Central Exclusive Higgs Production and the NMSSM

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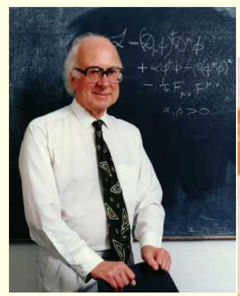
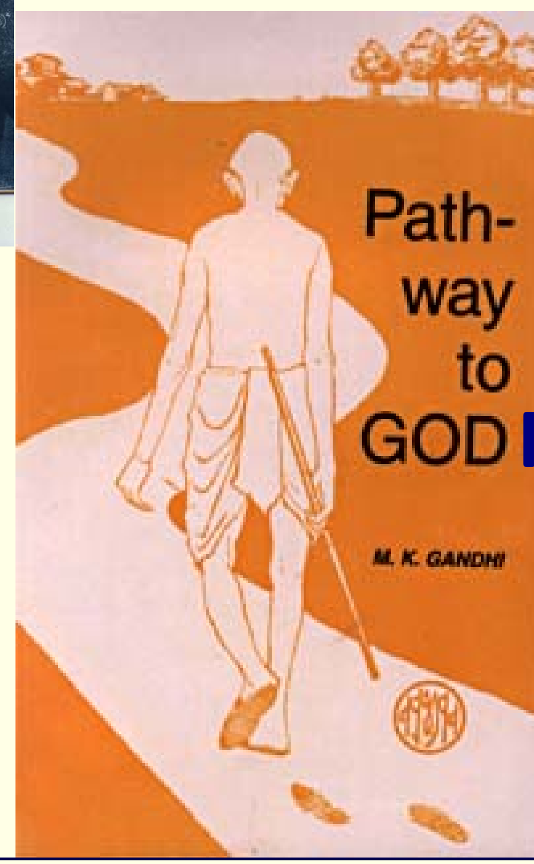
Outline

1. Why Supersymmetry?
2. Why not the MSSM?
3. Why the NMSSM?
4. Why $h \to aa$ with $m_a < 2m_b$?
5. Why $pp \to pph$?





Particle

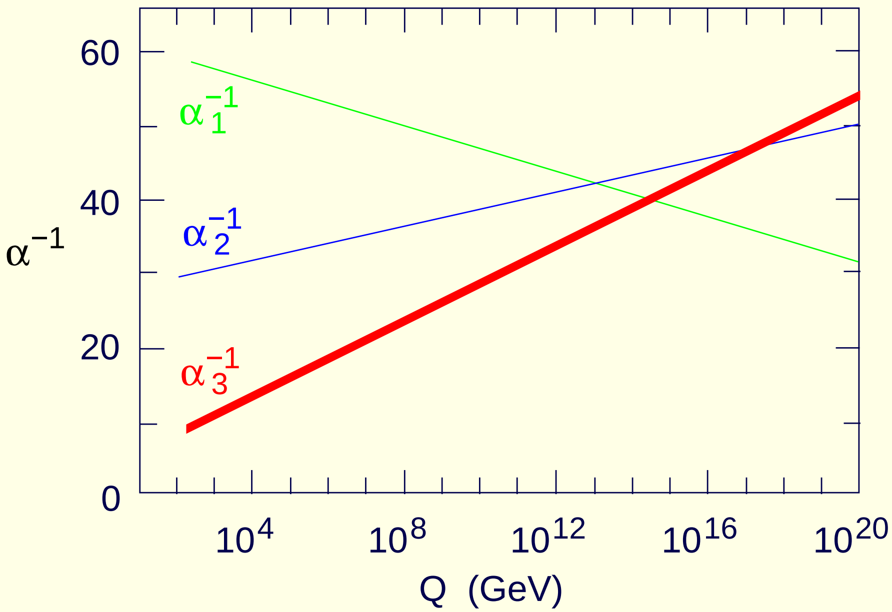
Why Supersymmetry?

- 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.
- SUSY cures the naturalness / hierarchy problem (quadratic divergences are largely canceled), and it does so without fine-tuning provided the SUSY breaking scale is $\lesssim 500~\mathrm{GeV}$.
- The MSSM comes close to being very nice.

  If we assume that all sparticles reside at the $\mathcal{O}(1~\mathrm{TeV})$ scale and that μ is also $\mathcal{O}(1~\mathrm{TeV})$, then, the MSSM has two particularly wonderful properties.

1. **Gauge Coupling Unification**

Standard Model



MSSM

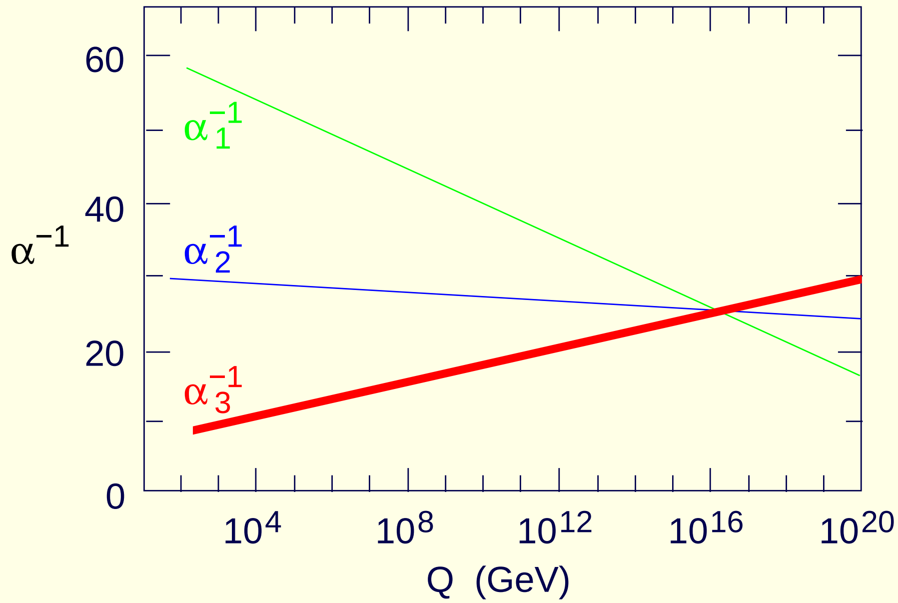


Figure 1: Unification of couplings constants ($\alpha_i = g_i^2/(4\pi)$) in the minimal supersymmetric model (MSSM) as compared to failure without supersymmetry.

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

2. RGE EWSB

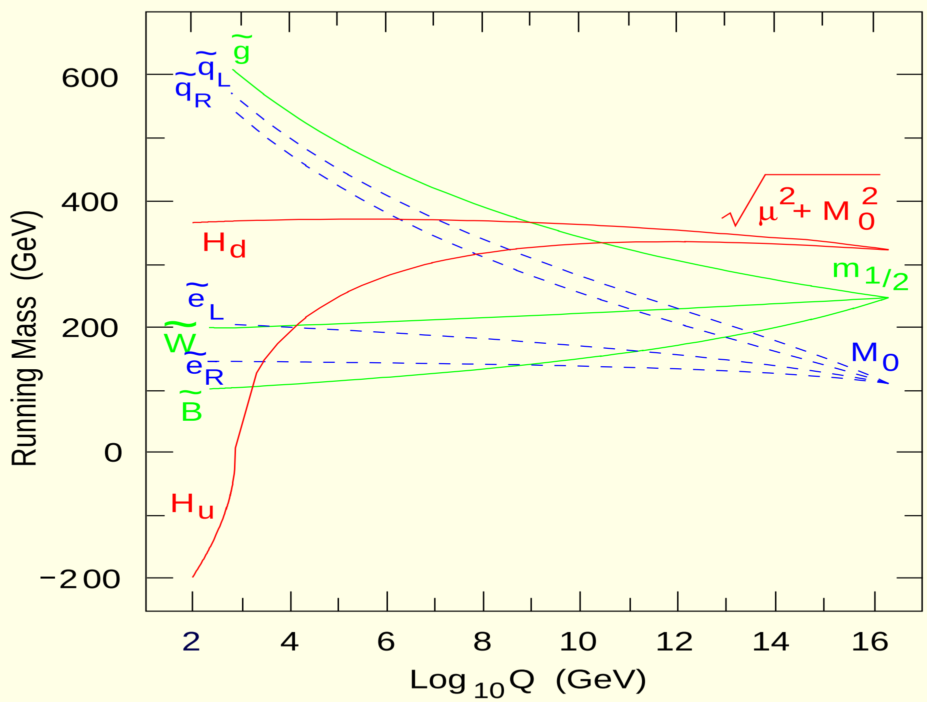


Figure 2: **Evolution of SUSY-breaking masses or masses-squared, showing how $m_{H_u}^2$ is driven < 0 at low $Q \sim \mathcal{O}(m_Z)$.**

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 ($m_{H_u}^2$) negative at a scale of order $Q \sim m_Z$, thereby automatically generating electroweak symmetry breaking ($\langle H_u \rangle = h_u, \langle H_d \rangle = h_d$), BUT MAYBE m_Z IS FINE-TUNED.

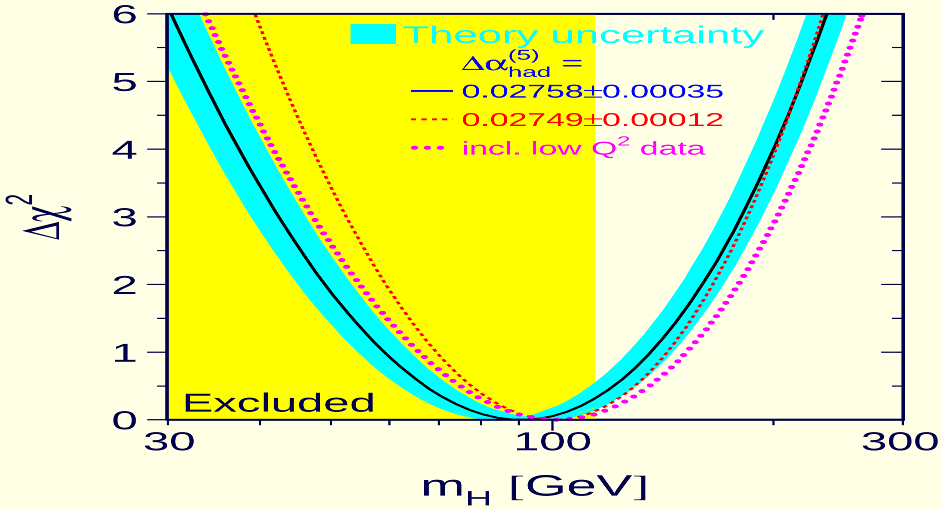
- **The Higgs Mass**

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

$$m_h^2 \sim m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} v^2 y_t^4 \sin^4\beta \log\left(\frac{m_{\widetilde{t}_1} m_{\widetilde{t}_2}}{m_t^2}\right) + \ldots$$

$$\stackrel{\text{large} \tan\beta}{\sim} (91\ \text{GeV})^2 + (38\ \text{GeV})^2 \log\left(\frac{m_{\widetilde{t}_1} m_{\widetilde{t}_2}}{m_t^2}\right). \quad (1)$$

A Higgs mass of order $100\ \text{GeV}$, 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?

Why not the MSSM?

- **The μ parameter** in $W \ni \mu \widehat{H}_u \widehat{H}_d$,[1] is dimensionful, unlike all other superpotential parameters. A **big question** is why is it $\mathcal{O}(1~\mathrm{TeV})$ (as required for EWSB and $m_{\widetilde{\chi}_1^\pm}$ lower bound), rather than $\mathcal{O}(M_U, M_{\mathrm{P}})$ or 0.

- **LEP limits:**

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

  There is still room, but we need $\sqrt{m_{\widetilde{t}_1} m_{\widetilde{t}_2}} \gtrsim 900~\mathrm{GeV}$. This leads to ....

- **Fine-tuning**

$$F = \mathrm{Max}_p \left| \frac{p}{m_Z} \frac{\partial m_Z}{\partial p} \right| , \tag{2}$$

where $p \in \left\{ M_{1,2,3}, m_Q^2, m_U^2, m_D^2, m_{H_u}^2, m_{H_d}^2, \mu, A_t, B\mu, \ldots \right\}$ (all at M_U).

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

$F > 20$ means worse than 5% fine tuning = bad.

Without large mixing, *i.e.* small A_t, F in the MSSM is much larger than this: $F > 100$ or so.

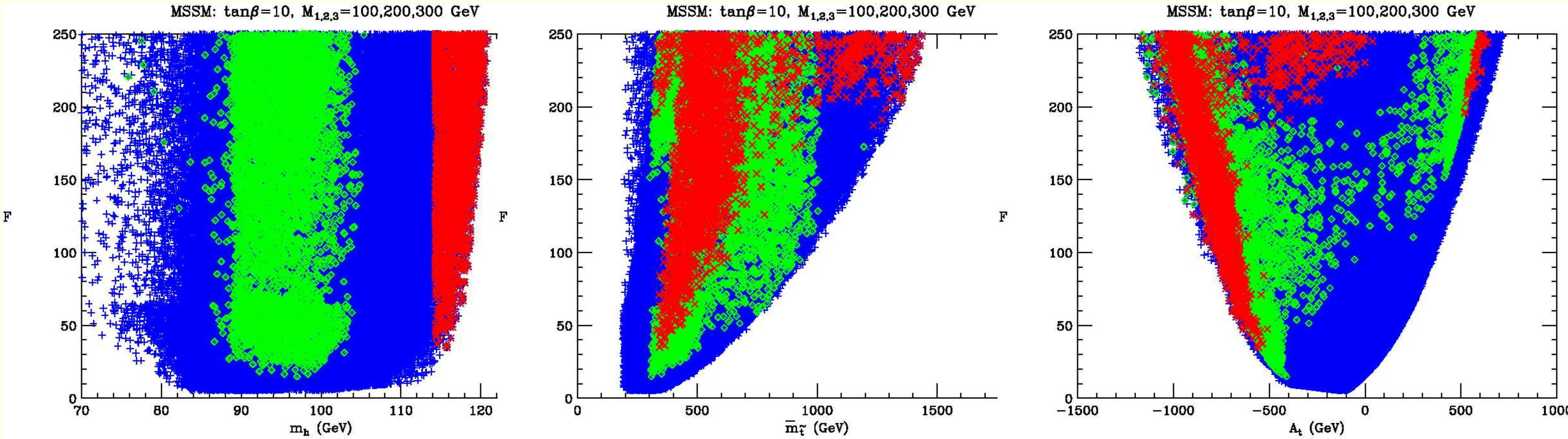


Figure 3: Fine tuning vs. m_h, $\bar{m}_{\tilde{t}}$, and A_t for randomly generated MSSM parameter choices with $\tan\beta = 10$ and $M_{1,2,3}(m_Z) = 100, 200, 300~\mathrm{GeV}$. Blue pluses correspond to parameter choices yielding $m_h < 114$ GeV that are ruled out by LEP limits on the Higgs mass and as a function of the ZZh coupling. Green diamonds are the mixed-Higgs scenarios with $m_h < 114~\mathrm{GeV}$ GeV that satisfy LEP limits due to reduced ZZh coupling. Red crosses are points with $m_h > 114$ GeV — these automatically satisfy LEP limits.

One can do somewhat better by having substantial mixing: for $A_t \sim -500\ \mathrm{GeV}$ (rather precisely) and $\bar{m}_{\tilde{t}} \sim 300\ \mathrm{GeV}$ (rather precisely) one can get $F \sim 15$.

This is not terrible, but it is certainly not as good as the NMSSM scenario we describe, for which $F \sim 5$ (*i.e.* no tuning) for extremely attractive GUT-scale parameter choices.

- The fine-tuning problems of the MSSM have motivated a large number of alternatives to the simple MSSM. These include large CP violation in the MSSM Higgs sector, extra dimensions, little Higgs models and so forth.
- But we (Dermisek, Gunion) think that the NMSSM is by far the most attractive.

Why the NMSSM?

1. The Next to Minimal Supersymmetric Model (NMSSM) maintains all the attractive features of the MSSM while avoiding all its problems.

2. In particular, the NMSSM solves the μ problem by adding just one extra singlet superfield, with superpotential $W \ni \lambda \widehat{S}\widehat{H}_u\widehat{H}_d$.

   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 $\langle S \rangle$ not be too small or too large.

   The latter is automatic if there are no dimensionful couplings in the superpotential since $\langle S \rangle$ is then of order the SUSY-breaking scale, which will be well below a TeV.

3. Further, there are very attractive scenarios in the NMSSM with no finetuning. To avoid finetuning, sparticles must be light, especially the stops; the optimal is $\sqrt{m_{\widetilde{t}_1}m_{\widetilde{t}_2}} \sim 350~\mathrm{GeV}$, somewhat above Tevatron limits but easily accessible at the LHC

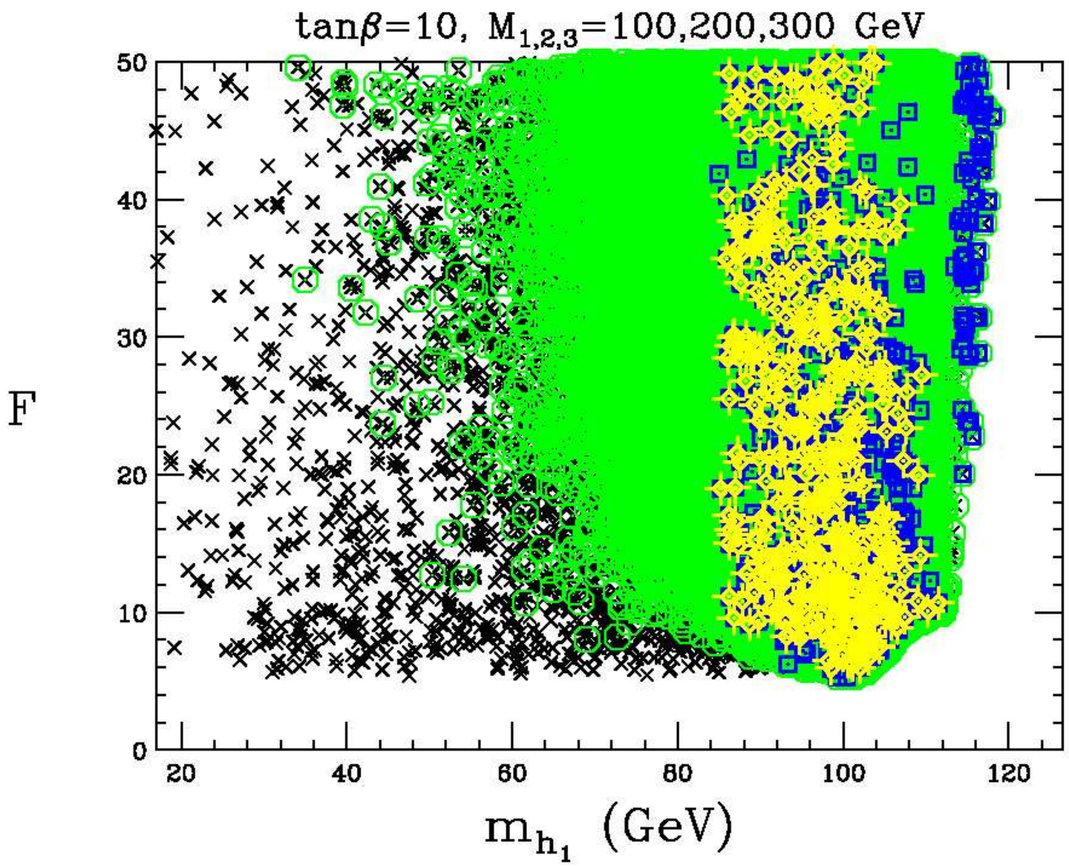


Figure 4: F vs. m_{h_1} for $M_{1,2,3} = 100, 200, 300$ GeV and $\tan\beta = 10$. Small $\times$ = no constraints other than global and local minimum, no Landau pole before M_U and neutralino LSP. The O's = stop and chargino limits imposed, but NO Higgs limits. The □'s = all LEP single channel, in particular $Z + 2b$, Higgs limits imposed. The large FANCY CROSSES are after requiring $m_{a_1} < 2m_b$, so that LEP limits on $Z + b's$, where $b's = 2b + 4b$, are not violated.

We see that for such stop masses, $m_{h_1} \sim 100$ GeV is predicted. This is perfect for precision electroweak, but what about LEP?

4. The points with smallest F are such that $m_{h_1} \sim 100$ GeV *and* $B(h_1 \to a_1 a_1) > 0.75$, with $m_{a_1} < 2m_b$ to avoid LEP limits.

   In the $h_1 \to a_1 a_1 \to \tau^+\tau^-\tau^+\tau^-$ channel, the LEP lower limit is $m_{h_1} > 89$ GeV.

   In the $h_1 \to a_1 a_1 \to 4j$ channel, the LEP lower limit is $m_{h_1} > 82$ GeV.

5. There is an intriguing coincidence.

   If $B(h_1 \to a_1 a_1) > 0.85$ and $B(h_1 \to b\bar{b}) \sim 0.1$, the 2.3σ LEP excess near $m_{b\bar{b}} \sim 98$ GeV in $e^+e^- \to Z + b's$ is perfectly explained.

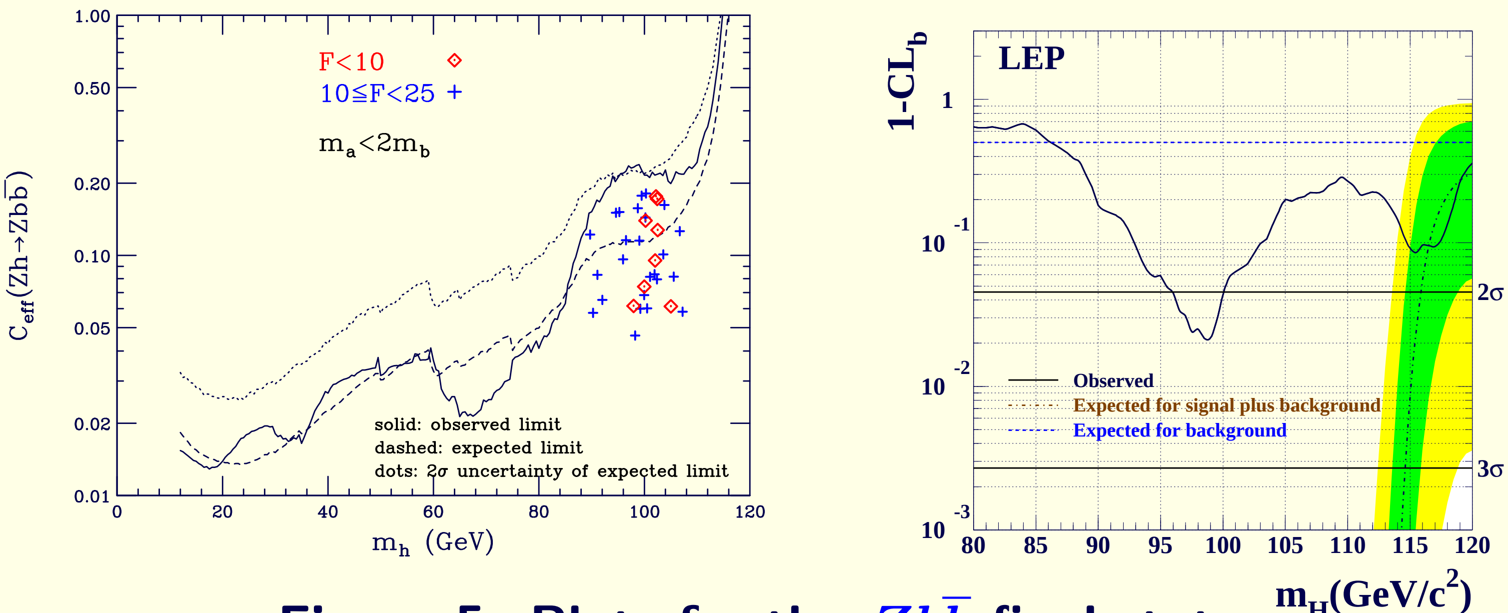


Figure 5: Plots for the $Zb\bar{b}$ final state.

6. **GUT-scale boundary conditions are generic 'no-scale'. That is, for the lowest F points we are talking about:**

$A_t(M_U)$, $A_\lambda(M_U)$, $A_\kappa(M_U)$ **are all small (see figure below) as are** $m^2_{H_u}(M_U)$, $m^2_{H_d}(M_U)$ **and** $m^2_S(M_U)$.

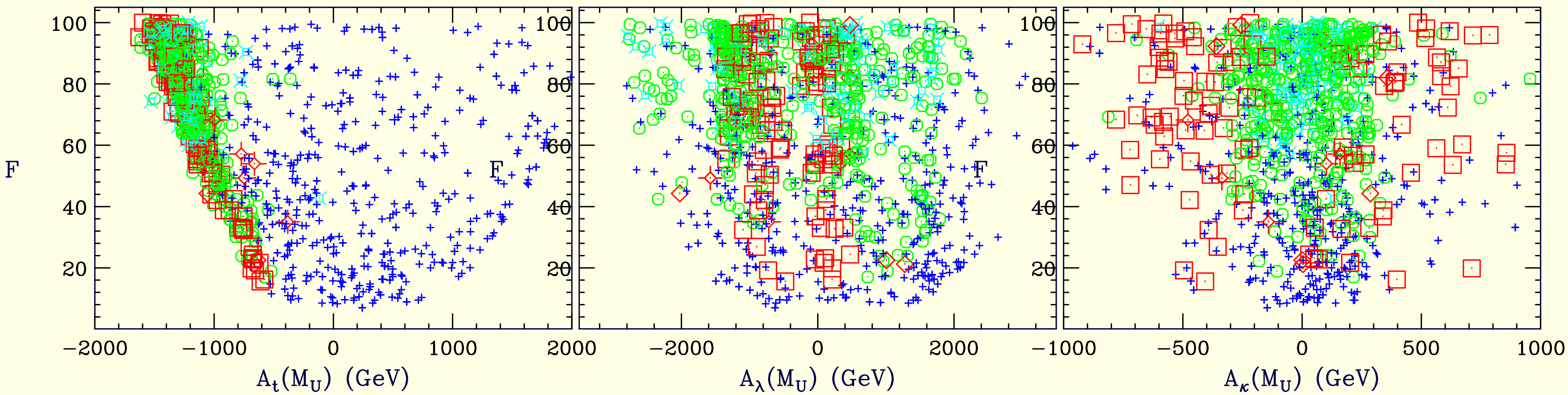


Figure 6: For fixed $M_{1,2,3}(m_Z) = 100, 200, 300$ GeV and $\tan\beta = 10$ we plot F as a function of $A_t(M_U)$, $A_\lambda(M_U)$ and $A_\kappa(M_U)$. All points have $F < 100$ and $m_{h_1} < 114$ GeV. The blue + points are ones with a very SM-like ZZh_1 coupling that escape LEP limits because $m_{a_1} < 2m_b$ and $h_1 \to a_1 a_1 \to 4\tau$ or $4j$ decays are dominant. All other points have $m_{a_1} > 2m_b$ with red boxes being analogous to the MSSM mixed Higgs scenarios with reduced ZZh_1 coupling. The green circles and cyan crosses are points for which h_1 has a large singlet component.

One possible issue for the proposed scenario.

Is a light a_1 with the right properties natural, or does this require fine-tuning of the GUT-scale parameters? To explore we need more understanding of

- **The parameters of the NMSSM**

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

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

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

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

  The final two input parameters are

$$\tan\beta = h_u/h_d \, , \quad \mu_{\rm eff} = \lambda s \, , \tag{5}$$

  where $h_u \equiv \langle H_u \rangle$, $h_d \equiv \langle H_d \rangle$ and $s \equiv \langle S \rangle$.

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

$$\lambda\ ,\ \kappa\ ,\ A_\lambda\ ,\ A_\kappa,\ \tan\beta\ ,\ \mu_{\rm eff}\ . \tag{6}$$

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.

- The naturalness of a light-a_1 scenario is the topic of hep-ph/0611142. We only state some results.
  - $m_{a_1} \to 0$ if $A_\kappa(m_Z), A_\lambda(m_Z) \to 0$ (associated with a $U(1)_R$ symmetry limit).

$$m_{a_1}^2 \simeq 3s\left(\frac{3\lambda A_\lambda v^2 \sin 2\beta}{2s^2} - \kappa A_\kappa\right)\Bigg|_{m_Z} \tag{7}$$

Although the $A_\lambda(m_Z), A_\kappa(m_Z) \to 0$ limit looks nice, in this limit

$B(h_1 \to a_1 a_1) \lesssim 0.2$, which is insufficient to decrease $B(h_1 \to b\bar{b})$ to the $\lesssim 0.2$ level needed for $m_{h_1} \sim 100~\mathrm{GeV}$ to escape LEP limits.

– However, a much more appealing choice is to be close to the $U(1)_R$ symmetry limit at the GUT scale by having $A_\kappa(M_U), A_\lambda(M_U) \sim 0$. Then, the renormalization group equations (RGE's) generate

$$A_\lambda(m_Z) \sim 100 - 200~\mathrm{GeV}\,, \quad A_\kappa(m_Z) \sim few~~\mathrm{GeV}\,. \tag{8}$$

Such values are exactly what we need for a variety of reasons.

1. Since $\mu_{\rm eff} = \lambda s$ with $\lambda < 0.25$ must be substantial, s is typically large and the contribution to $m_{a_1}^2$ of the A_λ term is as small as that of the A_κ term; $\Rightarrow m_{a_1}^2$ is small for the above $A_\kappa(m_Z)$ and $A_\lambda(m_Z)$ values.
2. Further, the RGE's often yield opposite signs for the $A_\kappa(m_Z)$ and $A_\lambda(m_Z)$ contributions to $m_{a_1}^2$ in Eq. (8) so that they partially cancel one another.
3. For appropriate M_U-scale boundary conditions, the cancellation can be totally automatic.
4. More generally, we can define a measure of the tuning needed to get

small m_{a_1} called G as:

$$G \equiv \mathrm{Min}\left\{\mathrm{Max}\left[|F_{A_\lambda}|,|F_{A_\kappa}|\right],|F_{A_\lambda}+F_{A_\kappa}|\right\}, \quad \text{with} \quad F_{A_\lambda} \equiv \frac{A_\lambda}{m_{a_1}^2}\frac{dm_{a_1}^2}{dA_\lambda}, \quad F_{A_\kappa} \equiv \frac{A_\kappa}{m_{a_1}^2}\frac{dm_{a_1}^2}{dA_\kappa}. \tag{9}$$

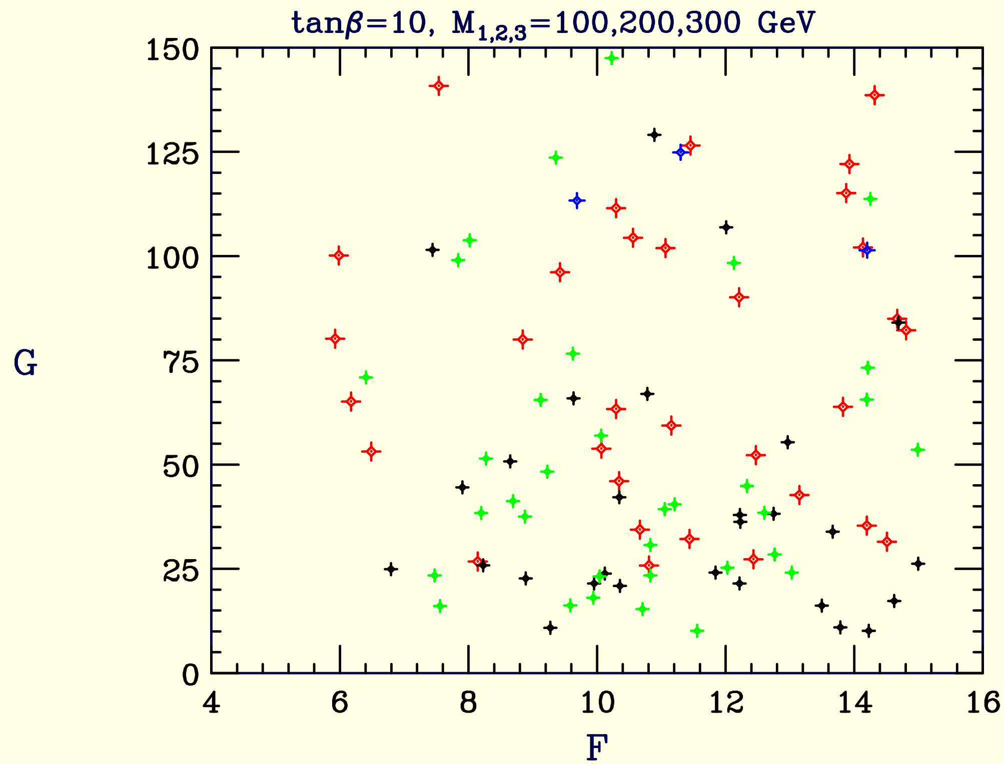


Figure 7: G vs. F for $M_{1,2,3} = 100, 200, 300$ GeV and $\tan\beta = 10$ for points with $F < 15$ having $m_{a_1} < 2m_b$ and large enough $B(h_1 \to a_1a_1)$ to escape LEP limits. The color coding is: blue $= m_{a_1} < 2m_\tau$; red $= 2m_\tau < m_{a_1} < 7.5$ GeV; green $= 7.5$ GeV $< m_{a_1} < 8.8$ GeV; and black $= 8.8$ GeV $< m_{a_1} < 9.2$ GeV.

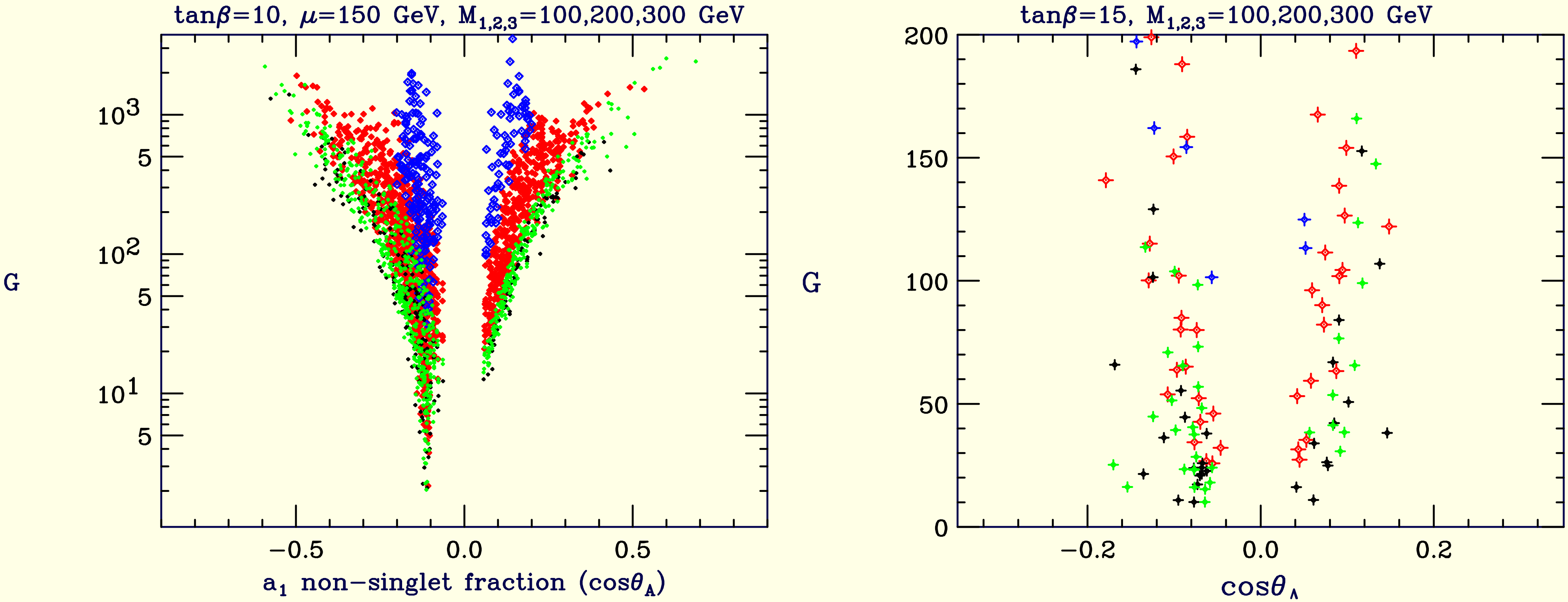


Figure 8: G vs. $\cos\theta_A$ for $M_{1,2,3} = 100, 200, 300$ GeV and $\tan\beta = 10$ from $\mu_{\rm eff} = 150$ GeV scan (left) and for points with $F < 15$ (right) having $m_{a_1} < 2m_b$ and large enough $B(h_1 \to a_1 a_1)$ to escape LEP limits. The color coding is: blue $= m_{a_1} < 2m_\tau$; red $= 2m_\tau < m_{a_1} < 7.5$ GeV; green $= 7.5$ GeV $< m_{a_1} < 8.8$ GeV; and black $= 8.8$ GeV $< m_{a_1} < 9.2$ GeV.

Small G implies it is quite natural to get small m_{a_1} without tuning the $A_\kappa(M_U)$ and $A_\lambda(M_U)$ values all that precisely.

In the plot $\cos\theta_A$ is defined as the coefficient of the MSSM-like doublet

Higgs component of the a_1:

$$a_1 = \cos\theta_A A_{MSSM} + \sin\theta_A A_S\,. \quad (10)$$

We observe:

1) The blue $+$'s, which are the points with $m_{a_1} < 2m_\tau$, have rather large G and tend to require precise tuning of A_λ and A_κ.

2) Really small G occurs for $m_{a_1} > 7.5~\mathrm{GeV}$ and $\cos\theta_A \sim -0.1$.

3) A lower bound on $|\cos\theta_A|$ is apparent. It arises because $B(h_1 \to a_1 a_1)$ falls below 0.75 for too small $|\cos\theta_A|$.

4) Such small $\cos\theta_A$ implies that the a_1 is mainly singlet and its coupling to $b\bar{b}$, being proportional to $\cos\theta_A \tan\beta$ is not enhanced.

Summary to this point:

- The NMSSM is intrinsically and phenomenologically superior to the MSSM.
- The 'ideal' scenario is fairly precisely specified:
  - $m_{h_1} \sim 100~\mathrm{GeV}$ for:

    $F < 10 - 15$, *i.e.* no fine tuning;

    Perfect precision electroweak.
  - $m_{a_1} < 2m_b$ and $|\cos\theta_A| > 0.06$ ($\tan\beta = 10$) for:

    Large enough $B(h_1 \to a_1 a_1)$ and absence of $a_1 \to b\bar{b}$ so as to escape LEP limits on $Z + b's$.

    Bonus: The LEP excess at $M_{2b} \sim 100~\mathrm{GeV}$ is perfectly described for a large fraction of the smallest F points.
  - $m_{a_1} > 2m_\tau$ and $\cos\theta_A \sim -0.1$ for minimizing the tuning of A_κ and A_λ associated with having $m_{a_1} < 2m_b$ and large $B(h_1 \to a_1 a_1)$.
- **Net Result:** Look for a $\sim 100~\mathrm{GeV}$ h_1 decaying via $h_1 \to a_1 a_1 \to \tau^+\tau^-\tau^+\tau^-$ or perhaps directly search for $a_1 \to \tau^+\tau^-$.

Detecting the h_1 and/or the a_1.

LHC

All standard LHC channels fail: $e.g.$ $B(h_1 \to \gamma\gamma)$ **is much too small because of large** $B(h_1 \to a_1 a_1)$**.**

The possible new LHC channels include:

1. $WW \to h_1 \to a_1 a_1 \to 4\tau$.

   Looks moderately promising but far from definitive results at this time.

2. $t\bar{t}h_1 \to t\bar{t}a_1a_1 \to t\bar{t}\tau^+\tau^-\tau^+\tau^-$.

   Study begun.

3. $\widetilde{\chi}^0_2 \to h_1\widetilde{\chi}^0_1$ **with** $h_1 \to a_1a_1 \to 4\tau$.

   (Recall that the $\widetilde{\chi}^0_2 \to h_1\widetilde{\chi}^0_1$ **channel provides a signal in the MSSM when** $h_1 \to b\bar{b}$ **decays are dominant.)**

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 event is quiet so that the tracks from the τ's appear in a relatively clean environment, allowing track counting and associated cuts.

   Our (JFG, Forshaw, Pilkington, Hodgkinson, Papaefstathiou) results are that one expects about 2 clean, i.e. reconstructed and tagged, events with no background per $30\ \mathrm{fb}^{-1}$ of luminosity.

   $\Rightarrow$ clearly a high luminosity game.

5. **The rather singlet nature of the a_1 and its low mass, imply that direct production/detection will be challenging at the LHC.**

   But, further thought is definitely warranted.

ILC

At the ILC, there is no problem since $e^+e^- \to ZX$ will reveal the $M_X \sim m_{h_1} \sim 100$ GeV peak no matter how the h_1 decays.

But the ILC is decades away.

B factories

As it turns out, $\Upsilon \to \gamma a_1$ decays hold great promise for a_1 discovery (or exclusion) as I now outline.

This kind of search should be pushed to the limit.

Perhaps this idea is gaining some traction with the B factory managers.

In particular, CLEO has started looking at their existing data and placed some useful, but not terribly constraining, new limits.

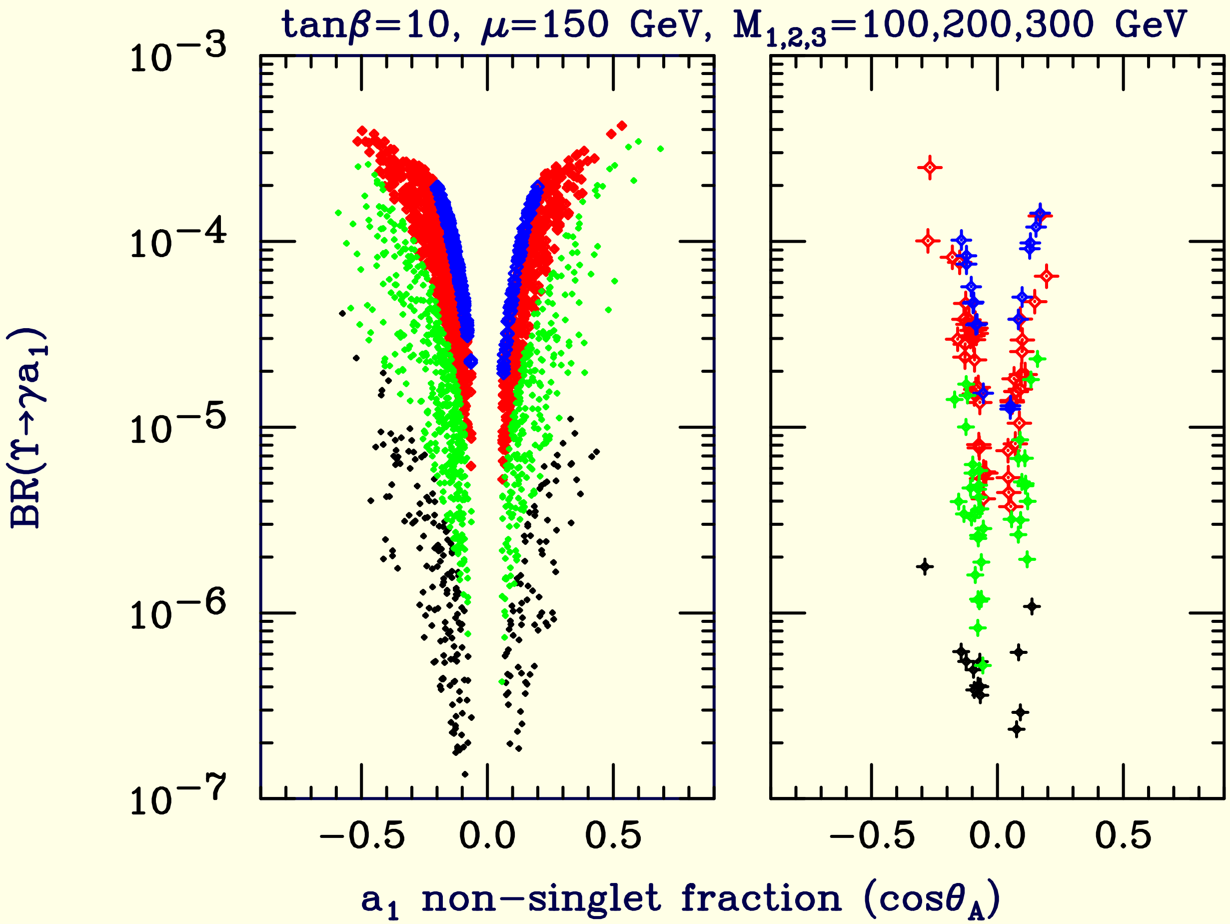


Figure 9: $B(\Upsilon \to \gamma a_1)$ for NMSSM scenarios with various ranges for m_{a_1} using color scheme of Fig. 8 (blue, red, green, black correspond to increasing m_{a_1} in that order). The left plot comes from an A_λ, A_κ scan, holding $\mu_{\rm eff}(m_Z) = 150$ GeV fixed. The right plot shows results for $F < 15$ scenarios with $m_{a_1} < 9.2$ GeV found in a general scan over all NMSSM parameters. The lower bound on $B(\Upsilon \to \gamma a_1)$ arises basically from the LEP requirement of $B(h_1 \to a_1 a_1) > 0.7$ which leads to the lower bound on $|\cos\theta_A|$ noted earlier.

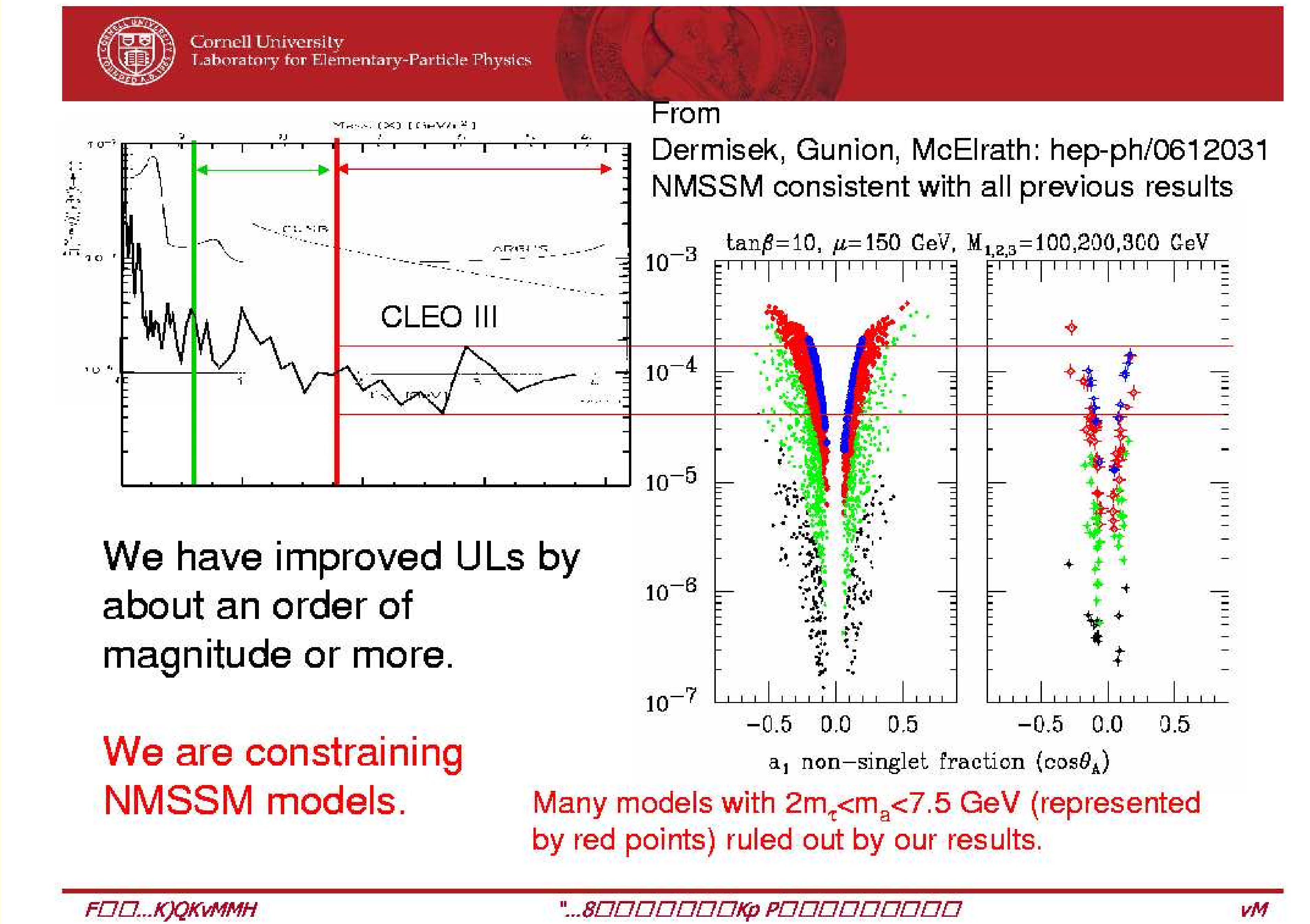


Figure 10: *New Limits from CLEO III (Krenick, Bottomonia, August 6, 2007) from* $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$*, which eliminates* $e^+e^- \to \gamma\tau^+\tau^-$ *background. Tag=2 prong (1 lepton)+* $\not{E}_T$*. Total of* 9 *Million* $\Upsilon(2S)$ *events.*

- Of course, we cannot exclude the possibility that $9.2~\mathrm{GeV} < m_{a_1} < 2m_b$.

  Phase space for the decay causes increasingly severe suppression.

  And, there is the small region of $M_\Upsilon < m_{a_1} < 2m_b$ that cannot be covered by Υ decays.

- However, if $B(\Upsilon \to \gamma a_1)$ sensitivity can be pushed down to the 10^{-7} level, one might discover the a_1.

  This would be very important input to the LHC program.

Further Comments

- Of course, one should consider $b \to s a_1$ inclusive decays (also exclusive).

  We are working on this and have some preliminary results based on the formulas given by Hiller.

  These results suggest that $b \to s a_1 \to s\mu^+\mu^-$ limits may exclude most of the $m_{a_1} < m_b$ scenarios, which in any case are less preferred by A_λ, A_κ tuning issues.

- $a_1 \to \gamma\gamma$ branching ratios remain very small in our scenarios because of the lower bound on $\cos\theta_A$, which implies that the a_1 has a minimum non-singlet component, in particular sufficient that a_1 decays to SM fermions dominate.

  For the general A_λ, A_κ scans with $B(h_1 \to a_1 a_1) > 0.7$ and $m_{a_1} < 2m_b$ imposed, $B(a_1 \to \gamma\gamma) < 4 \times 10^{-4}$ with values near $few \times 10^{-5}$ being very common.

  $\Rightarrow$ the a_1 search strategies suggested by Cheung and collaborators will not work for these scenarios.

  Is it conceivable that a super-B factory could detect a signal for $\Upsilon \to \gamma a_1 \to \gamma\gamma\gamma$ with branching ratio at the 10^{-10} level?

  This seems like a stretch to say the least. But, presumably backgrounds for three monochromatic photons are very tiny.

  Certainly detection in this channel would provide a very interesting discovery and/or check on the consistency of the model.

- Could the $\zeta(8.3)$ have been real?

  Obviously not at the level originally seen, but the mass fits perfectly with our scenarios.

Reconstruction of the h and a

The Collinearity Trick

- Since $m_a \ll m_h$, the a's in $h \to aa$ are highly boosted.

  $\Rightarrow$ the a decay products will travel along the direction of the originating a.

  $\Rightarrow$ $p_a \propto \sum$ visible 4-momentum of the charged tracks in its decay. Labelling the two a's with indices 1 and 2 we have

  $$p_i^{vis} = f_i \, p_{a,i} \qquad (11)$$

  where $1 - f_i$ is the fraction of the a momentum carried away by neutrals.

- The accuracy of this has now been tested in the $pp \to pph$ case, but after other cuts it is almost not needed.

- This reconstruction procedure will most likely be quite crucial in the $WW \to h$ case.

$pp \to pph$ with $h \to aa$

- The two unknowns, f_1 and f_2 can be determined using information from the forward proton detectors:

$$p_{a,1} + p_{a,2} = p_h \tag{12}$$

and p_h is measured.

- In fact, the situation is over constrained.

  Although the transverse momentum of the Higgs can be measured using the forward detectors it will typically be rather small. Assuming it to be zero leaves us with the three equations:

$$\frac{(p_1^{vis})_{x,y}}{f_1} + \frac{(p_2^{vis})_{x,y}}{f_2} = 0 \tag{13}$$

and

$$\frac{(p_1^{vis})_z}{f_1} + \frac{(p_2^{vis})_z}{f_2} = (\xi_1 - \xi_2)\frac{\sqrt{s}}{2} \tag{14}$$

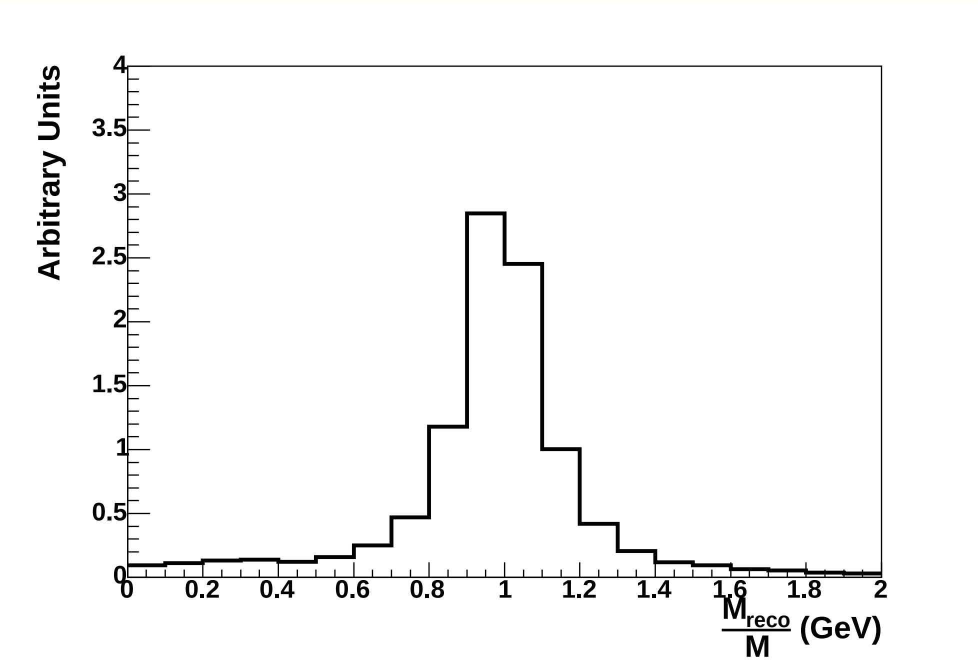
where x and y label the directions transverse to the beam axis and the $1-\xi_i$ are the longitudinal momenta of the outgoing protons expressed as fractions of the incoming momenta.

Solving (13) and (14) gives

$$f_1 = \frac{2}{(\xi_1-\xi_2)\sqrt{s}}\left[(p_1^{vis})_z - \frac{(p_2^{vis})_z(p_1^{vis})_{x,y}}{(p_2^{vis})_{x,y}}\right], \quad (15)$$

$$f_2 = -\frac{(p_2^{vis})_{x,y}}{(p_1^{vis})_{x,y}} f_1 . \quad (16)$$

Equations (15) and (16), provide two solutions depending on whether we solved using the (x,z) or (y,z) pair of equations.



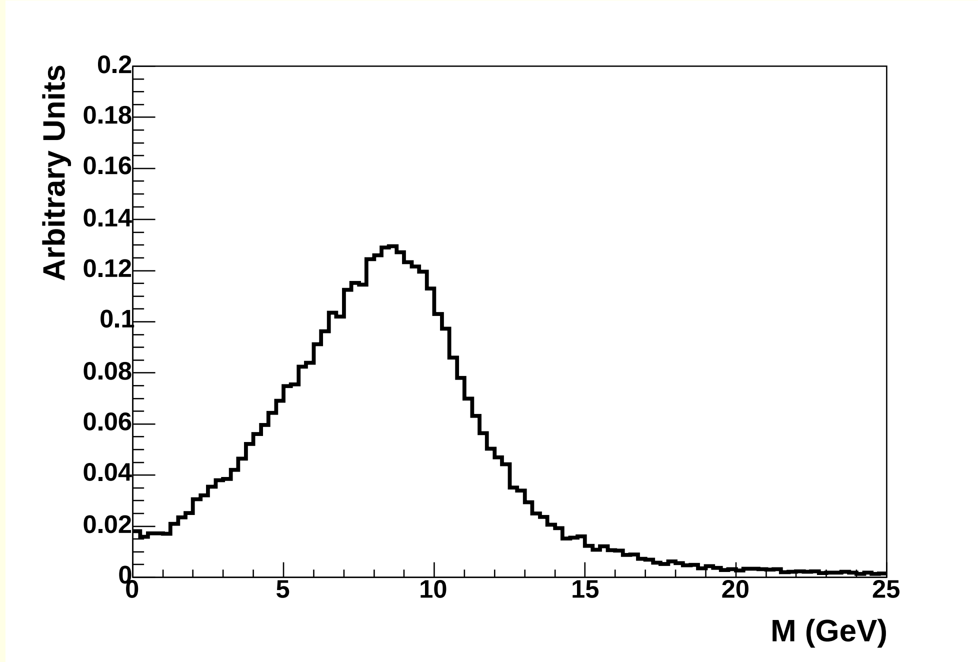


Figure 11: (a) The ratio of the reconstructed scalar Higgs mass to the mass measured by FP420 for the signal events only. (b) The reconstructed a mass for the signal events. The broad distribution is due to the breakdown of the collinearity approximation and detector effects are minimal.

- Figure 11(a) shows the ratio of the reconstructed m_h to that obtained using the forward detectors.

  We are able to make two measurements per event due to the over constrained nature of the system.

The distribution is broad, mainly as a result of the collinearity approximation and the missing momentum carried by neutral particles (this is a bigger effect than that due to detector smearing).

In the final analysis, we do not need to apply a cut on this variable because we have already adequately reduced the background.

- **In Figure 11(b), we show the reconstructed m_a mass distribution. A peak is clear and is at the correct mass.**

  In this case we are able to make four a mass measurements per event.

- **Of course, with only about 30 events the distributions will not look like these, but should be quite ok.**

$WW \to h$

- **In this case, we do not know the longitudinal momentum of the h, but we should have a good measurement of its transverse momentum from the tagging jets and other recoil jets.**

  In fact, in this case, it is very important that p_T^h be fairly large so that the a's are not back to back.

- **We then have the two equations:**

$$p_h^x = \frac{(p_1^{vis})_x}{f_1} + \frac{(p_2^{vis})_x}{f_2} \quad p_h^y = \frac{(p_1^{vis})_y}{f_1} + \frac{(p_2^{vis})_y}{f_2} \tag{17}$$

with solution

$$f_1 = \frac{(p_1^{vis})_y (p_2^{vis})_x - (p_1^{vis})_x (p_2^{vis})_y}{p_h^y (p_2^{vis})_x - p_h^x (p_2^{vis})_y} \quad f_2 = \frac{(p_1^{vis})_y (p_2^{vis})_x - (p_1^{vis})_x (p_2^{vis})_y}{-p_h^y (p_1^{vis})_x + p_h^x (p_1^{vis})_y} \tag{18}$$

- **Of course, this follows very much the same pattern as in $WW \to h_{\rm SM}$ with $h_{\rm SM} \to \tau^+\tau^-$ decays. Use of the collinear τ decay approximation and using the same equations for the visible τ decay products yields a pretty good $h_{\rm SM}$ mass peak in the LHC studies done of this mode.**

- **The success of the technique for determining m_h and m_a in the $pp \to pph$ case suggests it will work even when the diffractive forward proton information is not available.**

- **The main difference is that the techniques for and ability to isolate a di-tau system as opposed to a single tau have not yet been established at the LHC.**

Cautionary Notes

- While the $h_1 \to a_1 a_1$ with $a_1 \to \tau^+\tau^-$ and $m_{h_1} \sim 100~\mathrm{GeV}$ possibility certainly merits a strong effort to establish a viable discovery channel, nature could easily have chosen to be a bit more fine tuned.

  Light-a_1 finetuning, G

- While $m_{a_1} < 2m_\tau$ is less easily achieved than $m_{a_1} > 2m_\tau$, we should be prepared for this possibility.

  It yields a very difficult scenario for a hadron collider,

  $$h_1 \to a_1 a_1 \to 4j\,. \tag{19}$$

  Of course, a significant fraction will be charmed jets.

  A question is whether the $pp \to pph$ production mode might provide a sufficiently different signal from background that progress could be made.

If the a_1 is really light, then $h_1 \to 4\mu$ could be the relevant mode. This would seem to be a highly detectable mode, so don't forget to look for it — should be a cinch compared to 4τ.

m_Z-finetuning, F

- **In Fig. 4, the blue squares show that $m_{h_1} \sim 115~\mathrm{GeV}$ with m_{a_1} either below $2m_b$ or above $2m_b$ can be achieved if one accepts $F > 10$ rather than demanding the very lowest $F \sim 5$ finetuning measure.**

  Of course, we do not then explain the 2.3σ LEP excess, but this is hardly mandatory.

  And, $m_{h_1} \sim 115~\mathrm{GeV}$ is still ok for precision electroweak.

- **Thus, I would also advocate working on $pp \to pph$ (and other) signals assuming:**

  (a) $m_{h_1} \geq 115~\mathrm{GeV}$ with $h_1 \to a_1 a_1 \to \tau^+\tau^-\tau^+\tau^-$;

  (b) $m_{h_1} \geq 115~\mathrm{GeV}$ with $h_1 \to a_1 a_1 \to b\bar{b}b\bar{b}$.

  Obviously, the former channel analysis will be very similar to that Jeff will describe in the next talk.

The latter channel might be somewhat challenging. But, it should be pursued.

The basic thing to keep in mind:

For a primary Higgs with mass $\lesssim 150~\mathrm{GeV}$, dominance of $h_1 \to a_1 a_1$ decays, or even $h_2 \to h_1 h_1$ decays, is a very generic feature of any model with extra Higgs fields, supersymmetric or otherwise.

And, these Higgs could decay in many ways in the most general case.

One singlet

- String models with SM-like matter content that have been constructed to date have many singlet superfields.

  One should anticipate the possibility of several, even many different Higgs-pair states being of significance in the decay of the SM-like Higgs of the model.

Conclusions

- **The NMSSM naturally has small fine-tuning of all types,** *i.e.* **for:**

  1) EWSB, *i.e.* m_Z^2

  2) small $m_{a_1} < 2m_b$**, as needed for 1), and (simultaneously) large** $B(h_1 \to a_1 a_1)$**;**

  $m_{a_1} > 2m_\tau$ **is somewhat preferred by this** A_λ, A_κ **fine-tuning issue.**

- **If low fine-tuning is imposed for an acceptable SUSY model, we should expect:**

  – **a** h_1 **with** $m_{h_1} \sim 100~\mathrm{GeV}$ **and SM-like couplings to SM particles but with primary decays** $h_1 \to a_1 a_1$ **with** $m_{a_1} < 2m_b$**, where the** a_1 **is mainly singlet.**

    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.**
    Detection of the a_1 **could easily result from pushing on** $\Upsilon \to \gamma a_1$**.**

– the stops and other squarks are light;
– the gluino, and, by implication assuming conventional mass orderings, the wino and bino all have modest mass;

- Although SUSY will be easily seen at the LHC Higgs detection at the LHC will be a real challenge. Still, as described in the next talk, we have shown that a signal should emerge in CEP, assuming the cross section has not been overestimated.

- Even if the LHC sees the Higgs $h_1 \to a_1 a_1$ directly, it will not be able to get much detail. Only the ILC and possibly B-factory results for $\Upsilon \to \gamma a_1$ can provide the details needed to verify the model.

- 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.

  Low fine-tuning typically requires low SUSY masses which in turn typically imply $m_{h_1} \sim 100~\mathrm{GeV}$.

  And, to escape LEP limits large $B(h_1 \to a_1 a_1)$ with $m_{a_1} < 2m_b$ would be needed.

  In general, the a_1 might not need to be so singlet as in the NMSSM and

would then have larger $B(\Upsilon \to \gamma a_1)$.

- **If the LHC Higgs signal is really marginal in the end, and even if not, the 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 and that it carries most of the SM coupling strength to WW.**

- **A light a_1 allows for a light $\widetilde{\chi}_1^0$ to be responsible for dark matter of correct relic density: annihilation would be via $\widetilde{\chi}_1^0\widetilde{\chi}_1^0 \to a_1$. To check the details, properties of the a_1 will need to be known fairly precisely**

  The ILC might (but might not) be able to measure the properties of the very light $\widetilde{\chi}_1^0$ and of the a_1 in sufficient detail to verify that it all fits together.

  But, also $\Upsilon \to \gamma a_1$ decay information would help tremendously.