

# Probing the NMSSM $h \rightarrow aa$ Decay Scenario in Upsilon Decays

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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

R. Dermisek and J. Gunion, hep-ph/0611142 and hep-ph/0611197

R. Dermisek, J. Gunion and B. McElrath, hep-ph/0612031 \*\*\* today's focus

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

Thanks to Miguel Sanchis-Lozano who stressed the importance of this study.

# Outline

1. The LHC is coming, but is it guaranteed to find the Higgs of any SUSY model? Or, might  $\Upsilon$  decays provide the first (and only?) Higgs signal before the ILC?
2. **Why focus on SUSY?**  $\Rightarrow$  It remains the most attractive way to solve the hierarchy problem.
3. The Minimal SUSY Model (MSSM) is very attractive, but LEP limits on the lightest Higgs and the gluino imply that it is highly fine-tuned.
4. The Next to Minimal Supersymmetric Model (NMSSM) maintains all the attractive features of the MSSM while avoiding fine tuning, **especially if**  $m_{h_1} \sim 100$  GeV.
5. Low-fine-tuning NMSSM models with  $m_{h_1} \sim 100$  GeV require  $B(h_1 \rightarrow a_1 a_1) > 0.7$ , with  $m_{a_1} < 2m_b$  to avoid LEP limits.
6.  $m_{h_1} \sim 100$  GeV is perfect for precision electroweak and, with  $B(h_1 \rightarrow b\bar{b}) \sim 0.1$ , explains the  $2.3\sigma$  LEP excess near  $m_{b\bar{b}} \sim 98$  GeV in  $e^+e^- \rightarrow Z + b's$ .

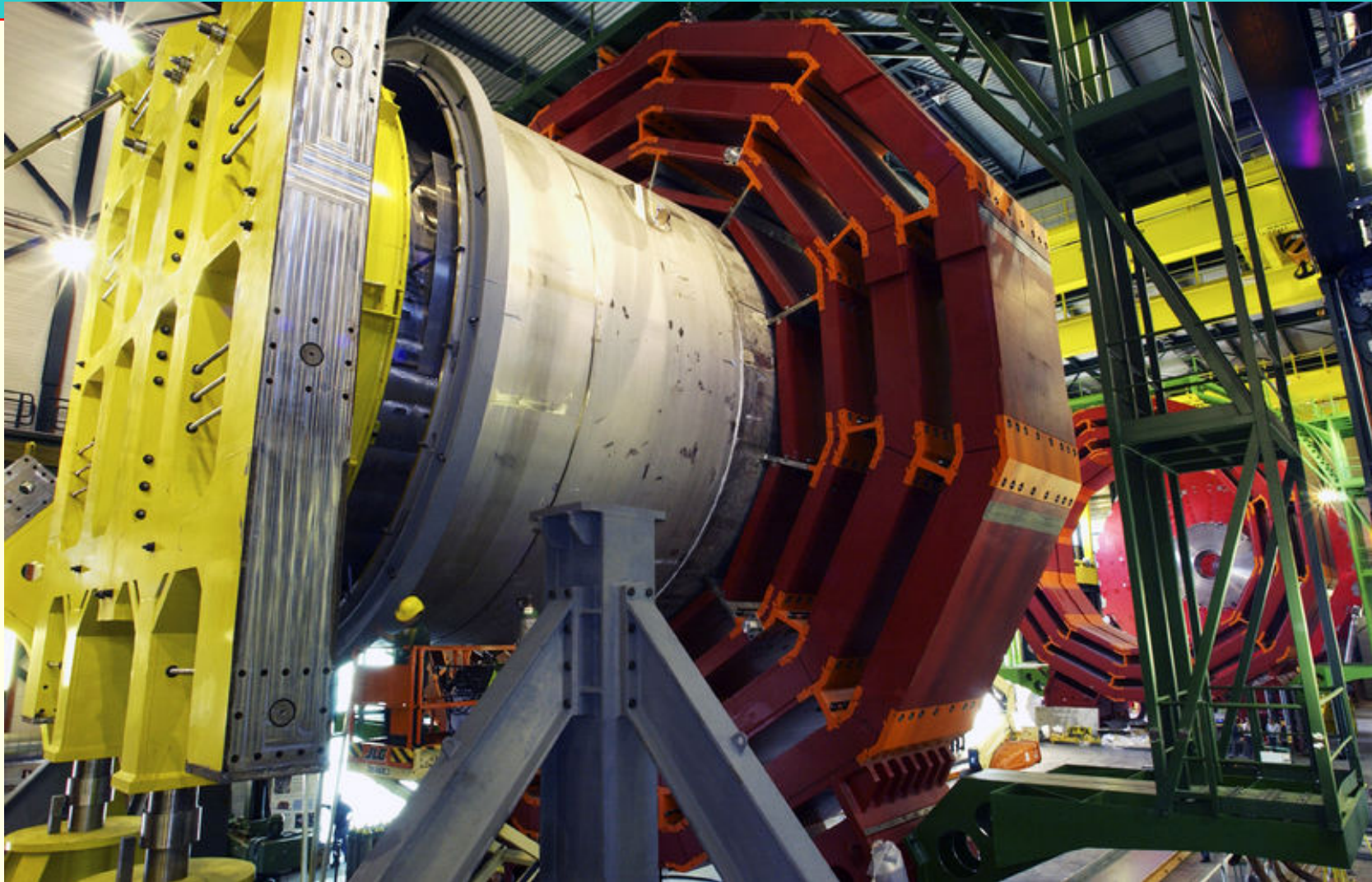
## 7. Collider Implications

One should look again at the LEP data for  $h \rightarrow aa$  Higgs signals, especially with  $aa \rightarrow 4\tau$ .

Higgs discovery at the LHC will be essentially impossible in all the standard modes explored to date. New modes based on  $h \rightarrow aa \rightarrow 4\tau$  or  $4j$  must be proven.

Sensitivity to  $B(\Upsilon \rightarrow \gamma a_1)$  down to  $10^{-6}$  (maybe  $10^{-7}$  would be needed) could find the  $a_1$  in the near future!

## The LHC is at hand



### The CMS Detector

**But will the LHC detectors detect the Higgs boson. The very attractive NMSSM SUSY scenario suggests we may have to work hard.**

# The Beauty of Supersymmetry

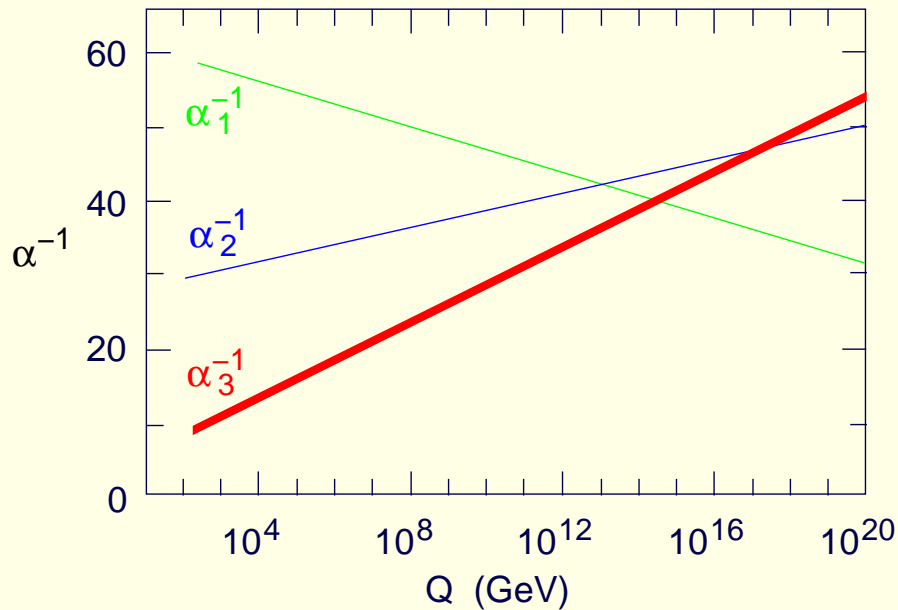
- SUSY is mathematically intriguing.
- SUSY is naturally incorporated in string theory.
- Scalar fields have a natural place in SUSY, and so there are candidates for the spin-0 fields needed for electroweak symmetry breaking and Higgs bosons.
- SUSY cures the naturalness / hierarchy problem (quadratic divergences are largely canceled) provided the SUSY breaking scale is of order  $\sim 1$  TeV.
- The MSSM comes close to being very nice.

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

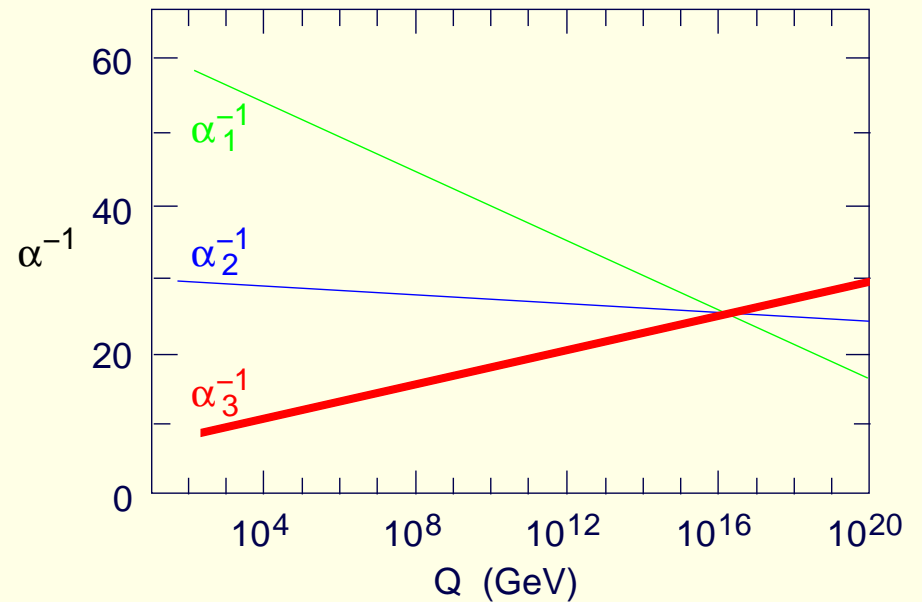
1.

# 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  $M_U \sim \text{few} \times 10^{16}$  GeV, close to  $M_P$ . High-scale unification correlates well with the attractive idea of gravity-mediated SUSY breaking.



## 2.

## RGE EWSB

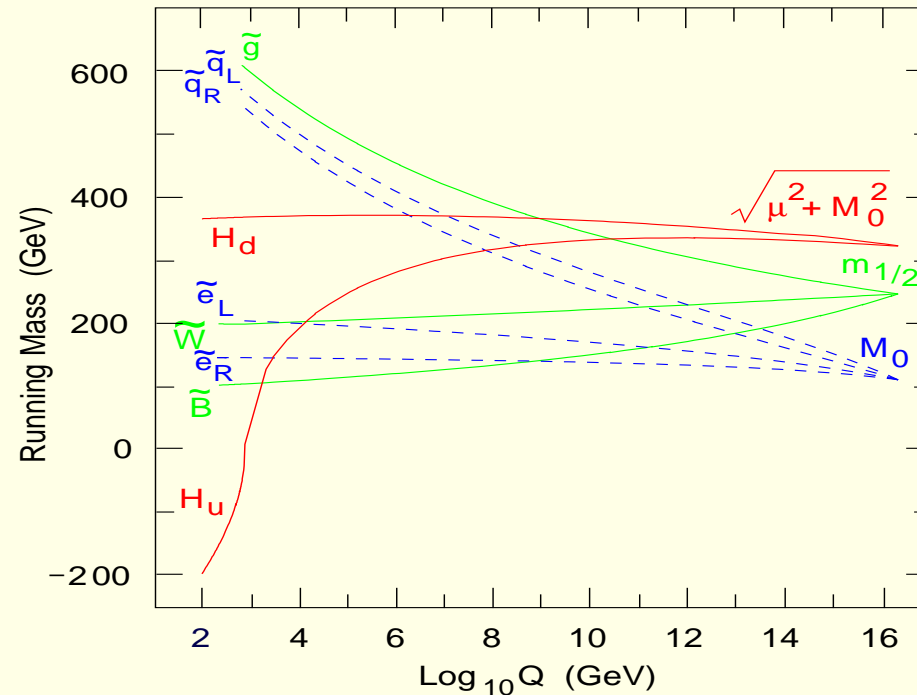


Figure 2: Evolution of SUSY-breaking masses or masses-squared, showing how  $m_{H_u}^2$  is driven  $< 0$  at low  $Q \sim \mathcal{O}(m_Z)$ .

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.**

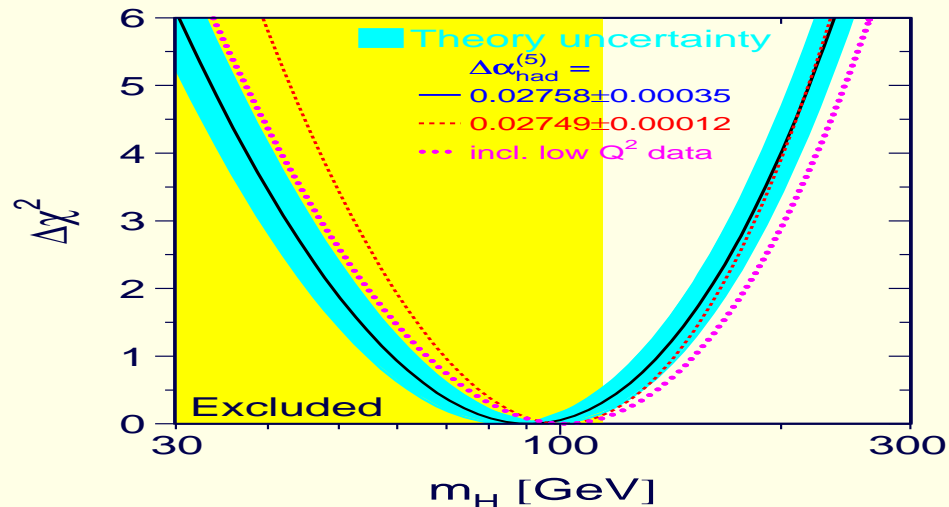
## The Higgs Mass

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

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

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

A Higgs mass of order 100 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, or is the MSSM too simple? We argue for the latter!



# MSSM Problems

- The  $\mu$  parameter in  $W \ni \mu \widehat{H}_u \widehat{H}_d$ ,<sup>1</sup> is dimensionful, unlike all other superpotential parameters. A big question is why is it  $\mathcal{O}(1 \text{ TeV})$  (as required for EWSB and  $m_{\tilde{\chi}_1^\pm}$  lower bound), rather than  $\mathcal{O}(M_U, M_P)$  or 0.

Currently no satisfactory approach within the MSSM context.

- **LEP limits:**

In the MSSM, the lightest Higgs boson is typically very SM-like (no time to discuss exceptions such as CP violation in the Higgs sector).

The LEP limit for a SM-like Higgs boson is  $m_h > 114.4 \text{ GeV}$ .

In contrast, if sparticles have masses below a TeV,  $m_h \sim 100 \text{ GeV}$  is the natural prediction.

From earlier formula, we need  $\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} > 900 \text{ GeV}$  for  $m_h > 114.4 \text{ GeV}$ . This leads to a new problem.

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

- **Fine-tuning**

$m_Z^2$  is very sensitive to GUT scale parameters if sparticles masses, especially those of the stops and the gluino, are large.

We need a very light gluino and a rather light stop to avoid fine-tuning.

A rigorous measure of fine-tuning is

$$F = \text{Max}_p \left| \frac{p}{m_Z} \frac{\partial m_Z}{\partial p} \right|, \quad (2)$$

where  $p$  runs over all GUT scale parameters.

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

In the MSSM, if  $m_h \sim 100$  GeV was ok (*i.e.* not LEP excluded), then small  $F < 20$  would be possible.

Instead, for heavy enough sparticles that  $m_h > 114.4$  GeV the smallest value of  $F$  (avoiding extreme stop mixing) is  $F \sim 125$  which is equivalent to worse than 1% fine tuning.

One can do somewhat better if stop mixing is very large — but never as good as the NMSSM scenario we describe, which has  $F < 15$ , even as small as  $F \sim 5$ , without any extreme parameter choices.

- **So, what direction should one head in?**

- CP-violating MSSM, e.g. CPX-like scenarios?

These don't solve the  $\mu$  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 these models are complicated and typically have problems of one kind or another, especially precision EW data.

- Hints from string theory.

**Extra singlet superfields are common in string models.**

If we make use of singlets in the simplest possible way (i.e. no associated gauge group and no dimensionful superpotential parameters)  $\Rightarrow$  **the NMSSM.**

# The NMSSM

- The NMSSM introduces just one extra singlet superfield, with superpotential  $W \ni \lambda \widehat{S} \widehat{H}_u \widehat{H}_d$ . The  $\mu$  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  $\sim 1$  TeV.
- However,  $\lambda \widehat{S} \widehat{H}_u \widehat{H}_d$  cannot be the end.

To avoid a massless axion, we require an additional superpotential term,  $W \ni \frac{1}{3} \kappa \widehat{S}^3$ .

Other possible superpotential terms with dimensionful parameters are absent if one demands that the superpotential be invariant under a  $Z_3$  symmetry.

If the  $Z_3$  is applied also to soft SUSY breaking terms, only  $\frac{1}{3} \kappa A_\kappa S^3$  is allowed in addition to  $\lambda A_\lambda S H_u H_d$ .

- **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) ( $\Rightarrow \tilde{\chi}_{1,2,3,4,5}^0$ ), an extra CP-even Higgs boson ( $\Rightarrow h_{1,2,3}$ ) and an extra CP-odd Higgs boson ( $\Rightarrow a_{1,2}$ ).

- **The parameters of the NMSSM**

Apart from  $\lambda$ ,  $\kappa$ ,  $A_\lambda$  and  $A_\kappa$  the other two crucial Higgs sector parameters are

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

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

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.

- To further study of the NMSSM Higgs sector, Ellwanger, Hugonie and I constructed NMHDECAY

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

It computes all aspects of the Higgs sector and checks against most LEP limits and various other constraints.

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

In a series of papers (beginning with JFG+Haber+Moroi at Snowmass 1996 and continued by JFG, Ellwanger, Hugonie, Moretti, Miller, .. .) we have demonstrated a significant “hole” in the LHC no-lose theorem for Higgs discovery.

Only if we avoid that part of parameter space for which  $h \rightarrow aa$  and similar decays are present is there a guarantee for finding a Higgs boson at the LHC in one of the nine “standard” channels (e.g.  $h \rightarrow \gamma\gamma$ ,  $t\bar{t}h$ ,  $a \rightarrow t\bar{t}b\bar{b}$ ,  $t\bar{t}h$ ,  $a \rightarrow t\bar{t}\gamma\gamma$ ,  $b\bar{b}h$ ,  $a \rightarrow b\bar{b}\tau^+\tau^-$ ,  $WW \rightarrow h \rightarrow \tau^+\tau^-$ , ...)

- The portion of parameter space with  $h \rightarrow aa, \dots$  is small  $\Rightarrow$  one is tempted to ignore it **were it not for the fact that it is where fine-tuning can be absent.**

As before, the canonical measure of fine-tuning employed is

$$F = \text{Max}_p F_p \equiv \text{Max}_p \left| \frac{d \log m_Z}{d \log p} \right|, \quad (4)$$

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

- **How do we get small fine-tuning?**

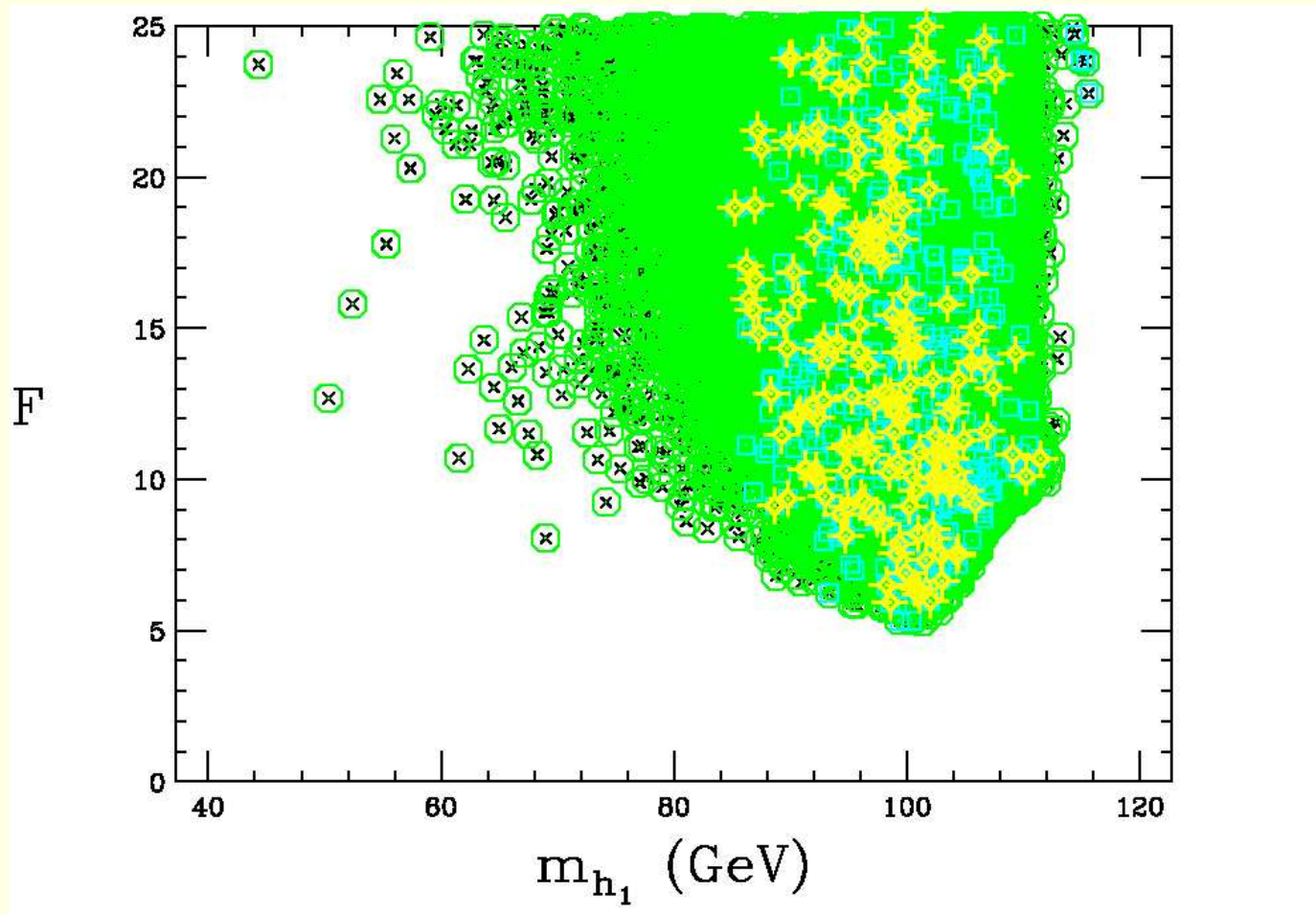
1.  $F$  can be small ( $F < 7, \Rightarrow$  fine-tuning no worse than 15%) for  $m_{h_1} \sim 100 \div 104$  GeV (in a totally unconstrained scan of parameter space this is just what one finds for moderate  $\tan \beta$ ). **Neither lower nor higher!** See figure on next page.

$m_{h_1} \sim 100$  GeV requires  $\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \sim 350$  GeV, as expected.

2.  $m_{h_1} \sim 100$  GeV is only LEP-allowed if the main decay is  $h_1 \rightarrow a_1 a_1$  and if  $a_1 \rightarrow \tau^+ \tau^-$  ( $2m_\tau < m_{a_1} < 2m_b$ ) or  $gg, q\bar{q}$  ( $m_{a_1} < 2m_\tau$ ) so that  $h_1 \rightarrow a_1 a_1 \rightarrow 4b's$  does not contribute to the strongly limited (for



$m_{h_1} < 110$  GeV)  $Z + b$ 's final state at LEP.



**Figure 3:**  $F$  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  $\circ$ 's = stop and chargino limits imposed, but **NO** Higgs limits. The  $\square$ '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.

3. **An important issue: How natural is a light  $a_1$  with  $B(h_1 \rightarrow a_1 a_1)$  large?** This is the topic of hep-ph/0611142. We only state some results. First some preliminaries.

- $m_{a_1} \rightarrow 0$  if  $A_\kappa(m_Z), A_\lambda(m_Z) \rightarrow 0$  (associated with a  $U(1)_R$  symmetry limit).
- However, in this limit  $B(h_1 \rightarrow a_1 a_1) \lesssim 0.2$ , which is insufficient to decrease  $B(h_1 \rightarrow b\bar{b})$  to the  $\lesssim 0.2$  level needed for  $m_{h_1} \sim 100$  GeV to escape LEP limits.
- If  $A_\kappa(M_U), A_\lambda(M_U) \sim 0$  (possibly a nice model choice), then renormalization group equations (RGE's) generate

$$|A_\lambda(m_Z)| \sim 100 - 200 \text{ GeV}, \quad |A_\kappa(m_Z)| \sim \text{few GeV}. \quad (5)$$

This is just what is needed to get large  $B(h_1 \rightarrow a_1 a_1)$ ; see below.

- What is actually crucial is the composition of  $a_1$  in terms of how much singlet Higgs,  $a_S$ , and how much doublet Higgs,  $A_{MSSM}$ :

$$a_1 \equiv \cos \theta_A A_{MSSM} + \sin \theta_A a_S. \quad (6)$$

To get  $B(h_1 \rightarrow a_1 a_1) > 0.7$ , as required by LEP limits for  $m_{h_1} \sim 100$  GeV, requires  $|\cos \theta_A| \gtrsim 0.05$  (at  $\tan \beta = 10$ ), and this can only

be achieved for  $|A_\lambda| \gtrsim 100$  GeV and  $|A_\kappa| \gtrsim \text{few}$  GeV, as predicted by RGE, as noted in Eq. (5).

4. So, is  $m_{a_1} < 2m_b$  with sufficiently large  $|A_\lambda|, |A_\kappa|$  to have  $|\cos \theta_A| \gtrsim 0.05$  achievable without fine tuning the GUT scale boundary conditions?

Answer 1: For certain types of  $M_U$ -scale boundary conditions, this can be totally automatic.

Answer 2: More generally, there is a measure called  $G$ . Small  $G$  implies it is quite natural to get small  $m_{a_1}$  even for fairly general  $M_U$ -scale boundary conditions.

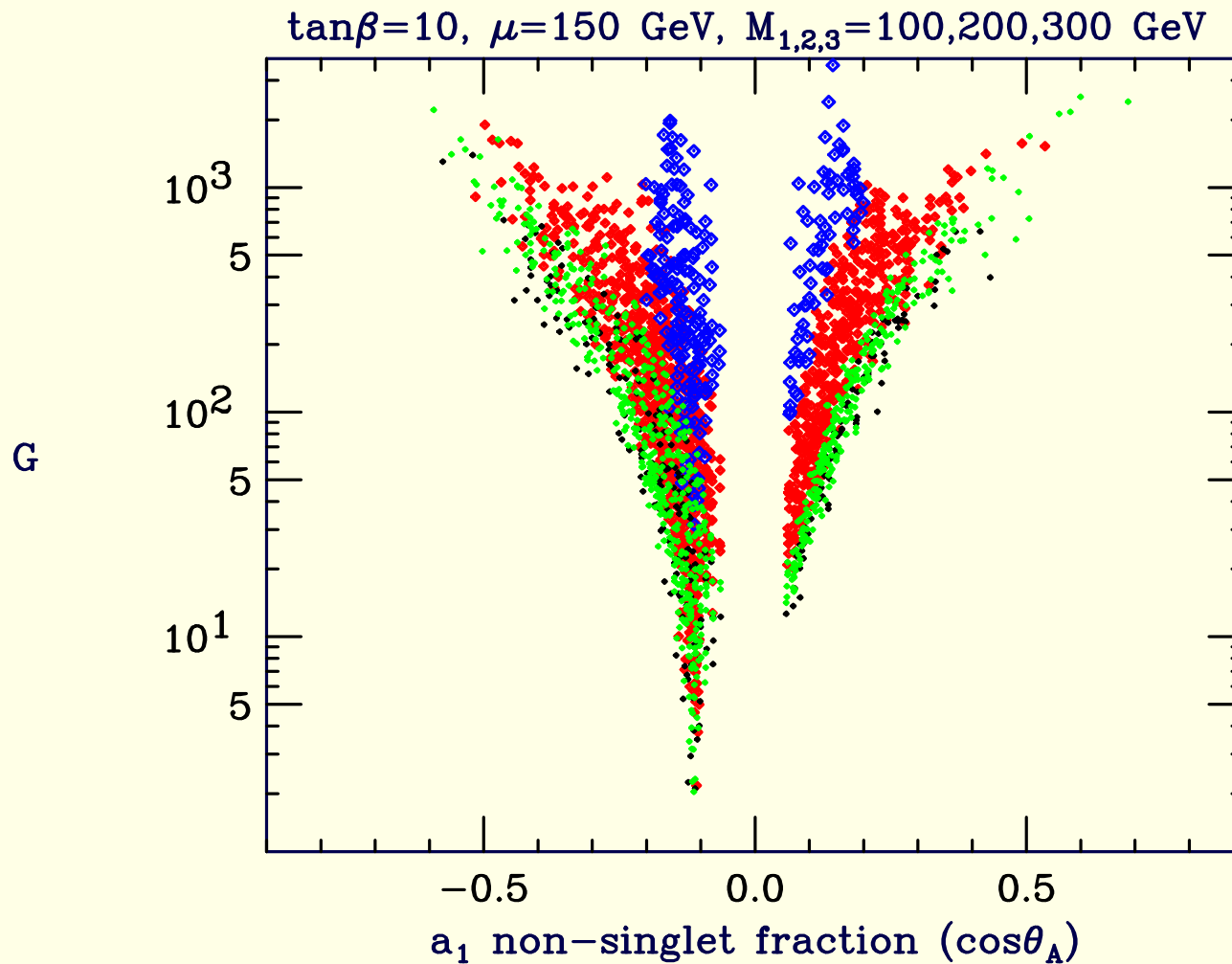
We plot  $G$  as a function of  $\cos \theta_A$  for various bins of  $m_{a_1}$  on the next page. All plotted points have  $B(h_1 \rightarrow a_1 a_1) > 0.7$ .

We see that small  $G$  is only achieved for the black, green and red points, and not for the blue points. The blue points have  $m_{a_1} < 2m_\tau$ .

**Net Result:** Small  $G$  requires  $m_{a_1} > 2m_\tau$  and  $\cos \theta_A \sim -0.1$ ,  
(at  $\tan \beta = 10$ ).

This  $\cos \theta_A$  value is just fine for large  $B(h_1 \rightarrow a_1 a_1)$ .

As stated earlier, an appropriate  $a_1$  scenario can be achieved without small  $G$  for some GUT boundary conditions. Thus, the above value of  $\cos \theta_A$  and mass region  $m_{a_1} > 2m_\tau$  should not be overly weighted in designing experiments.



**Figure 4:**  $G$  vs.  $\cos\theta_A$  for  $M_{1,2,3} = 100, 200, 300 \text{ GeV}$ ,  $\mu_{\text{eff}} = 150 \text{ GeV}$  and  $\tan\beta = 10$  for a selection of scenarios with  $B(h_1 \rightarrow a_1 a_1) > 0.7$  and  $m_{a_1} < 2m_b$ . The color coding is: blue =  $m_{a_1} < 2m_\tau$ ; red =  $2m_\tau < m_{a_1} < 7.5 \text{ GeV}$ ; green =  $7.5 \text{ GeV} < m_{a_1} < 8.8 \text{ GeV}$ ; and black =  $8.8 \text{ GeV} < m_{a_1} < 9.2 \text{ GeV}$ . The plot is for  $\tan\beta = 10$  and  $M_{1,2,3}(m_Z) = 100, 200, 300 \text{ GeV}$ .

## More Details on EWSB Fine-Tuning and LEP limits

- All low  $F$  scenarios have a rather SM-like  $h_1$  as regards  $WW$ ,  $ZZ$  and  $f\bar{f}$  couplings, it is just LEP limits require that the primary decay is  $h_1 \rightarrow a_1 a_1$ , leaving  $B(h_1 \rightarrow b\bar{b}) < 0.2$ .
- Putting the ( $m_{h_1} \sim 100$  GeV)  $F < 10$  scenarios with  $m_{a_1} > 2m_b$  through the full LEP LHWG analysis, one finds that all are excluded at somewhat more than the 99% CL since the combined  $Z + 2b$  and  $Z + 4b$  signals contribute too large a net  $Z + b$ 's signal.  $m_{h_1} \gtrsim 108$  GeV is needed to escape the  $Z + b$ 's constraint.
- The only way to achieve really low  $F$ , which comes with low  $m_{h_1} \sim 100$  GeV, and remain consistent with LEP is to have  $m_{a_1} < 2m_b$ , so that  $h_1 \rightarrow a_1 a_1 \rightarrow 4\tau$  or  $4j$ .

In this regard, it is important to note that LEP has never placed limits on the  $e^+e^- \rightarrow Zh \rightarrow Z4\tau$  channel for  $h$  masses larger than about 87 GeV.

- What about the remainder in the  $Zh \rightarrow Z + 2b$  channel. In fact, there

has been a long-standing excess in  $Z + 2b$  for  $M_{2b} \sim 100$  GeV.

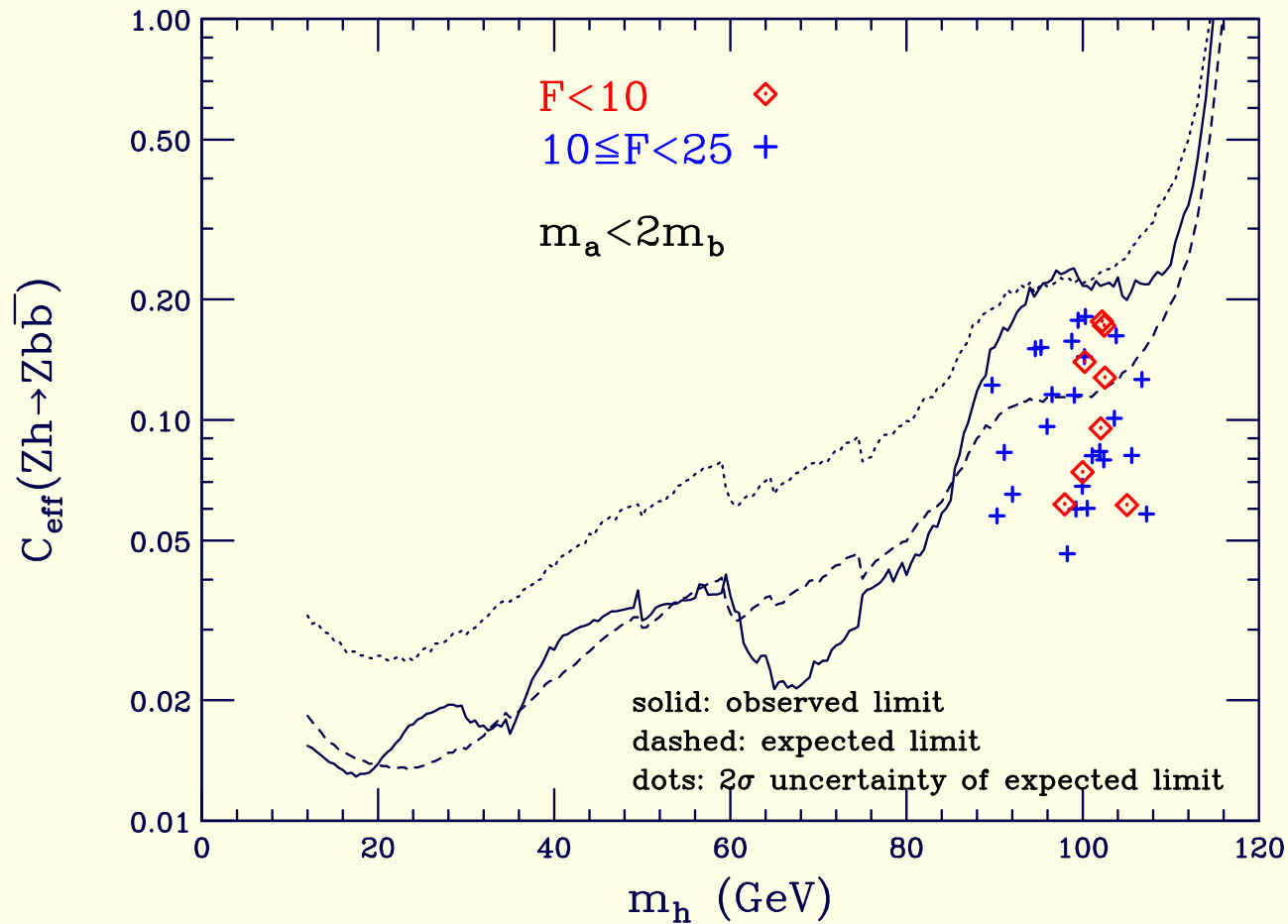


Figure 5: Observed LEP limits on  $C_{\text{eff}}^{2b}$  for the low- $F$  points with  $m_{a_1} < 2m_b$ . Note observed limit is far above expected limit (*i.e.* there is an excess of events) near 100 GeV.

Many of the plotted low- $F$  points can describe the excess perfectly.

Another view 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.)

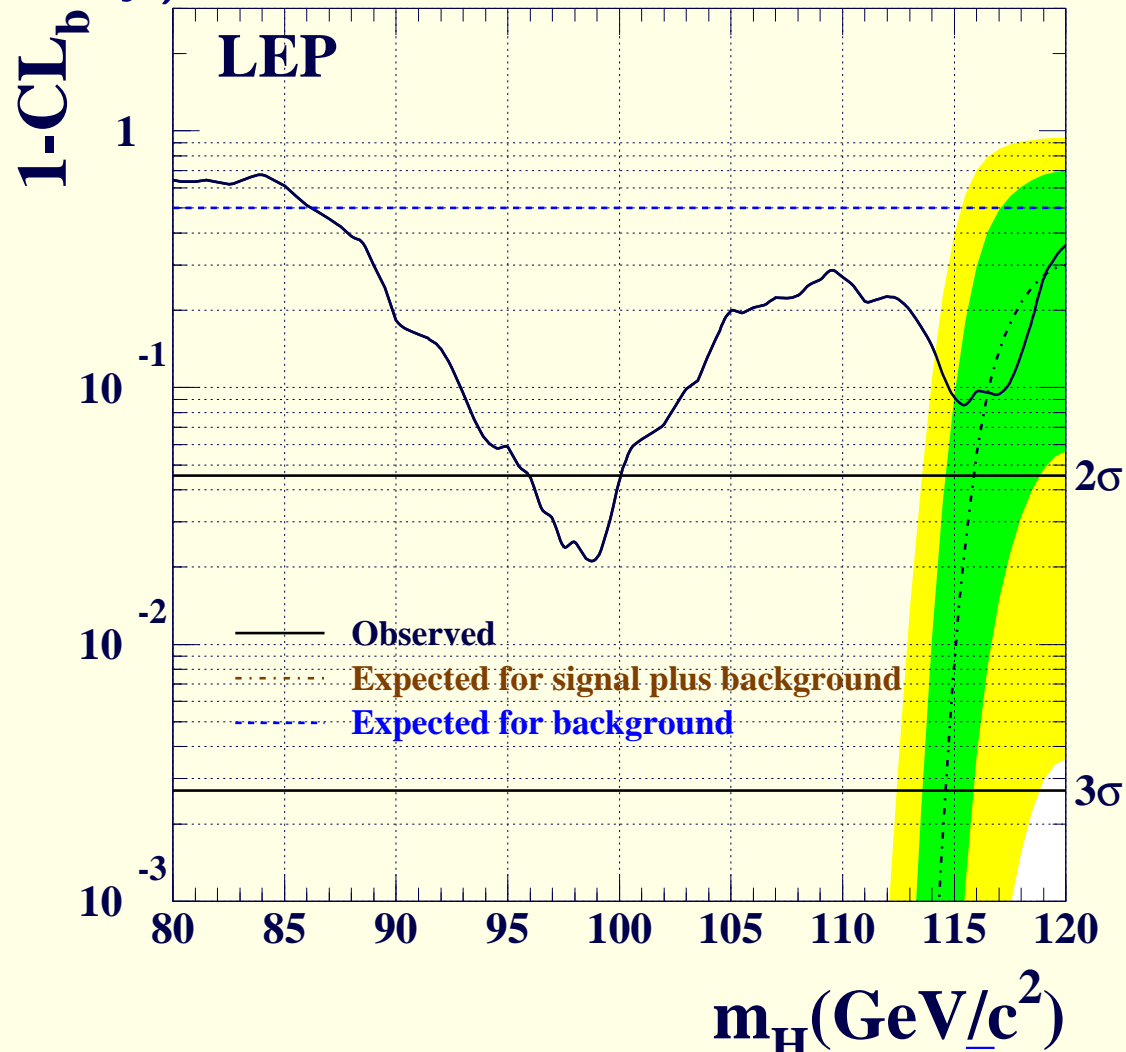


Figure 6: Plot of  $1 - CL_b$  for the  $Zb\bar{b}$  final state.

- There is an observed vs. expected discrepancy exactly where we want it at



$m_h \sim 100$  GeV! And because  $B(h_1 \rightarrow b\bar{b})$  is  $\sim 1/10$  the SM value for large  $B(h_1 \rightarrow a_1 a_1)$ , the discrepancy is of about the right size.

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

As stated earlier, if the  $a_1 a_1 \rightarrow 4\tau$  decay is the relevant scenario, the LEP limits run out for  $m_h > 87$  GeV.

If  $m_{a_1} < 2m_\tau$  and the  $a_1 a_1 \rightarrow (gg, q\bar{q}) + (gg, q\bar{q})$  decay is relevant, then we have the hadronic decay limits. They run out for  $m_h > 80$  GeV.

- 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.

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

## Summary to this point:

- The NMSSM is intrinsically a beautiful model, better than the MSSM theoretically even.
- $F < 10 - 15$  requires  $m_{h_1} \sim 100$  GeV,  $m_{a_1} < 2m_b$  and  $|\cos \theta_A| > 0.06$  ( $\tan \beta = 10$ ).
- LEP excess at  $M_{2b} \sim 100$  GeV is often perfectly described, since  $B(h_1 \rightarrow a_1 a_1) > 0.7$  typically implies  $B(h_1 \rightarrow b\bar{b}) \sim 0.1$ .
- $m_{h_1} \sim 100$  GeV is perfect for precision electroweak.

The question is, **how to find the  $h_1$  and/or the  $a_1$ ?**

- There is no time for details, but at the moment there is no proven way at the LHC. All standard channels fail: *e.g.*  $B(h_1 \rightarrow \gamma\gamma)$  is much too small because of large  $B(h_1 \rightarrow a_1 a_1)$ . The possible new channels include:

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

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

2.  $t\bar{t}h_1 \rightarrow t\bar{t}a_1 a_1 \rightarrow t\bar{t}\tau^+\tau^-\tau^+\tau^-$ .

Study begun.

3. **A third possibility:**  $\tilde{\chi}_2^0 \rightarrow h_1 \tilde{\chi}_1^0$  with  $h_1 \rightarrow a_1 a_1 \rightarrow 4\tau$ .  
(Recall that the  $\tilde{\chi}_2^0 \rightarrow h_1 \tilde{\chi}_1^0$  channel provides a signal in the MSSM when  $h_1 \rightarrow b\bar{b}$  decays are dominant.)
  4. **Last, but definitely not least: diffractive production**  $pp \rightarrow pp h_1 \rightarrow pp X$ .  
The mass  $M_X$  can be reconstructed with roughly a  $1 - 2$  GeV resolution, potentially revealing a Higgs peak, independent of the decay of the Higgs. Preliminary results are that one expects about 3 clean, i.e. reconstructed and tagged, events per  $30 \text{ fb}^{-1}$  of luminosity.  $\Rightarrow$  clearly a high luminosity game.
  5. The rather singlet nature of the  $a_1$  and its low mass, imply no direct production/detection possible at the LHC.
- At the ILC, there is no problem since  $e^+e^- \rightarrow ZX$  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.
  - As it turns out  $\Upsilon \rightarrow \gamma a_1$  decays hold great promise for  $a_1$  discovery (or exclusion) as we now outline. **They should be pushed to the limit.** The signal may even be present in the data available now! The only issue will be reaching quite small  $B(\Upsilon \rightarrow \gamma a_1)$ .

## Predictions for $B(\Upsilon \rightarrow \gamma a_1)$ for small $F$ scenarios

- One begins with the Wilczek formula:

$$R \equiv \frac{\Gamma_0(V(1^{--}) \rightarrow \gamma a)}{\Gamma_0(V(1^{--}) \rightarrow \mu^+ \mu^-)} = \frac{G_F m_Q^2}{\sqrt{2} \pi \alpha} \left( 1 - \frac{m_a^2}{M^2} \right) \quad (7)$$

which assumes 'standard'  $\gamma_5$  Yukawa coupling of the  $a$  with SM-like analogue strength. The  $_0$  means tree-level.

- Various corrections must then be made.

### 1. QCD radiative corrections ala Vysotsky and Nason:

$$\Gamma(V \rightarrow \gamma a) = \Gamma_0(V \rightarrow \gamma a) \left[ 1 - \frac{\alpha_s C_F}{\pi} a_P(z) + \mathcal{O}(\alpha_s^2) \right] \quad (8)$$

where  $z \equiv 1 - m_a^2/M^2$ .  $a_P(z)$  ranges from  $\sim 2$  at  $z = 0$  ( $m_{a_1} = M$ ) to  $\sim 6$  at  $z = 1$  ( $m_a = 0$ ). In relating to experimentally measured

$\Gamma(V \rightarrow \mu^+ \mu^-)$  from PDG, we must also include radiative corrections for this mode:

$$\Gamma(V \rightarrow \mu^+ \mu^-) = \Gamma_0(V \rightarrow \mu^+ \mu^-) \left[ 1 - \frac{4\alpha_s C_F}{\pi} \right]. \quad (9)$$

2. **Bound state corrections:** we employ the calculation of Pantaleone, Peskin, and Tye.

These corrections, while yielding a big suppression for a scalar Higgs, yield a very modest enhancement for a pseudoscalar. The enhancement is typically  $< 1\%$  for small  $m_a$ , rising to  $\sim 10\%$  for  $8 \lesssim m_a \lesssim 9.2$  GeV. For  $m_a \gtrsim 9.2$  GeV the  $a$  starts to mix with the  $\eta_b$ . We do not present results in this region since we doubt the reliability of available computations there.

3. **Relativistic Corrections:** we use those from Aznauryan, Grigoryan, and Matinyan.

$$R_{rel} = R_0 \left( \frac{M_Y^2 - m_a^2}{4m_b^2 - m_a^2} \right)^2 \left[ 1 - \frac{1}{3} \Delta \left( \frac{36m_b^2 + m_a^2}{4m_b^2 - m_a^2} \right) \right] \quad (10)$$

where

$$m_b^2 \Delta \equiv \frac{\int \psi(p^2) p^4 dp}{\int \psi(p^2) p^2 dp}, \quad (11)$$

with  $\psi(p^2)$  being the radial part of the wave function of the  $b$  quarks in the  $\Upsilon$ . We employ a value of  $\Delta$  that fits well their plots. The result is substantial suppression. For example,  $R_{rel} \sim \frac{1}{2} R_0$  for  $m_a < 4$  GeV. Suppression is even larger at large  $m_a$ .

- Coupling Correction:** The  $a_1$  does not couple with SM-analogue strength. Its coupling is enhanced by  $\tan \beta$  and suppressed by the smallness of its  $A_{MSSM}$  component fraction  $\cos \theta_A$  — the  $a_S$  singlet component does not couple to  $b\bar{b}$ . The precise coupling correction factor is then:

$$R_{a_1} = R_{\text{'SM-like' } a} \times (\tan \beta \cos \theta_A)^2. \quad (12)$$

## ● THE RESULTS

We will not plot points that violate the  $B(\Upsilon \rightarrow \gamma a_1)$  limits of Fig. 3 of [1], Fig. 4 of [2], and Fig. 7b of [3].

The first two limit  $B(\Upsilon \rightarrow \gamma X)$ , where  $X$  is any visible state.

The first provides the only strong constraint on the  $m_{a_1} < 2m_\tau$  region.

The third gives limits on  $B(\Upsilon \rightarrow \gamma X)B(X \rightarrow \tau^+\tau^-)$  that eliminate  $2m_\tau < m_{a_1} < 8.8$  GeV points with too high  $B(\Upsilon \rightarrow \gamma a_1)$  (for  $m_{a_1} > 2m_\tau$ ,  $B(a_1 \rightarrow \tau^+\tau^-) \sim 0.9$ ).

Since the inclusive photon spectrum from  $\Upsilon$  decays falls as  $E_\gamma$  increases, the strongest constraints are obtained for small  $m_{a_1}$ .

## References

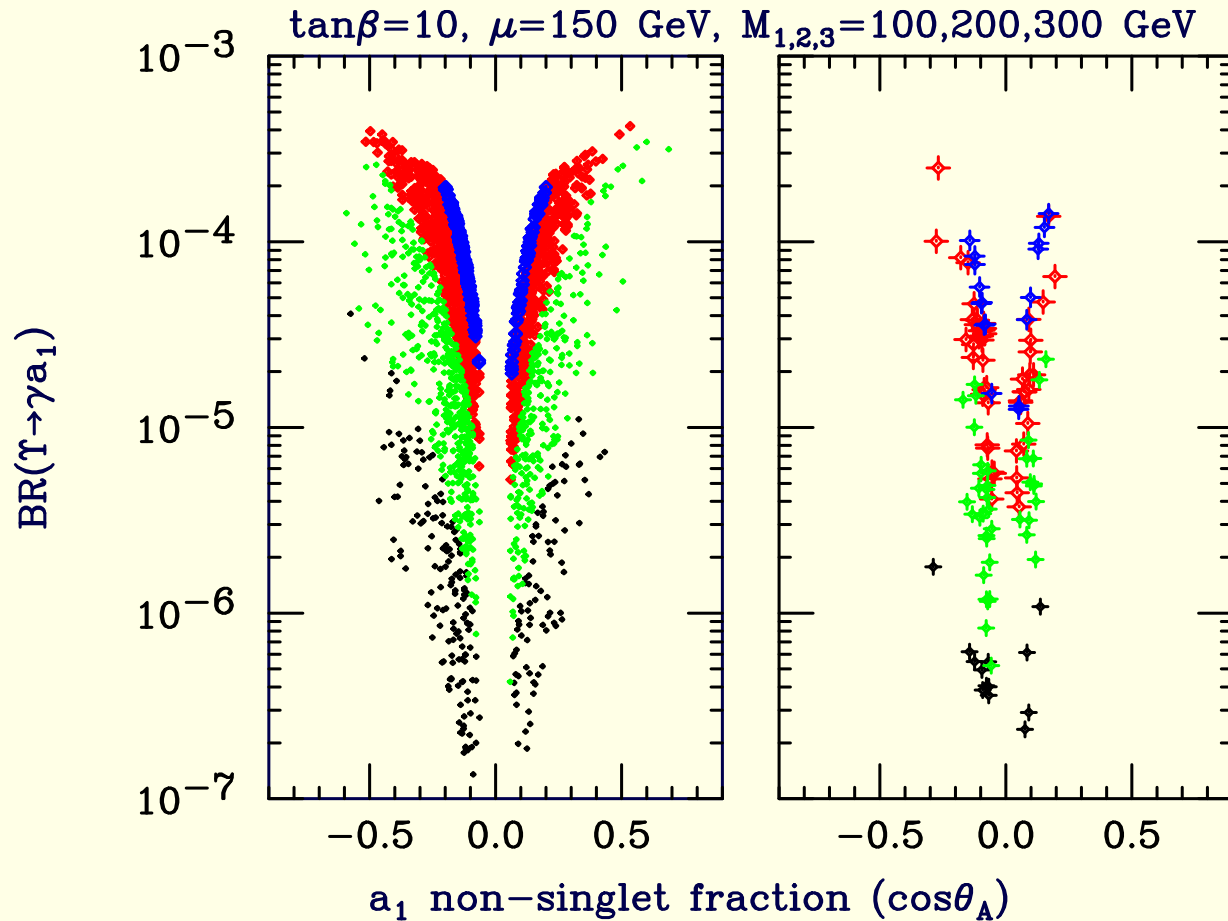
- [1] P. Franzini *et al.*, Phys. Rev. D 35, 2883 (1987).
- [2] H. Albrecht *et al.* [ARGUS Collaboration], Phys. Lett. B 154, 452 (1985).
- [3] H. Albrecht *et al.* [ARGUS Collaboration], Z. Phys. C 29, 167 (1985).

In the **first figure**, we focus on the  $\tan\beta = 10$  case with  $M_{1,2,3}(m_Z) = 100, 200, 300$  GeV for which our previous plots were given. Two types of plot are shown:

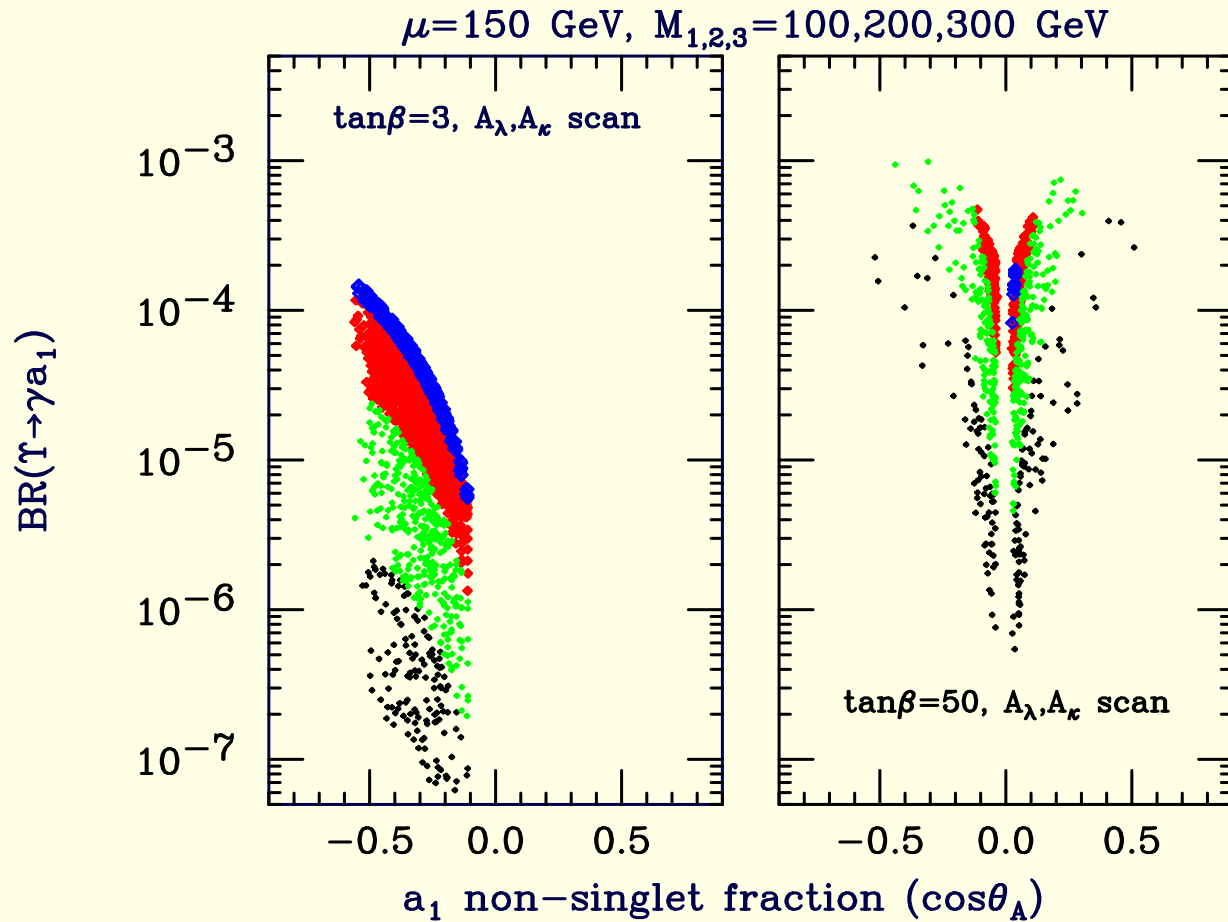
1. A scan in  $A_\lambda, A_\kappa$  space at fixed  $\mu_{\text{eff}} = 150$  GeV, requiring  $B(h_1 \rightarrow a_1 a_1) > 0.7$  and  $m_{a_1} < 9.2$  GeV.
2. Results for the  $F < 15$  points of Fig. 3.

In the **second figure**, we look at results for the  $A_\lambda, A_\kappa$  scans for  $\tan\beta = 3$  and  $\tan\beta = 50$ .





**Figure 7:**  $B(\Upsilon \rightarrow \gamma a_1)$  for NMSSM scenarios with various ranges for  $m_{a_1}$  using color scheme of Fig. 4 (blue =  $< 2m_\tau$ , red =  $[2m_\tau, 7.5]$ , green =  $[7.5, 8.8]$ , black =  $[8.8, 9.2]$ ). The left plot comes from the  $A_\lambda, A_\kappa$  scan described in the text, holding  $\mu_{\text{eff}}(m_Z) = 150 \text{ GeV}$  fixed. The right plot shows results for  $F < 15$  scenarios with  $m_{a_1} < 9.2 \text{ GeV}$  found in a general scan over all NMSSM parameters holding  $\tan\beta$  and  $M_{1,2,3}$  fixed as stated. **The lower bound on  $B(\Upsilon \rightarrow \gamma a_1)$  arises basically from the LEP requirement of  $B(h_1 \rightarrow a_1 a_1) > 0.7$ .**



**Figure 8:** We plot  $B(\Upsilon \rightarrow \gamma a_1)$  as a function of  $\cos\theta_A$  for the  $A_\lambda, A_\kappa$  scan, taking  $M_{1,2,3}(m_Z) = 100, 200, 300$  GeV,  $\mu_{\text{eff}}(m_Z) = 150$  GeV with  $\tan\beta = 3$  (left) and  $\tan\beta = 50$  (right). The point notation is as before: **blue** =  $< 2m_\tau$ , **red** =  $[2m_\tau, 7.5]$ , **green** =  $[7.5, 8.8]$ , **black** =  $[8.8, 9.2]$ .

● **Summary of  $B(\Upsilon \rightarrow \gamma a_1)$  results:**

1. There are some large  $B(\Upsilon \rightarrow \gamma a_1)$ 's that might or might not have  $A_\lambda, A_\kappa$  fine-tuning issues (large  $G$ ) waiting to be excluded by existing data.
2. At  $\tan \beta = 10$ , small  $G$  points with  $\cos \theta_A \sim -0.1$  (red, green and black) have  $B(\Upsilon \rightarrow \gamma a_1)$  ranging from  $\lesssim \text{few} \times 10^{-5}$  for  $2m_\tau < m_{a_1} < 7.5$  GeV (red) to  $\sim \text{few} \times 10^{-7}$  for  $8.8$  GeV  $< m_{a_1} < 9.2$  GeV (black).
3. At  $\tan \beta = 3$ , the  $B(\Upsilon \rightarrow \gamma a_1)$  range is suppressed further.
4. At  $\tan \beta = 50$ ,  $B(\Upsilon \rightarrow \gamma a_1) \gtrsim 10^{-6}$  for all points with  $m_{a_1} < 9.2$  GeV.
5. We stress again that the lower bounds on  $B(\Upsilon \rightarrow \gamma a_1)$  arise from the LEP requirement that  $B(h_1 \rightarrow a_1 a_1) > 0.7$ .
6. Of course, we cannot exclude the possibility that  $9.2$  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  $\Upsilon$  decays.
7. However, if  $B(\Upsilon \rightarrow \gamma a_1)$  sensitivity can be pushed down to the  $10^{-7}$  level, **you may well discover the  $a_1$ .**

## Conclusions

- The NMSSM can naturally have small fine-tuning of GUT-scale parameters for both:

- 1) Electroweak Symmetry Breaking, *i.e.* getting the measured value of  $m_Z^2$ ;
- 2) Small  $m_{a_1} < 2m_b$  and (simultaneously) large  $B(h_1 \rightarrow a_1 a_1)$ , both of which are needed to escape LEP limits for  $m_{h_1} \sim 100$  GeV [the latter being required for 1)].

$m_{a_1} > 2m_\tau$  is somewhat preferred by this latter fine-tuning issue.

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

- a  $h_1$  with  $m_{h_1} \sim 100$  GeV and SM-like couplings to SM particles but with primary decays  $h_1 \rightarrow a_1 a_1$  with  $m_{a_1} < 2m_b$ , where the  $a_1$  is mainly singlet. **The collider implications are:**

Higgs detection will be quite challenging at a hadron collider.

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

Higgs detection in  $\gamma\gamma \rightarrow h_1 \rightarrow a_1 a_1$  will be easy.

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

- the stops and other squarks are light;
- the gluino, and, by implication assuming conventional mass orderings, the wino and bino all have modest mass;
- Even if the LHC sees the Higgs  $h_1 \rightarrow a_1 a_1$  directly, it will not be able to get much detail. Only the ILC and possibly  $B$ -factory results for  $\Upsilon \rightarrow \gamma a_1$  can provide the details needed to verify the model.
- It is likely that other models in which the MSSM  $\mu$  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  $m_{h_1} \sim 100$  GeV.

And, to escape LEP limits in the  $Z + b$ 's channel, large  $B(h_1 \rightarrow a_1 a_1)$  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  $B(\Upsilon \rightarrow \gamma a_1)$ .

- Although SUSY will be easily seen at the LHC, **Higgs detection at the LHC**

may prove to be a real challenge.

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

- A light  $a_1$  allows for a light  $\tilde{\chi}_1^0$  to be responsible for dark matter of correct relic density: annihilation would be via  $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow a_1$ . 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  $\tilde{\chi}_1^0$  and of the  $a_1$  in sufficient detail to verify that it all fits together.

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

- Thus,

Large  $B$ -factory data sets, optimally using  $\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$  to tag the  $1S$  state, should be pursued with great vigor.

Unless, of course, it is found that backgrounds (most notably from  $\Upsilon \rightarrow \gamma \tau^+ \tau^-$ ) are insurmountable at the needed level.

What are the limits? We have had a brief look, but clearly this is a job for experimentalists.

- In the  $\gamma\tau^+\tau^-$  final state, the direct  $\gamma\tau^+\tau^-$  production cross section is 61 pb.

Using signal=background as the criterion, this becomes the limiting factor for branching ratios below the  $4 \times 10^{-5}$  level when running on the  $\Upsilon(1S)$ , and below the  $2 \times 10^{-4}$  level when running on the  $\Upsilon(3S)$ .

- To improve upon the latter, one can select a sample of known  $\Upsilon(1S)$  events by looking for dipion transitions from the higher resonances.

The dipion transition gives a strong kinematic constraint on the mass difference between the two  $\Upsilon$ 's.

When running on the  $\Upsilon(3S)$ , the effective cross section in  $\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$  is 179 pb (see archive Glenn:1998bd)

To limit  $B(\Upsilon \rightarrow \gamma a_1) \lesssim 10^{-6}$ ,  $5.6 \text{ fb}^{-1}/\epsilon$  would need to be collected on the  $\Upsilon(3S)$ , where  $\epsilon$  is the experimental efficiency for isolating the relevant events.

- This analysis can also be done on the  $\Upsilon(4S)$ , where the  $\Upsilon(3S)$  is produced via ISR. The effective  $\gamma_{ISR}\Upsilon(3S) \rightarrow \gamma_{ISR}\pi^+\pi^-\Upsilon(1S)$  cross section is 0.78 fb.

To limit  $B(\Upsilon \rightarrow \gamma a_1) \lesssim 10^{-6}$ ,  $1.3 \text{ ab}^{-1}/\epsilon$  would need to be collected.

- These integrated luminosities needed to probe  $B(\Upsilon \rightarrow \gamma a_1) \sim 10^{-6}$  would appear to be within reach at existing facilities and would allow discovery of the  $a_1$  for many of the favored NMSSM scenarios.



## Further Comments

- Of course, one should consider  $b \rightarrow sa_1$  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  $b \rightarrow sa_1 \rightarrow s\mu^+\mu^-$  limits may exclude most of the  $m_{a_1} < m_b$  scenarios, which in any case are less preferred by  $A_\lambda, A_\kappa$  tuning issues.

- $a_1 \rightarrow \gamma\gamma$  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  $A_\lambda, A_\kappa$  scans with  $B(h_1 \rightarrow a_1a_1) > 0.7$  and  $m_{a_1} < 2m_b$  imposed,  $B(a_1 \rightarrow \gamma\gamma) < 4 \times 10^{-4}$  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  $\Upsilon \rightarrow \gamma a_1 \rightarrow \gamma\gamma\gamma$  with branching ratio at the  $10^{-10}$  level?

The needed number of  $\Upsilon$ 's is 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.

In any case, we really hope that you will take the problem of Electroweak fine-tuning, and the NMSSM solution thereto, seriously.

After all, it fits perfectly with precision electroweak preference for a  $m_{h_1} \sim 100$  GeV Higgs and with the  $Z + 2b$  signal in the  $M_{2b} \sim 100$  GeV region.

If you do, there is a very compelling case for pushing  $\Upsilon \rightarrow \gamma a_1$  searches to the absolute extreme.