New (and Old) Perspectives on Higgs Physics

Jack Gunion
U.C. Davis

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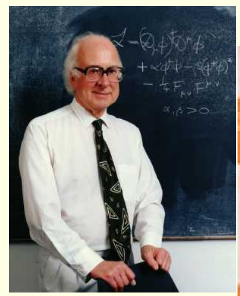
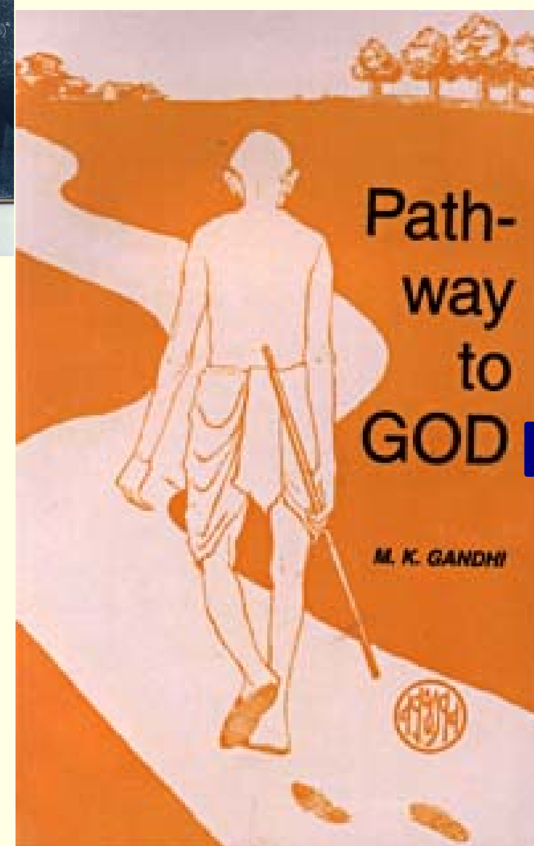




Particle

Introduction

The number one issue in Higgs physics is the solution of the hierarchy / fine-tuning problems that arise in the Standard Model and Higgs sector extensions thereof from quadratically divergent one-loop corrections to the Higgs mass.

Warning: there will be 3 kinds of fine-tuning that I will discuss;

1. one is the Higgs mass / quadratic divergence fine-tuning;
2. a second kind, sometimes called Electroweak fine-tuning, is the fine-tuning associated with getting the value of m_Z correct starting from GUT-scale parameters of some model;
3. a third will emerge in the supersymmetric context.

Were it not for the quadratic divergence fine-tuning problem, there is nothing to forbid the SM from being valid all the way up the to 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 $130 \lesssim m_{h_{\rm SM}} \lesssim 180$ GeV.

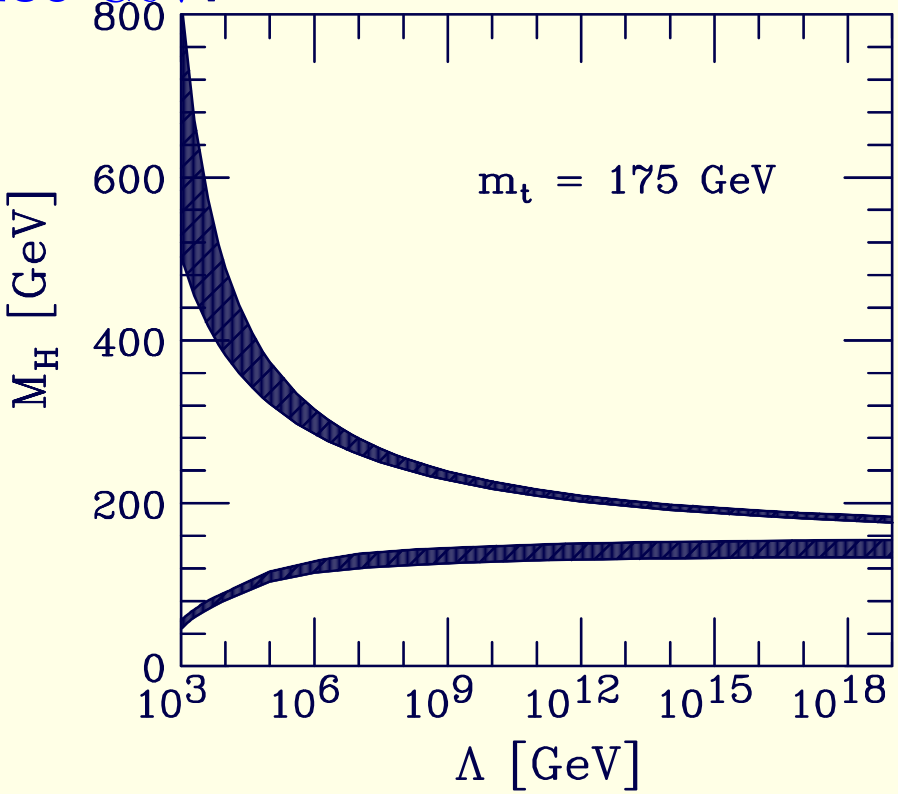


Figure 1: Triviality and global minimum constraints on $m_{h_{\rm SM}}$ vs. Λ.

However, the survival of the SM as an effective theory all the way up to $M_{\rm P}$ is unlikely due to the problem of "naturalness" and the associated Higgs mass / quadratic divergence fine-tuning issue.

We discuss this next.

Why the SM Higgs sector is probably wrong

- **Huge hierarchy:**

  To obtain the low Higgs mass favored by data (and required by WW scattering perturbativity) requires an enormous cancellation between top loop corrections (as well as W, Z and $h_{\rm SM}$ loops) and the bare Higgs mass of the Lagrangian.

$$m_{h_{\rm SM}}^2 = m_0^2 + \frac{3}{16\pi^2 v_{SM}^2}(2m_W^2 + m_Z^2 + m_{h_{\rm SM}}^2 - 4m_t^2)\Lambda^2 \tag{1}$$

  where $m_0^2 = 2\lambda v_{SM}^2$, where $v_{SM} \sim 174~{\rm GeV}$. ($V \ni \frac{1}{2}\lambda^2[(\Phi^\dagger\Phi)^2 - v_{SM}^2(\Phi^\dagger\Phi)]$ and $\langle\Phi\rangle = v_{SM}$.

  Assuming no particular connection between the contributions, we must fine tune m_0^2 to cancel the Λ^2 term with something like a precision of one part in 10^{32} if $\Lambda = M_{\rm P}$.

And, of course, λ must be very large and non-perturbative.

Keeping only the m_t term with $\Lambda \to \Lambda_t$, one measure of fine-tuning is:

$$F_t(m_{h_{\rm SM}}) = \left|\frac{\partial \delta m^2_{h_{\rm SM}}}{\partial \Lambda_t^2}\frac{\Lambda_t^2}{m^2_{h_{\rm SM}}}\right| = \frac{3}{4\pi^2}\frac{m_t^2}{v_{SM}^2}\frac{\Lambda_t^2}{m^2_{h_{\rm SM}}} \equiv K\frac{\Lambda_t^2}{m^2_{h_{\rm SM}}}\,. \qquad (2)$$

Too large a value of F_t at a given Λ_t implies that you must look for new physics at or below the scale

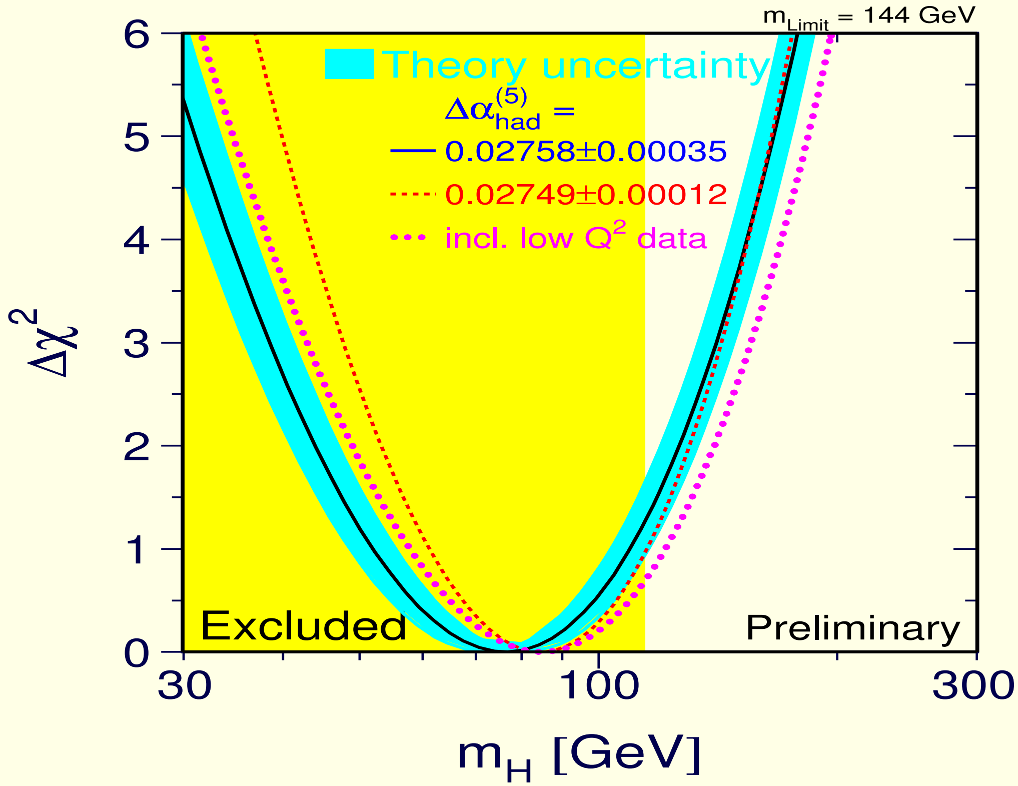
$$\Lambda_t \lesssim \frac{2\pi v_{SM}}{\sqrt{3} m_t} m_{h_{\rm SM}} F_t^{1/2} \sim 400 \text{ GeV} \left(\frac{m_{h_{\rm SM}}}{115 \text{ GeV}}\right) F_t^{1/2}, \qquad (3)$$

$F_t > 10$ is deemed problematical, implying (for the precision electroweak preferred SM $m_{h_{\rm SM}} \sim 100$ GeV mass) new physics somewhat below 1 TeV, in principle well within LHC reach.

Criteria for a "good" Higgs theory

- **It should allow for a light Higgs boson without fine-tuning to handle the quadratic divergence. We will return to discuss this more thoroughly. For now, we continue with purely phenomenological criteria.**

- **It should predict a Higgs with SM couplings to WW, ZZ and with mass in the range preferred by precision electroweak data. The latest plot is:**



This plot includes the latest m_W and m_t measurements which push the preferred $m_{h_{SM}}$ lower than before.

At 95% CL, $m_{h_{SM}} < 144~\mathrm{GeV}$ and the $\Delta\chi^2$ minimum is between $70~\mathrm{GeV}$ and $80~\mathrm{GeV}$.

- In an ideal model, the Higgs should have mass no larger than $100~\mathrm{GeV}$.

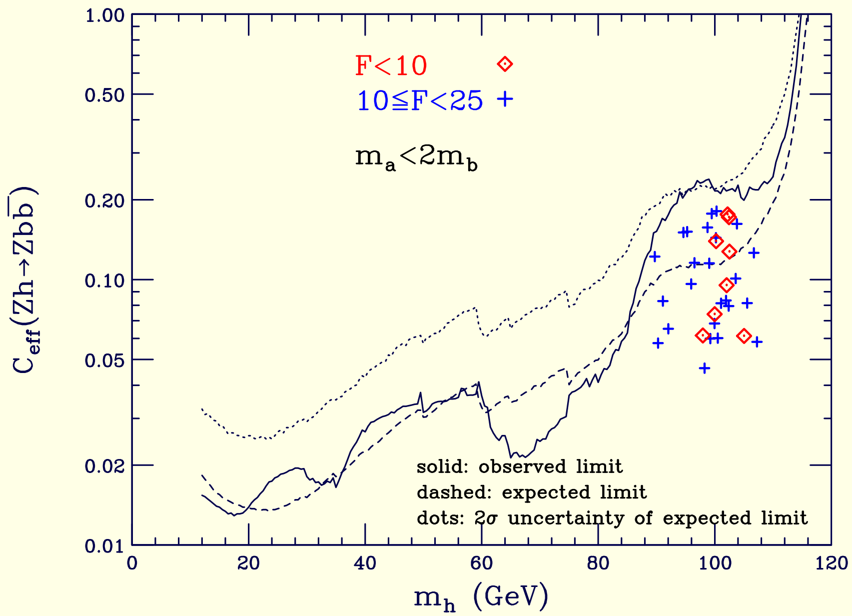
  But, at the same time, It should avoid the LEP limits on such a light Higgs. One generic possibility is for its decays to be non-SM-like.

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

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

Note that to have $m_H \leq 100~\mathrm{GeV}$ requires one of the final three modes or something even more exotic.

- **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.**



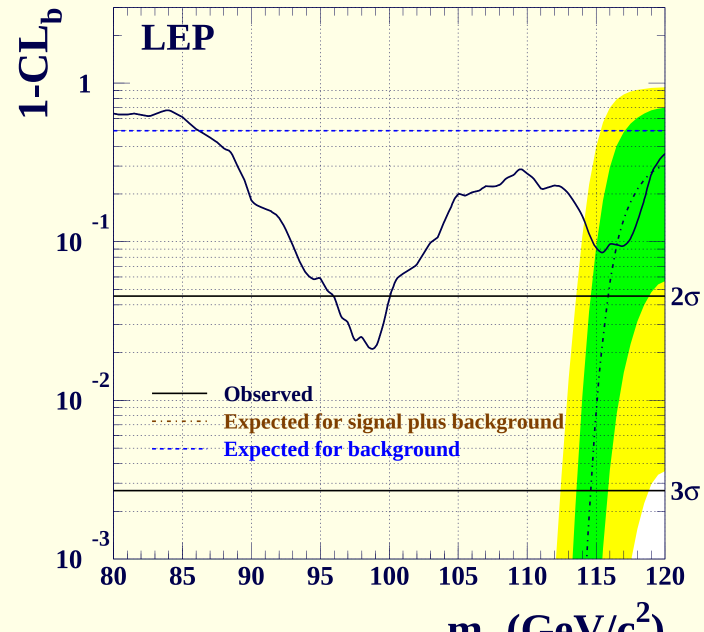


Figure 2: Plots for the $Zb\bar{b}$ final state.

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.**
2. **Or, you could have SM-like decay pattern but $g^2_{ZZH} \sim 0.1 g^2_{ZZh_{\rm SM}}$.**

- **Regarding 1., almost any additional decay channel will severely suppress the $b\bar{b}$ branching ratio.**

A Higgs of mass, *e.g.*, 100 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 (Gunion:1984yn,Li:1985hy,Gunion:1986nh).

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 $g_{haa} = c\,\frac{g m_h^2}{2 m_W}$ and ignoring phase space suppression, we find

$$\frac{\Gamma(h \to aa)}{\Gamma(h \to b\bar{b})} \sim 310\, c^2 \left(\frac{m_h}{100\ \mathrm{GeV}}\right)^2 . \quad (4)$$

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 2., one can share the ZZ coupling by sharing the SM vev among (perhaps many) fields with corresponding mass eigenstates with one vev squared being $0.1 \times v_{SM}^2$.

  A bit of care in setting the scenario up is needed to avoid seeing other Higgs while at the same time satisfying the precision EW constraint (Espinosa:1998xj with JFG)

$$\sum_i \frac{v_i^2}{v_{SM}^2} \ln m_{h_i} \lesssim \ln (144 \text{ GeV}) \,, \quad (5)$$

  where $\langle \Phi_j \rangle \equiv v_j$ and $\sum_j v_j^2 = v_{SM}^2 \sim (175 \text{ GeV})^2$.

  If you don't want LEP to have seen any sign of a Higgs boson, the PEW constraint can still be satisfied even if all the Higgs decay in SM fashion, so long as the eigenstates are not too much below 100 GeV and not degenerate.

  And, of course, with enough h_j eigenstates, Higgs decays will not be SM-like given the proliferation of $h_j \to h_i h_i$ and $h_j \to a_i a_i$ decays.

The combination of such decays and weakened production rates for the individual Higgs bosons would make Higgs detection very challenging at the LHC and require a high-L linear collider.

An interesting special case is to construct a 2HDM with $m_{h^0} = 98$ GeV and $g^2_{ZZh^0} = 0.1 g^2_{ZZh_{\rm SM}}$ and with $m_{H^0} = 116$ GeV (the other LEP excess) and $g^2_{ZZH^0} \sim 0.9 g^2_{ZZh_{\rm SM}}$ (Drees:2005jg and others).

- **But, these games alone do not solve the quadratic divergence problem (although they can delay it — see below).**

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

1. Recall that after including the one loop corrections we have

$$m_{h_{\rm SM}}^2 = \mu^2 + \frac{3\Lambda^2}{32\pi^2 v^2}(2m_W^2 + m_Z^2 + m_{h_{\rm SM}}^2 - 4m_t^2) \quad (6)$$

   where $\mu^2 = 2\lambda v_{SM}^2$.

   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. But, there are some tactics for delaying the fine-tuning problem.

   (a) $m_{h_{\rm SM}}$ could obey the "Veltman" (see also, Castro + Pestieau and Scadron+Delbourgo+Rupp) condition

$$m_{h_{\rm SM}}^2 = 4m_t^2 - 2m_W^2 - m_Z^2 \sim (317 \text{ GeV})^2 . \quad (7)$$

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. (6), 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.

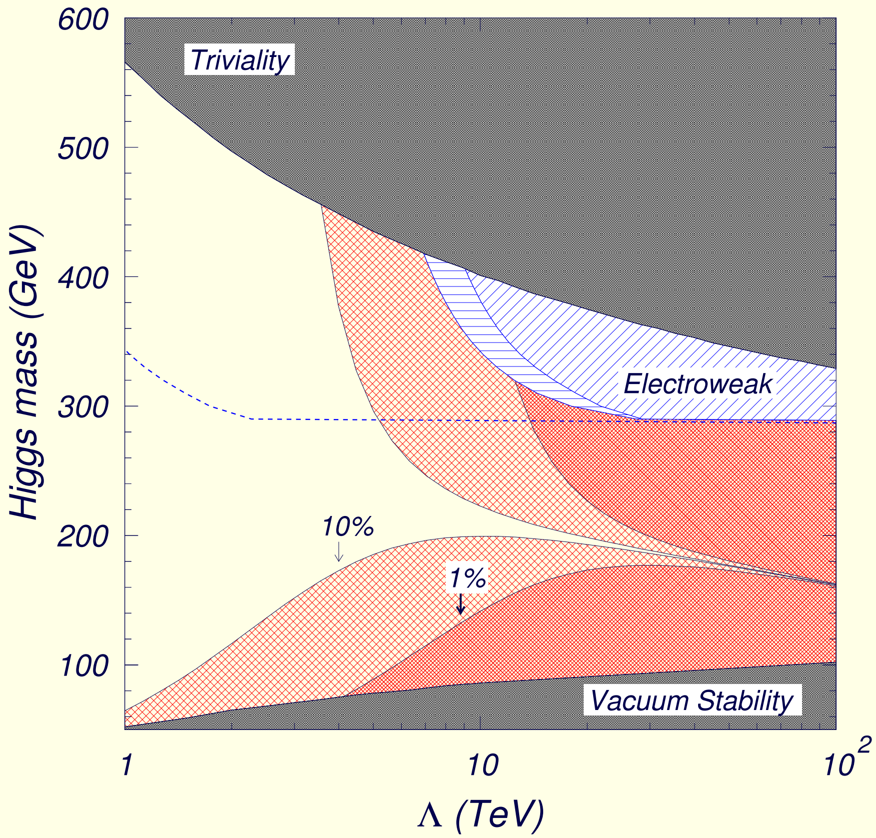


Figure 3: Fine-tuning constraints on Λ, from Kolda

The upper bound for Λ at which new physics must enter is largest for $m_{h_{\rm SM}} \sim 200~{\rm GeV}$ where the SM fine-tuning would be 10% if $\Lambda \sim 30~{\rm TeV}$. 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 $m_{h_{\rm SM}} < 144~{\rm GeV}$ at 95% CL.

(b) Return to the multi-doublet approach. Then (in the simplest case where all h_i have the same top quark Yukawa, but rescaled) 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

$$F_t^i = f_i^2 F_t(m_i) = K f_i^2 \frac{\Lambda_t^2}{m_i^2} \qquad (8)$$

$i.e.$ 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.

The Many Reasons we like 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.**

- **SUSY cures the naturalness / hierarchy problem (quadratic divergences are largely canceled), and it does so without Electroweak fine-tuning (see definition below) provided the SUSY breaking scale is $\lesssim 500~\mathrm{GeV}$.**

  As a reminder, the top quark loop (which comes with a minus sign) is cancelled by the loop of the spin-0 partner called "stop" (which loop comes with a plus sign). Thus, Λ_t^2 is effectively replaced by $\overline{m}_{\widetilde t}^2 \equiv m_{\widetilde t_1} m_{\widetilde t_2}$.

- **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

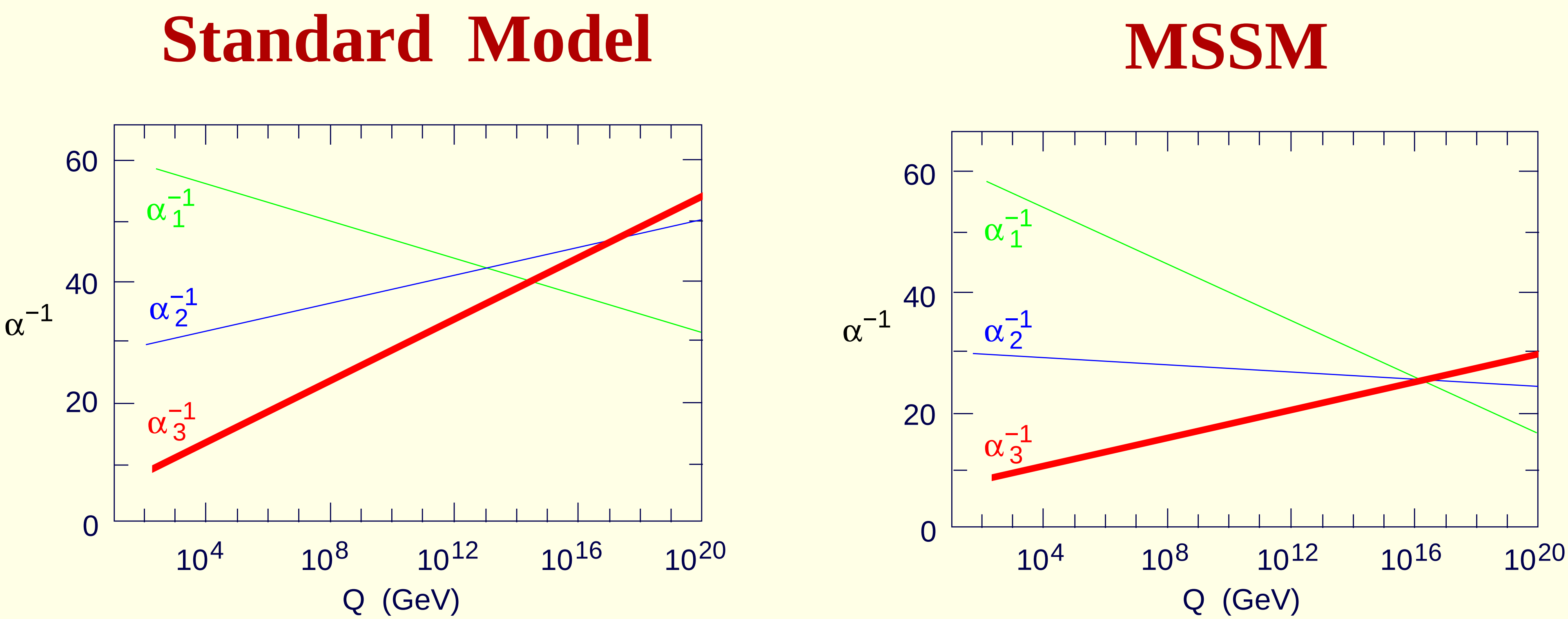


Figure 4: Unification of couplings constants ($\alpha_i = g_i^2/(4\pi)$) in the minimal supersymmetric model (MSSM) as compared to failure without supersymmetry.

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 correlates well with the attractive idea of gravity-mediated SUSY breaking.

2. **RGE EWSB**

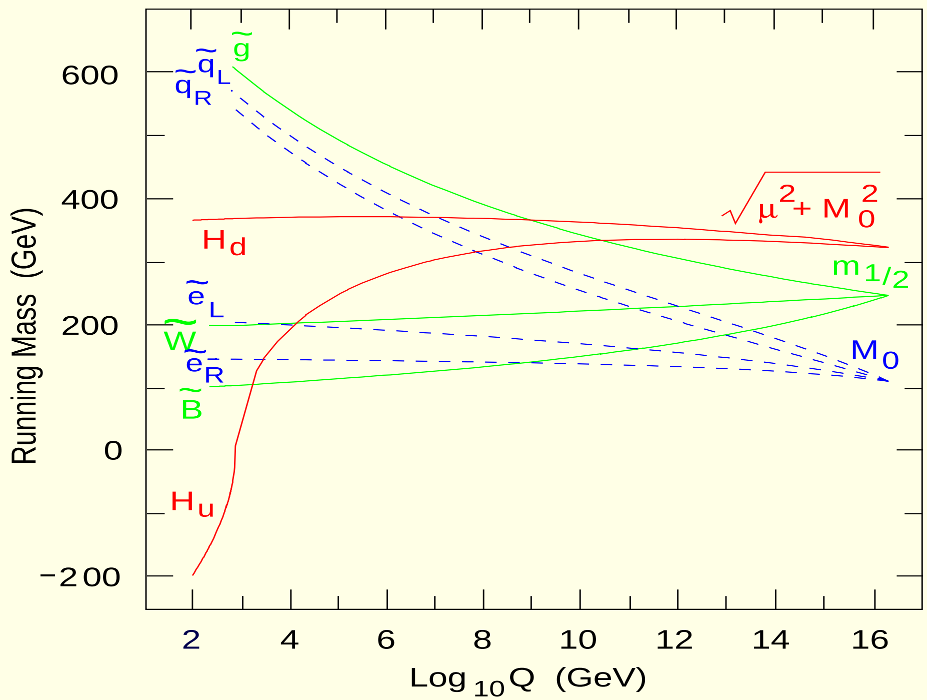


Figure 5: Evolution of the (soft) SUSY-breaking masses or masses-squared, showing how $m^2_{H_u}$ is driven < 0 at low $Q \sim \mathcal{O}(m_Z)$.

Starting with 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 natural prediction is that m_Z^2 should be somewhat, but not enormously, below the stop mass squared, the average value being denoted by $\overline{m}_{\widetilde{t}}^2$.

Then, 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 EWSB breaking parameters from M_U to m_Z.

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

- **The Higgs Mass**

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

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

$$\overset{\text{large} \tan\beta}{\sim} \quad (91 \text{ GeV})^2 + (38 \text{ GeV})^2 \log\left(\frac{m_{\widetilde{t}_1} m_{\widetilde{t}_2}}{m_t^2}\right). \tag{9}$$

A Higgs mass of order 100 GeV, as predicted for stop masses $\sim 2m_t$, is in wonderful accord with precision electroweak data and there is no fine-tuning required to get the right value of m_Z^2.

But, 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 cases that have a large Electroweak fine-tuning problem.

So, why haven't we seen the Higgs? Is SUSY wrong, are stops heavy (implying that fine adjustment is required to get correct m_Z), 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 ....

- Electroweak Fine-tuning (different from hierarchy fine-tuning)

$$F = \mathrm{Max}_p \left| \frac{p}{m_Z} \frac{\partial m_Z}{\partial p} \right| , \tag{10}$$

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

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).

These p's are the GUT-scale parameters that determine all the m_Z-scale SUSY parameters, and these in turn determine v_{SM}^2 to which m_Z^2 is proportional.

$F > 20$ 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.

- So, the question if what is the smallest F that can be achieved while keeping $m_h > 114~\mathrm{GeV}$ (as required in the MSSM since h decays are much like h_{SM} decays).

  The answer is:

  (a) For most of parameter space, $F > 100$ or so.

  (b) For a part of parameter space with large mixing between the stops, F can be reduced to 16 at best (6% fine-tuning), but this part of parameter space has many other peculiarities.

Our aim is $F \sim 5$.

- **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, in which a singlet superfield, $\widehat{S}$, is added to the MSSM superfields, is by far the most attractive.**

  In fact, we can have our cake and eat it by skinning the SUSY cat in just the right way!

  In particular, in the NMSSM we can have a Higgs with SM-like WW, ZZ couplings and mass $m_h \sim 100~\mathrm{GeV}$ (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.

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 Electroweak fine-tuning. To avoid Electroweak fine-tuning, sparticles must

be light, especially the stops; the optimal is $\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \sim 350~\mathrm{GeV}$, somewhat above Tevatron limits but easily accessible at the LHC

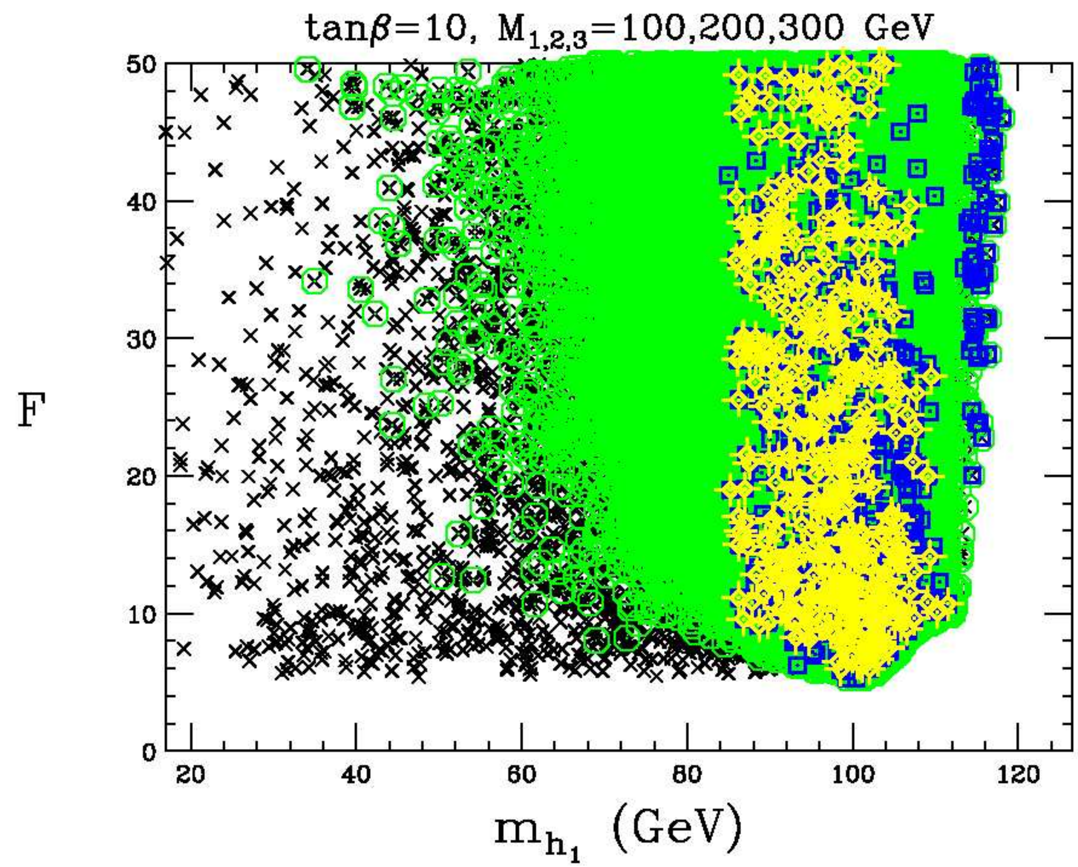


Figure 6: F vs. m_{h_1} for $M_{1,2,3} = 100, 200, 300~\mathrm{GeV}$ and $\tan\beta = 10$. Small $\times$ = no constraints other than global and local minimum, no Landau pole before M_U and neutralino LSP. The O's = stop and chargino limits imposed, but NO Higgs limits. The □'s = all LEP single channel,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

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.

   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. 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 $m_{b\bar{b}} \sim 98~\mathrm{GeV}$ 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 hep-ph/0611142. We only state some results.

- The NMSSM has a natural $U(1)_R$ symmetry obtained when certain parameters 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.**

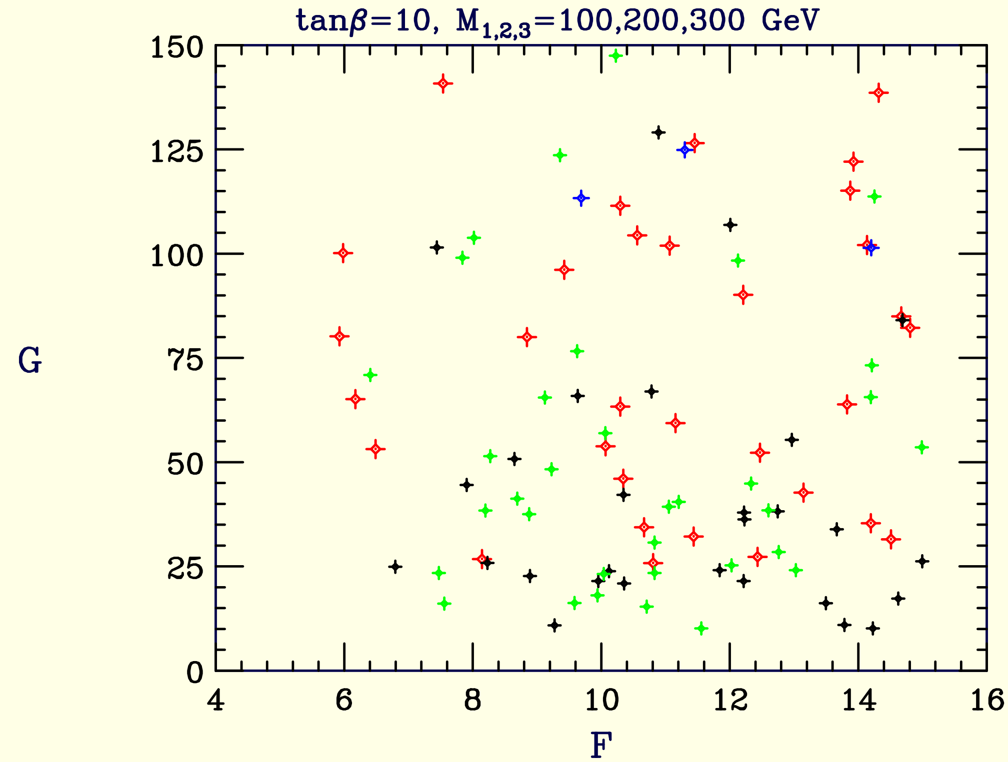


Figure 7: G vs. F for $M_{1,2,3} = 100, 200, 300$ GeV and $\tan\beta = 10$ for points with $F < 15$ having $m_{a_1} < 2m_b$ and large enough $B(h_1 \to a_1 a_1)$ to escape LEP limits. The color coding is: blue $= m_{a_1} < 2m_\tau$; red $= 2m_\tau < m_{a_1} < 7.5$ GeV; green $= 7.5$ GeV $< m_{a_1} <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

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

MSSM-like doublet Higgs component of the a_1:

$$a_1 = \cos\theta_A A_{MSSM} + \sin\theta_A A_S\,. \tag{11}$$

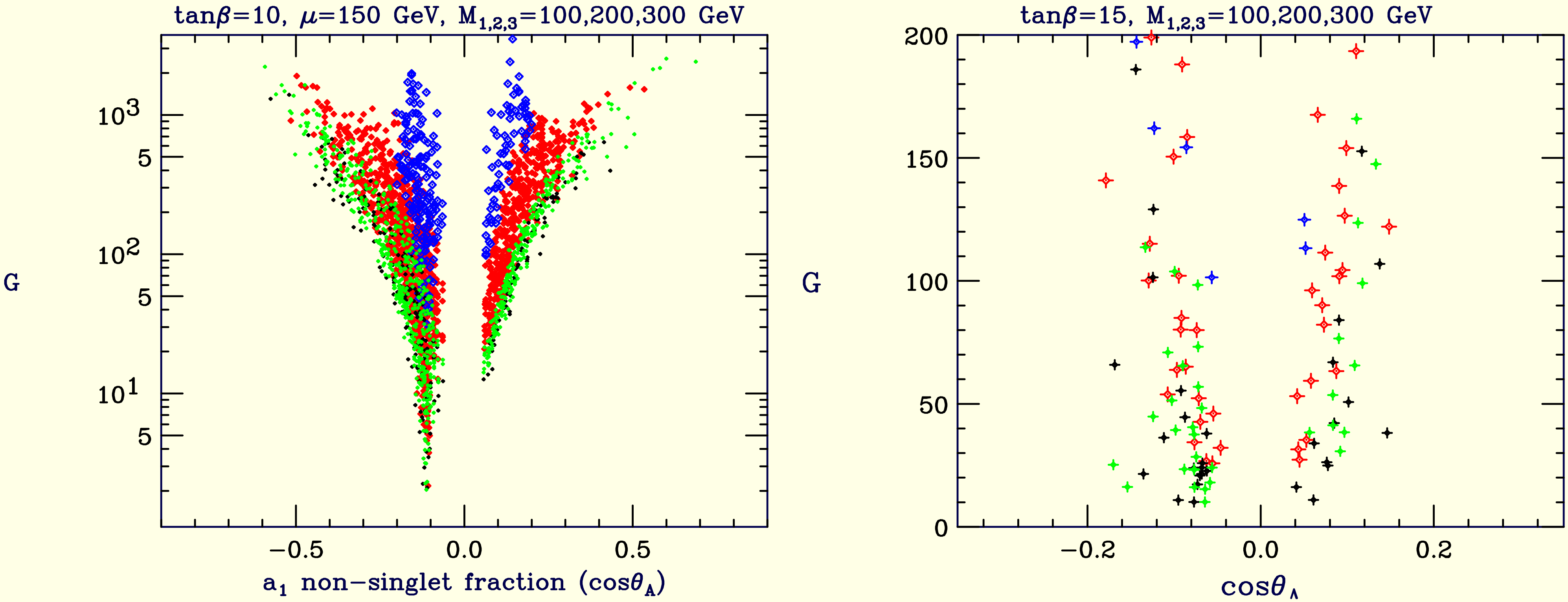


Figure 8: G vs. $\cos\theta_A$ for $M_{1,2,3} = 100, 200, 300$ GeV and $\tan\beta = 10$ from $\mu_{\rm eff} = 150$ GeV scan (left) and for points with $F < 15$ (right) having $m_{a_1} < 2m_b$ and large enough $B(h_1 \to a_1 a_1)$ to escape LEP limits. The color coding is: blue $= m_{a_1} < 2m_\tau$;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

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.

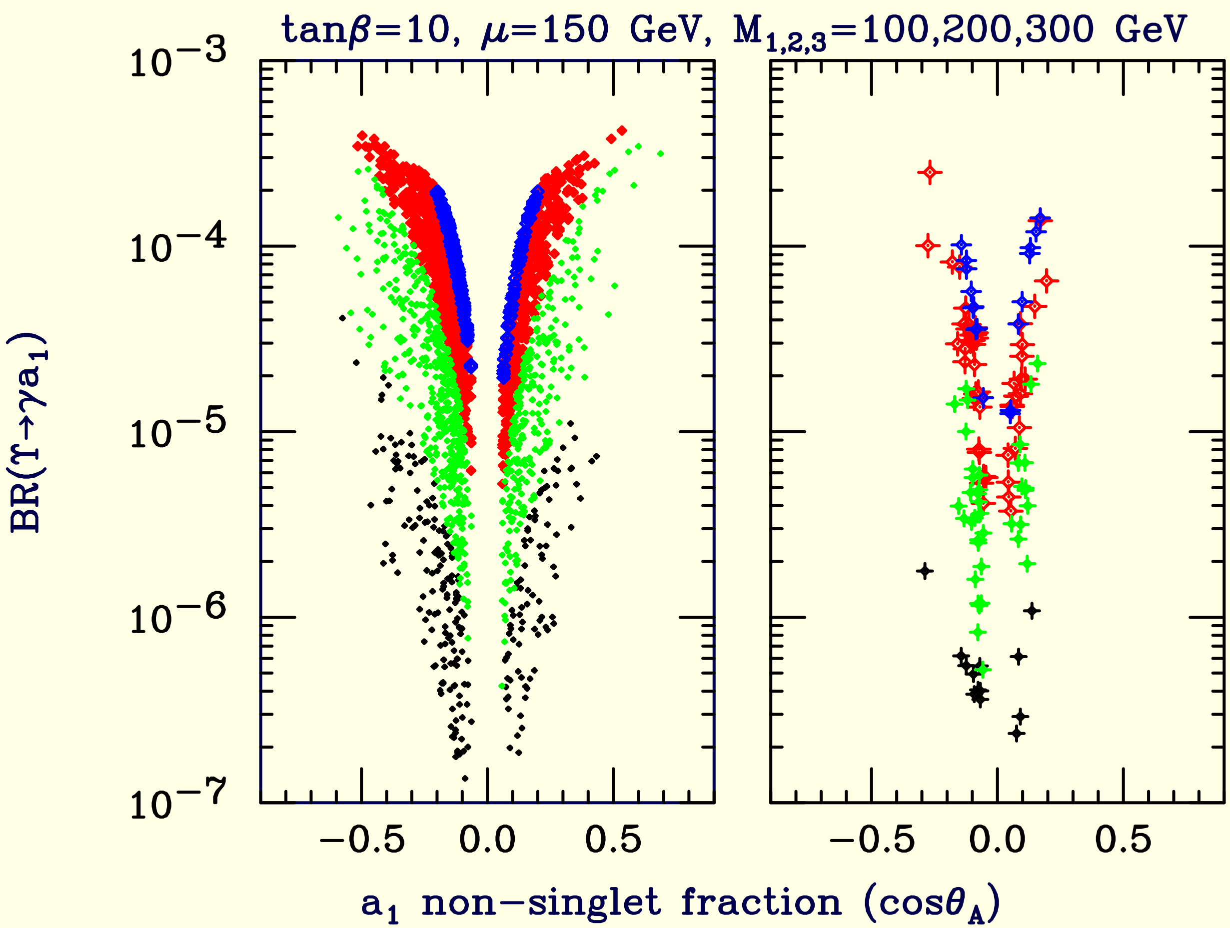


Figure 9: $B(\Upsilon \to \gamma a_1)$ for NMSSM scenarios with various ranges for m_{a_1} using color scheme of Fig. 8 (blue, red, green, black correspond to increasing m_{a_1} in that order). The left plot comes from an A_λ, A_κ scan, holding $\mu_{\rm eff}(m_Z) = 150~{\rm GeV}$ fixed. The right plot shows results for $F < 15$ scenarios with $m_{a_1} < 9.2~{\rm GeV}$ 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.

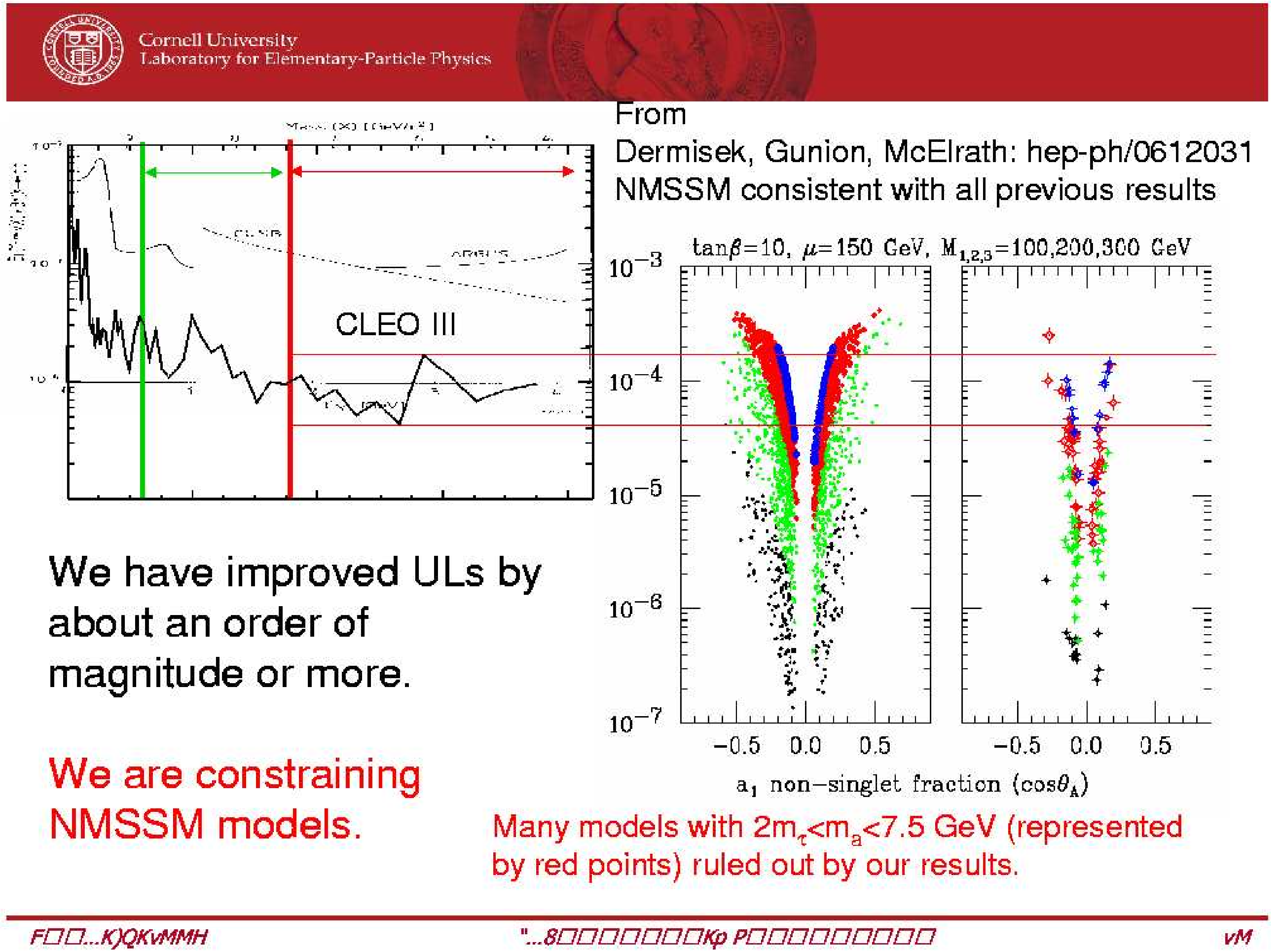


Figure 10: *New Limits from CLEO III (Krenick, Bottomonia, August 6, 2007) from* $\boldsymbol{\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)}$*, which eliminates* $\boldsymbol{e^+e^- \to \gamma\tau^+\tau^-}$ *background. Tag=2 prong (1 lepton)+* $\boldsymbol{\not{E}_T}$*. Total of* $\mathbf{9}$ *Million* $\boldsymbol{\Upsilon(2S)}$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

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,

$$h_1 \to a_1 a_1 \to 4j\,. \tag{12}$$

  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-fine-tuning, F

- In Fig. 6, the blue squares show that $m_{h_1} \sim 115$ 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, $m_{h_1} \sim 115$ GeV is still ok for precision electroweak.
- Thus, I would also advocate working on $pp \to pph$ (and other) signals assuming:

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

  (b) $m_{h_1} \geq 115$ 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 $m_{h_1} \sim 100$ GeV.

  Although the latter channel might appear challenging, there are several papers in the literature claiming that such a Higgs signal can be seen.

The basic thing to keep in mind:

For a primary Higgs with mass $\lesssim 150$ 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. **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. **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 the right a_1 scenario.

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

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

- **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;

- Although SUSY will be easily seen at the LHC Higgs detection at the LHC will be a real challenge. 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 $m_{h_1} \sim 100$ 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, 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.