Non Standard Higgs Decays and Implications

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Outline

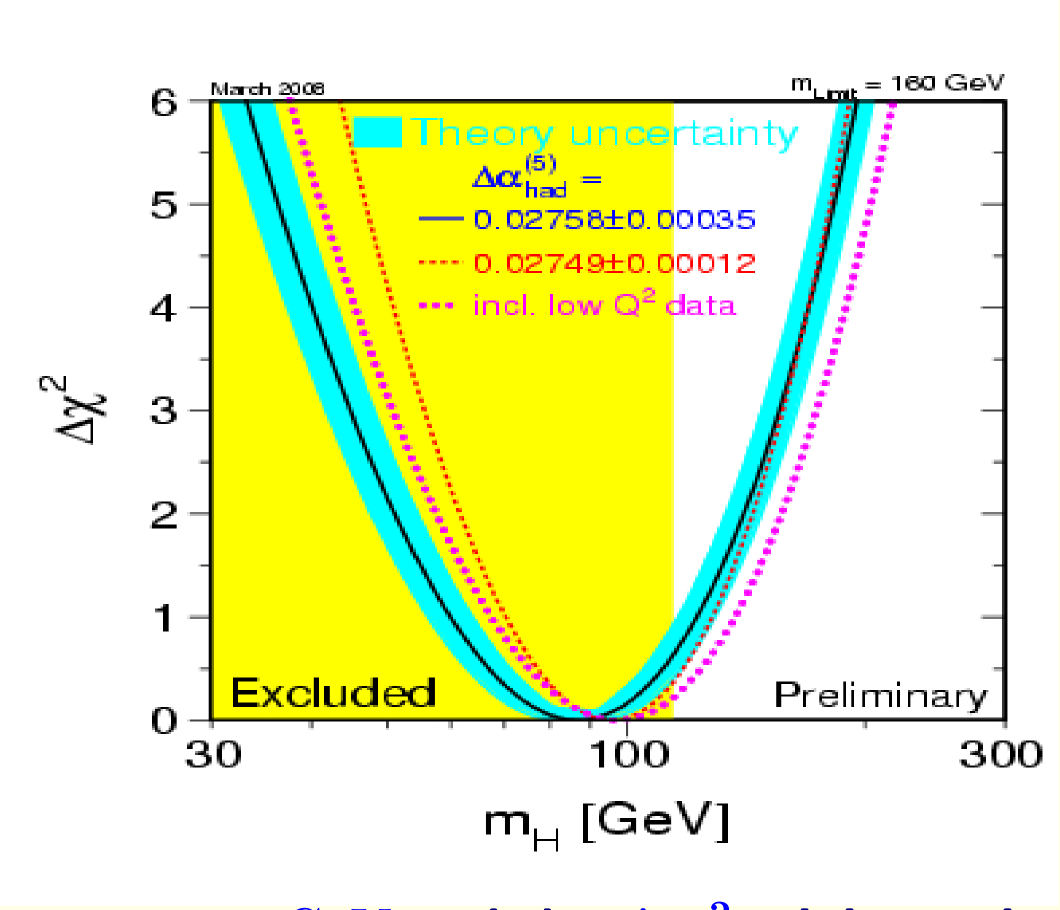
1. Motivation for Non-Standard Decays and Higgs Scenarios
2. Models
   (a) Only one Higgs carries all of ZZ, WW coupling.
   Non-SUSY
   SUSY
   (b) More than one Higgs carries ZZ, WW couplings.
   Non-SUSY
   SUSY
3. Implications for Discovery

- I will assume that precision electroweak (PEW) constraints are satisfied primarily by the presence of one or more Higgs bosons .

- It is the tension between this assumption and LEP Higgs limits that forces one to consider non-standard decays or non-standard Higgs scenarios.

2(a): Motivation for Non-Standard Decays — single H

- The latest plot of $\Delta\chi^2(PEW)$ vs. m_H is:



At 95% CL, $m_{h_{\rm SM}} < 160~{\rm GeV}$ and the $\Delta\chi^2$ minimum is near $85~{\rm GeV}$ when all data are included.

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

The blue-band plot may be misleading due to the discrepancy between the "leptonic" and "hadronic" measurements of $\sin^2\theta_W^{eff}$, which yield $\sin^2\theta_W^{eff} = 0.23113(21)$ and $\sin^2\theta_W^{eff} = 0.23222(27)$, respectively. The SM has a CL of only 0.14 when all data are included.

If only the leptonic $\sin^2\theta_W^{eff}$ measurements are included, the SM gives a fit with CL near 0.78. However, the central value of $m_{h_{\rm SM}}$ is then near $50~{\rm GeV}$ with a 95% CL upper limit of $\sim 105~{\rm GeV}$ (Chanowitz, xarXiv:0806.0890).

- Thus, in an ideal model, a Higgs with SM-like ZZ coupling should have mass no larger than $105~{\rm GeV}$.

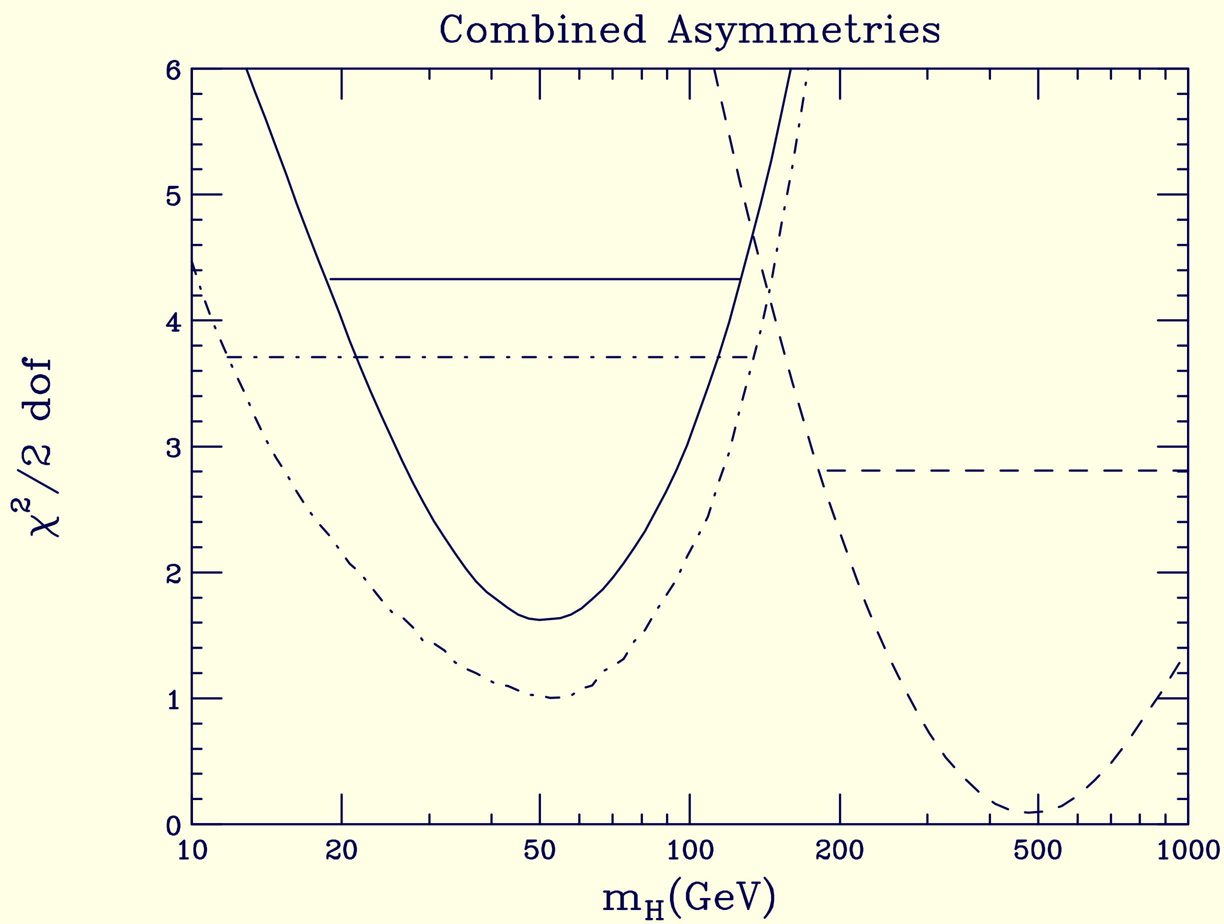


Figure 1: χ^2 distributions as a function of m_H from the combination of the three leptonic asymmetries A_{LR}, A^{ℓ}_{FB}, $A_{\ell}(P_{\tau})$ (solid line); the three hadronic asymmetries A^{b}_{FB}, A^{c}_{FB}, and Q_{FB} (dashed line); and the three m_H-sensitive, nonasymmetry measurements, m_W, Γ_Z, and R_l (dot-dashed line). The horizontal lines indicate the respective 90% symmetric confidence intervals.

But, at the same time, the H must escape the LEP limits on m_H.

Table 1: LEP m_H Limits for a H with SM-like ZZ coupling, but varying decays. See (S. Chang, R. Dermisek, J. F. Gunion and N. Weiner, Ann. Rev. Nucl. Part. Sci. 58, 75 (2008) [arXiv:0801.4554 [hep-ph]]).

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?			

To have $m_H \leq 105$ GeV requires one of the final three modes.

N.B. The 4τ mode LEP limit can be raised to higher mass. Chris Tully and postdoc are working on the 4τ final state in L3 context with $Z \to \nu\bar{\nu}$. Perhaps in 6 months or so will know something.

- **Perhaps the ideal Higgs should be such as to predict the 2.3σ excess at**

$M_{b\bar{b}} \sim 98\ \mathrm{GeV}$ seen in the $Z + b\bar{b}$ final state.

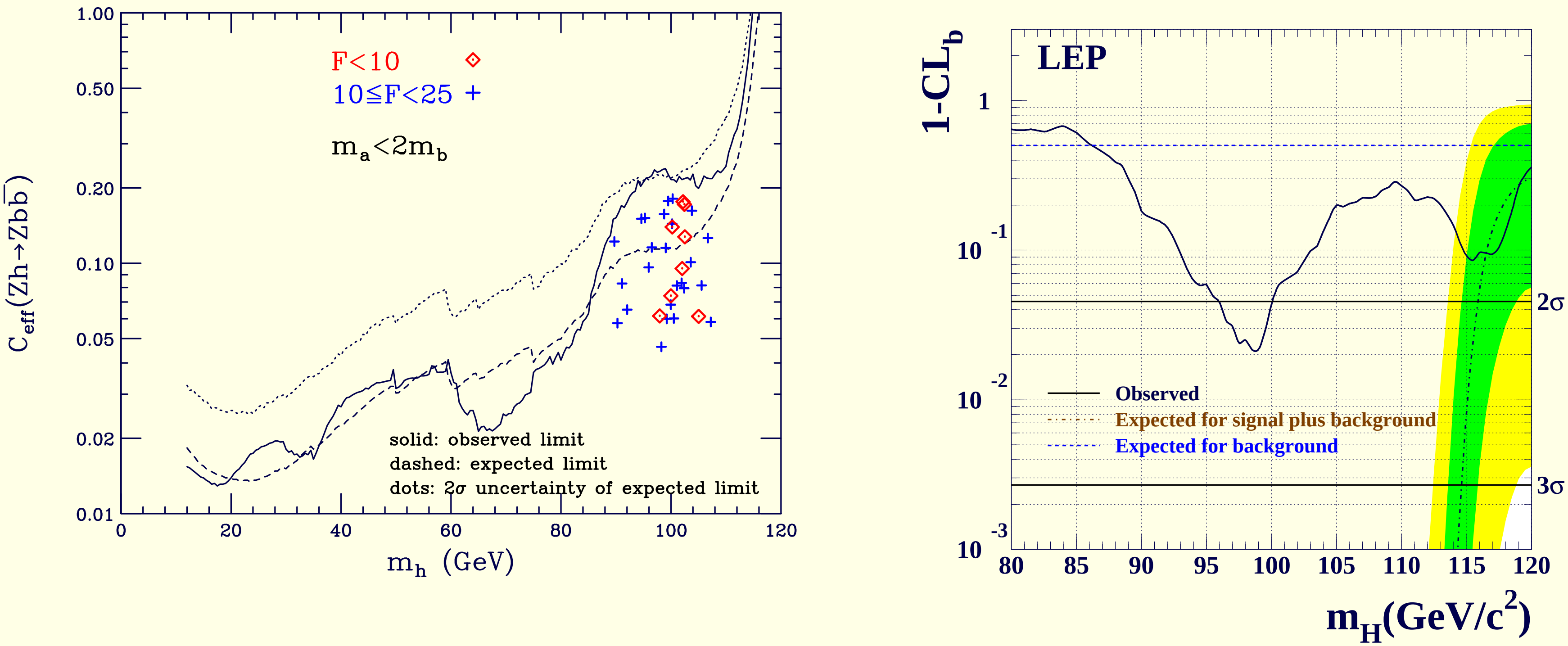


Figure 2: Plots for the $Zb\bar{b}$ final state. F is the m_Z-fine-tuning measure for the NMSSM.

The simplest possibility for explaining the excess is to have $m_H \sim 100\ \mathrm{GeV}$ and $B(H \to b\bar{b}) \sim 0.1 B(H \to b\bar{b})_{SM}$ (assuming H has SM ZZ coupling as desired for precision electroweak) with the remaining H decays being to one of the poorly constrained channels.

1. One generic way of having a low LEP limit on m_H is to suppress the $H \to b\bar{b}$ branching ratio by having a light a (or h)with $B(H \to aa) > 0.7$ and $m_a < 2m_b$ (in order to avoid LEP $Z + 4b$ limit at $110~\mathrm{GeV}$, i.e. above ideal).

   This point of view was first stressed in (R. Dermisek and J. F. Gunion, Phys. Rev. Lett. 95, 041801 (2005) [arXiv:hep-ph/0502105]; R. Dermisek and J. F. Gunion, Phys. Rev. D 73, 111701 (2006) [arXiv:hep-ph/0510322])

   Even before the relevance to the PEW/LEP tension was noticed, the possible importance of $H \to aa$ decays has been known to be a generic possibility for some time from SUSY models. (See many papers –e.g.: J. R. Ellis, J. F. Gunion, H. E. Haber, L. Roszkowski and F. Zwirner, Phys. Rev. D 39, 844 (1989); B. A. Dobrescu, G. L. Landsberg and K. T. Matchev, Phys. Rev. D 63, 075003 (2001) [arXiv:hep-ph/0005308].)

   Since the $Hb\bar{b}$ coupling is so small, very modest Haa coupling suffices.

   The basic expressions for the decays make the reason clear.

$$\Gamma(H \to aa) = \frac{1}{2}\frac{g_{Haa}^2}{16\pi m_H}\lambda(1, m_a^2/m_H^2, m_a^2/m_H^2)\,. \qquad (1)$$

Defining $g_{Haa} = c\frac{gm_H^2}{2m_W}$, if $c = 1$ (as can be the case if H is SM-like) and if we ignore phase space suppression, this gives

$$\Gamma(H \to aa) = \frac{g^2 m_H^3}{128\pi m_W^2} \sim 0.17\ \mathrm{GeV}\left(\frac{m_H}{100\ \mathrm{GeV}}\right)^3 \quad vs. \tag{2}$$

$$\Gamma(H \to b\bar{b}) \sim 0.003\ \mathrm{GeV}\left(\frac{m_H}{100\ \mathrm{GeV}}\right) \quad and \tag{3}$$

$$\Gamma(H \to ZZ) = \frac{1}{2}\Gamma(H \to WW) = \frac{g^2 m_H^3}{128\pi m_W^2}\,. \tag{4}$$

$c \sim 0.13$ makes the aa mode equal to the $b\bar{b}$ mode, and such c's are common in models. Thus, Higgs pair modes can easily dominate until we pass above the WW threshold.

Models in which this arises:

(a) The general 2HDM-II models with $H = h^0$, $a = A^0$, and additional H^0 and $h^\pm$.

For a Higgs potential of special form (T. Farris, J. F. Gunion and H. E. Logan, Snowmass 2001, P121, [arXiv:hep-ph/0202087]) the A^0 can be very light and

$c = 1$. The $h^0 \to A^0 A^0$ mode would be dominant for $m_{h^0} < 2m_W$.

(b) This scenario is **not** possible in the MSSM (without CP violation) because of mass relations between h^0 and A^0 and LEP lower bounds on m_{A^0}.

(c) The scenario is generically present if you start adding singlets to the SM.

Several groups have explored simply adding one singlet to the SM.

i. S. Chang, P. J. Fox and N. Weiner, arXiv:hep-ph/0608310.

Here, they simply add to the SM a singlet a with interaction with the SM doublet of form

$$\mathcal{L} \ni \frac{c'}{2} a^2 |H|^2 \quad \stackrel{\langle a \rangle = 0}{\Rightarrow} \quad g_{Haa} = \frac{c' v}{\sqrt{2}}, \tag{5}$$

$c' > 0.04$ will allow a $m_H \sim 100~\mathrm{GeV}$ Higgs to escape detection so long as the a's **do** decay and $B(a \to b\bar{b})$ is small or absent.

How will the a decay.? If there is no mixing of the a with some other A, then it could be totally stable and therefore invisible in the detector, but this means $m_H > 114\ \mathrm{GeV}$ is required by LEP.

They suggest a heavy vector-like colored quark with a interaction of form:

$$\mathcal{L} \ni \overline{\psi}(M + i\gamma_5 \lambda a)\psi \tag{6}$$

Integrating out the heavy ψ gives loop diagram generated effective couplings of $a \to \gamma\gamma, gg$. The result in one particular model with a bunch of ψ's is

$$B(H \to 4\gamma) \sim 1.4 \times 10^{-5}\,, \quad B(H \to 2g2\gamma) \sim 7.6 \times 10^{-3}\,. \tag{7}$$

The one loop generation of these a couplings imply the possibility of non-prompt a decay:

$$c\tau_a \sim \frac{1}{\Gamma_{a\to gg}} = 1\,\mathrm{cm}\left(\frac{30\ \mathrm{GeV}}{m_a}\right)^3 \left(\frac{M}{450\ \mathrm{TeV}}\right)^2 \left(\frac{0.1}{\lambda\, b_3}\right)^2 \tag{8}$$

This would enhance Higgs discovery prospects.

ii. In (R. Schabinger and J. D. Wells, Phys. Rev. D 72, 093007 (2005) [arXiv:hep-ph/0509209]; M. Bowen, Y. Cui and J. Wells, arXiv:hep-ph/0701035) they introduce a singlet scalar Φ with

$$\mathcal{L} \ni \eta|\Phi|^2|H|^2 \tag{9}$$

which causes eigenstate mixing if $\langle\Phi\rangle$ and $\langle H\rangle$ are **both** non-zero, leading to eigenstates h and H.

In one scenario, for which $B(H \to hh)$ is possibly large, the heavier H is mainly doublet and the h can be mainly singlet, but not entirely so, and will decay to the heaviest fermions if there are no hidden-sector particles for it to decay to. They were not thinking about very small m_h, but for PEW and LEP escape we would want $m_h < 2m_b$. If there is a substantial hidden sector connected to the h, then it could be that h will decay mainly invisibly, which is more strongly constrained.

iii. Another set of papers on this general extra singlets game is: (V. Barger, P. Langacker, M. McCaskey, M. Ramsey-Musolf and G. Shaughnessy, Phys. Rev.

D 79, 015018 (2009) [arXiv:0811.0393 [hep-ph]]. V. Barger, P. Langacker, M. McCaskey, M. J. Ramsey-Musolf and G. Shaughnessy, Phys. Rev. D 77, 035005 (2008) [arXiv:0706.4311 [hep-ph]]. V. Barger, P. Langacker, I. Lewis, M. McCaskey, G. Shaughnessy and B. Yencho, Phys. Rev. D 75, 115002 (2007) [arXiv:hep-ph/0702036]. V. Barger, P. Langacker and G. Shaughnessy, Phys. Rev. D 75, 055013 (2007) [arXiv:hep-ph/0611239]. V. Barger, P. Langacker and G. Shaughnessy, AIP Conf. Proc. 903, 32 (2007) [arXiv:hep-ph/0611112].)

(d) The model in which a SM-like light Higgs and rather singlet-like light scalar are both almost automatic in the NMSSM (with $h_{1,2,3}$, $a_{1,2}$, $h^{\pm}$).

It is the h_1 that is light and SM-like and the a_1 is mainly singlet and has a small mass that is protected by a $U(1)_R$ symmetry. Large $B(h_1 \to a_1 a_1)$ is easy to achieve.

The many attractive features of the NMSSM are well known:

i. Solves μ problem.

ii. Preserves MSSM gauge coupling unification.

iii. Preserves radiative EWSB.

iv. Preserves dark matter (assuming R-parity is preserved).

v. Like any SUSY model, solves quadratic divergence hierarchy problem.

vi. Has additional attractive features when $m_{h_1} \sim 90 - 100~\mathrm{GeV}$ is allowed because of $h_1 \to a_1 a_1$ decays with $m_{a_1} < 2m_b$:

A. Allows minimal fine-tuning for getting m_Z (i.e. v) correct after evolving from GUT scale M_U. (R. Dermisek and J. F. Gunion, Phys. Rev. D 73, 111701 (2006) [arXiv:hep-ph/0510322])

This is because $\widetilde{t}_1, \widetilde{t}_2$ can be light ($\sim 350~\mathrm{GeV}$ is just right) . Also need $m_{\tilde{g}}$ not too far above $300~\mathrm{GeV}$.

(In MSSM, such low stop masses are not acceptable since m_{h^0} would be below LEP limits; large $m_{\tilde{t}} \Rightarrow m_Z$ fine tuning would be large, especially if m_{h^0} is SM-like.)

B. An a_1 with large $B(h_1 \to a_1 a_1)$ and $m_{a_1} < 2m_b$ can be achieved without fine-tuning of the A_λ and A_κ soft-SUSY breaking parameters that control the a_1 properties. (R. Dermisek and J. F. Gunion, Phys. Rev. D 75, 075019 (2007) [arXiv:hep-ph/0611142].)

The a_1 is largely singlet ($e.g.$10% at amplitude level if $\tan\beta \sim 10$) and $\sim 7~\mathrm{GeV} \lesssim m_{a_1}$ (but below $2m_b$) in the best cases.

2. A 2nd SUSY possibility is a model in which $h^0 \to \widetilde{\chi}_2^0 \widetilde{\chi}_1^0$ with $\widetilde{\chi}_2^0 \to f\overline{f}\widetilde{\chi}_1^0$, yielding the not so well constrained (at LEP) $f\overline{f}\not{E}_T$ type final state (S. Chang and N. Weiner, JHEP 0805, 074 (2008) [arXiv:0710.4591 [hep-ph]; see also, S. Chang and T. Gregorio, in preparation).

The $\widetilde{\chi}_2^0 \to f\overline{f}\widetilde{\chi}_1^0$ decay can be via $\widetilde{\chi}_2^0 \to Z^* \widetilde{\chi}_1^0$ with $Z^* \to \ell^+\ell^-, \ldots$ or $\widetilde{\chi}_2^0 \to \phi \widetilde{\chi}_1^0$ with $\phi \to \tau^+\tau^-$ (not $b's$ as LEP would then require $m_{h^0} \gtrsim 110~\mathrm{GeV}$).

This type of model does not rely on R-parity violation;
$\Rightarrow$ that $\widetilde{\chi}_1^0$ remains a dark matter candidate.

3. Multi-singlet extensions of the NMSSM will expand the possibilities.

Indeed, typical string models predict a plethora of light a's, light h's and light $\widetilde{\chi}$'s .

One string-based model is the $U(1)'$ Extended MSSM of (T. Han, P. Langacker and B. McElrath, Phys. Rev. D 70, 115006 (2004) [arXiv:hep-ph/0405244].

) I review its features.

– This model has an extra $U(1)'$ gauge group added to the MSSM along with a singlet $\widehat{S}$ as well as 3 other $\widehat{S}_{1,2,3}$; all are charged under the $U(1)'$, but not under the SM groups.
– This model will illustrate the potentialities of $U(1)'$ MSSM extensions and especially the challenges associated with the Higgs sector.
– The superpotential is

$$W = \lambda \widehat{S}\widehat{H_u}\widehat{H_d} + \kappa \widehat{S}_1\widehat{S}_2\widehat{S}_3. \tag{10}$$

– $U(1)'$ charges are chosen to be non-trivial for all $\widehat{S}$, $\widehat{S}_{1,2,3}$ but such as to allow only these terms with dimensionless parameters.

– The model has 6 CP-even Higgs states, $h_{1,2,3,4,5,6}$ and 4 CP-odd states $a_{1,2,3,4}$, as well as 9 neutralinos $\widetilde\chi_{1,2,3,4,5,6,7,9}$ where the 1st indices go with $\widetilde B$, $\widetilde Z$, $\widetilde{H}_u$ and $\widetilde{H}_d$ of the MSSM subcomponent.

Problems and features of the model.

* Anomaly cancellation in the model requires additional SM-exotic chiral supermultiplets.
* Gauge coupling unification requires extra matter at high scales.
* Baryogenesis? Dark matter?
* There has been no study to assess fine-tuning with respect to GUT-scale parameters. Can it be as small as in the NMSSM? Below you will see that I am skeptical.

The following branching ratio figures for the h_1 and a_1 (all plotted points obey LEP exclusions) show the following.

(a) The interesting $m_{h_1} < 100~\mathrm{GeV}$ points are the solid blue and solid red points in Fig. 3 with large $B(h_1 \to \widetilde\chi_1^0, \widetilde\chi_{k>1})$.

(b) For $m_{h_1} < 100~\mathrm{GeV}$, there are very few points in Fig. 3 with large $B(h_1 \to a_k^0 a_j^0)$.

(c) Fig. 4 shows this is because essentially no points with $m_{a_1} < 2m_b$

were found that obeyed LEP limits.

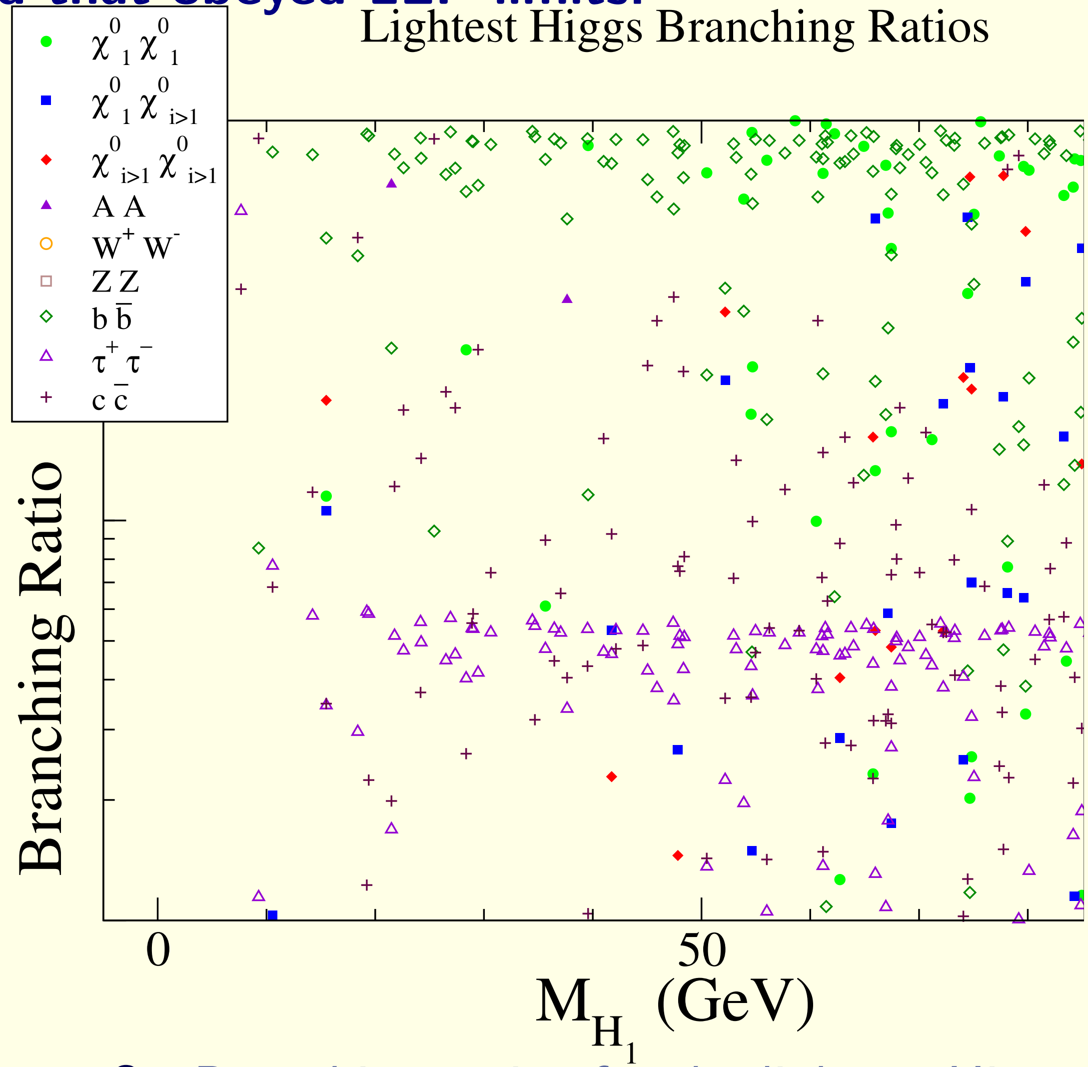


Figure 3: *Branching ratios for the lightest Higgs.*

(d) **The many $m_{h_1} < 100~\mathrm{GeV}$ solid green and open green points with large $B(h_1 \to \widetilde\chi^0_1\widetilde\chi^0_1)$ or $B(h_1 \to b\bar{b})$ evade LEP limits because of reduced h_1ZZ coupling. If the $h_{k>1}$ with large h_kZZ coupling have**

$m_{h_k} > 114$ GeV, **there will be a high level of m_Z fine-tuning.**

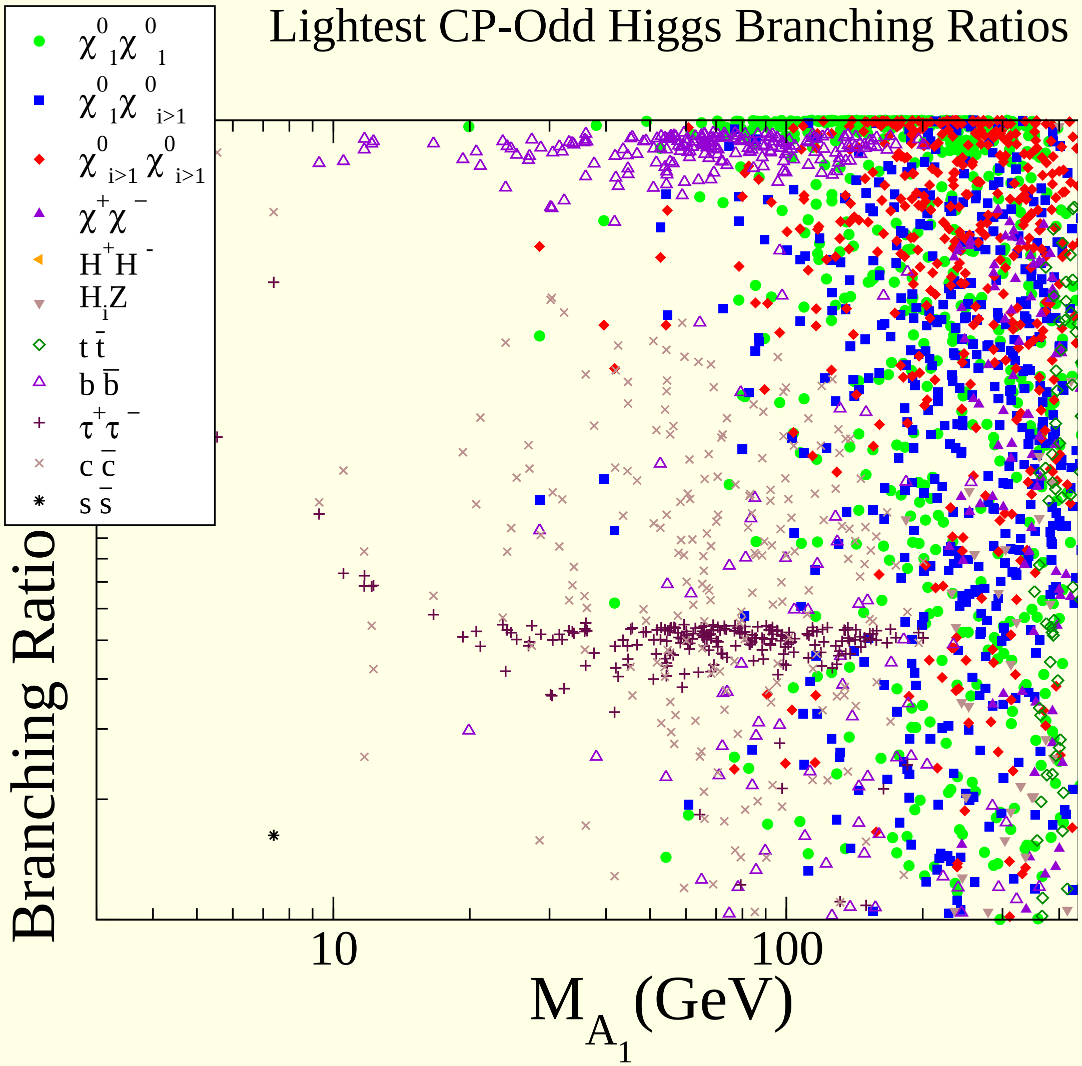


Figure 4: *Branching ratios for the lightest CP-odd A_1.*

(e) So far, the NMSSM is the best game in town!

4. A 3rd SUSY possibility is to have a SM-like H decaying to a pair of LSP's ($H \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$ or $\widetilde{\tau}\widetilde{\tau}$ or $\ldots$) with the LSP's ($\widetilde{\chi}_1^0$, $\widetilde{\tau}$, $\ldots$) decaying in some exotic fashion to a partially visible final state (purely invisible $\widetilde{\chi}_1^0 \widetilde{\chi}_1^0$ would $\Rightarrow m_H > 115~\mathrm{GeV}$ required by LEP).

   In such scenarios, you lose dark matter.

   A popular choice is to use RPV violating decays of the $\widetilde{\chi}_1^0$ (L. M. Carpenter, D. E. Kaplan and E. J. Rhee, arXiv:0804.1581 [hep-ph]; T. Banks, L. M. Carpenter and J. F. Fortin, JHEP 0809, 087 (2008) [arXiv:0804.2688 [hep-ph]]. See also: M. Carena, S. Heinemeyer, C. E. M. Wagner and G. Weiglein, Phys. Rev. Lett. 86, 4463 (2001) [arXiv:hep-ph/0008023].).

$$W \ni \mu_i L_i \bar{H} + \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c, \quad (11)$$

   One has a choice of leptonic R-parity violation or baryonic R-parity violation, but proton stability implies you can't have both. You can have both types of R-parity violation simultaneously.

   LEP requires $m_{\widetilde{\chi}_1^0} \gtrsim 35 - 45~\mathrm{GeV}$.

LSP	LLE	LQD	UDD
$\widetilde{\chi}_0$	$4\tau + 2\nu$	$4b/4c + 2\nu, 2b + 2c + 2\nu, 2b + 2c + 2\tau, 3b + c + \tau + \nu, b + 3c + \tau + \nu$	$2b + 2c + 2q$
$\widetilde{g}$	-	$4b/4c + 2\nu, 2b + 2c + 2\nu, 2b + 2c + 2\tau, 3b + c + \tau + \nu, b + 3c + \tau + \nu$	$2b + 2c + 2q$
$\widetilde{b}$	—	$2b + 2\nu, 2c + 2\tau, b + c + \nu + \tau$	$2c + 2q$
$\widetilde{\tau}$	$2\tau + 2\nu$	$2b + 2c$	—

Table 2: Higgs decay final states for all possible LSPs and RPV operators

LSP	Signature	Mass Bound	Search
$\widetilde{\chi}_0$	$4q + 2\nu$	105 GeV	WW^* with invisible Z decay
$\tilde{g}$	$4q + 2\nu$	105 GeV	WW^* with invisible Z decay
$\tilde{b}$	$2q + 2\nu$	103 GeV	SUSY squark search
-	$2b + 2\nu$	111 GeV	SUSY squark search
-	$4q$	105 GeV	WW^* with invisible Z decay
$\tilde{\tau}$	$\tau\overline{\tau} + 2\nu$	104 GeV	WW^*
-	$l\bar{l} + 2\nu$	104 GeV	WW^*
-	$4q$	105 GeV	WW^* with invisible Z decay

Table 3: Higgs Mass Lower Bounds for Various Channels. For decays not listed current searches do not severely constrain the Higgs mass.

EXP	LLE	LQD	UDD
DELPHI	$\widetilde{\tau} > 45$	-	$\widetilde{b} > 45$
OPAL	$\widetilde{\tau} > 45$	$\widetilde{\tau} > 45$	$b > 45$
L3	$\widetilde{\tau} > 70$	-	$\widetilde{b} > 30$
ALEPH	$\widetilde{\tau} > 45$	$\widetilde{\tau} >40$, $\widetilde{b} >30$	$\widetilde{b} > 45$

Table 4: LEP2 experiment searches for scalars decaying directly through RPV

5. A non SUSY possibility is $H \to$ a pair of hidden valley states. (M. J. Strassler, arXiv:hep-ph/0607160.)

   In these models, we have some strongly bound V-mesons that are relatively light and couple to a SM-like H.

   Then, one can have, for example,

$$H \to VV \to Z'Z' \to b\bar{b}b\bar{b} \tag{12}$$

   where the $V - Z'$ mixing is employed, which mixing could be sufficiently small to give a displaced vertex for the decay.

   Of course, if these V-mesons can mix with a residual A^0 from a two-doublet Higgs sector, then the $V - Z'$ mixing is not the main decay mechanism; rather $V \to b\bar{b}, \ldots$ via the $V - A^0$ mixing.

If the V-hadrons have to decay by $V - Z'$ mixing, then if the V-hadron spectrum is sufficiently complex, each V in the primary VV pair could cascade to less massive V until the final V has to decay via mixing with the Z'. $\Rightarrow$ much more complex states.

6. The final model I will discuss somewhat later is one in the SM-H is light and yet has escaped LEP detection because the H width is effectively large in visible channels. This kind of scenario arises in the "unparticle" models of the Higgs and in models where there are many visibly decaying h_i's spread out in mass.

   Will discuss "room" for such a scenario at low m_H later; answer is that there is a lot of room

A few further points regarding a light a

- Upsilon decays and (it turns out at larger m_a below $2m_b$) $gg \to a \to \mu^+\mu^-$ strongly constrain $C_{ab\bar{b}}$, where the generic $C_{af\bar{f}}$ is defined by

$$\mathcal{L}_{af\bar{f}} \equiv iC_{af\bar{f}} \frac{ig_2 m_f}{2m_W} \bar{f}\gamma_5 f a \,. \qquad (13)$$

- The extracted $C_{ab\bar{b}}$ limits (JFG, arXiv:0808.2509; see also Ellwanger and Domingo) are quite model-independent. The extracted limits on $C_{ab\bar{b}}$ appear in Fig. 5,

- The most unconstrained region is that with $m_a > 8$ GeV, especially 9 GeV $< m_a < 12$ GeV. $=$ region with least "light-a_1" tuning in NMSSM.

- Except for this region, a further factor of 3 improvement to $C_{ab\bar{b}} < 0.3$ would start to rule out or observe the $a = a_1$ of the most favored NMSSM scenarios.

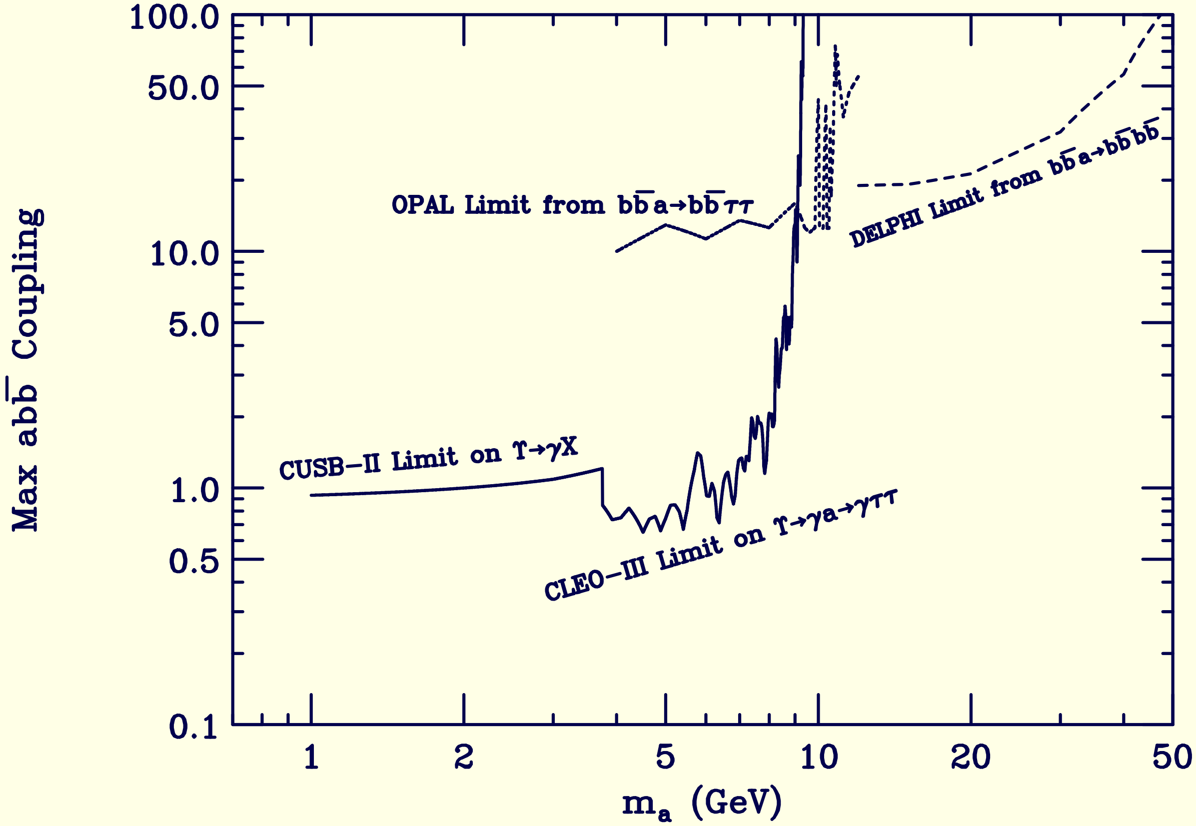


Figure 5: Limits on $C_{ab\bar{b}}$.

- **In the ~ 9 GeV $\lesssim m_a \lesssim 12$ GeV region only the OPAL limits are relevant.**

  Those presented depend upon how the $a \leftrightarrow \eta_b$ states mixing is modeled. A particular model (Drees+Hikasa: Phys.Rev.D41:1547,1990) is employed.

Perhaps now that the first η_b state has been observed, this region can be better pinned down. I have not incorporated recent work by Domingo *et al.* (arXiv:0810.4736) which models this mixing in a manner consistent with the available information. In any case, models predict many η-type states in this region, not just the one that has been observed.

- Given $C_{ab\bar{b}}$ limits, an interesting question is whether there is any possibility that a light a could be responsible for the observed a_μ discrepancy which is of order $\Delta a_\mu \sim 30 \times 10^{-10}$.

- One finds that only in the small window in m_a from about $8~\mathrm{GeV}$ ($9.5~\mathrm{GeV}$ for 2HDM-II) up to $\sim 12~\mathrm{GeV}$, where $C_{ab\bar{b}}$ limits are the weakest ($C_{ab\bar{b}} \lesssim 15 - 60$), might it be possible.

  But, such large values for $C_{ab\bar{b}}$ in the case of the NMSSM a_1 would tend to have large fine tuning associated with the required "light-a_1" scenario (more singlet a_1 preferred).

2(b): Models in which several, perhaps many, Higgses carry the ZZ coupling

1. NMSSM Scenarios with $\tan\beta < 3$. (R. Dermisek and J. F. Gunion, arXiv:0811.3537 [hep-ph].)

   - It is possible to have h_1, h_2, h^+ all light but escaping LEP and Tevatron detection by virtue of decays to a_1 with $m_{a_1} < 2m_b$.
   - h_1 need not be exactly SM-like — h_2 can be light enough ($\sim 100~\mathrm{GeV}$) for precision electroweak when $g^2_{h_2WW}$ is substantial.
   - Relevant scenarios arise most often for $C_{ab\bar{b}} \gtrsim 1$ especially if $\tan\beta = 2$. Current limits imply that $m_{a_1} > 7.5~\mathrm{GeV}$ is needed to have this large a value.
   - The multiple LEP (and Tevatron) escapes:

   (a) $B(h_1 \to a_1 a_1)$ is large, and $e^+e^- \to Zh_1 \to Za_1a_1 \to Z4\tau$ is only constrained for $m_{4\tau} < 89~\mathrm{GeV}$ (at best — lower if ZZh_1 coupling is somewhat suppressed).

(b) $B(h^+ \to W^+ a_1)$ is often large, and $e^+e^- \to h^+h^- \to W^+W^- a_1 a_1$ with $a_1 \to 2\tau$ was not directly searched for.

(c) $B(h^+ \to \tau^+ \nu)$ is frequently significant (but never dominant) and for cases with $m_{h^\pm}$ close to m_W, $e^+e^- \to h^+h^- \to \tau^+\tau^- 2\nu_\tau$ could explain the 2.8σ deviation from lepton universality in W decays measured at LEP.

(d) $B(h_2 \to a_1 a_1)$ and/or $B(h_2 \to Z a_1)$ are large.
Thus, even if $e^+e^- \to Z h_2$ has large σ (which is often the case since m_{h_2} is not large), would not have seen it since the $h_2 \to Z a_1$ decay was never looked for and an incomplete job was done on $h_2 \to a_1 a_1 \to 4\tau$.

(e) For $\tan\beta = 1.7$ it is easy to find cases where $e^+e^- \to Z h_1 \to Z b\bar{b}$ and/or $e^+e^- \to Z h_2 \to Z b\bar{b}$ would yield a substantial contribution to the LEP $0.1 \times SM$ excess near $m_{b\bar{b}} \sim 98~\mathrm{GeV}$.

Table 5: Selected $\tan\beta = 1.7$ points for which m_{h_1} and corresponding m_{h_2} lie within the LEP excess region and the corresponding $g^2_{ZZh_1} B(h_1 \to b\bar{b})$ and $g^2_{ZZh_2} B(h_2 \to b\bar{b})$ values. All have large $C_{ab\bar{b}}$ and $m_{a_1} > 7.5~\mathrm{GeV}$.

m_{h_1}	$C_V^2(h_1)B(h_1 \to b\bar{b})$	m_{h_2}	$C_V^2(h_2)B(h_2 \to b\bar{b})$
93.1	0.0684	96.2	0.1590
90.7	0.0560	96.6	0.1726
90.2	0.1171	97.2	0.1468
88.3	0.0557	97.0	0.1803
87.8	0.0974	97.5	0.1609
90.7	0.0560	96.6	0.1727
92.7	0.1748	97.2	0.1037
90.9	0.0599	97.1	0.1416

- To observe or constrain the a_1 for these $m_{a_1} > 7.5~\mathrm{GeV}$, large $C_{ab\bar{b}}$ scenarios will most likely require both B-factory Υ results and Tevatron high luminosity data.
- High Tevatron L would also better limit $B(t \to h^+ b)$ which at the moment is allowed up to the 40% level as these decays are included in the way CDF and D0 determine the $t\bar{t}$ cross section for the $h^+ \to W^+ a_1$.

2. **Worst case scenario** (J. R. Espinosa and J. F. Gunion, Phys. Rev. Lett. 82, 1084 (1999) [arXiv:hep-ph/9807275]).

- In principle you can have many Higgs bosons each with a fraction of the ZZ, WW coupling squared and spread out in mass in such a way that LEP constraints are obeyed even if masses below $100~\mathrm{GeV}$.

  If these many Higgses can be light enough, then PEW constraints will be obeyed with an effective EW mass that is well below $100~\mathrm{GeV}$.
- In more detail, suppose we have a set of (possibly mixed) doublet Higgs states, h_i, that share the WW, ZZ couplings according to $g^2_{h_i ZZ} = f_i^2 g^2_{h_{\rm SM} ZZ}$ where $\sum_i f_i^2 = 1$ is required.

  In the unmixed case, $f_i = v_i/v$.

  The PEW constraint reduces to (P. H. Chankowski, T. Farris, B. Grzadkowski, J. F. Gunion, J. Kalinowski and M. Krawczyk, Phys. Lett. B 496, 195 (2000) [arXiv:hep-ph/0009271]; R. Barbieri, L. J. Hall and V. S. Rychkov, Phys. Rev. D 74, 015007 (2006) [arXiv:hep-ph/0603188]. R. Barbieri and L. J. Hall, arXiv:hep-ph/0510243.)

$$T = \sum_i f_i^2 T_{SM}(m_{h_i})\,, \quad S = \sum_i f_i^2 S_{SM}(m_{h_i})\,. \qquad (14)$$

Recalling that the T_{SM} and S_{SM} functions are basically logarithmic, we end up with a requirement for ideal consistency of $m_{EW} < 100\ \mathrm{GeV}$ where $\log m_{EW} = \sum_i f_i^2 \log m_i$ or

$$m_{EW} = \prod_i m_i^{f_i^2} \,. \tag{15}$$

One can ask: how low a value of m_{EW} is possible while obeying LEP constraints?

If there is mixing and there are light a_i's floating around (as there easily could be given that we have lots of uneaten imaginary components), then we cannot be certain of how each h_i decays.

$\Rightarrow$ we must use a decade mode independent analysis.

The only such public analysis is that of the OPAL collaboration (G. Abbiendi *et al.* [OPAL Collaboration], Eur. Phys. J. C 27, 311 (2003) [arXiv:hep-ex/0206022]).

Most importantly Tables 7 and 8 of this paper give an analysis using $10\ \mathrm{GeV}$ bins.

Working with J. Cammin and M. Klute (they did this analysis) we have come up with an input theoretical spectrum that is fully consistent with their decay-mode independent LEP limits and has a very low m_{EW}. The spectrum (in terms of integrals over $10~\mathrm{GeV}$ bins) is:

$$f_i^2 = 0.1, 0.1, 0.5, 0.3\,, \quad \text{for the bins} \quad [40,50], [50,60], [60,70], [70,80]~\mathrm{GeV}\,. \tag{16}$$

This gives

$$m_{EW} \sim 64~\mathrm{GeV}\,!!! \tag{17}$$

This is not yet an optimized result. (There is a resolution-correlation matrix that makes optimization a bit tricky, but we will soon have the "optimal" result.)

- One can now ask: have we worsened the fine tuning in order to get a low m_{EW}?

  For the SM Higgs boson, the dominant quadratic divergence arises from a virtual top quark loop,

$$\delta m^2_{h_{\rm SM}} = -\frac{3}{4\pi^2}\frac{m_t^2}{v^2}\Lambda_t^2\,, \tag{18}$$

where Λ_t is the high energy cutoff and $v = 176~\mathrm{GeV}$. We define a fine-tuning measure

$$F_t(m_{h_{\rm SM}}) = \left|\frac{\partial \delta m_{h_{\rm SM}}^2}{\partial \Lambda_t^2}\frac{\Lambda_t^2}{m_h^2}\right| = \frac{3}{4\pi^2}\frac{\Lambda_t^2}{m_{h_{\rm SM}}^2} \equiv c\frac{\Lambda_t^2}{m_{h_{\rm SM}}^2}\,. \quad (19)$$

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

$$\Lambda_t \lesssim \frac{2\pi v}{\sqrt{3}m_t} m_{h_{\rm SM}} F_t^{1/2} \sim 400~\textbf{GeV}\left(\frac{m_{h_{\rm SM}}}{115~\textbf{GeV}}\right) F_t^{1/2}, \quad (20)$$

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

- In the multi-doublet model, each h_i has its top quark loop contribution to $m_{h_i}^2$ scaled by f_i^2.
  As a result, the standard fine tuning associated with a common cutoff Λ_t

for all the top loops for each of the h_i is

$$F_t^i = f_i^2 F_t(m_i) = c f_i^2 \frac{\Lambda_t^2}{m_i^2} \,. \quad (21)$$

This formula says that we can lower the m_i without necessarily worsening the fine tuning provided f_i^2 is lowered by a corespondiing amount.
In our example, the worst bin is the $[60, 70]~\mathrm{GeV}$ bin for which

$$\Lambda_t \lesssim 400~\textbf{GeV} \frac{1}{0.5} \left(\frac{65~\mathrm{GeV}}{115~\textbf{GeV}} \right) F_t^{1/2} \stackrel{F_t=10}{\sim} 1.4~\mathrm{TeV} \,. \quad (22)$$

$\Rightarrow$ We have gained a bit of leeway compared to the SM $m_{h_{\rm SM}} = 100~\mathrm{GeV}$ result.

- In the SUSY context, more than two doublets destroys gauge coupling unification (but helps in the SM context).
  In SUSY, we only want to add singlets.
  If the singlets mix with the doublet H_u and H_d fields, creating a bunch of low mass eigenstates each with uncertain decays and each having

some f_i, then we can again further lower m_{EW} compared to the simplest MSSM or NMSSM cases.

However, since to begin with it was only the H_u that carried the Λ_t fine-tuning problem, fine-tuning will not be improved compared to the MSSM.

3. Unhiggs models work in close analogy with the multi-doublet mixing discussion above.

   The only difference is that all the bins are correlated for a particular model choice. A. Falkowski and I are working to see what the possibilities are. Some work along this line appears in (arXiv:0804.3534 [hep-ph], T. Binoth and J. J. van der Bij, arXiv:hep-ph/9908256).

4. In the Higgs-graviscalar mixing models (see also the stealthy Higgs model (J. J. van der Bij, arXiv:0804.3534 [hep-ph], T. Binoth and J. J. van der Bij, arXiv:hep-ph/9908256, T. Binoth and J. J. van der Bij, Z. Phys. C 75, 17 (1997) [arXiv:hep-ph/9608245]), where the invisible width is very large, one must just run the predicted Higgs shape past the limits of $e^+e^- \to Z + inv$ on a bin-by-bin

basis.

This was done in (G. Abbiendi *et al.* [OPAL Collaboration], Eur. Phys. J. C 49, 457 (2007) [arXiv:hep-ex/0610056]) with the result that an H with SM ZZ coupling but large $\Gamma(H \to inv)$ is excluded even for $m_H = 114~\mathrm{GeV}$. This is because the limits on the $Z + X$ with $X = inv$ channel quickly become very strong as M_X decreases below $114~\mathrm{GeV}$. So, if you spread out the H into a large range of M_X the lower reaches of M_X are excluded.

Thus, a small invisible width gives you the lowest possible value of m_H if $H \to inv$ is dominant.

Detecting the h_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 (see, A. Belyaev *et al.*, arXiv:0805.3505 [hep-ph] and our work, JFG+Tait+Z. Han, below).

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: 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. 6 for a variety of luminosity and triggering assumptions.

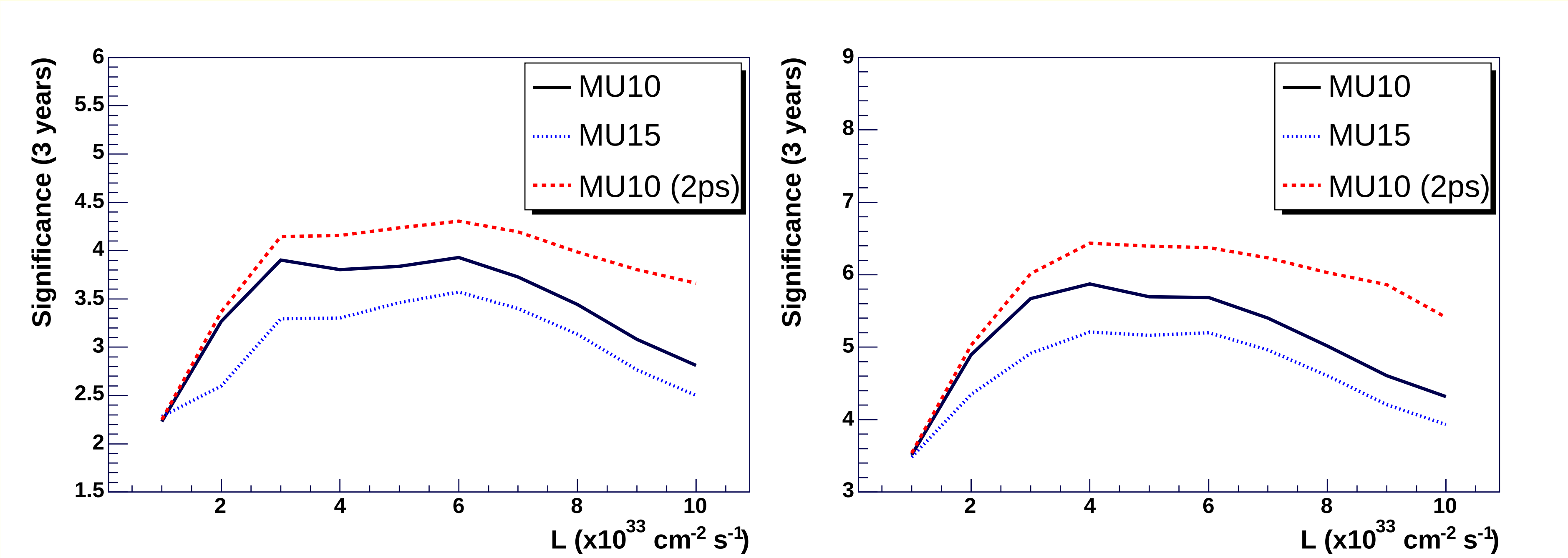


Figure 6: (a) The significance for three years of data acquisition at each luminosity. (b) Same as (a) but with twice the data. Different lines represent different μ trigger thresholds and different forward detector timing. Some experimentalists say more efficient triggering is possible, doubling the number of events at given luminosity.

CMS folk claim we can increase our rates by about a factor of 2 to 3 using additional triggering techniques.

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

$$p_i^{vis} = f_i \, p_{a,i} \tag{23}$$

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

- **$pp \to pph$ case**
  The accuracy of this has now been tested in the $pp \to pph$ case, and gives an error for m_h of order $5~\mathrm{GeV}$, but this is less accurate than m_h determination from the tagged protons and so is not used.

However, we are able to make *four* m_a determinations per event.

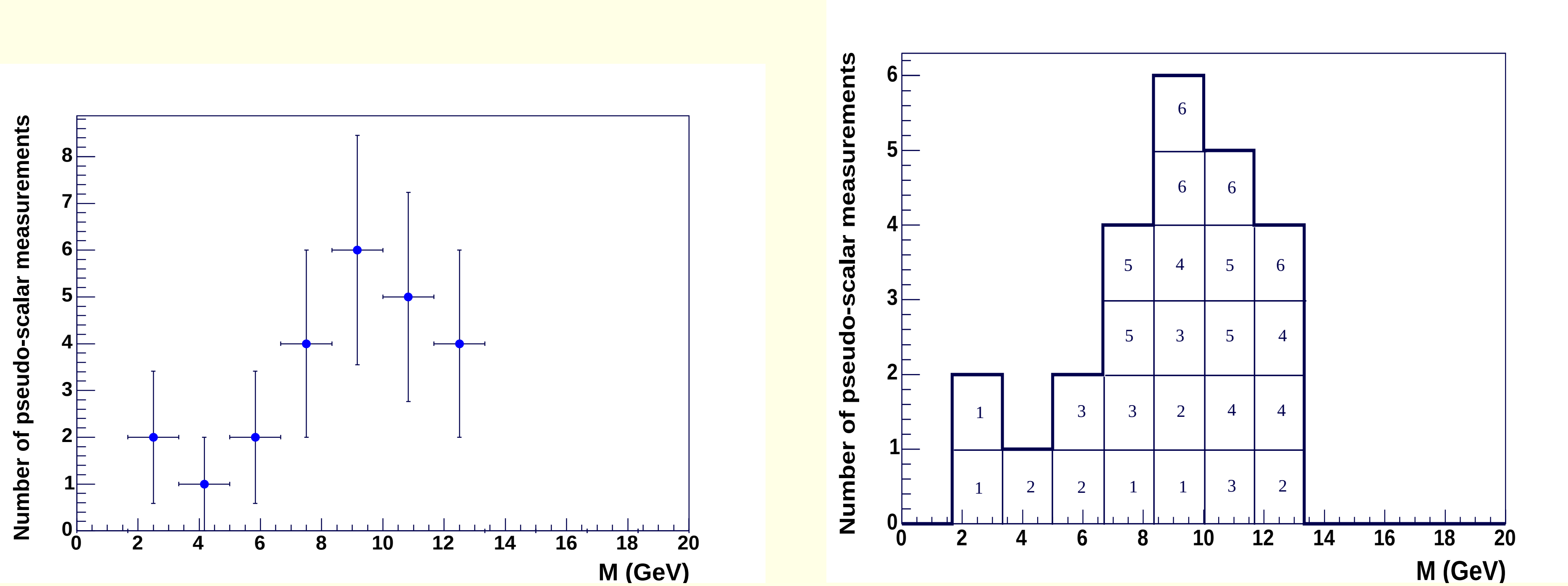


Figure 7: (a) A typical a mass measurement. (b) The same content as (a) but with the breakdown showing the 4 Higgs mass measurements for each of the 6 events, labeled $1 - 6$ in the histogram.

Figure 7 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 input value of $9.7~\mathrm{GeV}$.

- $WW \to h$

For $m_h = 100~\mathrm{GeV}$ and SM-like WWh coupling, $\sigma(WW \to h) \sim 7~\mathrm{pb}$, 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 that can be solved for f_1 and f_2:

$$p_h^x = \frac{(p_1^{vis})_x}{f_1} + \frac{(p_2^{vis})_x}{f_2} \quad p_h^y = \frac{(p_1^{vis})_y}{f_1} + \frac{(p_2^{vis})_y}{f_2}\,. \tag{24}$$

Of course, this follows very much the same pattern as in $WW \to h_{\mathrm{SM}}$ with $h_{\mathrm{SM}} \to \tau^+\tau^-$ 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

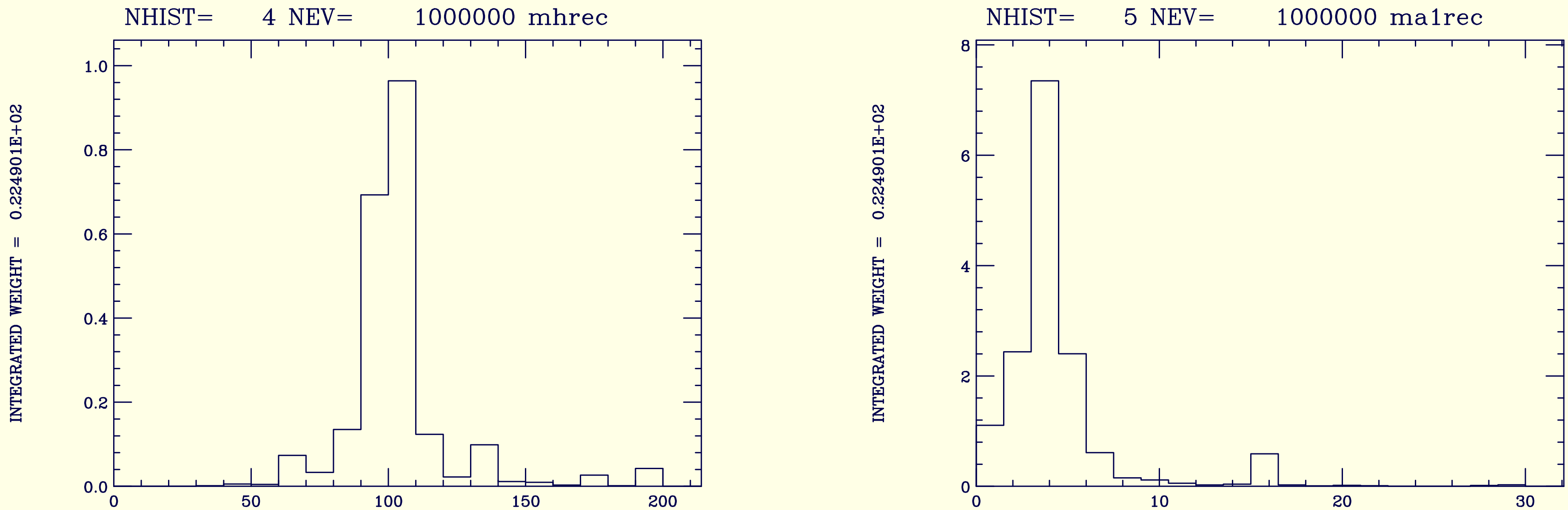


Figure 8: (a) A typical h mass distribution. (b) A typical a mass distribution. No cuts imposed; signal only

- We have now developed cuts that we are relatively certain will control backgrounds nicely. These cuts do not change the mass reconstruction above significantly, even after including PGS (CMS) smearing.

ILC

At the ILC, there is no problem since $e^+e^- \to ZX$ will reveal a $M_X \sim m_{h_1} \sim 90 - 100~\mathrm{GeV}$ peak no matter how the h_1 decays.

If there are many Higgs, then the excesses in various bins of M_X will be apparent even if there is a broad sort of spectrum and X has a mixture of decays.

But the ILC is decades away.

Conclusions

- **The Higgs sector is very sensitive to new light states.**

  In the NMSSM case, Higgs decays expose the extended Higgs sector.

  In other cases, Higgs decays provide a very unique window on even more dramatic new physics.

  Probably, we have only touched the surface of the possibilities.

- **The Higgs could be pretty hard to find, requiring lots of integrated luminosity in the NMSSM cases studied.**

  However, if (a) SUSY is present to cure the quadratic-divergence fine-tuning problem and (b) if something like the m_Z fine-tuning arguments are appropriate and (c) the GUT scale is large (implicit in there being a possible m_Z fine-tuning), then SUSY should be light.

We could easily spend many years seeing lots of SUSY particles, but failing to detect the Higgs.

If WW scattering is perturbative and SUSY is seen, probably there is a light Higgs even if we cannot see it — unfortunately it is not terribly easy to check for signs of strong WW scattering.

- **While I have outlined a number of quite interesting possibilities, I have not embarked on the models that link multiple-singlet theories to the CDF multi-muon events excess.**

  There are lots of multiple-singlet scenarios

  – **(a) that give excellent precision electroweak because there is a SM-like h with $m_h < 100~\mathrm{GeV}$ (that escapes LEP limits because of large $B(h \to aa)$, a being some light scalar or pseudoscalar state decaying to something other than $b\bar{b}$ or $\widetilde{\chi}_1^0\widetilde{\chi}_1^0$) and**

  – **(b) for which the Higgs sector provides the CDF multi-muon excesses through a chain of Higgs bosons ending with (large $c\tau$) decays of the final Higgs bosons a_{light} to $\tau^+\tau^-$ pairs .**

If one of the Higgs in the multi-Higgs chain dominates the SM-like h primary decays (it can't be the final Higgs since the latter has to be very! singlet $\Rightarrow B(h \to a_{light}a_{light})$ will be small) then we would have to look for the SM-like h in $\geq 6\tau$ final states.

Of course, the big question is where are the multi-electron event excesses that should accompany the multi-muon events.