An Ideal Higgs Boson

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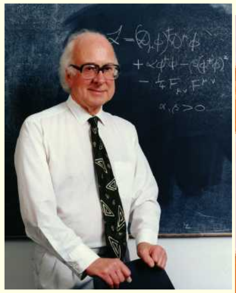
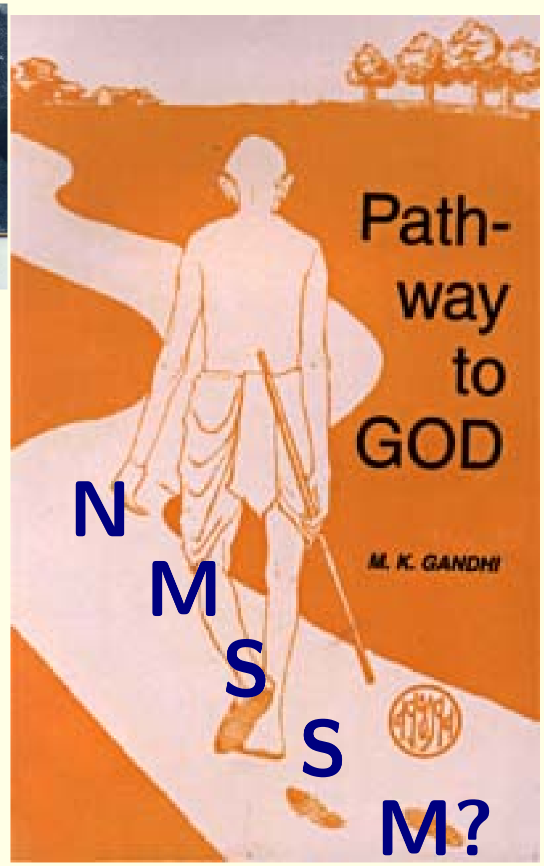
Outline

1. Criteria for an "ideal" Higgs boson.
2. Why the SM Higgs sector cannot be ideal.
3. Means for delaying SM problems.
4. Why Supersymmetry.
5. Why the MSSM Higgs sector is not quite ideal.
6. How and Why the NMSSM Higgs sector can be ideal.
7. Implications for Higgs detection at the LHC.
8. Other experimental consequences.





The Particle

The NMSSM is an attractive possibility!

Warning: To understand why the NMSSM path is particularly attractive, one will have to worry about many types of "fine-tuning": i) quadratic-divergence; ii) electroweak; iii) μ; iv) dark matter; v) electroweak baryogenesis; and vi) light-pseudoscalar.

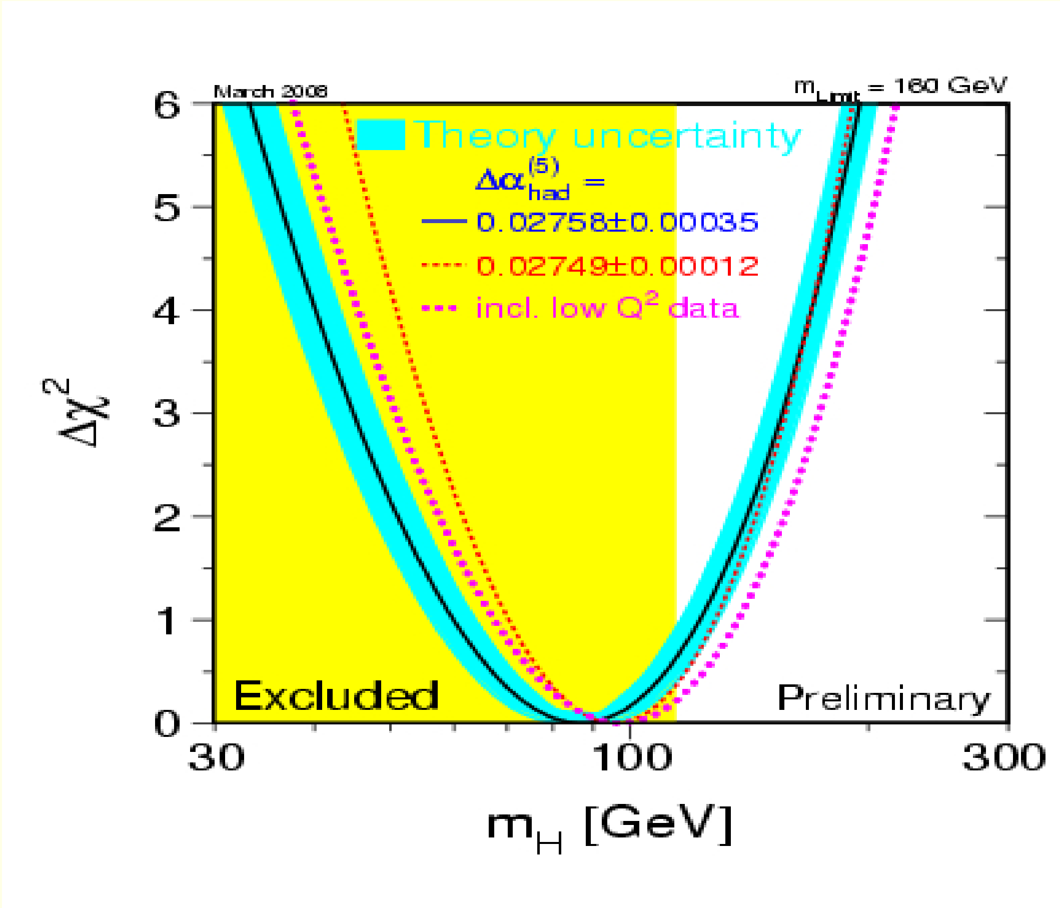
Criteria for an ideal Higgs theory

- **The theory should allow for a light Higgs boson without fine-tuned cancellation of the quadratic divergence. This I term the "quadratic-divergence" fine-tuning issue.**

- **Whatever theory is employed to remove the quadratic divergence should also predict m_Z^2 or equivalently v^2 without having to fine-tune the high scale (e.g. GUT-scale) parameters of the theory. I term this the "electroweak symmetry breaking" ("EWSB") fine-tuning issue.**

  We will return to discuss these two issues more thoroughly. For now, we continue with purely phenomenological criteria.

- **The theory should predict a Higgs (or collection of Higgses) with SM coupling-squared (or summed coupling-squared) to WW, ZZ and with mass (or weighted average mass) in the range preferred by precision electroweak data. The latest plot is:**



At 95% CL, $m_{h_{\rm SM}} < 160$ GeV and the $\Delta\chi^2$ minimum is between 80 GeV and 105 GeV depending in particular upon what value of $\Delta\alpha^5$ is employed and whether $\sin^2\theta_{lep}$ is the hadronic value or leptonic value or the world average.

The latest m_W and m_t measurements also prefer $m_{h_{\rm SM}} \sim 100$ GeV.

- **Thus, in an ideal model, the Higgs should have mass no larger than 105 GeV.**

But, at the same time, It should avoid the LEP limits on such a light Higgs. One generic possibility is for its decays to be non-SM-like.

Table 1: LEP m_H Limits for a H with SM-like ZZ coupling, but varying decays.

Mode	SM modes	2τ or $2b$ *only*	$2j$	$WW^* + ZZ^*$	$\gamma\gamma$	$\not{E}$	$4e, 4\mu, 4\gamma$
Limit (GeV)	114.4	115	113	100.7	117	114	114?
Mode	$4b$	4τ	any (e.g. $4j$)	$2f + \not{E}$			
Limit (GeV)	110	86	82	90?			

Note that to have $m_H \leq 105$ GeV requires one of the final three modes or something even more exotic. We also note that the mode-independent limit of 82 GeV still makes some assumptions about the nature of the final state and for some final states is probably (no explicit statements from LEP collaborations are available) lower.

- **Perhaps its properties should be such as to predict the 2.3σ excess at**

$M_{b\bar{b}} \sim 98$ GeV **seen in the** $Z + b\bar{b}$ **final state. The possibilities are:**

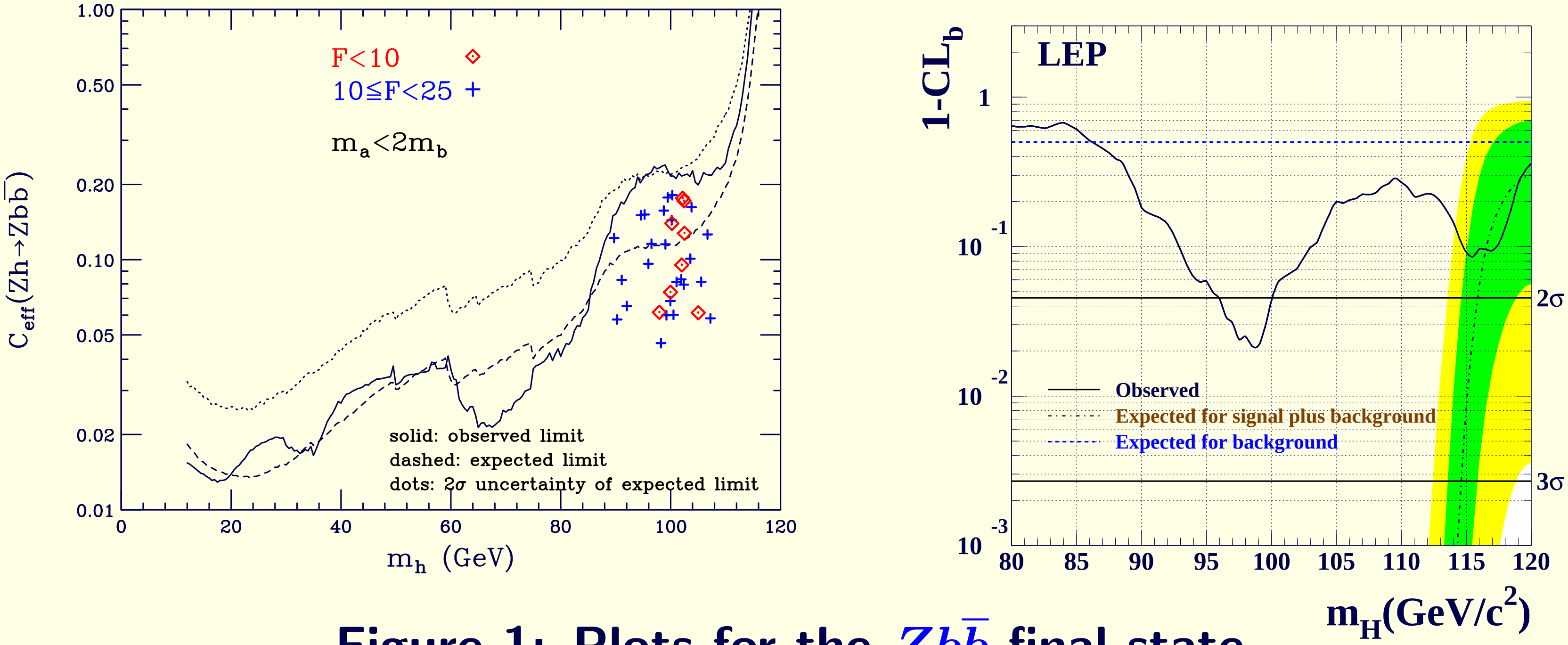


Figure 1: Plots for the $Zb\bar{b}$ **final state.**

1. **Very roughly, to give the excess seen** $B(H \to b\bar{b}) \sim 0.1 B(H \to b\bar{b})_{SM}$ **is required if** H **has SM** ZZ **coupling.**
2. **Or, you could have SM-like decay pattern but** $g^2_{ZZH} \sim 0.1 g^2_{ZZh_{\rm SM}}$. **However, in this latter case there must be other Higgs bosons with "average" mass near** 100 GeV **such that** $\sum_i g^2_{ZZh_i} = g^2_{ZZh_{\rm SM}}$.

- **Number 1 is the simplest possibility, and is easily achieved.**

Indeed, almost any additional decay channel will severely suppress the $b\bar{b}$ branching ratio.

A Higgs of mass, *e.g.*, $100~\mathrm{GeV}$ has a decay width into Standard Model particles that is only $2.6~\mathrm{MeV}$, or about 10^{-5} of its mass.

It doesn't take a large Higgs coupling to some new particles for the decay width to these new particles to dominate over the decay width to SM particles (early references = Gunion:1984yn,Li:1985hy,Gunion:1986nh – full review arXiv:0801.4554).

For example, compare the decay width for $h \to b\bar{b}$ to that for $h \to aa$, where a is a light pseudoscalar Higgs boson. Writing $\mathcal{L} \ni g_{haa} haa$ with $g_{haa} = c\,\frac{gm_h^2}{2m_W}$ and ignoring phase space suppression, we find

$$\frac{\Gamma(h \to aa)}{\Gamma(h \to b\bar{b})} \sim 310\, c^2 \left(\frac{m_h}{100~\mathrm{GeV}}\right)^2 . \tag{1}$$

This expression includes QCD corrections to the $b\bar{b}$ width as given in HDECAY which decrease the leading order $\Gamma(h \to b\bar{b})$ by about 50%.

The decay widths are comparable for $c \sim 0.057$ when $m_h = 100~\mathrm{GeV}$. Values of c at this level or substantially higher (even $c = 1$ is possible) are generic in BSM models containing an extended Higgs sector.

- Regarding possibility #2 (many light Higgs bosons), one easily arrange to satisfy LEP limits and fit precision electroweak data (Espinosa+JFG, hep-ph/9807275).
- But, these games alone do not solve the quadratic divergence fine-tuning nor EWSB fine-tuning problems (after implementing in SUSY), although they can delay it — see below.
- Finally, perhaps the Higgs should be such as to allow for a strong 1st-order phase transition in the early universe for electroweak baryogenesis. Easiest if $m_H \lesssim 100~\mathrm{GeV}$ for H with SM WW/ZZ coupling.

Why the SM Higgs sector cannot be ideal

First, let us recall that were it not for the quadratic divergence fine-tuning problem, there is nothing to forbid the SM from being valid all the way up to the Planck scale. The two basic theoretical constraints are:

- the Higgs self coupling should not blow up below scale Λ; $\Rightarrow$ upper bound on $m_{h_{\rm SM}}$ as function of Λ.

- the Higgs potential should not develop a new minimum at large values of the scalar field of order Λ; $\Rightarrow$ lower bound on $m_{h_{\rm SM}}$ as function of Λ.

These two constraints imply that the SM can be valid all the way up to $M_{\rm P}$ if $130 \lesssim m_{h_{\rm SM}} \lesssim 180~{\rm GeV}$.

- However, $m_{h_{\rm SM}} \lesssim 100~{\rm GeV}$, as needed for ideal Higgs phenomenology, would require $\Lambda \lesssim 10^5~{\rm GeV}$ and, in any case, is excluded by LEP data, which requires $m_{h_{\rm SM}} \geq 114.4~{\rm GeV}$.

One must go to multi-Higgs approaches to satisfy the purely phenomenological ideal Higgs requirements.

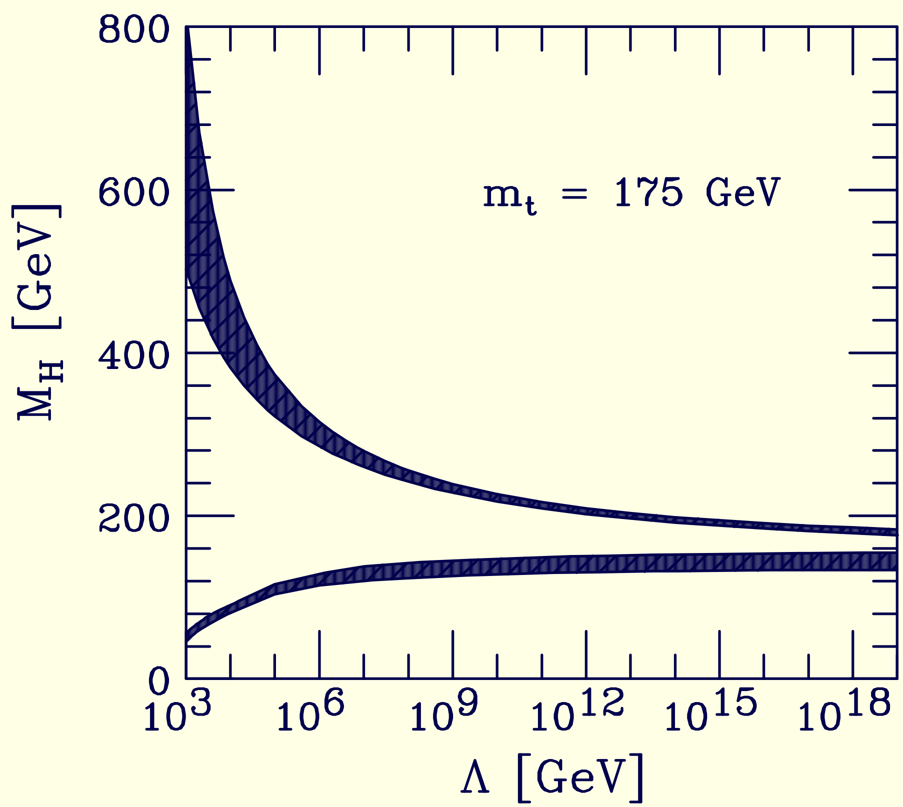


Figure 2: Triviality and global minimum constraints on $m_{h_{\rm SM}}$ vs. Λ.

- **Quantum corrections to the Higgs mass-squared lead to severe quadratic-divergence fine-tuning unless new physics enters at a low scale.**

Recall that after including the one loop corrections we have

$$m_{h_{\rm SM}}^2 = \mu^2 + \frac{3\Lambda^2}{32\pi^2 v^2}(2m_W^2 + m_Z^2 + m_{h_{\rm SM}}^2 - 4m_t^2) \tag{2}$$

where $\mu^2 = 2\lambda v_{SM}^2$, and λ is the quartic coupling in the Higgs potential.

The μ^2 and Λ^2 terms have entirely different sources, and so a value of $m_{h_{\rm SM}} \sim m_Z$ should not arise by fine-tuned cancellation between the two terms.

And, even if you do have a fine-tuned cancellation the theory is out of control for large Λ since large μ^2 requires large λ.

Although you can never cure the quadratic fine-tuning problem without new physics, there are some tactics for delaying it to quite large Λ values.

Purely Higgs sector approaches for delaying fine-tuning from quadratic divergences

1. $m_{h_{\rm SM}}$ could obey the "Veltman" condition,

$$m^2_{h_{\rm SM}} = 4m_t^2 - 2m_W^2 - m_Z^2 \sim (317~{\rm GeV})^2 \,. \tag{3}$$

At higher loop order, one must carefully coordinate the value of $m_{h_{\rm SM}}$ with the value of Λ.

Just as we do not want to have a fine-tuned cancellation of the two terms in Eq. (2), we also do not want to insist on too fine-tuned a choice for $m_{h_{\rm SM}}$ (in the SM, there is no symmetry that predicts this value).

$\Rightarrow$ **cannot continue the game to too high a Λ.**

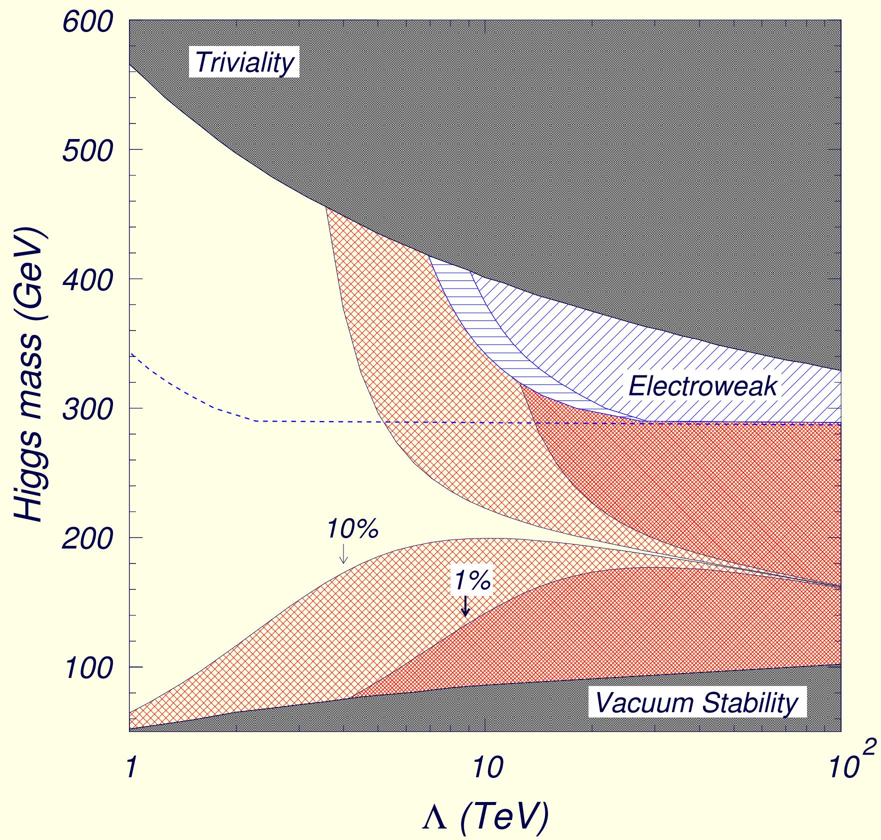


Figure 3: Fine-tuning constraints on Λ, from Kolda + Murayama, hep-ph/0003170.

The upper bound for Λ at which new physics must enter is largest for $m_{h_{\rm SM}} \sim 200~\mathrm{GeV}$ where the SM fine-tuning would be 10% if $\Lambda \sim 30~\mathrm{TeV}$. At this point, one would have to introduce some kind of new physics.

However, we already know that there is a big problem with this approach — the latest m_t and m_W values when combined with LEP precision electroweak data require $m_{h_{\rm SM}} < 160~{\rm GeV}$ at 95% CL.

2. **Return to the multi-doublet approach. Then (in the simplest case where all h_i have the same top quark Yukawa, but rescaled by v_i/v_{SM}) each h_i has its top quark loop mass correction scaled by $f_i^2 \equiv \frac{v_i^2}{v_{SM}^2}$ and thus**

$$F_t^i = f_i^2 F_t(m_i) = K f_i^2 \frac{\Lambda_t^2}{m_i^2} \tag{4}$$

i.e. **significantly reduced.**

Thus, multiple mixed Higgs allow a much larger Λ_t for a given maximum acceptable common F_t^i.

One should note one possibly good feature of delaying new physics:

large Λ_t implies significant corrections to low-E phenomenology from Λ_t-scale physics are less likely.

A model with 4 doublets can allow $\Lambda_t \sim 5\ \mathrm{TeV}$ before the hierarchy fine-tuning problem becomes significant.

- **However, in the end, there is always going to be a Λ or Λ_t for which we get into trouble.**

$\Rightarrow$ Ultimately we will need new physics.

So, why not have it right away (*i.e.* at $\Lambda \lesssim 1\ \mathrm{TeV}$) and avoid the above somewhat ad hoc games.

This is the approach of supersymmetry, which (unlike Little Higgs or UED or ....) solves the hierarchy problem once and for all.

Why Supersymmetry

- SUSY is mathematically intriguing.

- SUSY is naturally incorporated in string theory.

- Elementary 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.

- Dark matter = Lightest Supersymmetric Particle (LSP) is natural.

- SUSY cures the quadratic-divergence fine-tuning problem, and it does so without EWSB fine-tuning (see definition below) provided the SUSY breaking scale is $\lesssim 500~\mathrm{GeV}$.

  In particular, the top quark loop (which comes with a minus sign) is canceled by the loop of the spin-0 partner "stop" (which loop comes with a plus sign). Thus, Λ_t^2 is effectively replaced by $\overline{m}_{\widetilde t}^2 \equiv \frac{1}{2}(m_{\widetilde t_L}^2 + m_{\widetilde t_R}^2)$.

- **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**

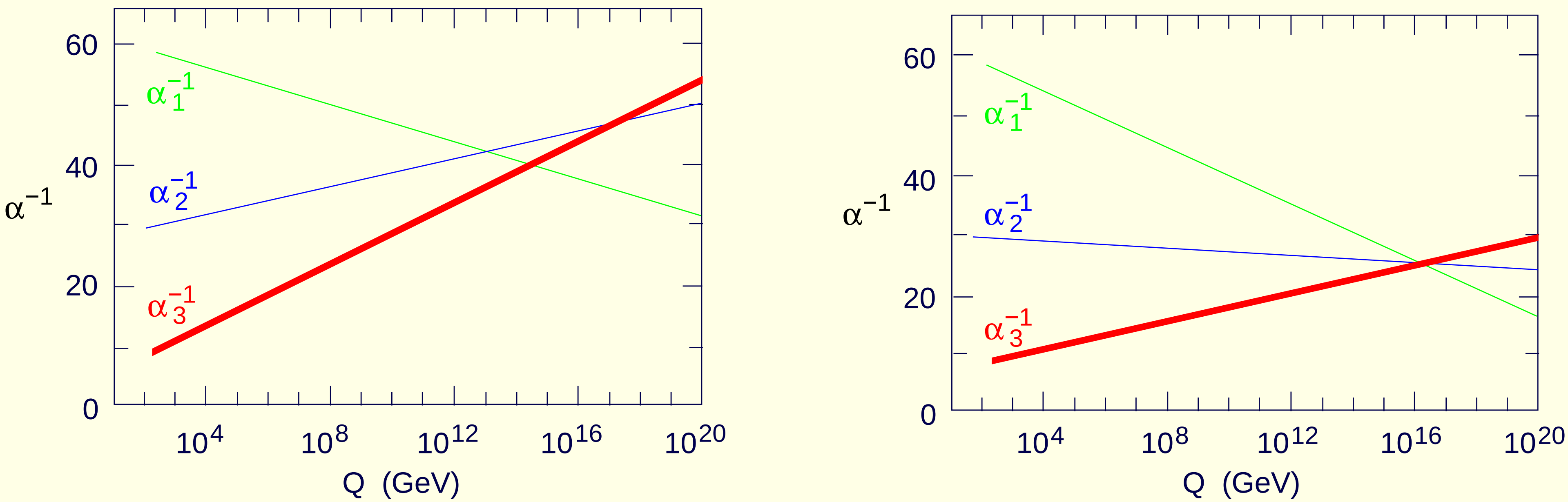


Figure 4: Unification of couplings constants ($\alpha_i = g_i^2/(4\pi)$) in the minimal supersymmetric model (MSSM) as compared to failure without supersymmetry.

The MSSM sparticle content + two-doublet Higgs sector $\Rightarrow$ gauge coupling unification at $M_U \sim few \times 10^{16}\ \mathrm{GeV}$, close to M_{P}. (High-

scale unification fits nicely with gravity-mediated SUSY breaking.)

2. $\boxed{\text{RGE EWSB}}$

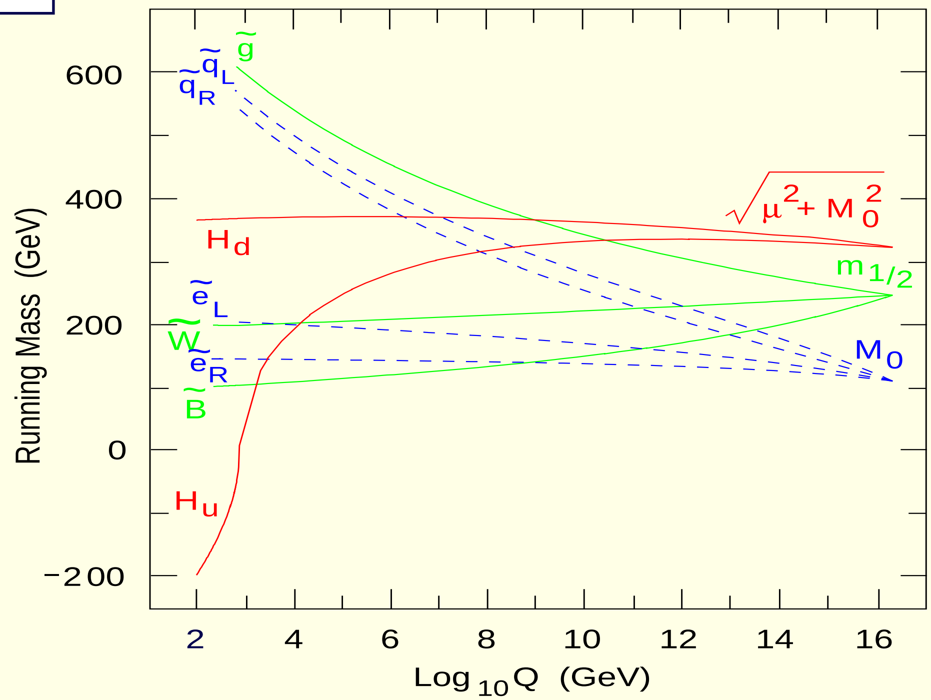


Figure 5: **Evolution of the (soft) SUSY-breaking masses or masses-squared, showing how $m^2_{H_u}$ is driven < 0 at low $Q \sim \mathcal{O}(m_Z)$.**

Starting with 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 ($\langle H_u \rangle = h_u, \langle H_d \rangle = h_d$),

Why the MSSM is not ideal

1. 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.

   Getting the appropriate μ value is a severe fine-tuning problem for the MSSM. There are many suggested approaches, but ....

2. m_Z IS FINE-TUNED.

   So long as $\overline{m}_{\widetilde{t}}^2$ is not too far above m_Z^2, getting m_Z^2 correct does not involve any highly precise cancellations of the different contributions to m_Z^2 (really the Higgs field vev-squared v_{SM}^2) as determined by evolving the SUSY breaking parameters from M_U to m_Z.

   However, such a choice for $\overline{m}_{\widetilde{t}}^2$ creates a problem!!!!

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

3. The Higgs Mass

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

$$m_h^2 \sim m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} v^2 y_t^4 \sin^4\beta \log\left(\frac{\overline{m}_{\widetilde{t}}^2}{m_t^2} + \frac{X_t^2}{\overline{m}_{\widetilde{t}}^2}\left[1 - \frac{X_t^2}{12\overline{m}_{\widetilde{t}}^2}\right]\right)$$

$$\overset{\text{large} \tan\beta}{\sim} (91 \text{ GeV})^2 + (38 \text{ GeV})^2 \log\left(\frac{\overline{m}_{\widetilde{t}}^2}{m_t^2} + \ldots\right). \qquad (5)$$

Here, $X_t = A_t - \frac{\mu}{\tan\beta}$ determines the amount of stop-squark mixing.

For stop masses $\sim 2m_t$, $m_h \sim 100$ GeV, in perfect accord with precision electroweak data and EWSB fine-tuning is minimal.

The Problem: LEP rules out a SM-like Higgs boson (h has very SM-like properties in the MSSM) with mass below ~ 114 GeV, except in some special (strong Higgs mixing) cases that have a significant EWSB fine-tuning problem.

4. **EWSB Fine-tuning** (different from quadratic-divergence fine-tuning)

$$F = \mathrm{Max}_p \left| \frac{p}{m_Z} \frac{\partial m_Z}{\partial p} \right|, \tag{6}$$

where $p \in \left\{ M_{1,2,3}, m^2_Q, m^2_U, m^2_D, m^2_{H_u}, m^2_{H_d}, \mu, A_t, B\mu, \ldots \right\}$ (all at M_U).

These p's are the GUT-scale parameters that determine all the m_Z-scale SUSY parameters, and these (via RGEs) determine $m^2_Z \propto v^2_{SM}$.

$F > 20$ means worse than 5% fine-tuning of the GUT-scale parameters is required is required to get the right value of m_Z. This would be **bad**.

5. So, what is the smallest F that can be achieved in the MSSM?

   (a) For most of parameter space, $m_h > 114~\mathrm{GeV}$ is required. Then, $F > 100$ or so unless there is large stop mixing, in which case $F > 30$ at best.

   (b) For special cases characterized by large Higgs mixing, F can be reduced to 16 at best (6% fine-tuning), but this part of parameter space requires many precise correlations among soft-SUSY-breaking parameters (see JFG+Dermisek, arXiv:0709.2269).

Absence of EWSB fine-tuning corresponds to $F \sim 5$, *i.e.* $\lesssim 20\%$ tuning of GUT-scale parameters.

6. For the part of MSSM parameter space allowed after Higgs mass constraints are imposed, electroweak baryogenesis, and to some extent correct relic LSP abundance, require fine-tuning of soft-SUSY-breaking parameters.

7. In the NMSSM, we can have our cake and eat it too by skinning the SUSY cat in just the right way!
   (a) In particular, in the NMSSM we can have a Higgs with SM-like WW, ZZ couplings and mass $\sim 100~\mathrm{GeV}$ (and $F \sim 5$ will therefore be possible) without violating LEP limits. Indeed, it is the lightest CP-even Higgs h_1 that will have all the properties of the "ideal" Higgs described earlier.
   (b) Overall SUSY parameters are such that the LSP abundance requires less fine-tuning and the light Higgs mass means electroweak baryogenesis is generically ok.

How and Why the NMSSM Higgs Sector can be ideal.

1. **The Next to Minimal Supersymmetric Model (NMSSM), in which a singlet superfield $\widehat{S}$ is added to the MSSM, maintains all the attractive features (GUT unification, RGE EWSB) of the MSSM while avoiding all its problems.**

2. **In particular, the NMSSM solves the μ problem for a superpotential of form $W \ni \lambda \widehat{S}\widehat{H}_u\widehat{H}_d + \frac{1}{3}\kappa\widehat{S}^3$.**

   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 since there are no dimensionful couplings in the superpotential, which implies that $\langle S\rangle$ 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 EWSB fine-tuning. To avoid EWSB fine-tuning, 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 accessible at the LHC. Also, the gluino should be light.

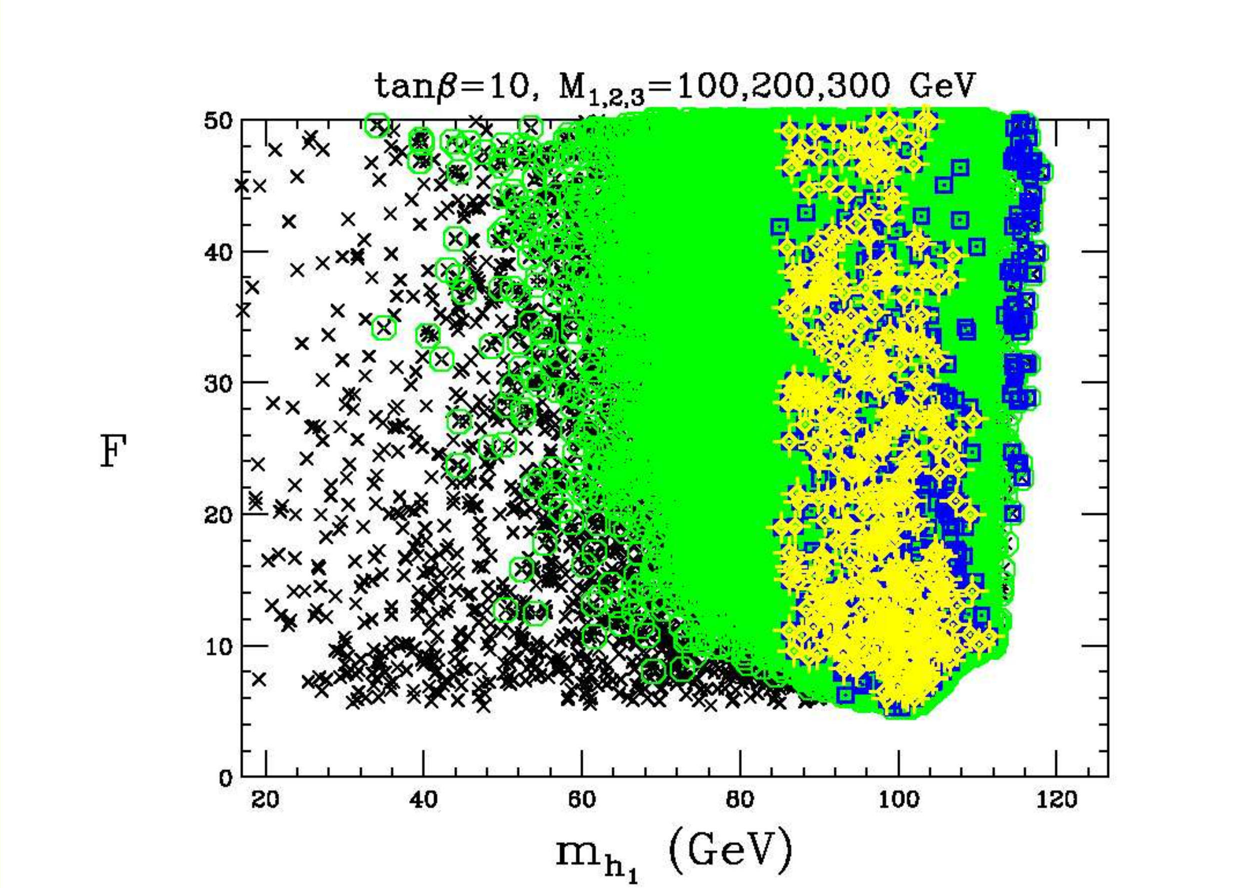


Figure 6: F vs. m_{h_1} for $M_{1,2,3} = 100, 200, 300~\mathrm{GeV}$ and $\tan\beta = 10$. Small $\times$ = no constraints other than global and local minimum, no Landau pole before M_U and neutralino LSP. The O's = stop and chargino limits imposed, but NO Higgs limits. The □'s = all LEP single channel, 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. Taken from Dermisek+JFG, arXiv:0705.4387.

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

4. The points with smallest F are such that $m_{h_1} \sim 100~\mathrm{GeV}$ *and* $B(h_1 \to a_1 a_1) > 0.75$, with $m_{a_1} < 2m_b$ to avoid LEP limits on $Z + b's$ ($b's = 2b + 4b$).

   In the $h_1 \to a_1 a_1 \to \tau^+\tau^-\tau^+\tau^-$ channel, the LEP lower limit is $m_{h_1} > 87~\mathrm{GeV}$.

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

5. If $B(h_1 \to a_1 a_1) > 0.75$ to avoid LEP limits then $B(h_1 \to b\bar{b}) \sim 0.1$ is common and the 2.3σ LEP excess near $m_{b\bar{b}} \sim 98~\mathrm{GeV}$ in $e^+e^- \to Z + b's$ is perfectly explained.

6. GUT-scale boundary conditions are generic 'no-scale'. That is, for the lowest F points we are talking about, almost all the soft-SUSY-breaking parameters are small at the GUT scale. This is a particularly attractive possibility in the string theory context.

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?

- The naturalness of a light-a_1 scenario is the topic of Dermisek +JFG, hep-ph/0611142. I only state some results.

- The NMSSM has a natural $U(1)_R$ symmetry when the soft-SUSY-breaking A_λ and A_κ in $V \ni \lambda A_\lambda S H_u H_d + \frac{1}{3}\kappa A_\kappa S^3$ are set to zero.

  If this limit is applied at scale m_Z, then, $m_{a_1} = 0$.

  But, it turns out that then $B(h_1 \to a_1 a_1) \lesssim 0.3$ which does not allow escape from the LEP limit.

  However, the much more natural idea would be to impose the $U(1)_R$ symmetry at the GUT scale.

  Then, the renormalization group often generates exactly the values for the parameters needed to obtain a light a_1 with large $B(h_1 \to a_1 a_1)$.

- We measure the tuning needed to get small m_{a_1} and large $B(h_1 \to a_1 a_1)$ using G (the "light-a_1 tuning measure"). We want small G.

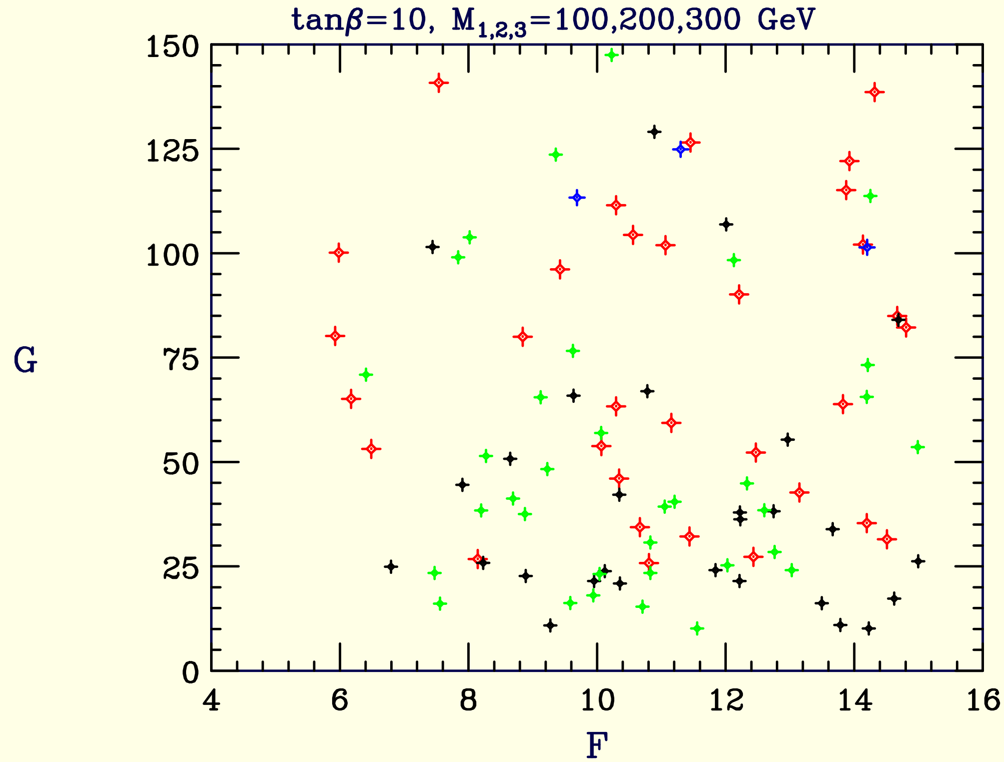


Figure 7: G vs. F for $M_{1,2,3} = 100, 200, 300$ GeV and $\tan\beta = 10$ for points with $F < 15$ having $m_{a_1} < 2m_b$ and large enough $B(h_1 \to a_1 a_1)$ to escape LEP limits. The color coding is: blue $= m_{a_1} < 2m_\tau$; red $= 2m_\tau < m_{a_1} < 7.5$ GeV; green $= 7.5$ GeV $< m_{a_1} <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

A phenomenologically important quantity is $\cos\theta_A$, the coefficient of the

MSSM-like doublet Higgs component of the a_1:

$$a_1 = \cos\theta_A A_{MSSM} + \sin\theta_A A_S\,. \tag{7}$$

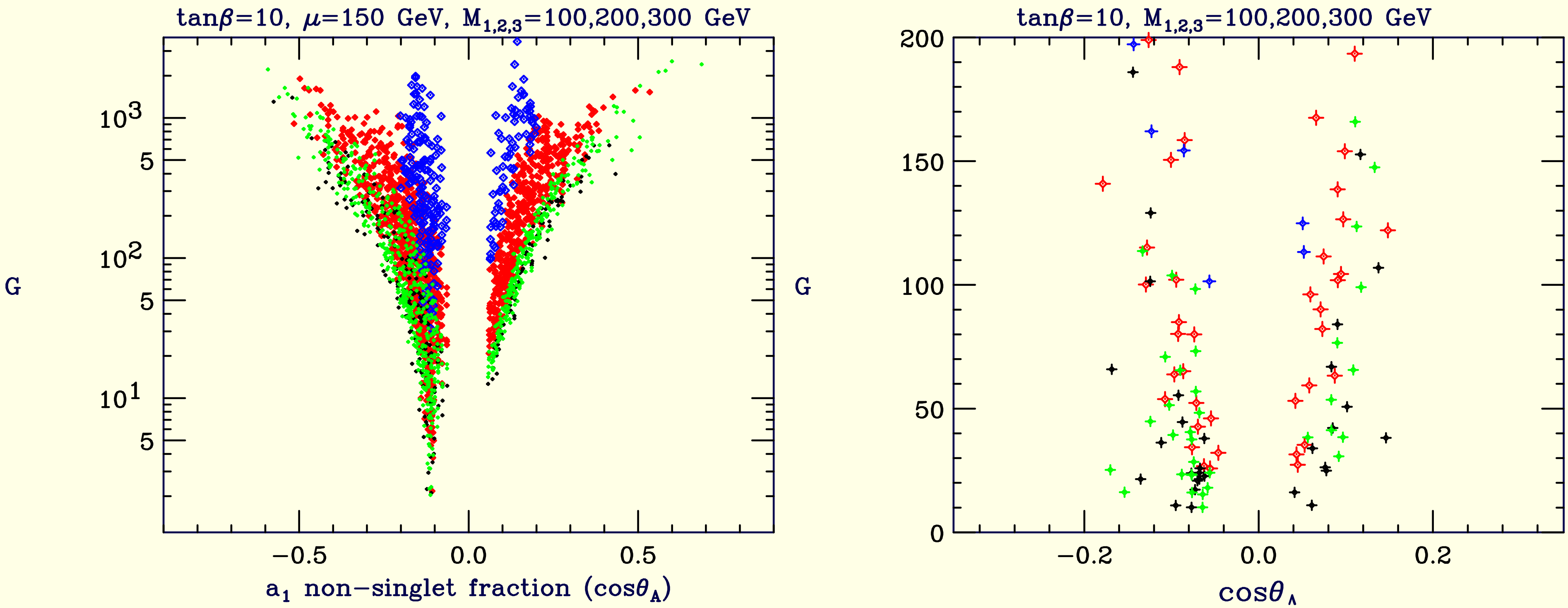


Figure 8: G vs. $\cos\theta_A$ for $M_{1,2,3} = 100, 200, 300$ GeV and $\tan\beta = 10$ from $\mu_{\rm eff} = 150$ GeV scan (left) and for points with $F < 15$ (right) having $m_{a_1} < 2m_b$ and large enough $B(h_1 \to a_1 a_1)$ to escape LEP limits. The color coding is: blue $= m_{a_1} < 2m_\tau$;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

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 (the relevant soft parameters) at scale M_U.

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) The preferred small $\cos\theta_A \sim -0.1$ implies that the a_1 is mainly singlet and its coupling to $b\overline{b}$, being proportional to $\cos\theta_A \tan\beta$ is not enhanced. However, it is also not that suppressed, which has important implications.

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 (a) $F < 10$, *i.e.* no fine tuning, and (b) 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 $a_1 \to b\overline{b}$ 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 light-a_1 tuning 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. $t\bar{t}h_1 \to t\bar{t}a_1 a_1 \to t\bar{t}\tau^+\tau^-\tau^+\tau^-$.

   Study begun.

3. $\widetilde{\chi}_2^0 \to h_1 \widetilde{\chi}_1^0$ **with** $h_1 \to a_1 a_1 \to 4\tau$.

   (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.)**

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 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: arXiv:0712.3510) results are that one expects about 3 clean, *i.e.* reconstructed and tagged, events with very small background (~ 0.1 event) per $90\ \mathrm{fb}^{-1}$ of luminosity.

$\Rightarrow$ clearly a high luminosity game.

We estimate the significance, S, of the observation by equating the probability of $s+b$ events given a Poisson distribution with mean b to the probability of S standard deviations in a Gaussian distribution.

Signal significances are plotted in Fig. 9 for a variety of luminosity and

triggering assumptions.

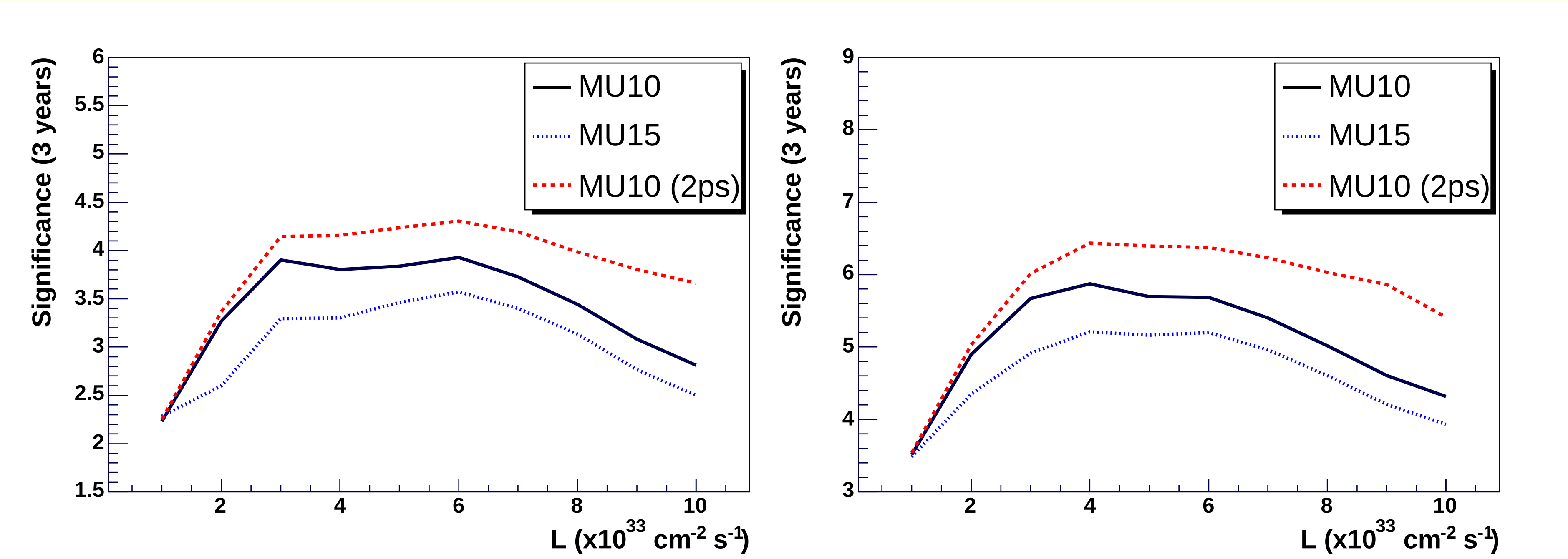


Figure 9: **(a) The significance for three years of data acquisition at each luminosity. (b) Same as (a) but with twice the data. Different lines represent different μ trigger thresholds and different forward detector timing. Some experimentalists say more efficient triggering is possible, doubling the number of events at given luminosity.**

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. Labeling the two a's with indices 1 and 2 we have

$$p_i^{vis} = f_i \, p_{a,i} \tag{8}$$

  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:

$$p_{a,1} + p_{a,2} = p_h \tag{9}$$

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:

$$\frac{(p_1^{vis})_{x,y}}{f_1} + \frac{(p_2^{vis})_{x,y}}{f_2} = 0 \tag{10}$$

and

$$\frac{(p_1^{vis})_z}{f_1} + \frac{(p_2^{vis})_z}{f_2} = (\xi_1 - \xi_2)\frac{\sqrt{s}}{2} \tag{11}$$

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 (10) and (11) gives

$$f_1 = \frac{2}{(\xi_1 - \xi_2)\sqrt{s}} \left[(p_1^{vis})_z - \frac{(p_2^{vis})_z (p_1^{vis})_{x,y}}{(p_2^{vis})_{x,y}} \right], \tag{12}$$

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

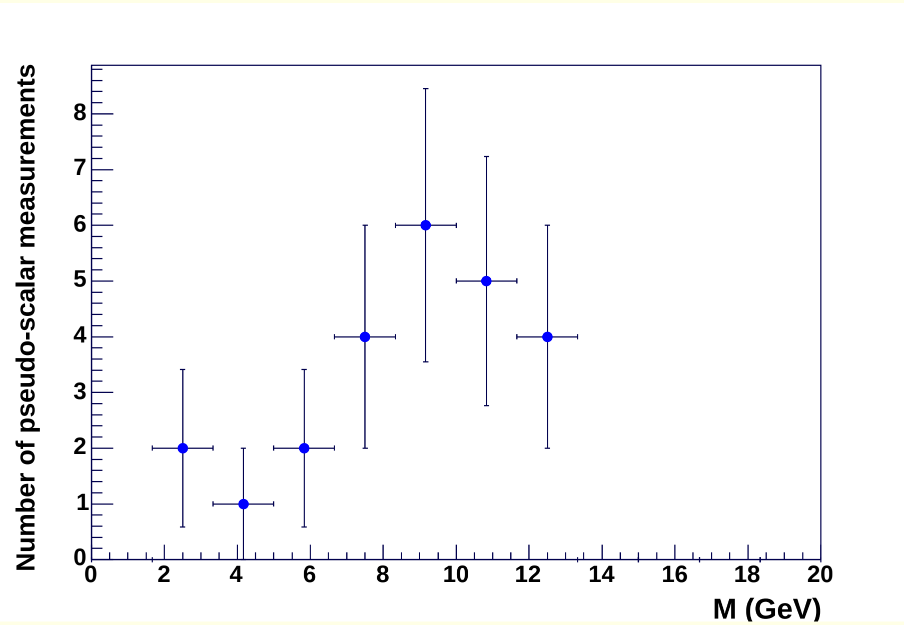
Equations (12) and (13), provide two solutions depending on whether we solved using the (x, z) or (y, z) pair of equations.

Note that we are able to make $4 = 2 \times 2$ a mass measurements per event.

Figure 10 shows the distribution of masses obtained for $180\ \mathrm{fb}^{-1}$ of data collected at 3×10^{33} cm^{-2}s^{-1}, corresponding to about 6 Higgs events and therefore 24 m_a entries.

In the right-hand figure the integer in each box labels one of the 6 signal events.

By considering many pseudo-data sets, we conclude that a typical experiment would yield $m_a = 9.3 \pm 2.3$ GeV, which is in re-assuringly good agreement with the expected value of 9.7 GeV.



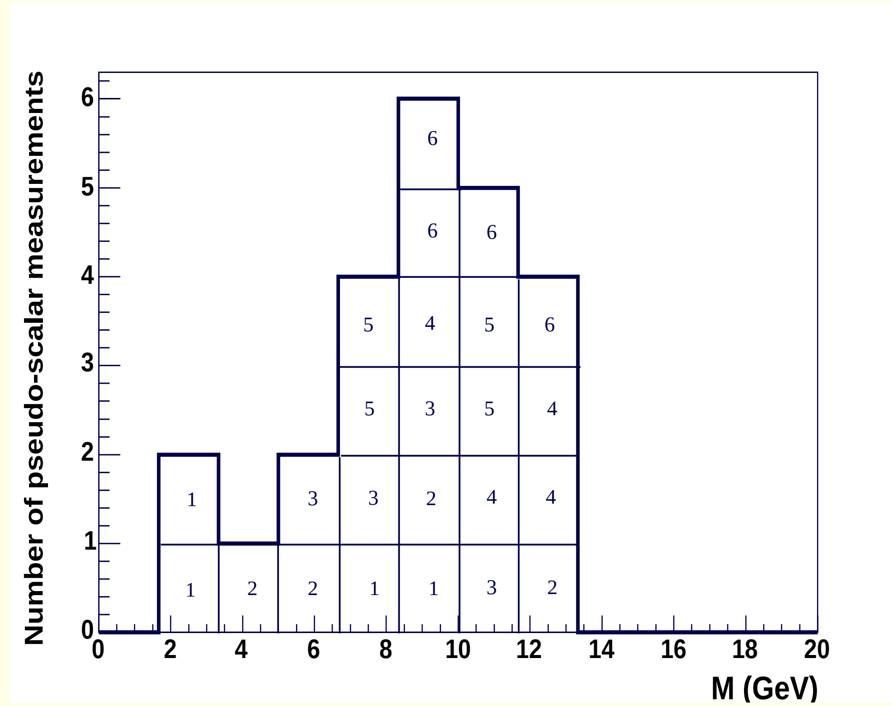


Figure 10: (a) A typical a mass measurement. (b) The same content as (a) but with the breakdown showing the 4 Higgs mass measurements for each of the 6 events, labeled $1-6$ in the histogram.

$$\boxed{WW \to h}$$

- For $m_h = 100$ GeV and SM-like WWh coupling, $\sigma(WW \to h) \sim 7$ pb, implying 7×10^5 events before cuts for $L = 100~\mathrm{fb}^{-1}$.

- **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, p_T^h must be large enough that the a's are not back to back; this is the case for almost all events even before cuts.
- **We then have the two equations:**

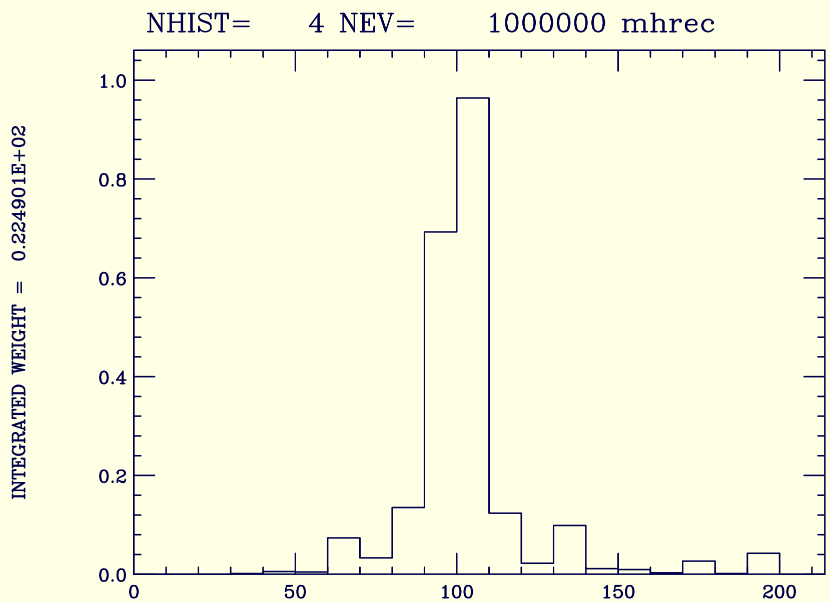
$$p_h^x = \frac{(p_1^{vis})_x}{f_1} + \frac{(p_2^{vis})_x}{f_2} \quad p_h^y = \frac{(p_1^{vis})_y}{f_1} + \frac{(p_2^{vis})_y}{f_2} \tag{14}$$

  with solution

$$f_1 = \frac{(p_1^{vis})_y (p_2^{vis})_x - (p_1^{vis})_x (p_2^{vis})_y}{p_h^y (p_2^{vis})_x - p_h^x (p_2^{vis})_y} \quad f_2 = \frac{(p_1^{vis})_y (p_2^{vis})_x - (p_1^{vis})_x (p_2^{vis})_y}{-p_h^y (p_1^{vis})_x + p_h^x (p_1^{vis})_y} \tag{15}$$

- **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.**
- **A signal only Monte-Carlo run without lepton or tag jet momentum**

smearing yields encouraging results



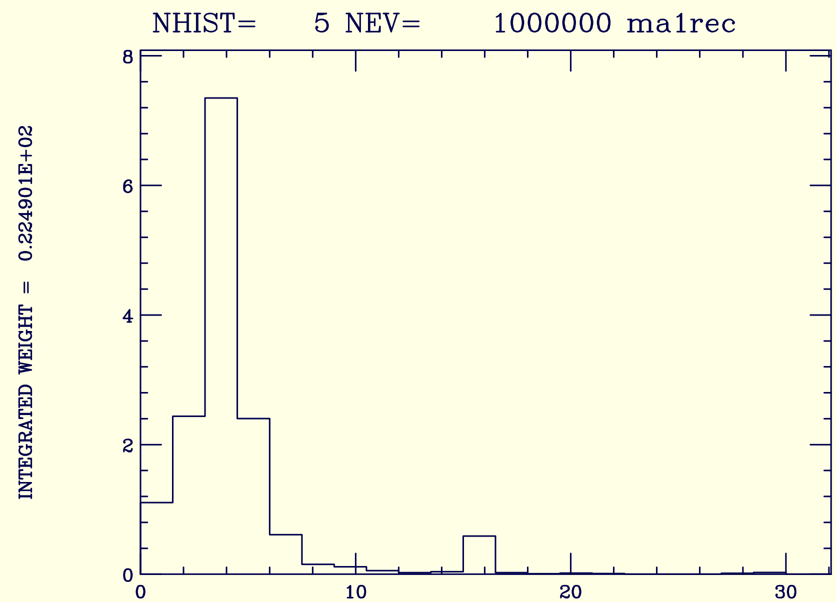


Figure 11: (a) A typical h mass distribution. (b) A typical a mass distribution. No cuts imposed; signal only

- **The main issue 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 so backgrounds are yet to be determined.**

ILC

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

This idea has gained some traction with the B factory managers.

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

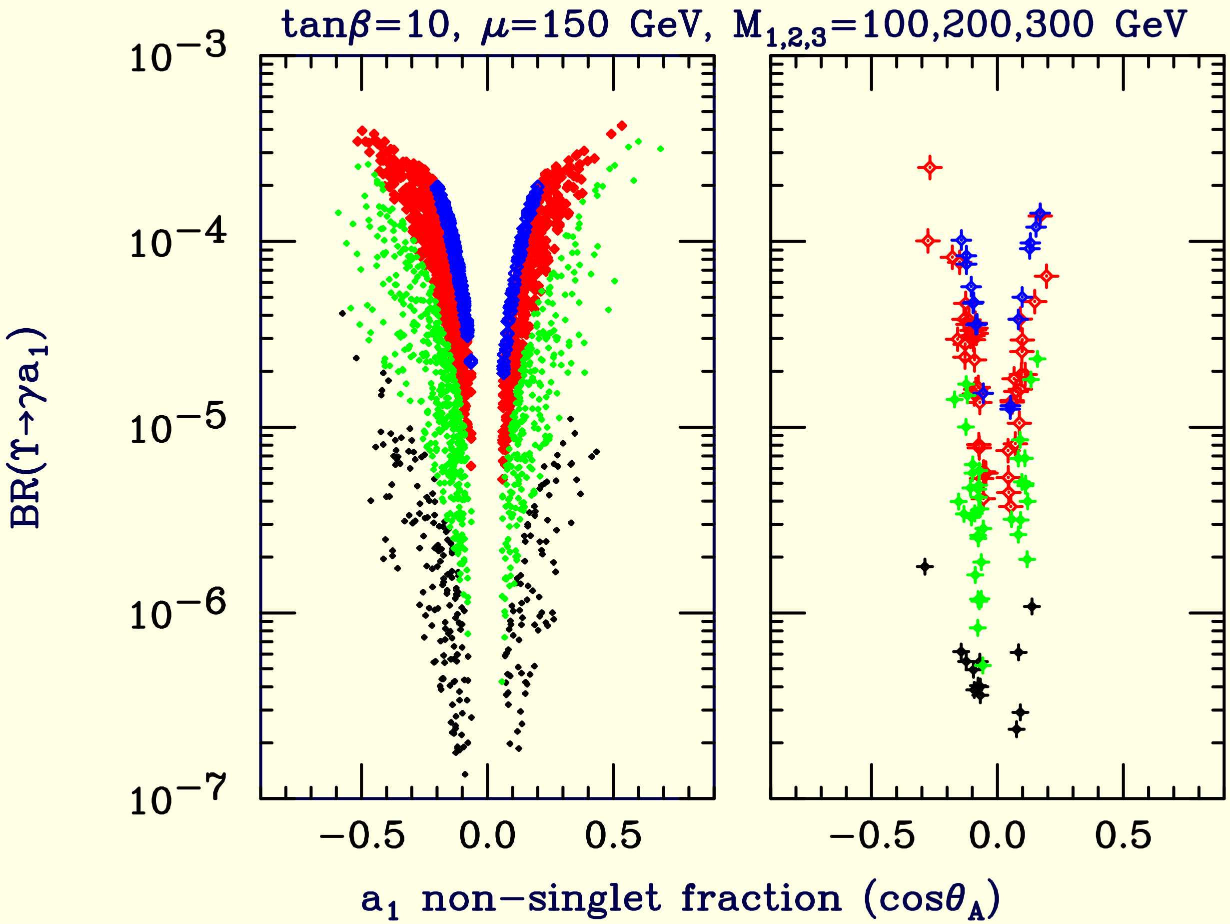


Figure 12: $B(\Upsilon \to \gamma a_1)$ for NMSSM scenarios. The left plot comes from an A_λ, A_κ scan, holding $\mu_{\rm eff}(m_Z) = 150$ GeV fixed. The right plot shows results for $F < 15$ scenarios with $m_{a_1} < 9.2$ GeV found in a general scan over all NMSSM parameters. color coding is: blue $= m_{a_1} < 2m_\tau$; 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. 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. Recall: small G requires green or black.

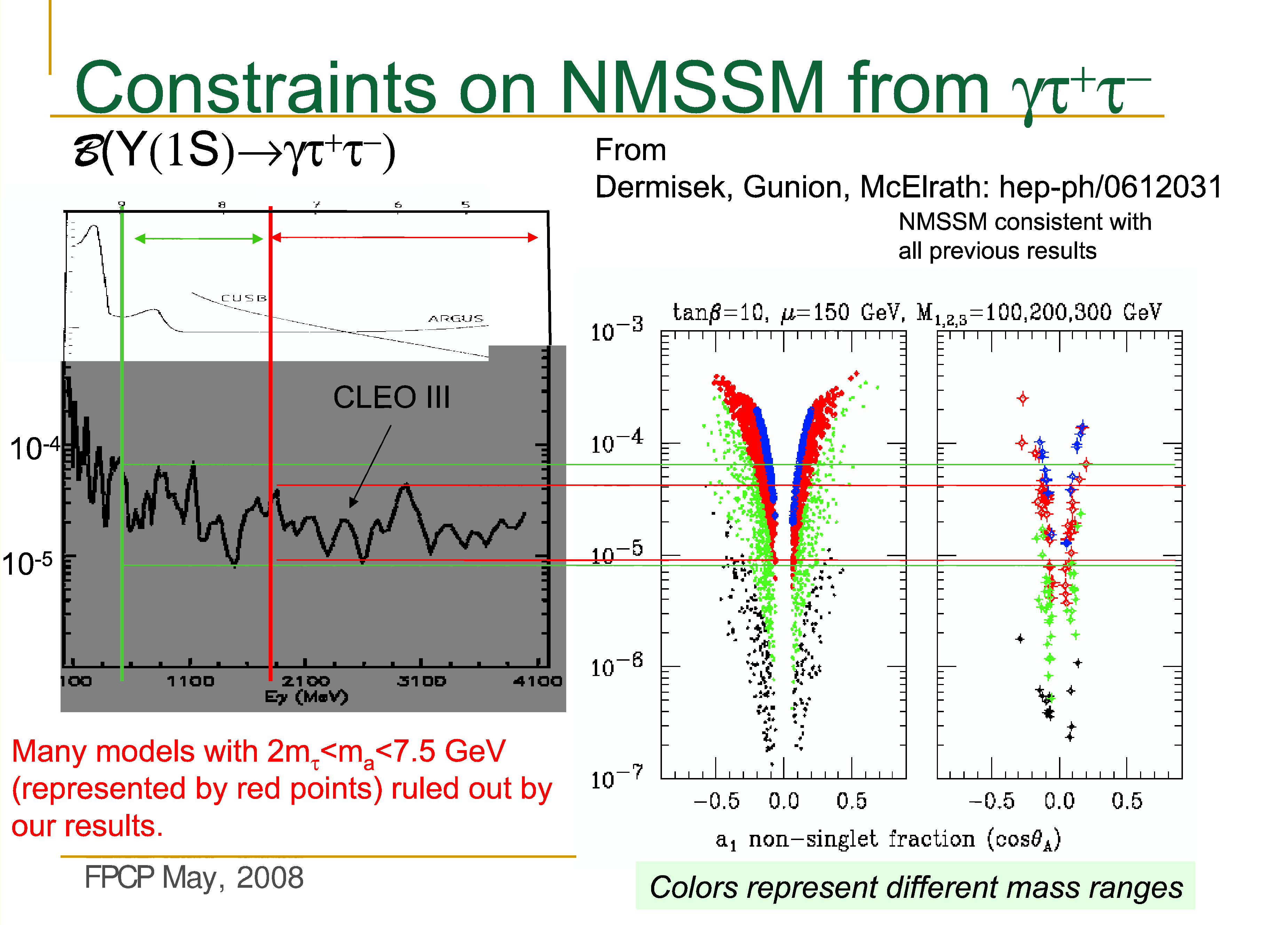


Figure 13: **PRELIMINARY New Limits from CLEO III from $\Upsilon(1S) \to \gamma\tau^+\tau^-$. Total of 22 Million $\Upsilon(1S)$ events.**

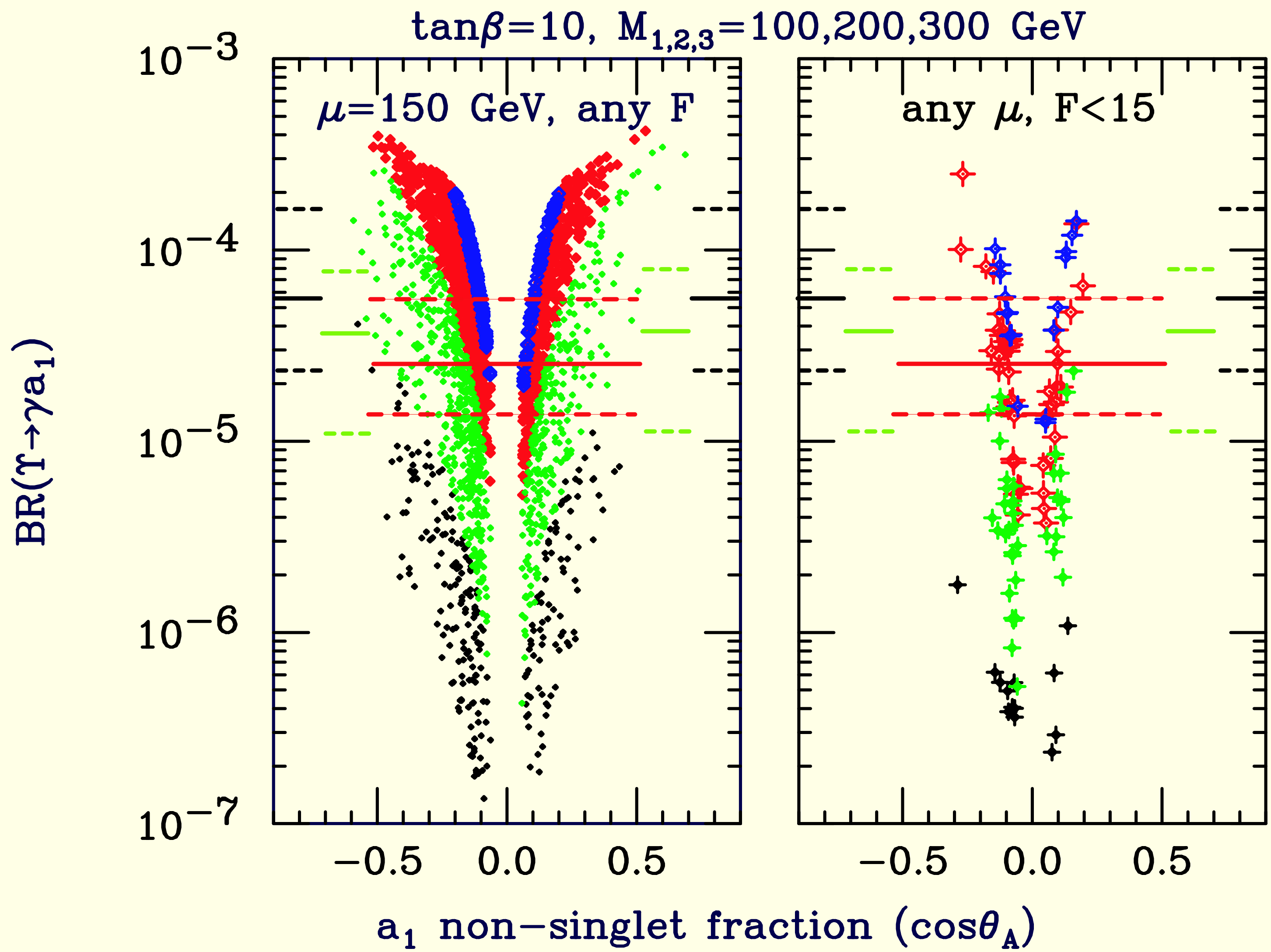


Figure 14: **PRELIMINARY** **New Limits from CLEO III from** $\Upsilon(1S) \to \gamma\tau^+\tau^-$**. Total of** 22 **Million** $\Upsilon(1S)$ **events. Limits for** $m_{a_1} < 2m_\tau$ **(blue lines) assume** $a_1 \to \mu^+\mu^-$**, which is too simple. Left plot: fixed** $\mu = 150\ \mathrm{GeV}$ **scan without constraint on** F**; right plot: all** $F < 15$ **points in general scan. Both scans are for** $\tan\beta = 10$**,** $M_{1,2,3} = 100, 200, 300\ \mathrm{GeV}$**.**

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

  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.

- **Note: For preferred $B(\Upsilon \to \gamma a_1)$ levels, the a_1 contribution to a_μ (which contribution is < 0, $i.e.$ in the wrong direction) is negligible.**

Cautionary Notes

1. **Relaxing Fine-Tuning:**

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 fine-tuning, 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,

$$h_1 \to a_1 a_1 \to 4j \,. \tag{16}$$

Since $2m_D > 2m_\tau$, charm will not play a role, but, $j = g, s, \ldots$ will be present for $m_{a_1} > 3m_\pi$.

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-fine-tuning, F

- In Fig. 6, 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 $F \sim 5$ fine-tuning 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 mentioned earlier for $m_{h_1} \sim 100 \text{ GeV}$.

Although the latter channel might appear challenging, there are several papers in the literature (Cheung, K *et al.*, hep-ph/0703149 and Carena, M. *et al.*, arXiv:0712.2466) claiming that such a Higgs signal can be seen.

The basic thing to keep in mind:

For a primary Higgs with mass $\lesssim 150 \text{ GeV}$, 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.

2. $\boxed{\text{One singlet}}$

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.

3. $\boxed{\text{Other SUSY decays.}}$

A particular case that arises in models with extra singlets is $h_1 \to \widetilde{\chi}_2^0 \widetilde{\chi}_1^0$ with $\widetilde{\chi}_2^0 \to f \overline{f} \widetilde{\chi}_1^0$.

Once again, the very small $b\overline{b}$ width of a Higgs with SM-like couplings to SM particles means that this mode could easily dominate if allowed.

LEP constraints allow $m_{h_1} < 100~\mathrm{GeV}$ if this is an important decay channel.

Higgs discovery would be really challenging if $h_1 \to a_1 a_1 \to 4\tau$ and $h_1 \to \widetilde{\chi}_2^0 \widetilde{\chi}_1^0 \to f \overline{f} \not{E}$ were both present.

Conclusions

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

  1) Quadratic divergence fine-tuning is erased ab initio.

  2) EWSB, $i.e.$ m_Z^2, fine-tuning can be avoided for $m_{h_1} \lesssim 100~\mathrm{GeV}$, which is consistent with LEP limits when $m_{a_1} < 2m_b$ and $BR(h_1 \to a_1 a_1) > 0.75$.

  3) Light-a_1 fine-tuning to achieve $m_{a_1} < 2m_b$ and (simultaneously) large $B(h_1 \to a_1 a_1)$ can be avoided.

  $m_{a_1} > 2m_\tau$ is preferred to minimize light-a_1 fine-tuning.

  4) Electroweak baryogenesis becomes entirely viable, not just because $m_{h_1} < 100~\mathrm{GeV}$, but also because of extra terms in NMSSM potential.

  5) There is much more freedom in obtaining correct relic LSP density ($e.g.$ LSP can have singlet component).

- **If low fine-tuning is imposed for an acceptable SUSY model, the NMSSM example suggests 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.

Consequences

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;

- In short, SUSY will be easily seen at the LHC, but Higgs detection requires hard work. Still, it now appears possible with high luminosity using doubly-diffractive $pp \to pph_1 \to pp4\tau$ events.

- 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 $B(h_1 \to a_1 a_1 + \ldots)$ with most final states not decaying to b's ($e.g.~m_{a_1} < 2m_b$) would be needed. In general models, there would be many channels in $\ldots$ and detection of any one channel would be a huge challenge.

  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.