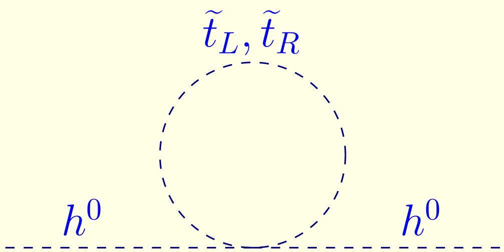
$$\mathcal{L}_{Yukawa} = -\frac{y_t}{\sqrt{2}} H^0 \bar{t}_L t_R + h.c. \quad \text{with } H^0 = v + h^0 \text{ and } m_t = \frac{y_t v}{\sqrt{2}} \Rightarrow \tag{1}$$

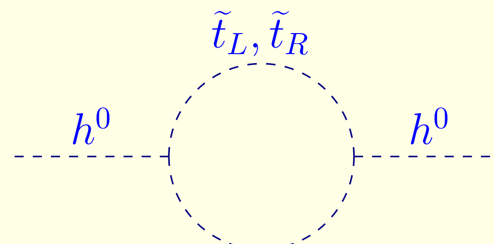


$$\delta m_h^2 = -\frac{3y_t^2}{8\pi^2}\left[\Lambda^2 - 3m_t^2 \ln\left(\frac{\Lambda^2+m_t^2}{m_t^2}\right) + \ldots\right]$$

If $\Lambda \sim M_U$, then a huge cancellation is required between the bare mass-squared for the h^0 and this 1-loop correction in order that the Higgs have mass below $\sim 1~\mathrm{TeV}$ (as required by WW scattering unitarity). This is the naturalness or hierarchy problem.

The SUSY solution to this is to cancel away the quadratic (and logarithmic) Λ^2 dependencies using stop loops.





The cancellation will be total in the exact SUSY limit ($m_t = m_{\widetilde{t}_L} = m_{\widetilde{t}_R}$ and h^0 couplings to $\widetilde{t}_{R,L}$ as predicted by SUSY).

Since the Higgs quartic self-couplings are given by gauge couplings, *if SUSY is exact* **one finds that**

$$m_h^2 \leq m_Z^2 \cos^2 2\beta \,, \tag{2}$$

There will be a finite 1-loop residual if SUSY is broken by $m_{\widetilde{t}_L}, m_{\widetilde{t}_R} > m_t$, as appears to be required by experimental limits on superpartners.

The MSSM

- **The Minimal Supersymmetric Model contains superpartners for all observed particles and exactly two Higgs doublet superfields, $\widehat{H}_u$ and $\widehat{H}_d$ (required by anomaly cancellation and to give masses to both up and down quarks).**

Chiral Supermultiplet	spin-0	spin-$1/2$	$SU(3) \times SU(2)_L \times U(1)$ Q#'s
	Squark	Quark	
$\widehat{Q}$	$\begin{pmatrix} \widetilde{u} \\ \widetilde{d} \end{pmatrix}$	$\begin{pmatrix} u \\ d \end{pmatrix}$	$(3, 2, 1/3)$
$\widehat{\bar{u}}$	$\widetilde{\bar{u}}$	$\bar{u}$	$(\bar{3}, 1, -4/3)$
$\widehat{\bar{d}}$	$\widetilde{\bar{d}}$	$\bar{d}$	$(\bar{3}, 1, 2/3)$
	Slepton	Lepton	
$\widehat{L}$	$\begin{pmatrix} \widetilde{\nu} \\ \widetilde{e} \end{pmatrix}$	$\begin{pmatrix} \nu \\ e \end{pmatrix}$	$(1, 2, -1)$
$\widehat{\bar{e}}$	$\widetilde{\bar{e}}$	$\bar{e}$	$(1, 1, 2)$
	Higgs	Higgsino	
$\widehat{H}_u$	$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$\begin{pmatrix} \widetilde{H}_u^+ \\ \widetilde{H}_u^0 \end{pmatrix}$	$(1, 2, 1)$
$\widehat{H}_d$	$\begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$\begin{pmatrix} \widetilde{H}_d^0 \\ \widetilde{H}_d^- \end{pmatrix}$	$(1, 2, -1)$
Gauge Supermultiplet	spin-$1/2$	spin-1	
gluinos, gluons	$\widetilde{g}$	g	$(8, 1, 0)$
winos, W-bosons	$\widetilde{W}^{\pm,0}$	$W^{\pm,0}$	$(1, 3, 0)$
bino, B-boson	$\widetilde{B}$	B	$(1, 1, 0)$

- **Of course, since we don't see sleptons and squarks, we know that SUSY is broken.**

  We break SUSY softly, meaning that we do it in such a way as to not destroy the cancellation of Λ^2 divergences.

  This means we introduce soft masses, m_Q^2, m_U^2, m_D^2, m_L^2, m_E^2 (for squarks and sleptons), $M_{1,2,3}$ (for bino, wino, and gluino), $m_{H_u}^2$, $m_{H_d}^2$ for the Higgs bosons and a μ parameter for the Higgsinos. We also have the soft-SUSY-breaking scalar trilinear couplings such as A_t appearing in $A_t \lambda_t \widetilde{Q}_t H_u \overline{\widetilde{t}}$ and similarly for A_b and A_τ. Finally, there is the soft $B\mu$ parameter appearing in $B\mu H_u H_d$.

  In order to cure the naturalness / hierarchy problem, all these mass parameters should be of order $\mathcal{O}(1~\mathrm{TeV})$.

  This μ parameter appears at the superpotential level, $\mu \widehat{H}_u \widehat{H}_d$,[1] and is unlike all other superpotential parameters in that it is dimensionful. A big question is why is it $\mathcal{O}(1~\mathrm{TeV})$ (as required above), rather than $\mathcal{O}(M_U, M_\mathrm{P})$.

  But, let us assume that this is true for now so that all sparticles reside at the $\mathcal{O}(1~\mathrm{TeV})$ scale.

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

- **Then, the MSSM has two particularly wonderful properties.**

1. **Gauge Coupling Unification**

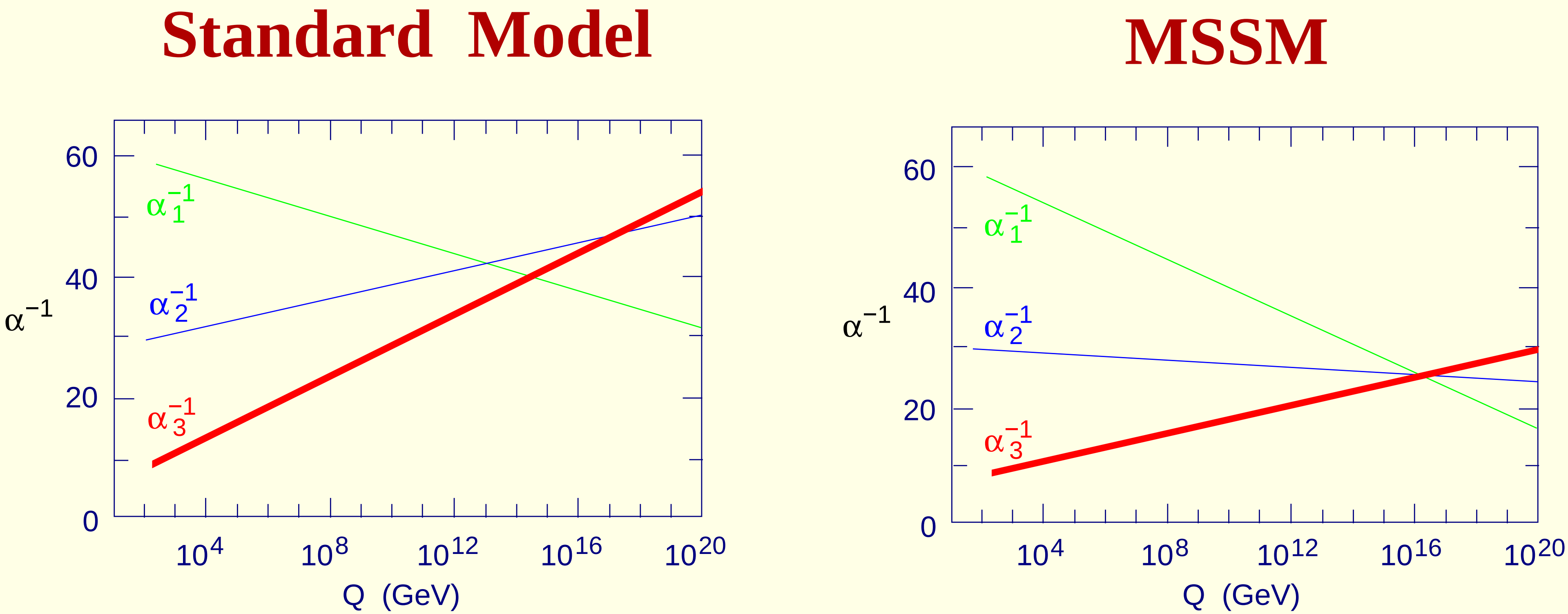


Figure 1: Unification of couplings constants ($\alpha_i = g_i^2/(4\pi)$) in the minimal supersymmetric model (MSSM) as compared to failure without supersymmetry.

The MSSM sparticle content + two-doublet Higgs sector ⇒ gauge coupling unification at $M_U \sim few \times 10^{16}\ \mathrm{GeV}$, close to M_{P}. High-scale unification correlates well with the attractive idea of gravity-mediated SUSY breaking.

2. RGE EWSB

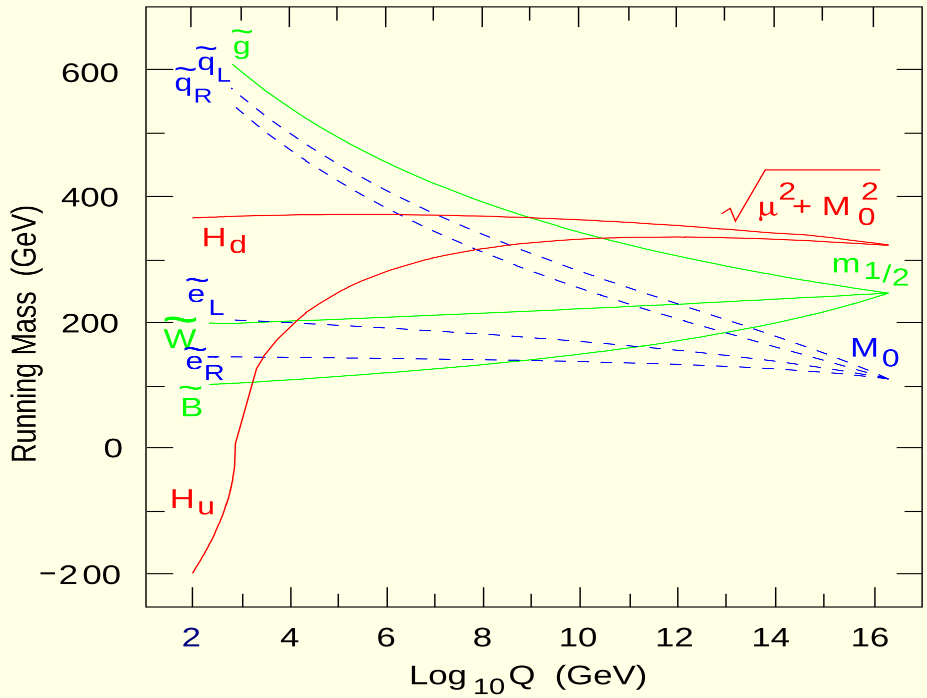


Figure 2: Evolution of SUSY-breaking masses or masses-squared, showing how $m^2_{H_u}$ is driven < 0 at low $Q \sim \mathcal{O}(m_Z)$.

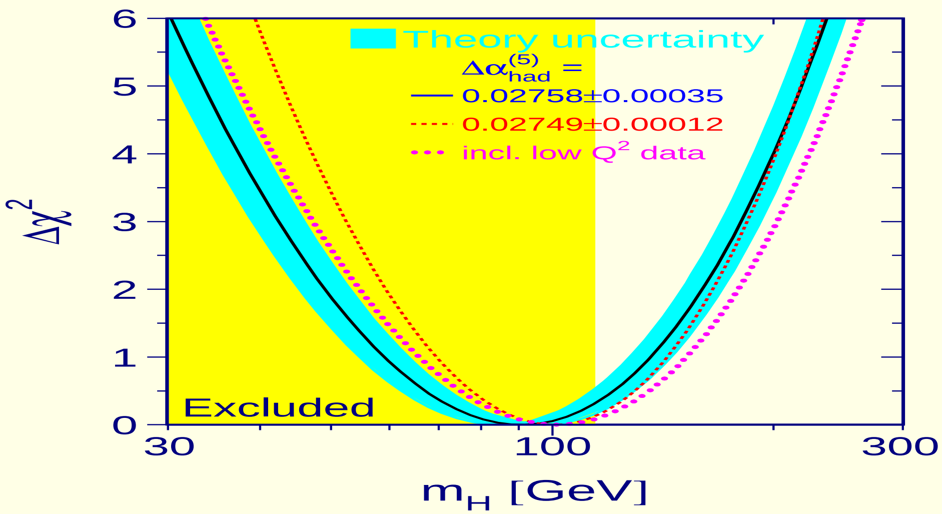
Starting with universal soft-SUSY-breaking masses-squared at M_U, the RGE's predict that the top quark Yukawa coupling will drive one of the soft-SUSY-breaking Higgs masses squared ($m^2_{H_u}$) negative at a scale of order $Q \sim m_Z$, thereby automatically generating electroweak symmetry breaking ($\langle H_u \rangle = h_u, \langle H_d \rangle = h_d$).

- **The Higgs Mass**

In the presence of soft-SUSY-breaking, the light Higgs has ($\tan\beta = h_u/h_d$)

$$\begin{aligned} m_h^2 &\sim m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} v^2 y_t^4 \sin^4\beta \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \ldots \\ &\overset{\text{large}\tan\beta}{\sim} (91\ \mathrm{GeV})^2 + (38\ \mathrm{GeV})^2 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right). \end{aligned} \tag{3}$$

A Higgs mass of order $100\ \mathrm{GeV}$, as predicted for stop masses $\sim 2m_t$, is in wonderful accord with precision electroweak data.



So, why haven't we seen the Higgs? Is SUSY wrong, are stops heavy, or is the MSSM too simple?

MSSM Problems

- The LEP limits on Higgs bosons have pushed the CP-conserving MSSM into an awkward corner of parameter space characterized by large $\tan\beta$ and large $\sqrt{m_{\widetilde{t}_1} m_{\widetilde{t}_2}}$. For $m_{\widetilde{t}_L} = m_{\widetilde{t}_R} = 1~\mathrm{TeV} \equiv m_{\mathrm{SUSY}}$, we have the MSSM exclusion plots shown.

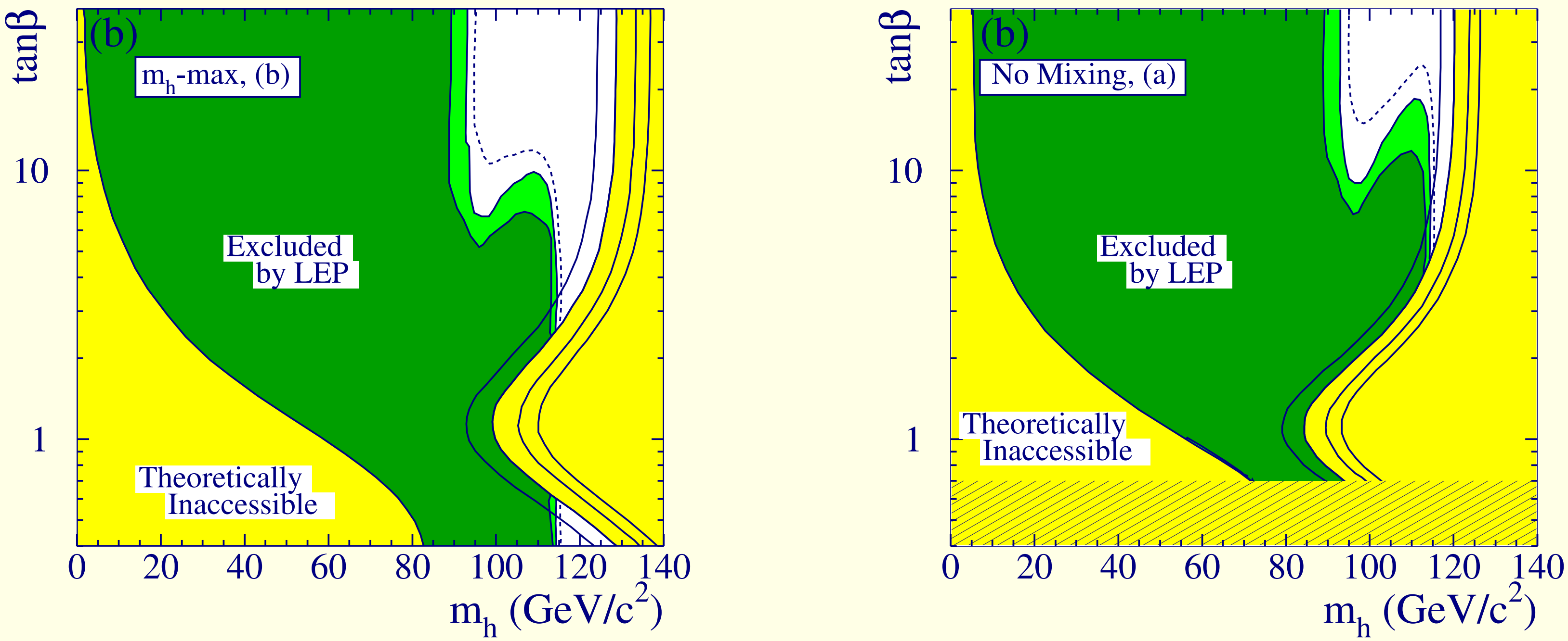


Figure 3: Maximal-mixing ($X_t = A_t - \mu\cot\beta = -2m_{\mathrm{SUSY}} = -2~\mathrm{TeV}$, $\mu > 0$) and no-mixing (with $\mu > 0$) LEP exclusions at 90% CL. From CERN-PH-EP/2006-001.

There is still room, but the allowed region implies that the model is very fine-tuned. Roughly, we need $\sqrt{m_{\widetilde{t}_1} m_{\widetilde{t}_2}} \gtrsim 900~\mathrm{GeV}$.

Fine-tuning refers to the following. Minimization of the Higgs potential gives (at scale m_Z)

$$\frac{1}{2} m_Z^2 = -\mu^2 + \frac{m_{H_d}^2 - \tan^2\beta m_{H_u}^2}{\tan^2\beta - 1} \tag{4}$$

and the m_Z-scale $\mu, m_{H_u}^2, m_{H_d}^2$ parameters are sensitive to their GUT scale values yielding at $\tan\beta = 10$ (similar to $\tan\beta = 2.5$ results in Kane and King hep-ph/9810374 and Bastero-Gil, Kane, and King hep-ph/9910506)

$$\begin{aligned} m_Z^2 &= -2.0\mu^2(M_U) + 5.9 M_3^2(M_U) + 0.8 m_Q^2(M_U) + 0.6 m_U^2(M_U) \\ &\quad -1.2 m_{H_u}^2(M_U) - 0.7 M_3(M_U) A_t(M_U) + 0.2 A_t^2(M_U) + \ldots \end{aligned}$$

Unless there are large cancellations (fine-tuning), one would expect that

$$m_Z \sim 2M_3(M_U), m_Q(M_U), m_u(M_U) \sim m_{\widetilde{g}}, m_{\widetilde{t}}. \tag{5}$$

We would need a very light gluino, and a rather light stop, to avoid fine-tuning. Or you can have cancellations/correlations. For example, to get

$\frac{\partial m_Z}{\partial M_3(M_U)} = 0$, **one requires, using**

$$\begin{aligned} A_t(m_Z) &\sim -2.3 M_3(M_U) + .2 A_t(M_U) \\ M_3(m_Z) &\sim 3 M_3(M_U) \\ m^2_{\widetilde{t}}(m_Z) &\sim 5.0 M_3^2(M_U) + .6 m^2_{\widetilde{t}}(M_U) + .2 A_t(M_U) M_3(M_U)\,, \end{aligned} \quad (6)$$

$$A_t(m_Z) = -3 M_3(m_Z) \sim -900 \text{ GeV}\,, \quad \textbf{for } M_3(m_Z) = 300 \text{ GeV}. \quad (7)$$

But, then other derivatives are significant. Thus, we define

$$F = \mathrm{Max}_p \left| \frac{p}{m_Z} \frac{\partial m_Z}{\partial p} \right| \quad (8)$$

$$p \in \left\{ M_{1,2,3}, m^2_Q, m^2_U, m^2_D, m^2_{H_u}, m^2_{H_d}, \mu, A_t, B\mu, \ldots \right\} \quad (9)$$

all referring to M_U scale values.

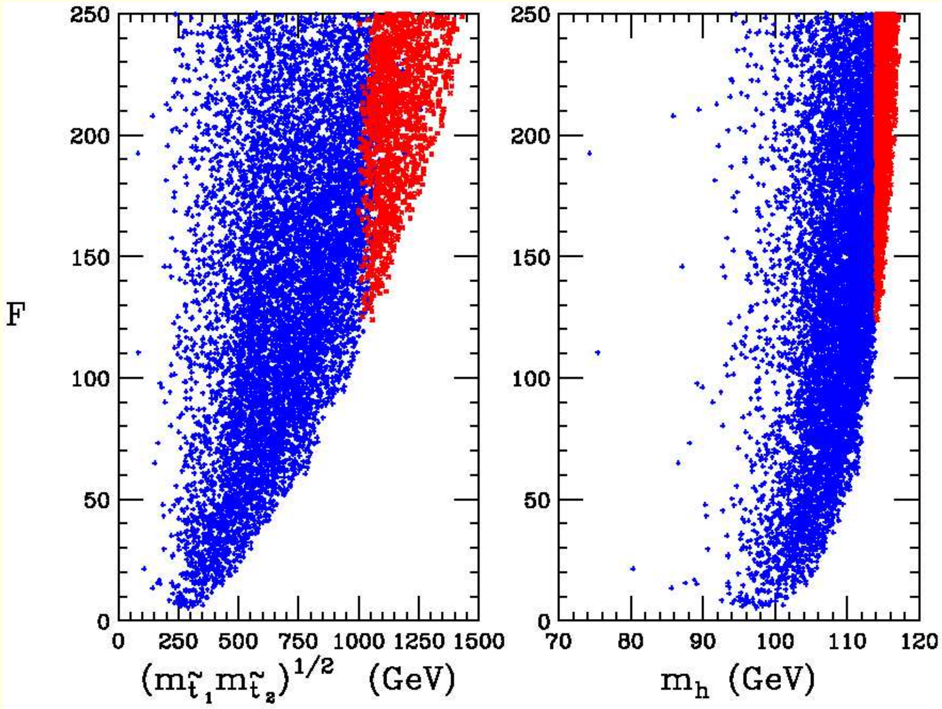


Figure 4: F in the MSSM. The $+$ points have $m_h < 114~\mathrm{GeV}$, and are experimentally excluded. The $\times$ points have $m_h \geq 114~\mathrm{GeV}$. Scan was over $|A_t| < 500~\mathrm{GeV}$. Plot is for $\tan\beta = 10$, $M_{1,2,3} = 100, 200, 300~\mathrm{GeV}$ (at scale m_Z). All other parameters were scanned over.

Essentially all the blue points fail LEP limits due to $m_h < 114~\mathrm{GeV}$.

Note that if $m_h \sim 100~\mathrm{GeV}$ were ok, then smallest F occurs there.

Thus, if A_t is restricted to modest values (as for this figure) then the

MSSM has very large fine-tuning. One can do better by taking very large A_t values, as shown in the next figure.

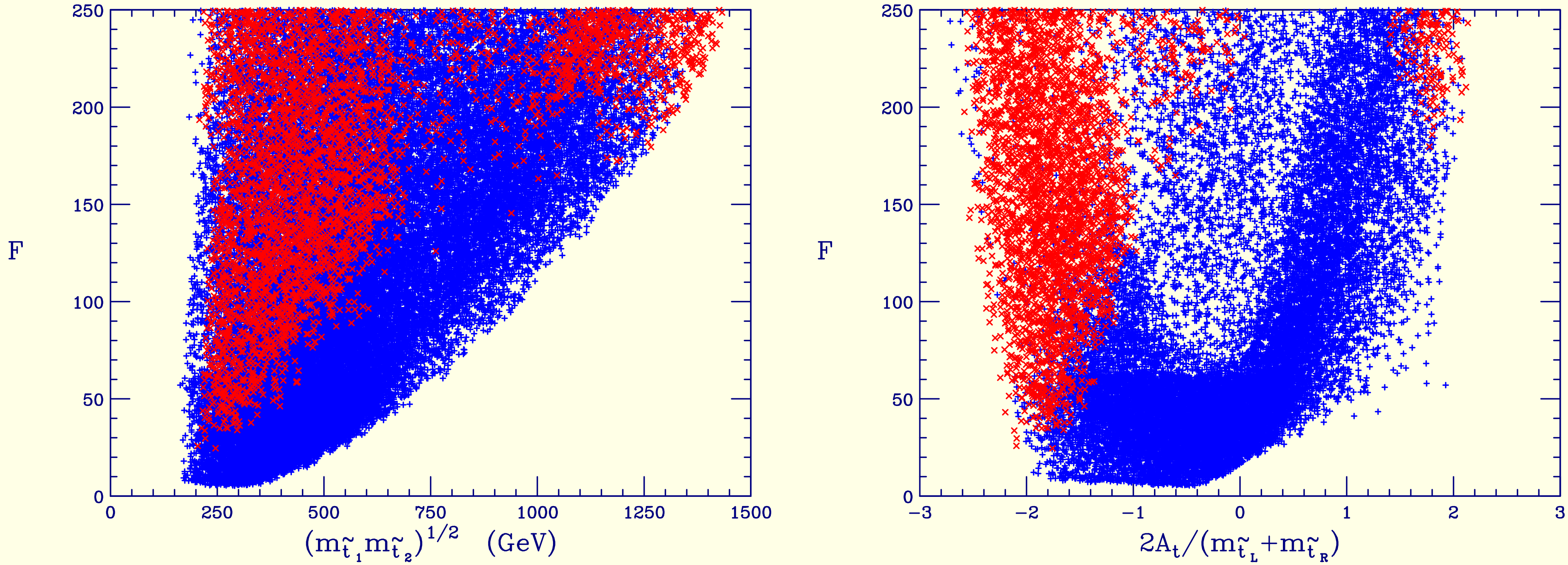


Figure 5: F **in the MSSM. The** $+$ **points have** $m_h < 114~\mathrm{GeV}$**. The** $\times$ **points have** $m_h \geq 114~\mathrm{GeV}$**. Scan was over** $|A_t| < 4~\mathrm{TeV}$**. Plot is for** $\tan\beta = 10$, $M_{1,2,3} = 100, 200, 300~\mathrm{GeV}$ **(at scale** m_Z**). All other parameters were scanned over.**

The figure shows clearly that large negative $A_t(m_Z)$ is required to get anything like reasonable F for allowed $m_h \geq 114~\mathrm{GeV}$ points, and even then $F \gtrsim 30$.

- A second problem for the MSSM is that 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.

- But a much bigger and more fundamental problem is that 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 $\mathcal{O}(M_{\mathrm{P}})$ (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?

- **CP-violating MSSM, e.g. CPX-like scenarios?**
  These don't solve the μ issue, and nature has shown very little inclination for CP-violation as large as that needed to significantly alter the CP-conserving situation.
- **Large extra dimensions, little Higgs, Higgsless, ...**
  All worth exploring, but ...
- **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

- 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:

$$W_\lambda = \widehat{Q}\widehat{H}_u \mathrm{h_u}\widehat{U}^C + \widehat{H}_d\widehat{Q}\mathrm{h_d}\widehat{D}^C + \widehat{H}_d\widehat{L}\mathrm{h_e}\widehat{E}^C + \lambda\widehat{S}\widehat{H}_u\widehat{H}_d\,, \tag{10}$$

The superpotential presented in Eq. (10), and its derived Lagrangian, contain an extra global U(1) Peccei-Quinn (PQ) Symmetry. Assigning PQ charges, Q^{PQ}, according to

$$\widehat{Q}: -1, \widehat{U}^C: 0, \widehat{D}^C: 0, \widehat{L}: -1, \widehat{E}^C: 0, \widehat{H}_u: 1, \widehat{H}_d: 1, \widehat{S}: -2, \tag{11}$$

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

$$\widehat{\Psi}_i \in \{\widehat{Q},\ \widehat{U}^C,\ \widehat{D}^C,\ \widehat{L},\ \widehat{E}^C,\ \widehat{H}_u,\ \widehat{H}_d,\ \widehat{S}\}\,. \tag{12}$$

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 $n < 3$).

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 $\Psi \rightarrow e^{i2\pi/3}\Psi$.

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 $\propto 1/M_{\rm P}$ at tree-level may give rise at the loop level to quadratically divergent tadpole contributions (cut off at $M_{\rm P}$) in the

Lagrangian, of the form (Nilles, Lahanas, Ellwanger, Bagger, Jain, Abel, Kolda, etal)

$$\mathcal{L}_{\rm soft} \supset t_S S \sim \frac{1}{(16\pi^2)^n} M_{\rm P} M_{\rm SUSY}^2 S \,, \tag{13}$$

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)

  As Abel showed, the potentially harmful non-renormalizable terms are either even superpotential terms or odd Kähler potential terms, both of which will be eliminated if we impose an additional Z_2^R symmetry (namely, the $\theta = \pi$ subgroup of $U(1)_R$, where all superfields change by $e^{i\theta}$ and the superpotential changes by $e^{3i\theta}$) on all operators to guarantee that the loop-induced tadpole terms that might be present (of form $t_S S$) 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. (Of course, the standard superpotential has "accidentally" a larger symmetry.)

  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 $2 \leq n \leq 4$. For example, a superpotential term of form $\widehat{S}^7/M_{\rm P}^4$ (which is ok under Z_2^R) generates at 4-loops (Abel) the tadpole form $\delta V \sim \left(\frac{1}{16\pi^2}\right)^4 m_{\rm SUSY}^3 (S + S^*)$.

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

- **Net Result**

  Since the only *relevant* 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.

- **Further**, all the good properties of the MSSM (coupling unification and RGE EWSB, in particular) are preserved under singlet addition.

- **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

$$\lambda\ \widehat{S}\widehat{H_u}\widehat{H_d} + \frac{\kappa}{3}\ \widehat{S}^3 \tag{14}$$

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

$$\lambda A_\lambda S H_u H_d + \frac{\kappa}{3} A_\kappa S^3 \,. \tag{15}$$

The final two input parameters are

$$\tan\beta = h_u/h_d \,, \quad \mu_{\rm eff} = \lambda s \,, \tag{16}$$

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

$$\lambda \ , \ \kappa \ , \ A_\lambda \ , \ A_\kappa, \ \tan\beta \ , \ \mu_{\rm eff} \ . \tag{17}$$

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 for Higgs discovery 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. $h \to \gamma\gamma$, $t\bar{t}h, a \to t\bar{t}b\bar{b}$, $t\bar{t}h, a \to t\bar{t}\gamma\gamma$, $b\bar{b}h, a \to b\bar{b}\tau^+\tau^-$, $WW \to h \to \tau^+\tau^-$, ...

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".

- 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.

  As before, the canonical measure of fine-tuning that Dermisek and I employ is

$$F = \mathrm{Max}_p F_p \equiv \mathrm{Max}_p \left| \frac{d \log m_Z}{d \log p} \right| , \tag{18}$$

  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?**

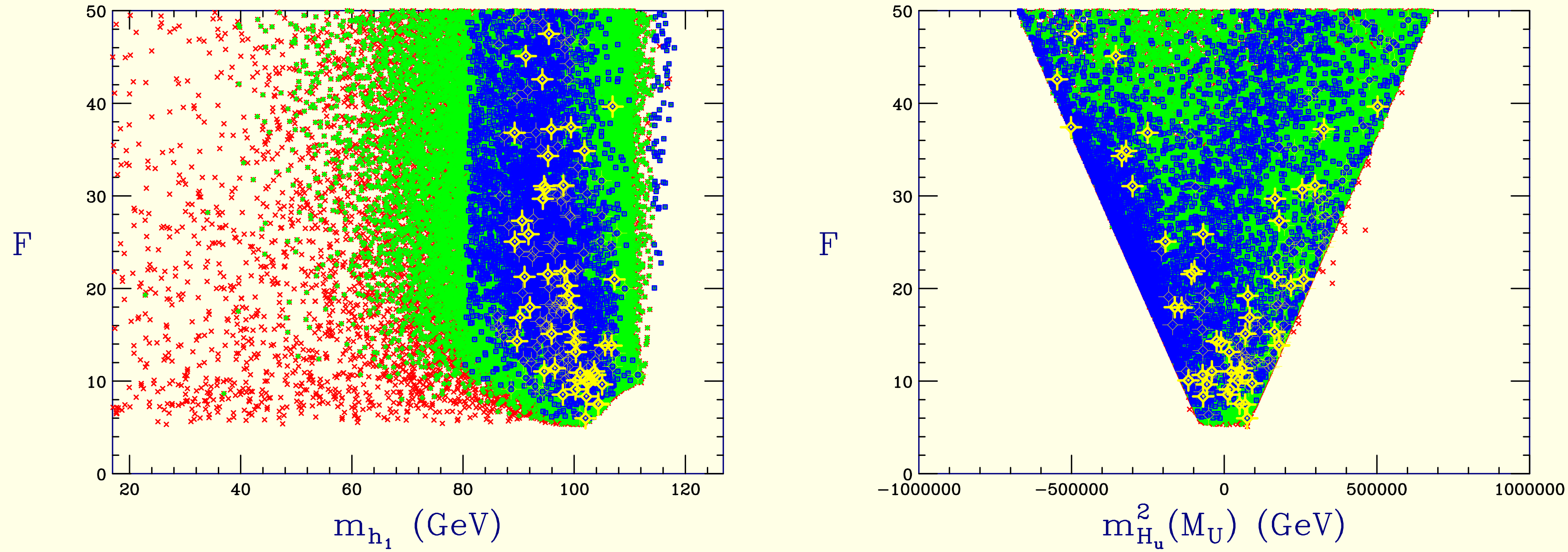


Figure 6: F vs. m_{h_1} (left) and F vs. $m^2_{H_u}(M_U)$ (right), for $M_{1,2,3} = 100, 200, 300~\mathrm{GeV}$ and $\tan\beta = 10$. Small $\times$ are results with no constraints other than global and local minimum, no Landau pole before M_U and neutralino LSP. The $\diamond$'s are after imposing stop and chargino limits, but NO Higgs limits. The $\square$'s are after imposing all single channel Higgs limits. And the large fancy crosses are after requiring $m_{a_1} < 2m_b$.

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 $h_1 \to a_1 a_1$ and $a_1 \to \tau^+\tau^-$ (because $m_{a_1} < 2m_b$) so as to hide the h_1 in this mass range (more later).
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.

   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.
4. 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).
5. There is no discernible dependence of F on κA_κ within the range of κA_κ that gives a light a_1.
6. Small F is associated with small values for $m^2_{H_u}(M_U)$, $m^2_{H_d}(M_U)$ and $m^2_S(M_U)$, as illustrated for $m^2_{H_u}$ in Fig. 6.

Fine-Tuning and new LEP limits

- **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 $h_1 \to a_1 a_1$ 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 $M_{1,2,3} = 100, 200, 300$ 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.

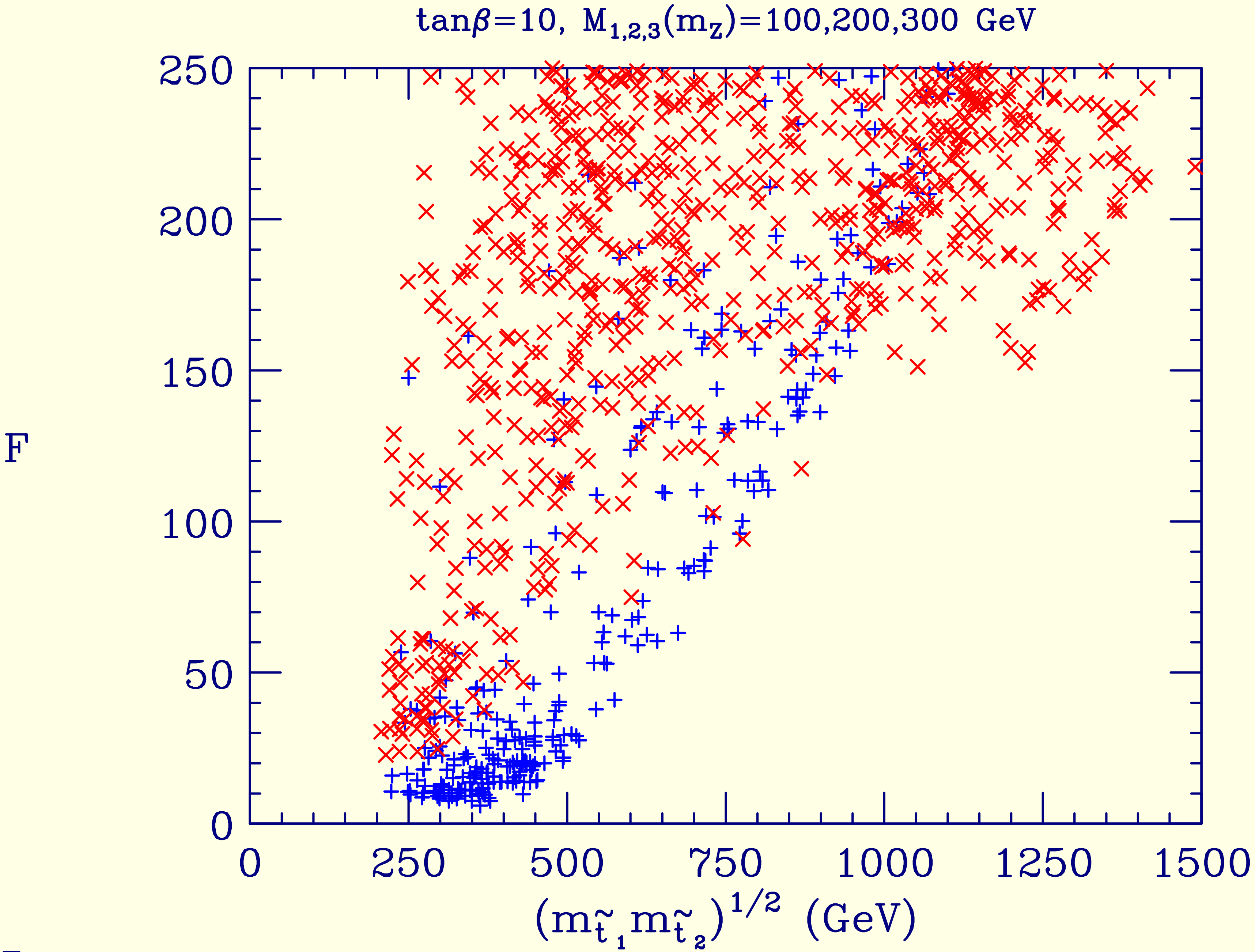


Figure 7: $\boldsymbol{F}$ **as a function of root mean stop mass after latest** *single-channel* **LEP limits. Both** $m_{h_1} < 114$ GeV **(+) and** $m_{h_1} \geq 114$ GeV **(×) points are allowed.**

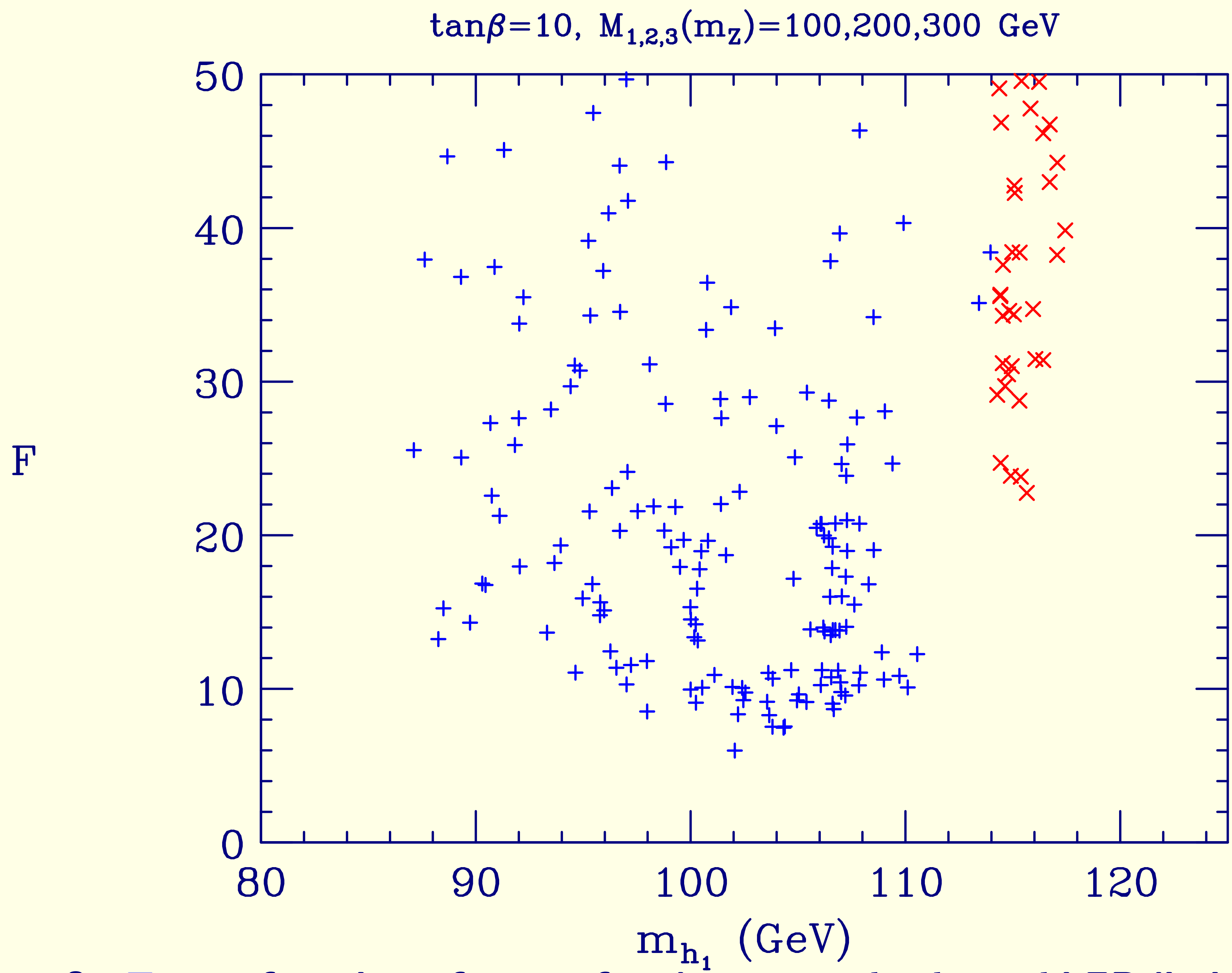


Figure 8: F **as a function of** m_{h_1} **after latest** *single-channel* **LEP limits.**

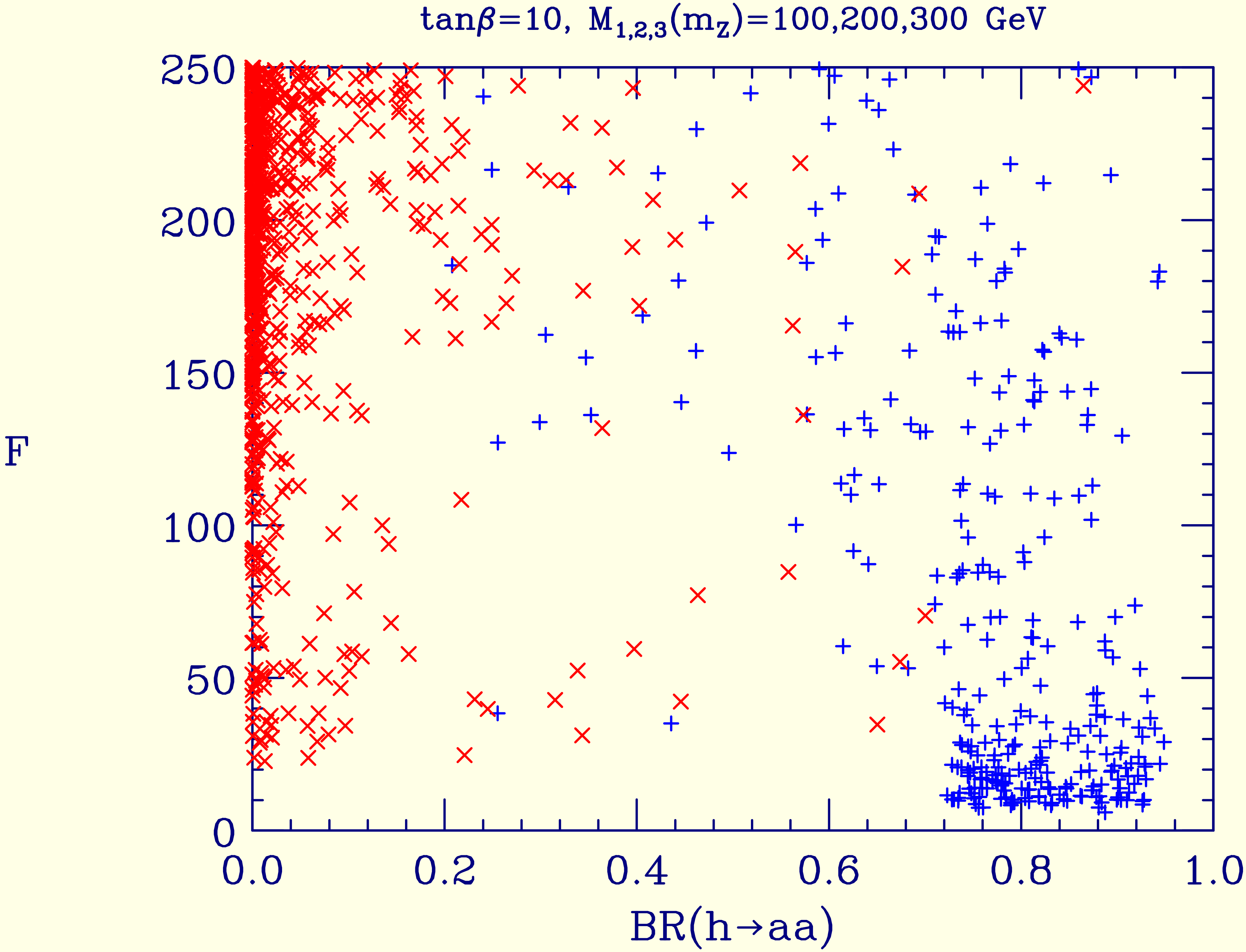


Figure 9: F **as a function of** $B(h_1 \to a_1 a_1)$ **after latest** *single-channel* **LEP limits. Note that** $h_1 \to a_1 a_1$ **can be dominant even when** m_{h_1} **is large enough that the decay is not needed to escape LEP limits.**

Among the points with low F, there are ones with $m_{a_1} > 2m_b$ and ones with $m_{a_1} < 2m_b$. The former have problems unless $m_{h_1} \gtrsim 110~\mathrm{GeV}$.

In particular, the $Z2b$ and $Z4b$ channels are not actually independent.

- 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 $h_1 \to b\overline{b}$ 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 $m_{h_1} \sim 100~\mathrm{GeV}$, and remain consistent with LEP is to have $m_{a_1} < 2m_b$.

  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 $87~\mathrm{GeV}$.)

- **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 $\kappa A_\kappa \to 0$.**

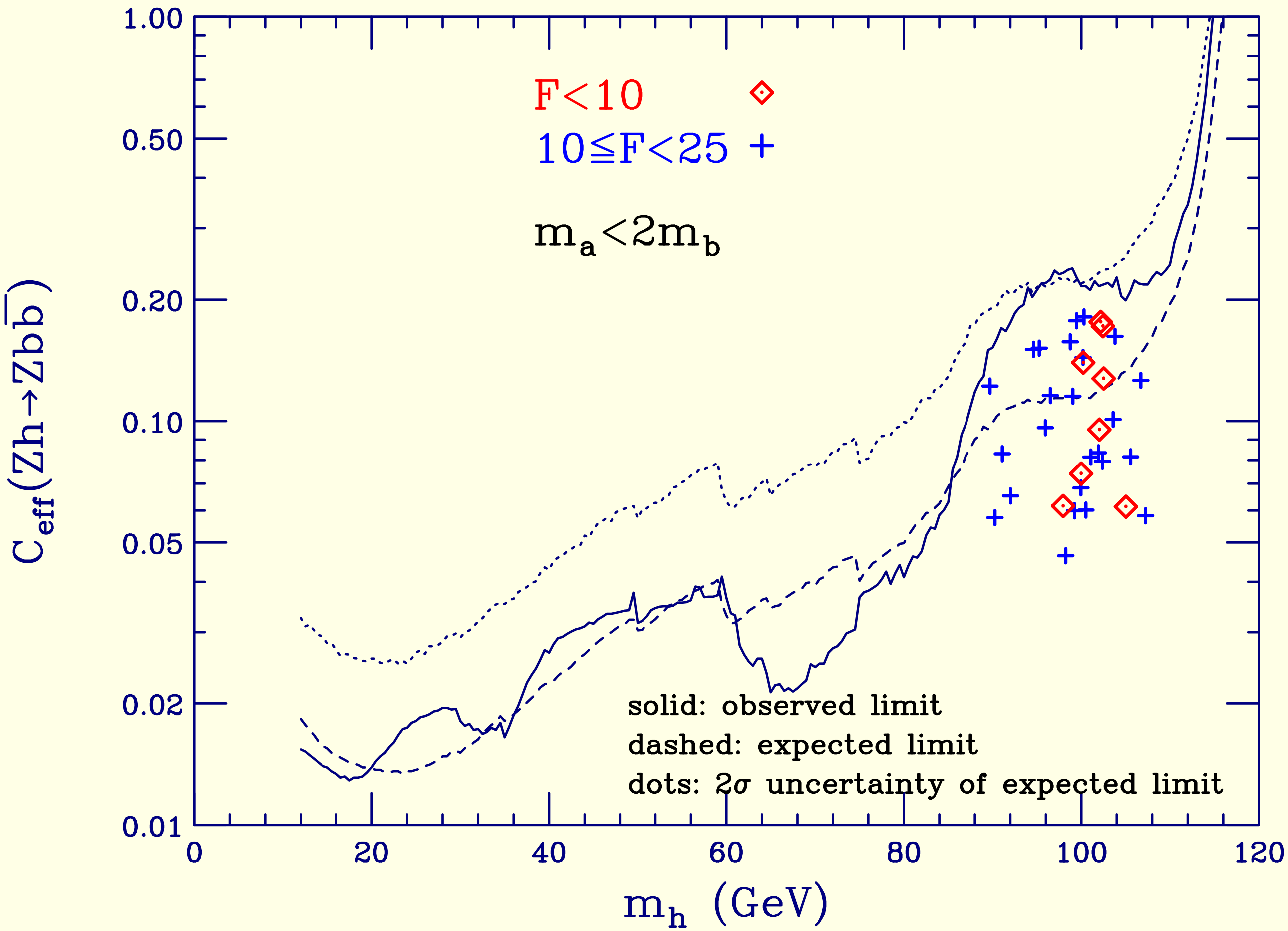


Figure 10: Observed LEP limits on C^{2b}_{eff} for the low-F points with $m_{a_1} < 2m_b$.

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.)

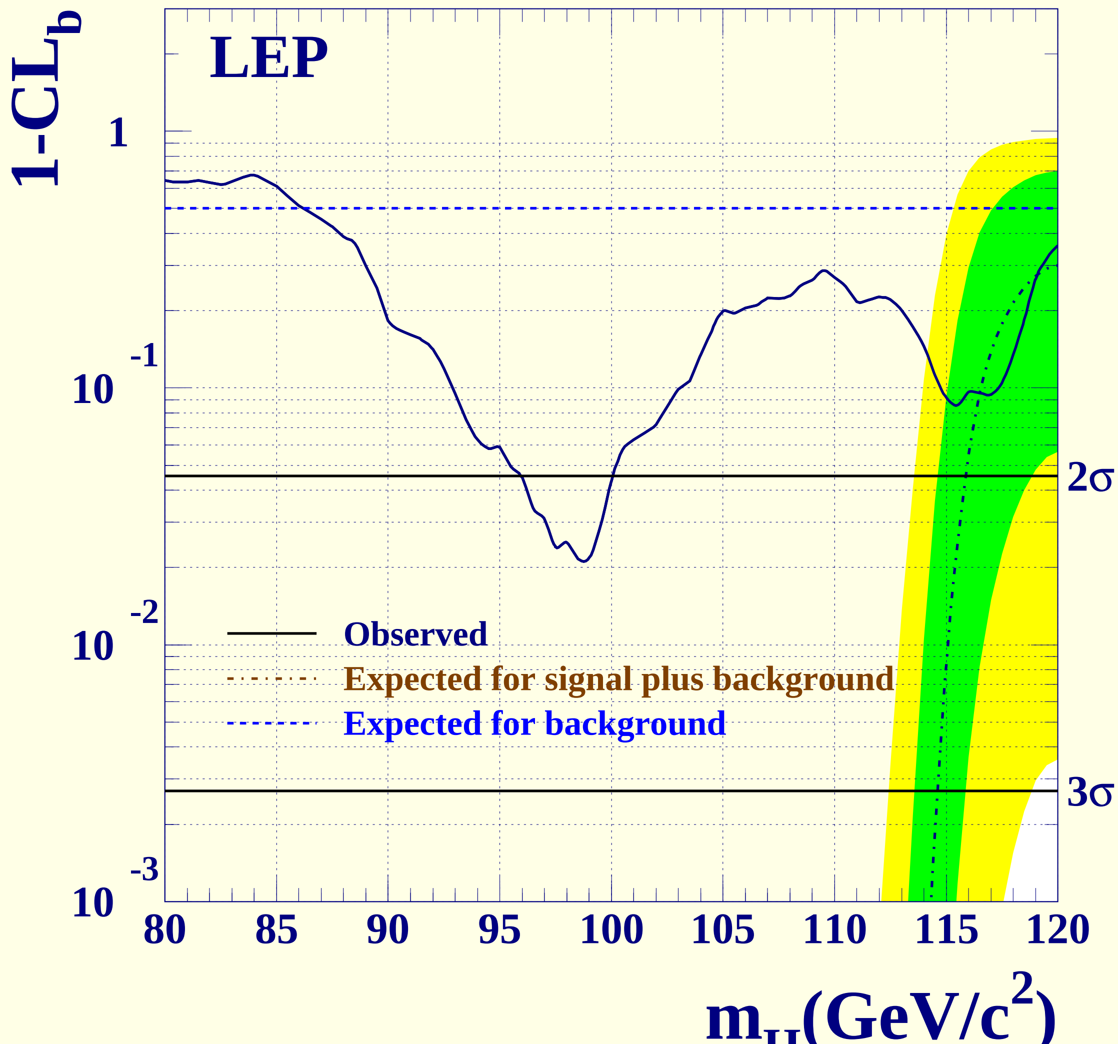


Figure 11: Plot of $1 - CL_b$ for the $Zb\bar{b}$ final state.

- **There is an observed vs. expected discrepancy exactly where we want it! And because $B(h_1 \to b\bar{b})$ is $1/10$ the SM value, the discrepancy is of about the right size.**

- **Are there other relevant limits on the kind of scenario we envision?**

  If the $a_1 a_1 \to 4\tau$ decay is the relevant scenario, the LEP limits run out for $m_h > 87$ GeV.

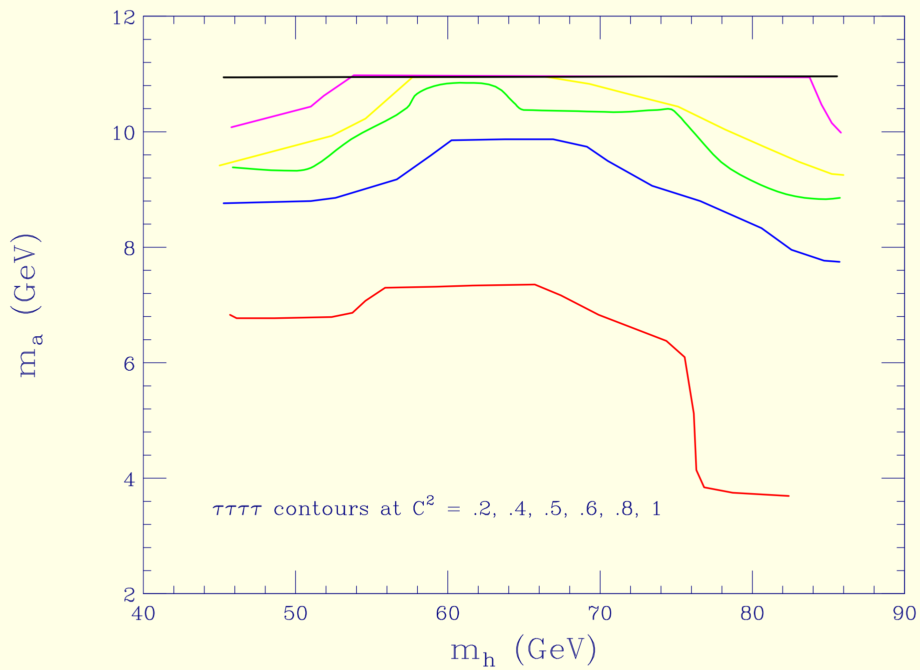


Figure 12: Contours of limits on $C^2 = [g^2_{Zh}/[g^2_{Zh}]_{SM}] \times BR(h \to aa) \times [BR(a \to \tau^+\tau^-)]^2$ at $C^2 = 0.2$, 0.4, 0.5, 0.6, 0.8 and 1 (red, blue, green, yellow, magenta, and black, respectively). For example, if $C^2 > 0.2$, then the region below the $C^2 = 0.2$ contour is excluded at 95% CL.

If the $a_1 a_1 \to (gg, q\overline{q}) + (gg, q\overline{q})$ decay is relevant, then we have the hadronic decay limits. They run out for $m_h > 80$ GeV.

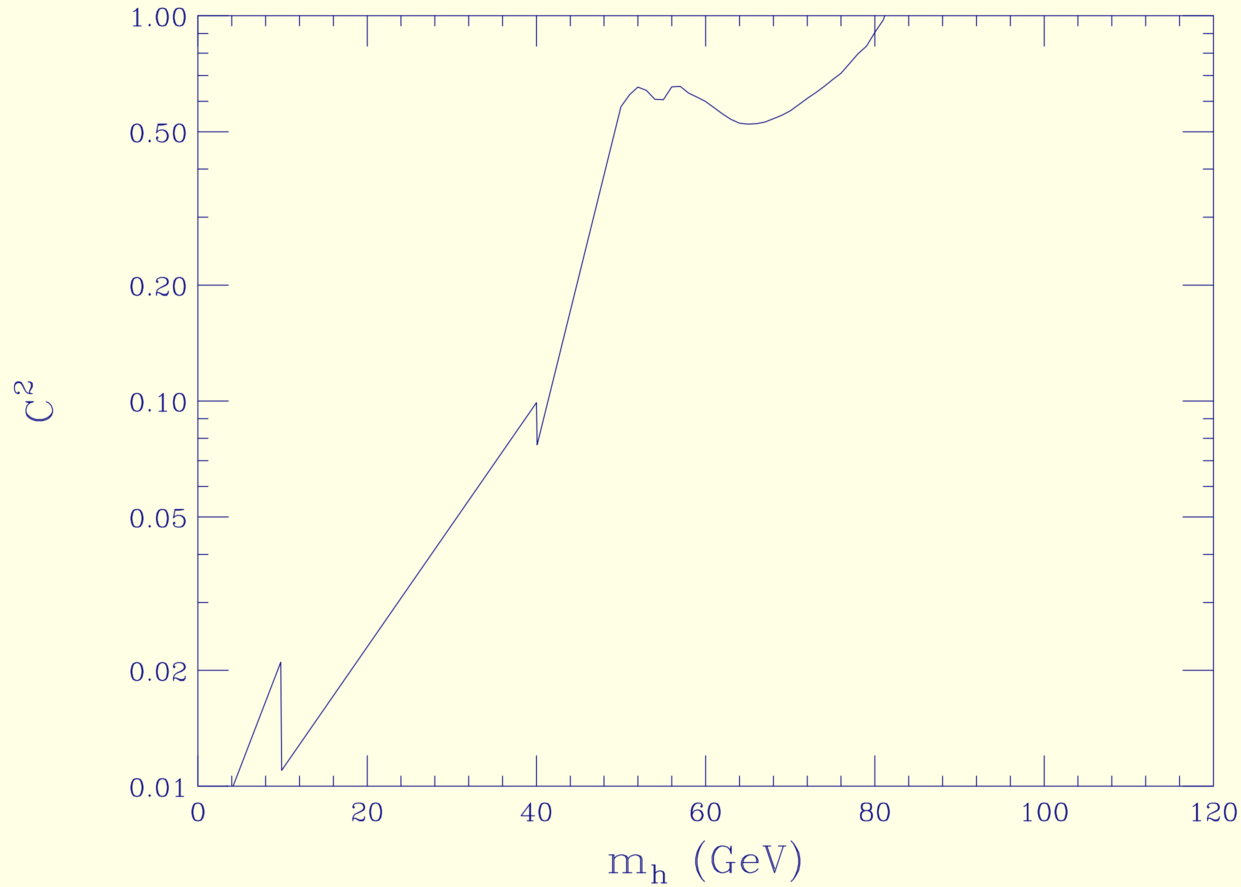


Figure 13: **Plot of the 95% CL limit on $C^2 = [g^2_{Zh}/[g^2_{Zh}]_{SM}] \times BR(h \to$ hadrons$)$, where h is only assumed to decay to hadrons, not any specific number of jets.**

Or, if we say that the gg or $q\overline{q}$ from each a_1 overlap to form a single 'jet', then we have the limits in the 'jet-jet' channel. They give $C^2 \lesssim 0.4$ for $m_h \sim 100~\mathrm{GeV}$ and might be relevant. A detailed analysis is needed.

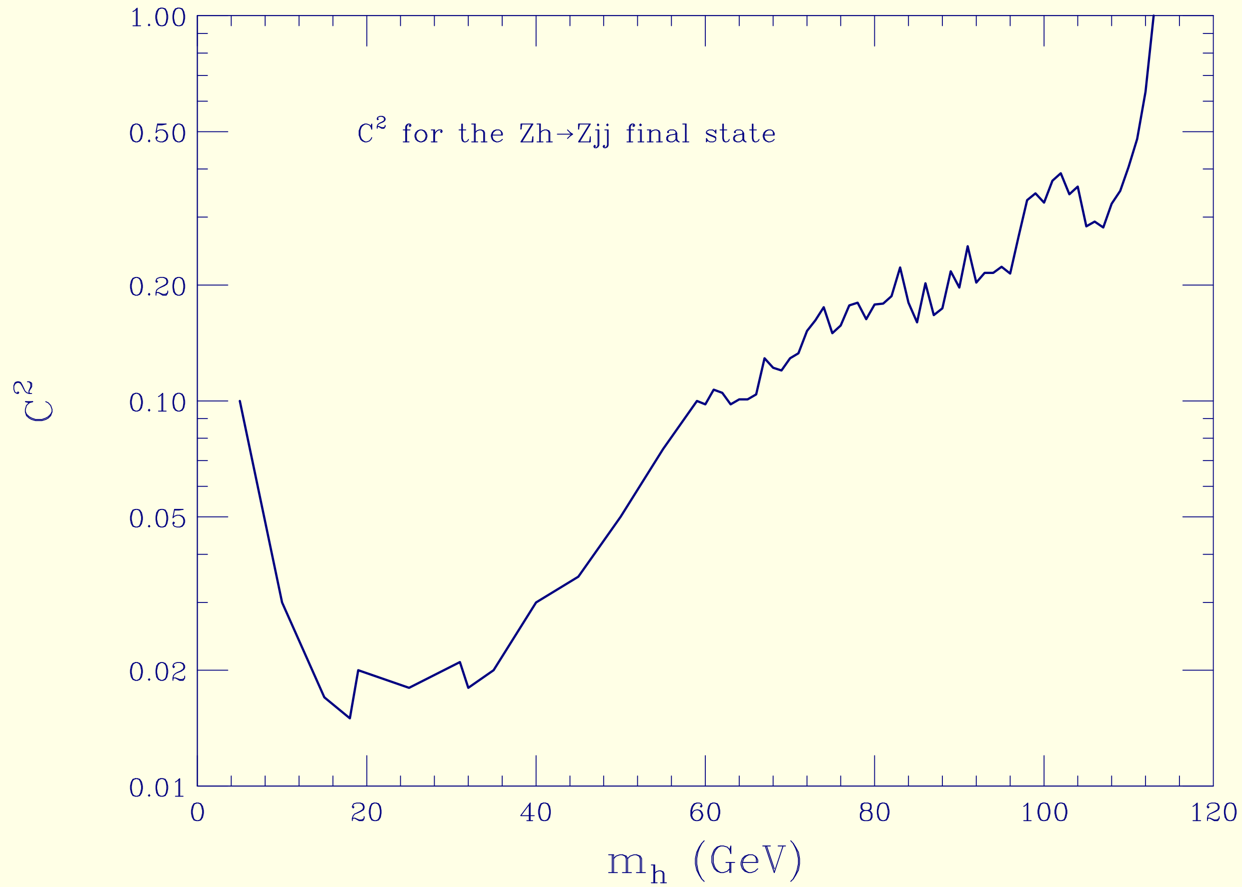


Figure 14: 95% CL upper limit on $C^2 = [g^2_{Zh}/[g^2_{Zh}]_{SM}] \times BR(h \to jj)$ from LEP analyzes.

- To 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. Well, we didn't do it, but Philip Bechtle did it for us.

  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 $\tan\beta = 10$, $M_{1,2,3}(m_Z) = 100, 200, 300$ 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 $m_{h_1} \lesssim 100$ 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.

- 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.

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

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.

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).

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.

There is one tricky point. One cannot get low-F scenarios satisfying LEP limits in the exact $A_\kappa = A_\lambda = 0$ limit.

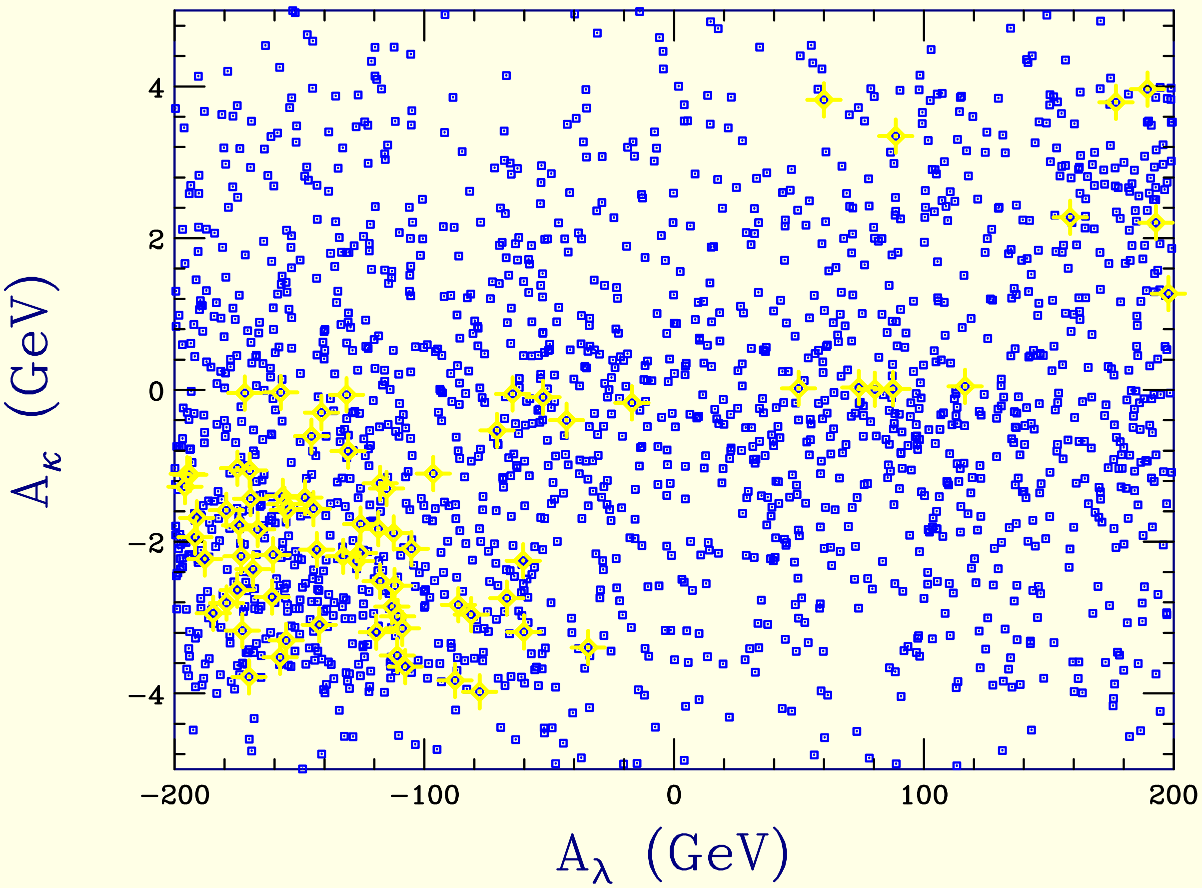


Figure 15: A_κ vs. A_λ for $M_{1,2,3} = 100, 200, 300~\mathrm{GeV}$ and $\tan\beta = 10$. As before, the □'s are after imposing all single channel Higgs limits. And the large fancy crosses are after requiring $m_{a_1} < 2m_b$.

What one finds is that $B(h_1 \to a_1 a_1)$ is too small to escape LEP bounds in the $A_\kappa = A_\lambda = 0$ limit. (It is of order 0.2 to 0.4, as compared to the ~ 0.8 we need.)

We don't regard this as a real difficulty. After all, there are radiative corrections to A_λ in particular (from SUSY breaking) that will normally generate a small value for this parameter even if it is zero at the Lagrangian level.

In short, a light, singlet a_1 with the required $B(h_1 \to a_1 a_1)$ is very natural in 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 $h_1 \to a_1a_1 \to \tau^+\tau^-\tau^+\tau^-$ 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 $B(h_1 \to a_1a_1)[B(a_1 \to \tau^+\tau^-)]^2 \sim 0.85(0.93)^2 \sim 0.65$ yields 10^5 events in the 4τ channel.
   This means it may be realistic to consider $WW \to h_1 \to a_1a_1 \to 4\tau$ 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.

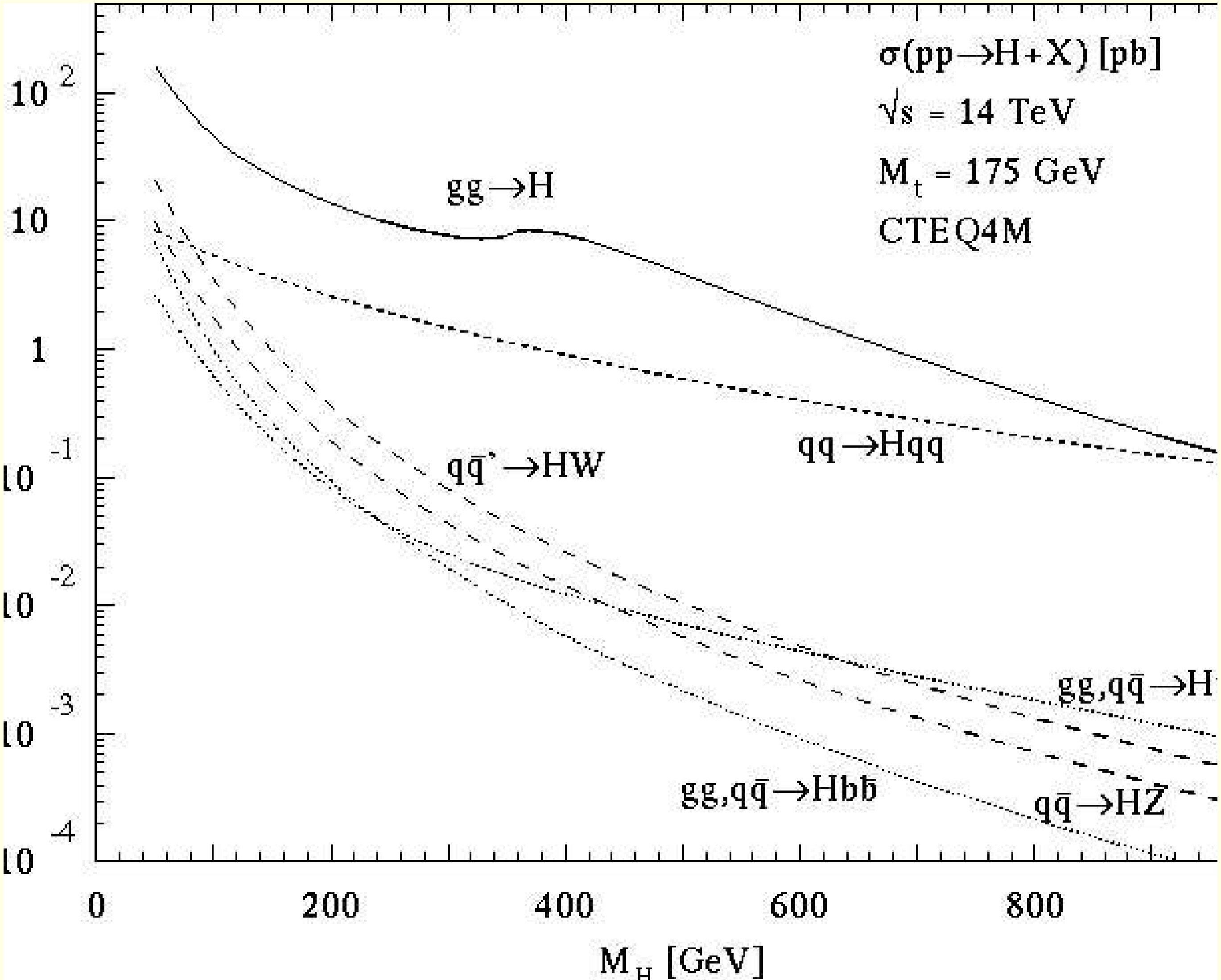


Figure 16: The standard Higgs production cross sections at the LHC.

- 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. $B(4\tau \to 2 \text{ or more } \mu's) \sim 15\%$ $\Rightarrow$ 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%.
- 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.

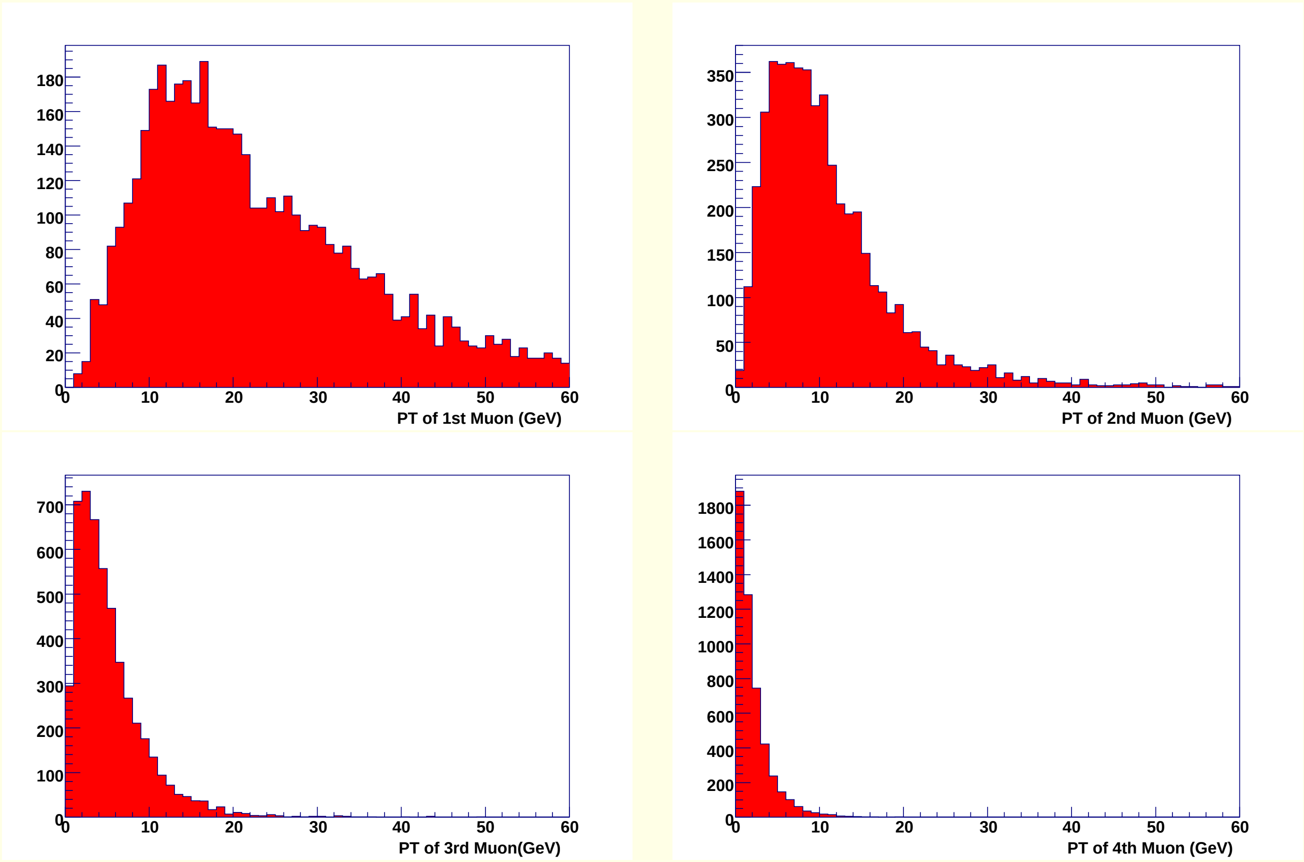


Figure 17: p_T's of the 4 μ's, ordered. Requiring four detectable muons kills the signal almost completely.

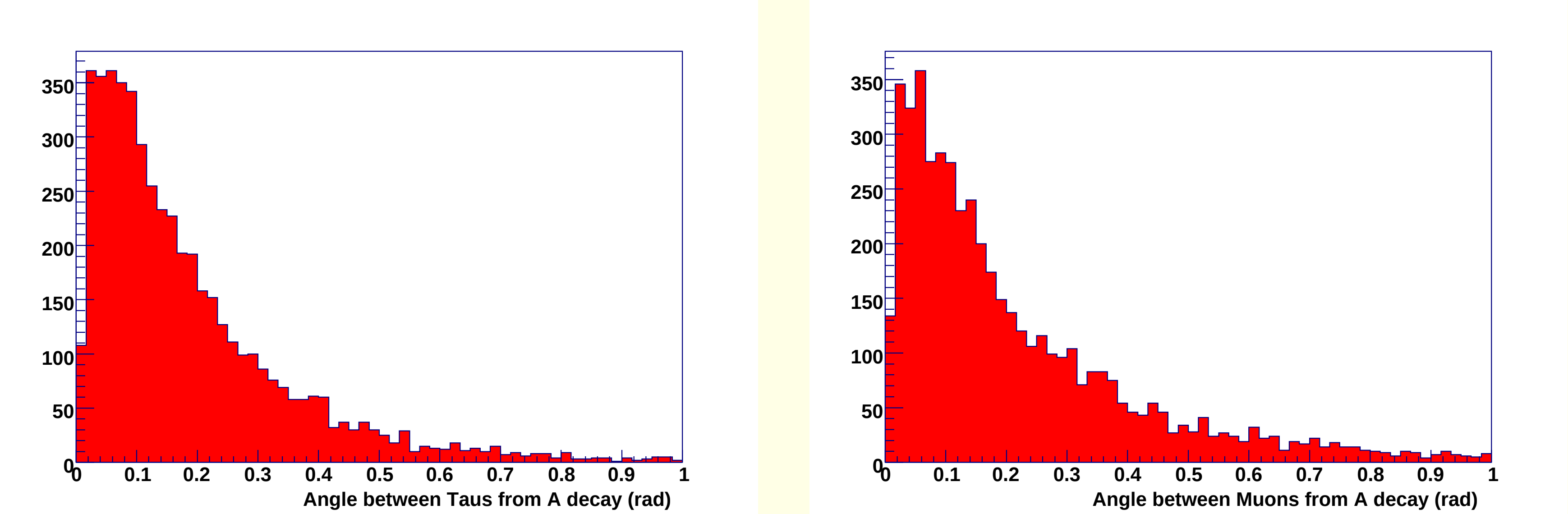


Figure 18: Angles between τ's and μ's from one a_1 decay.

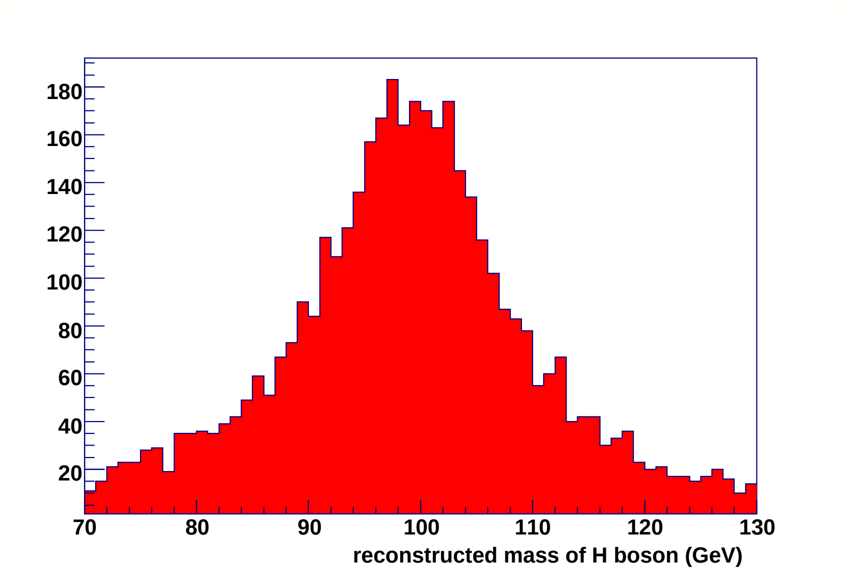


Figure 19: Reconstructed m_{h_1} using collinear approximation and the three most energetic μs.

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. A third possibility: $\widetilde{\chi}_2^0 \to h_1\widetilde{\chi}_1^0$ with $h_1 \to a_1a_1 \to 4\tau$.
   (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.)
   - A study of the $h_1 \to a_1a_1 \to 4\tau$ decay mode is needed.

– 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 $1-2~\mathrm{GeV}$ 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 $\sigma \sim 1 \div 3~\mathrm{fb}$ for $m_{h_1} \sim 100~\mathrm{GeV}$ and ggh_1=SM-like.
   – At low-$\mathcal{L}$, suppose we accumulate $L = 30~\mathrm{fb}^{-1}$, $\Rightarrow$ $30 \div 90$ 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 $B(4\tau \to 2$ 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** ($L = 30~\mathrm{fb}^{-1}$): $events \lesssim 90 \times 0.06 \times 0.5 \lesssim 3$.
  $\Rightarrow$ must do at high luminosity in presence of overlapping events.

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

  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).

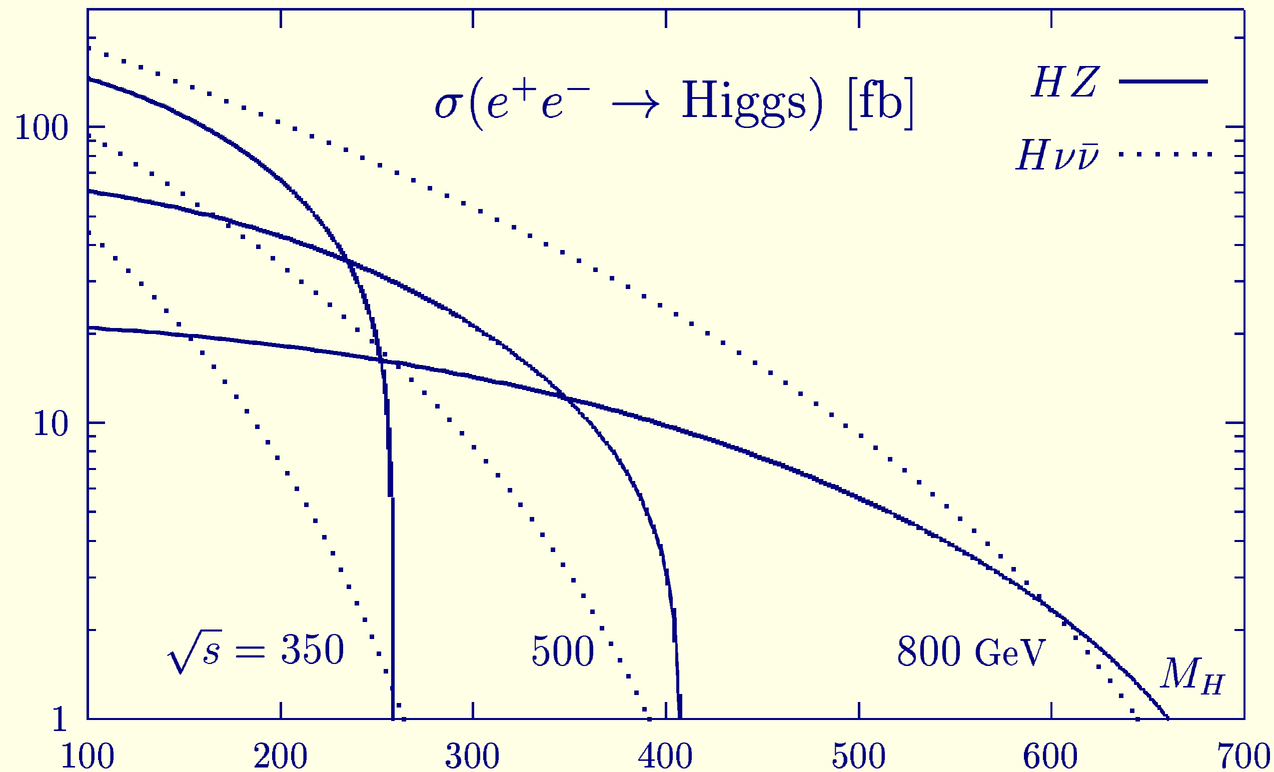


Figure 20: Cross sections at the ILC.

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.

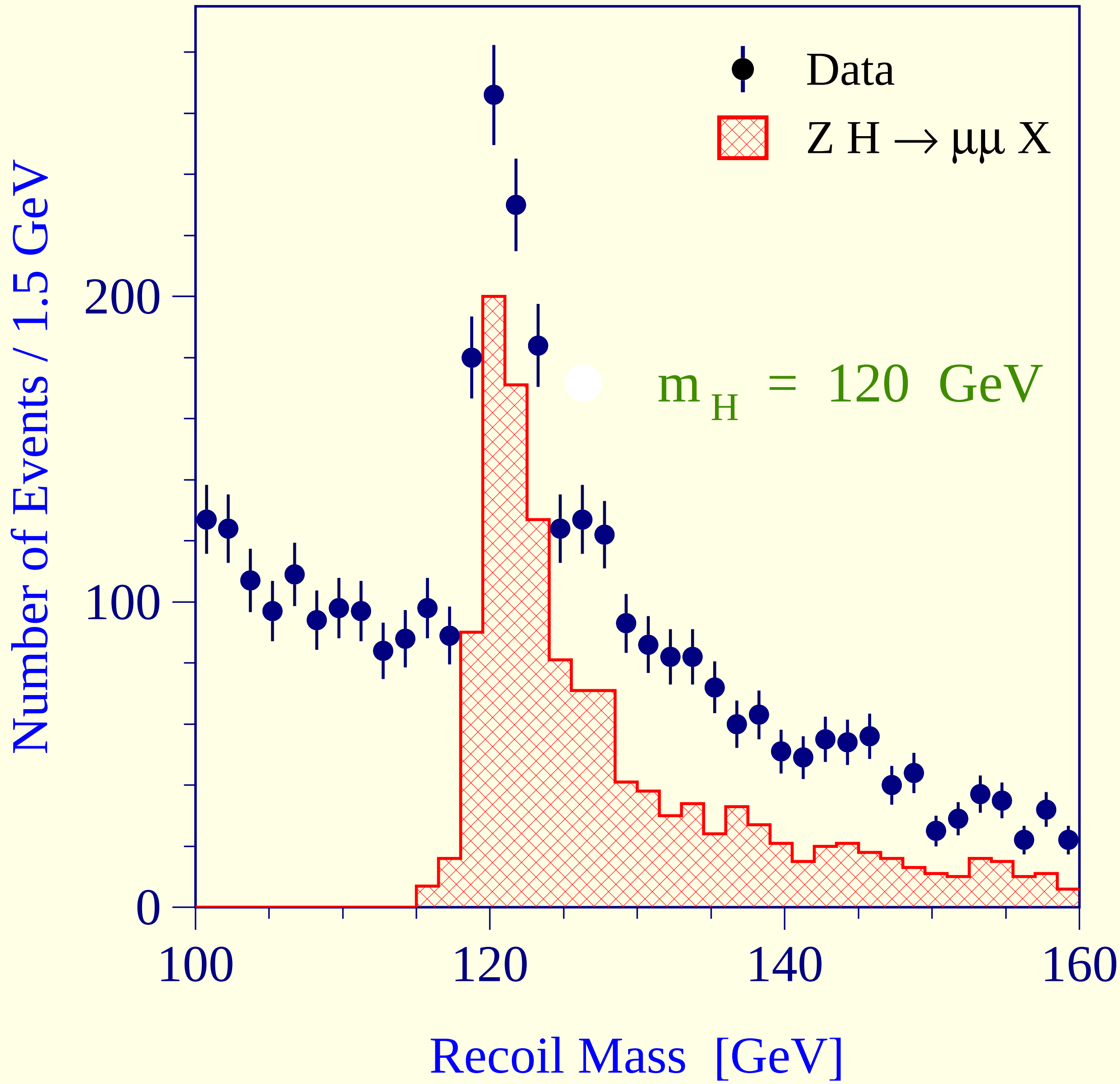


Figure 21: Decay-mode-independent Higgs M_X peak in the $Zh \to \mu^+\mu^- X$ mode for $L = 500~\mathrm{fb}^{-1}$ at $\sqrt{s} = 350~\mathrm{GeV}$, taking $m_h = 120~\mathrm{GeV}$..

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 $h \to b\overline{b}$ 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 $Zh \to Zb\overline{b}$ 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 will provide unique information about $\lambda, \kappa, A_\lambda, A_\kappa$.

  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 $b\overline{b}$, $\tau^+\tau^-$, . . . (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 $m_{h_1} \gtrsim 108 \div 110~\mathrm{GeV}$ 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. $t\bar{t}h_1 \to t\bar{t}a_1a_1 \to t\bar{t}4b$.
     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.

Dark Matter bibliography

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Relevant NMSSM Basics

We will be focusing on the lightest CP-odd Higgs boson, the a_1, and on the lightest neutralino, the $\widetilde{\chi}_1^0$, which will be stable (assuming conventional R-parity conservation).

An important issue will be the composition of these states.

- The eigenvector of the lightest neutralino, $\widetilde{\chi}_1^0$, in terms of gauge eigenstates is:

$$\widetilde{\chi}_1^0 = \epsilon_u \tilde{H}_u^0 + \epsilon_d \tilde{H}_d^0 + \epsilon_W \tilde{W}^0 + \epsilon_B \tilde{B} + \epsilon_s \tilde{S}, \qquad (19)$$

  where ϵ_u, ϵ_d are the up-type and down-type higgsino components, ϵ_W, ϵ_B are the wino and bino components and ϵ_s is the singlet component of the lightest neutralino.

- We write the lightest CP-odd Higgs as:

$$a_1 = \cos\theta_A A_{\rm MSSM} + \sin\theta_A A_s, \qquad (20)$$

  where A_s is the CP-odd component of the singlet S field and $A_{\rm MSSM} \equiv A$ is the state that would be the MSSM pseudoscalar Higgs if the singlet were not present. θ_A is the mixing angle between these two states.

There is also a third imaginary linear combination of H_u^0, H_d^0 and S that we have removed by a rotation in β. This field becomes the longitudinal component of the Z after electroweak symmetry is broken.

- In the basis $\widetilde{\chi}^0 = (-i\widetilde{\lambda}_1, -i\widetilde{\lambda}_2, \psi_u^0, \psi_d^0, \psi_s)$, the tree-level neutralino mass matrix takes the form (defining $x \equiv \langle S \rangle$)

$$\mathcal{M}_{\widetilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & \frac{g_1 v_u}{\sqrt{2}} & -\frac{g_1 v_d}{\sqrt{2}} & 0 \\ 0 & M_2 & -\frac{g_2 v_u}{\sqrt{2}} & \frac{g_2 v_d}{\sqrt{2}} & 0 \\ \frac{g_1 v_u}{\sqrt{2}} & -\frac{g_2 v_u}{\sqrt{2}} & 0 & -\mu & -\lambda v_d \\ -\frac{g_1 v_d}{\sqrt{2}} & \frac{g_2 v_d}{\sqrt{2}} & -\mu & 0 & -\lambda v_u \\ 0 & 0 & -\lambda v_d & -\lambda v_u & 2\kappa x \end{pmatrix} . \qquad (21)$$

In the above, the upper 4×4 matrix corresponds to $\mathcal{M}_{\widetilde{\chi}^0}^{\mathrm{MSSM}}$.

From the lower 3×3 matrix, we find that if $\lambda v_{u,d} = (\mu/x) v_{u,d}$ are small compared to $|\mu|$ and/or $2|\kappa x|$ then the singlino decouples from the MSSM and has mass

$$m_{\mathrm{singlino}} \simeq \sqrt{\lambda^2 v^2 + 4\kappa^2 x^2} = \sqrt{\mu^2 v^2 / x^2 + 4\kappa^2 x^2} \, . \qquad (22)$$

If $2|\kappa x|$ and λv are both $< M_1, M_2, |\mu|$, then the $\widetilde\chi_1^0$ will tend to be singlino-like. If λv is small and $2|\kappa x|$ and M_1 are similar in size and $< M_2, |\mu|$, then the $\widetilde\chi_1^0$ will be a bino – singlino mixture.

- We already know that the a_1 becomes very singlet-like ($\cos\theta_A \to 0$) if κA_κ is small. This is our preferred Higgs scenario, but we will not focus purely on it.

- The critical process controlling dark matter Ωh^2 is the annihilation $\widetilde\chi_1^0\widetilde\chi_1^0 \to a_1 \to X$. Studies of this in the NMSSM context when $m_{\widetilde\chi_1^0}$ is fairly substantial appear in [2]. Our work [1] focuses on very small values of $m_{\widetilde\chi_1^0}$ and m_{a_1}.

- So, a first question is how close in mass can the a_1 be to twice the mass of the $\widetilde\chi_1^0$. The answer is: as close as you like so long as the $\widetilde\chi_1^0$ is not too purely singlet. One can see numerically and analytically that $m_{a_1} < 2m_{\widetilde\chi_1^0}$ by a significant amount when the $\widetilde\chi_1^0$ is mostly singlino.

  Thus, to explain dark matter, a $\widetilde\chi_1^0$ with substantial bino component is preferred. For this, M_1 must be small if m_{a_1} is small, but the $\widetilde\chi_1^0$ must have significant singlino component to evade LEP limits at small $m_{\widetilde\chi_1^0}$.

- We generated many scenarios and processed them all through NMHDECAY. We note that the web version of NMHDECAY includes $Z \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$ limits. The version we used also included additional constraints not in NMHDECAY on scenarios with a light $\widetilde{\chi}_1^0$ and a_1 coming from

  1. δa_μ – a positive value of order 7×10^{-10} ($\tau^+\tau^-$ data) or 25×10^{-10} (direct e^+e^- data) is desirable..;
  2. rare K decays;
  3. rare B decays;
  4. Υ and J/Ψ decays.

  Even if the limits on $B(\Upsilon \to \gamma \widetilde{\chi}_1^0 \widetilde{\chi}_1^0)$ are improved by a factor of 10, there are still solutions with good Ωh^2, even for this limited scan.

- **MSSM benchmark**

  To benchmark the NMSSM, we first consider a light bino which annihilates through the exchange of an MSSM-like CP-odd Higgs ($\cos\theta_A = 1$). The results for this case are shown in Fig. 22.

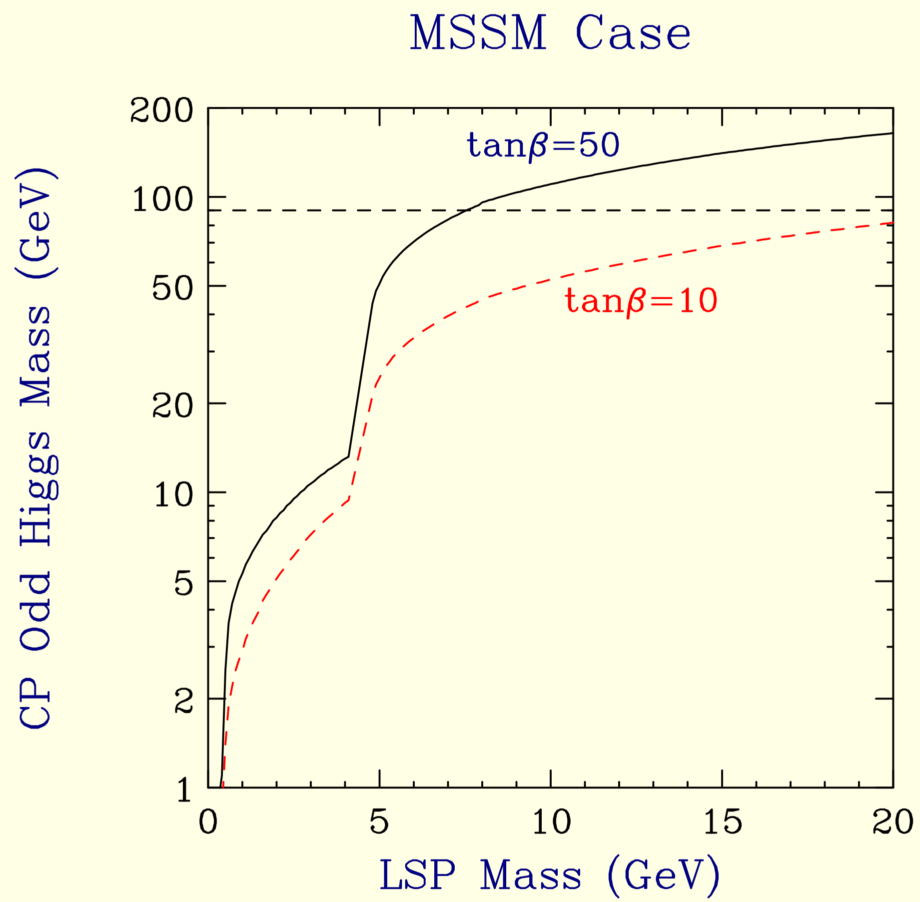

Figure 22: **The CP-odd Higgs mass required to obtain the measured relic density for a light neutralino in the MSSM. Models above the curves produce more dark matter than in observed. These results are for the case of a bino-like neutralino with a small higgsino admixture ($\epsilon_B^2 = 0.94$, $\epsilon_u^2 = 0.06$). The horizontal dashed line is the LEP lower bound.**

In this figure, the thermal relic density of LSP neutralinos exceeds the

measured value for CP-odd Higgses above the solid and dashed curves, for values of $\tan\beta$ of 50 and 10, respectively.

Shown as a horizontal dashed line is the lower limit on the the MSSM CP-odd Higgs mass from collider constraints.

This figure demonstrates that even in the case of very large $\tan\beta$, the lightest neutralino must be heavier than about $7~\mathrm{GeV}$. For moderate values of $\tan\beta$, the neutralino must be heavier than about $20~\mathrm{GeV}$.

- **NMSSM sample points**

  In the NMSSM framework, there is much more freedom.

  One can construct a huge number of points that satisfy all experimental constraints and give good Ωh^2.

  This is true even restricting to small $m_{\widetilde{\chi}_1^0}$ and associated small m_{a_1}.

  These points can have a range of characteristics.

  Below, I present two of the points that satisfy all constraints and give good Ωh^2

Table 3: Sample point 1: note singlet-like h_1.

λ	κ	$\tan\beta$	μ	A_λ	A_κ	M_1	M_2
0.436736	-0.049955	1.79644	-187.931	-458.302	-40.4478	1.92375	390.053

m_{a_1}	$\cos\theta_A$
7.17307	-0.193618

m_{h_1}	ξ_u	ξ_d	ξ_S
73.8217	0.1127	-0.0277	0.9932

$m_{\widetilde\chi_1^0}$	$\epsilon_{\tilde B}$	$\epsilon_{\tilde W}$	ϵ_u	ϵ_d	$\epsilon_{\tilde S}$
3.49603	-0.781466	-0.00594669	0.11476	0.26493	0.553099

δa_μ	BR($b \to s\mu^+\mu^-$)	BR($\Upsilon \to \gamma + A_1$)
1.24968e-10	3.1597e-09	8.12331e-06

$\langle\sigma v\rangle$	Ωh^2
4.55841e-26 cm^3/s	0.107689

The above point has:

1. a light $\widetilde\chi_1^0$, that is mainly bino, but with significant singlino component;
2. a singlet-like h_1;
3. a quite singlet-like a_1;
4. a small δa_μ that neither hurts nor helps;
5. excellent Ωh^2.

Table 4: Sample point 2: note MSSM-like h_1.

λ	κ	$\tan\beta$	μ	A_λ	A_κ	M_1	M_2
0.224982	-0.47912	7.58731	-174.624	-421.908	-30.6106	21.0909	984.116

m_{a_1}	$\cos\theta_A$
46.6325	-0.570716

m_{h_1}	$\sqrt{\xi_u^2+\xi_d^2}$
117.72	0.999

$m_{\widetilde\chi_1^0}$	$\epsilon_{\tilde B}$	$\epsilon_{\tilde W}$	ϵ_u	ϵ_d	$\epsilon_{\tilde S}$
22.3693	-0.971512	-0.00241597	0.00204445	0.236626	0.0127527

δa_μ	BR($b\to s\mu^+\mu^-$)
-1.37801e-10	3.16178e-09

$\langle\sigma v\rangle$	Ωh^2
2.17478e-26 cm^3/s	0.108649

The above point has:

1. a modest mass $\widetilde\chi_1^0$, that is almost purely bino;
2. a SM-like h_1;
3. an a_1 with substantial non-singlet component;
4. a small δa_μ that neither hurts nor helps;
5. excellent Ωh^2.

- Given that our scans show that we can freely adjust the masses and nature of the a_1 and $\widetilde{\chi}_1^0$, while still satisfying all constraints, we find it appropriate to simply fix the compositions of the a_1 and $\widetilde{\chi}_1^0$ and vary m_{a_1} and $m_{\widetilde{\chi}_1^0}$ so as to illustrate what mass ranges can give appropriate Ωh^2 for a sample set of composition choices and several $\tan\beta$ values.

  This kind of plot is presented in Fig. 23. The results shown are for a CP-odd Higgs which is a mixture of MSSM-like and singlet components specified by $\cos^2\theta_A = 0.6$. The $\widetilde{\chi}_1^0$ is bino-like with a small higgsino admixture as specified by $\epsilon_B^2 = 0.94$, $\epsilon_u^2 = 0.06$.

  For each pair of contours (solid black, dashed red, and dot-dashed blue), the region between the lines is the space in which the neutralino's relic density does not exceed the measured density.

  The solid black, dashed red, and dot-dashed blue lines correspond to $\tan\beta = 50$, 15 and 3, respectively. Also shown as a dotted line is the contour corresponding to the resonance condition, $2m_{\widetilde{\chi}_1^0} = m_{a_1}$.

  For the $\tan\beta = 50$ or 15 cases, neutralino dark matter can avoid being overproduced for any a_1 mass below $\sim 20-60$ GeV, as long as $m_{\widetilde{\chi}_1^0} > m_b$. For smaller values of $\tan\beta$, a lower limit on m_{a_1} can apply as well.

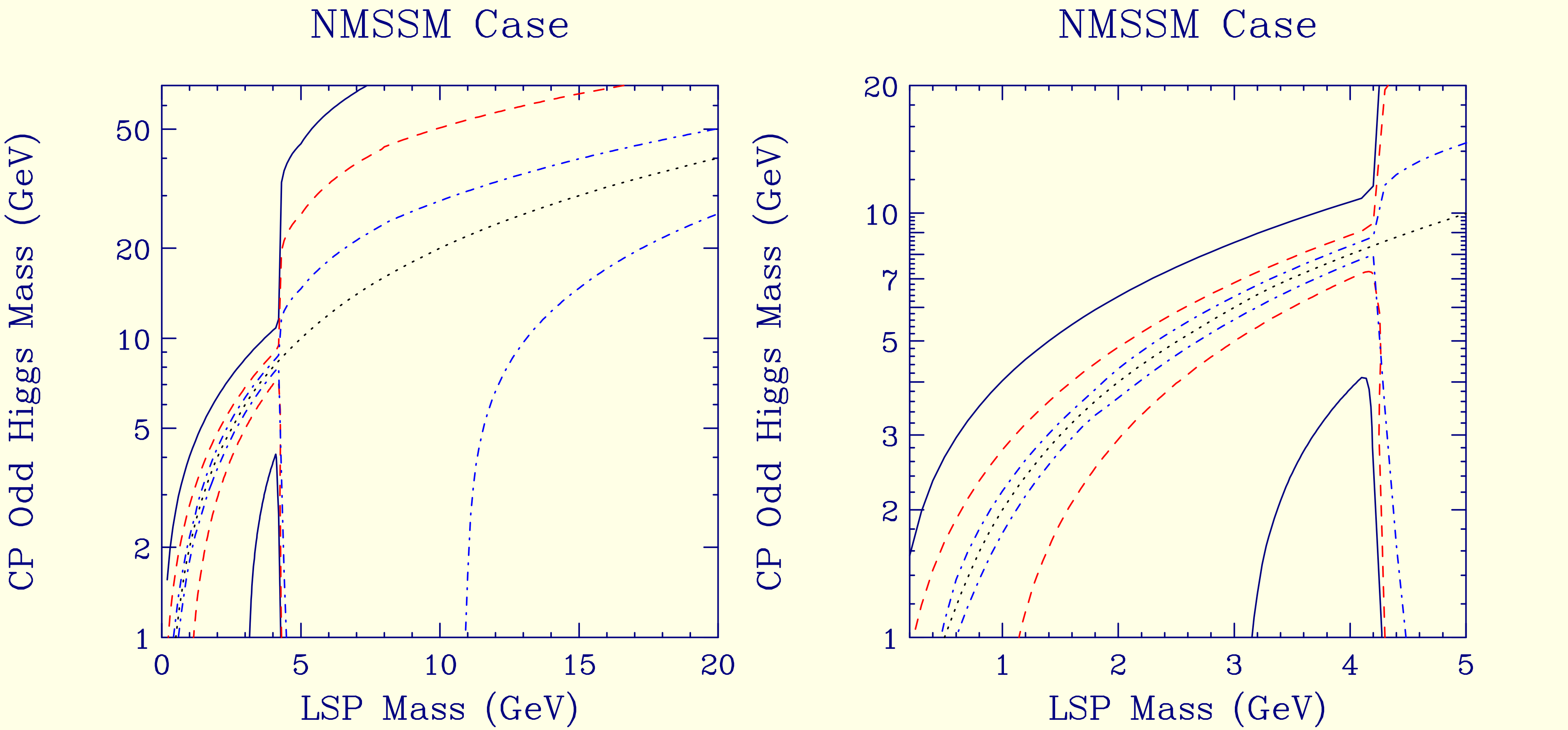

Figure 23: The CP-odd Higgs mass required to obtain the measured relic density for a light neutralino in the NMSSM. Legend: $\tan\beta = 50$ =black; $\tan\beta = 15$ =red; $\tan\beta = 3$ =blue. The RH plot is a repeat of the LH plot for the smallest $m_{\widetilde{\chi}_1^0}$ values. Region between lines $\Rightarrow \Omega h^2 < 0.1$.

For neutralinos lighter than the mass of the b-quark (see RH plot), annihilation is generally less efficient.

- **In the figure, we focused on the case of a bino-like LSP. If the LSP is mostly, but not purely, singlino, it is also possible to generate the observed relic abundance in the NMSSM.**

A number of features differ for the singlino-like case in contrast to a bino-like LSP, however.

1. **First, as discussed earlier, for pure singlino an LSP mass that is chosen to be precisely at the Higgs resonance, $m_{a_1} \simeq 2m_{\widetilde\chi_1^0}$, is not possible for this case: m_{a_1} is always less than $2m_{\widetilde\chi_1^0}$ by a significant amount.**
2. **Second, in models with a singlino-like LSP, the a_1 is generally also singlet-like and the product of $\tan^2\beta$ and $\cos^4\theta_A$ is typically very small. This limits the ability of a singlino-like LSP to generate the observed relic abundance.**
   Overall, annihilation is too inefficient for an LSP that is more than 80% singlino.

A sample point is presented in the table below.

Table 5: Sample point 3: singlino-like $\widetilde{\chi}_1^0$.

λ	κ	$\tan\beta$	μ	A_λ	A_κ	M_1	M_2
0.415867	-0.029989	1.78874	-175.622	-455.387	-39.671	7.1098	289.115

m_{a_1}	$\cos\theta_A$
8.35008	-0.187349

m_{h_1}	$\sqrt{\xi_u^2 + \xi_d^2}$
63.3851	0.229555

$m_{\widetilde{\chi}_1^0}$	$\epsilon_{\tilde{B}}$	$\epsilon_{\tilde{W}}$	ϵ_u	ϵ_d	$\epsilon_{\tilde{S}}$
-3.97588	-0.369729	0.0261634	0.252368	0.256015	0.856377

δa_μ	BR($b \longrightarrow s\mu^+\mu^-$)
-1.17325e-10	3.16148e-09

$\langle\sigma v\rangle$	Ωh^2
4.0846e-26 cm^3/s	0.120289

The above point has:

1. a light $\widetilde{\chi}_1^0$, that is mainly singlino;
2. a singlet-like h_1;
3. an a_1 with small non-singlet component;
4. a small δa_μ that neither hurts nor helps;
5. acceptable Ωh^2.

Direct DM Detection Possibilities

To give one example, for $\tan\beta = 50$, $\lambda = 0.2$ and a Higgs mass of $120~\mathrm{GeV}$, we estimate a neutralino-proton elastic scattering cross section on the order of $4 \times 10^{-42}~\mathrm{cm}^2$ ($4 \times 10^{-3}~\mathrm{fb}$) for either a bino-like or a singlino-like LSP.

This value may be of interest to direct detection searches such as CDMS, DAMA, Edelweiss, ZEPLIN and CRESST. To account for the DAMA data, the cross section would have to be enhanced by a local over-density of dark matter .

Implications for the LHC and ILC

- The LHC must be sensitive to a very light LSP.

  Not a problem since missing momentum is just as good as missing mass.

  However, it seems likely that the LHC will only set an upper limit on $m_{\widetilde\chi_1^0}$.

  There are the standard SPS1a and SPS1a-like decay chains that can be used to do this.

- At the ILC, we will want to get a direct handle on $m_{\widetilde{\chi}_1^0}$. It seems that this will be straightforward unless it is quite singlet-like.

  One needs to study how well the composition of the $\widetilde{\chi}_1^0$ can be determined at the ILC. We need to get all 5 components.

- Another difficulty for checking a light $\widetilde{\chi}_1^0$ scenario, will be the necessity to observe and measure the composition of the a_1.

  At the LHC, studies for a light a_1 are needed.

  Of course, all processes are suppressed as $\cos\theta_A \to 0$, so we could have trouble if the a_1 is singlet-like.

  The ILC environment will be much cleaner and one could hope to more easily see a very light a_1 in the relevant final states (that depend up m_{a_1}). Again, singlet suppression will take place.

  Also, don't forget that $\gamma\gamma \to a_1$ production has a substantial rate, although the backgrounds and such have not been examined for very low a_1. In principle, as shown by JFG and B. Grzadkowksi, various γ polarization asymmetries can be employed to determine that the a_1 observed is precisely CP-odd (implying a CP conserving NMSSM Higgs sector).

Higgs Conclusions

- If low fine-tuning is imposed for an acceptable model, we should expect:
  - a $m_{h_1} \sim 100~\mathrm{GeV}$ Higgs decaying via $h_1 \to a_1 a_1$.

    Higgs detection will be quite challenging at a hadron collider.

    Higgs detection at the ILC is easy using the missing mass $e^+e^- \to ZX$ method of looking for a peak in M_X.

    Higgs detection in $\gamma\gamma \to h_1 \to a_1 a_1$ will be easy.
  - The very smallest F values are attained when:
    * h_2 and h_3 have "moderate" mass, i.e. in the $300~\mathrm{GeV}$ to $700~\mathrm{GeV}$ mass range;
    * the a_1 mass is $< 2m_b$ and the a_1 has a substantial singlet component.
    * the stops and other squarks are light;
    * the gluino, and, by implication assuming conventional mass orderings, the wino and bino all have modest mass;

- Detailed studies of the $WW \to h_1 \to a_1 a_1$, $t\bar{t}h_1 \to t\bar{t}a_1 a_1$, diffractive $pp \to pph_1$ and $\widetilde{g}$ cascades with $\widetilde{\chi}_2^0 \to h_1 \widetilde{\chi}_1^0$ channels (with $h_1 \to 4b$ or 4τ) by the experimental groups at both the Tevatron and the LHC should receive significant priority.

- **It is likely that other models in which the MSSM μ parameter is generated using additional scalar fields can achieve small fine-tuning in a manner similar to the NMSSM.**

- **In general, very natural solutions to the fine-tuning and little hierarchy problems are possible in relatively simple extensions of the MSSM.**

  One does not have to employ more radical approaches or give up on small fine-tuning!

  Further, small fine-tuning probably requires a light SUSY spectrum in all such models and SUSY should be easily explored at both the LHC (and very possibly the Tevatron) and the ILC and $\gamma\gamma$ colliders.

  Only Higgs detection at the LHC will be a real challenge.

  Ability to check perturbativity of $WW \to WW$ at the LHC might prove to be very crucial to make sure that there really is a light Higgs accompanying light SUSY.

Dark Matter Conclusions

- We should avoid getting trapped in the MSSM Dark Matter scenarios.

  After all the MSSM has significant problems.

- Nature (string theory?) may well yield something like the NMSSM.

  Certainly, the NMSSM provides a good baseline in which to explore how much more flexibility there is for DM predictions and scenarios.

- If the NMSSM is any guide, we need to pay more attention to the possibility of a quite light $\widetilde{\chi}_1^0$ associated with a a_1 with about twice the mass.

  Such scenarios generate many possible signals in Υ decays and direct detection that could provide first hints. Maybe the DAMA observation or the $511~\mathrm{keV}$ photon are such a hint (but not both).

- Studies are needed to determine if the ILC can determine the $\widetilde{\chi}_1^0$ and a_1 properties to the precision needed to confirm that a light $\widetilde{\chi}_1^0$ is the source of DM (at least partially). IT MAY NOT BE EASY.