

# **Higgs Signals: The Proliferation of Known Unknowns**

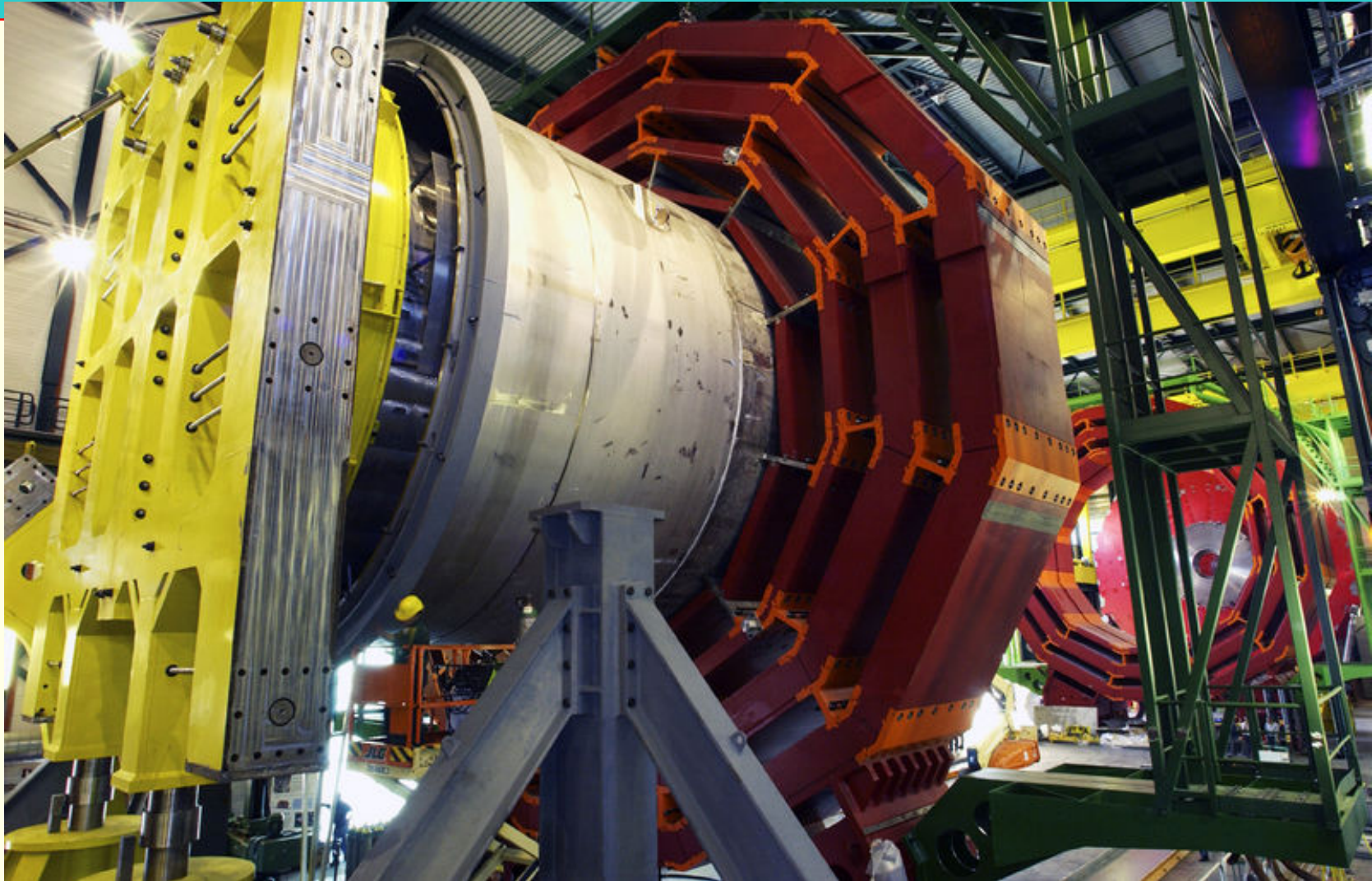
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## Outline

1. The LHC is coming, but even if there is a Higgs boson sector how will we see it?
2. There are **many** possibilities for the Higgs sector and each new approach can give a significantly different channel to focus on for Higgs discovery.
3. Probably one should give some weight to solving the hierarchy problem and to fine-tuning within models that solve this problem (e.g. the MSSM and NMSSM).
4. My focus will be on Higgs bosons, broadly defined as CP-even or CP-odd spin zero states.

## The LHC is at hand

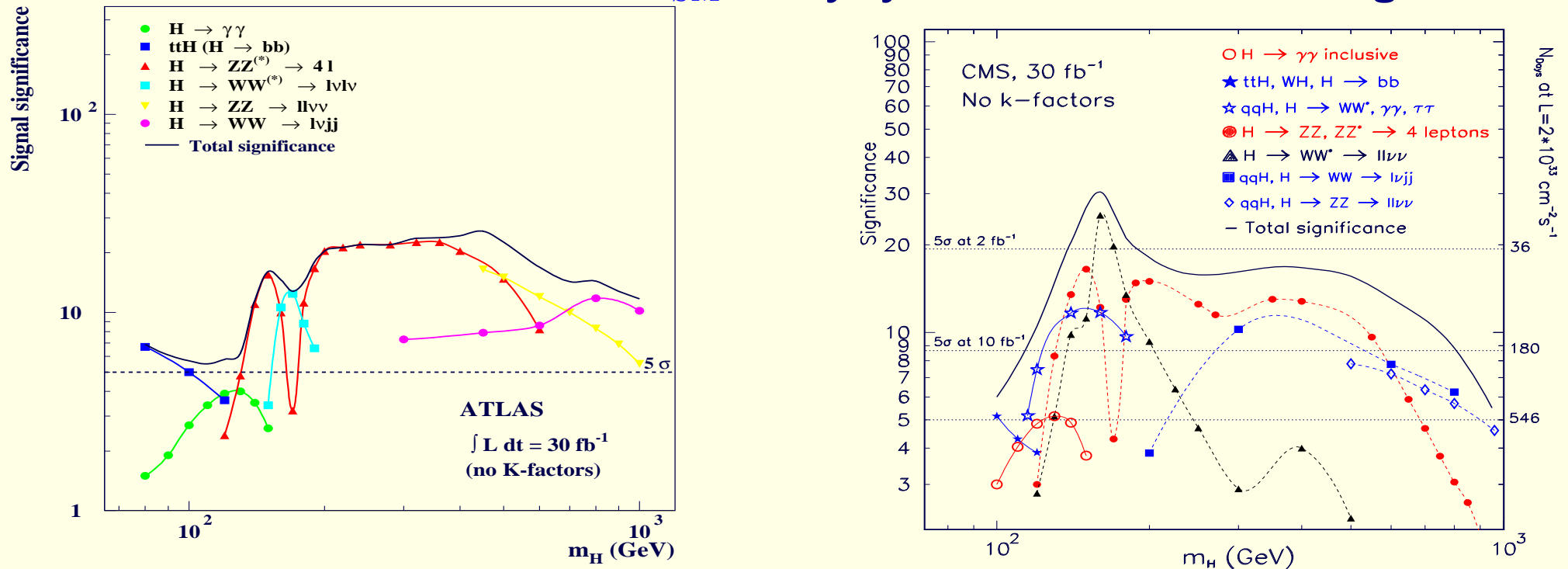


**The CMS Detector**

**But will the LHC detectors detect the Higgs boson. The signal(s) might be quite unexpected.**

# The SM

- The main channels for the  $h_{SM}$  decays yield all the usual LHC signals.



**Figure 1:** SM Higgs signal significance as function of the Higgs boson mass. The curves show the signal significance for an integrated luminosity of  $30 \text{ fb}^{-1}$  for ATLAS (left) and CMS (right).

What about the rare  $\mu^+\mu^-$  decay channel? **Pretty tough!** See below. But enhanced in e.g. gauge phobic models where  $WW, ZZ$  decays are all suppressed but fermionic couplings are SM-like. In general,  $\mu^+\mu^-$  final state could be important to reveal non-SM-like features of a Higgs boson.

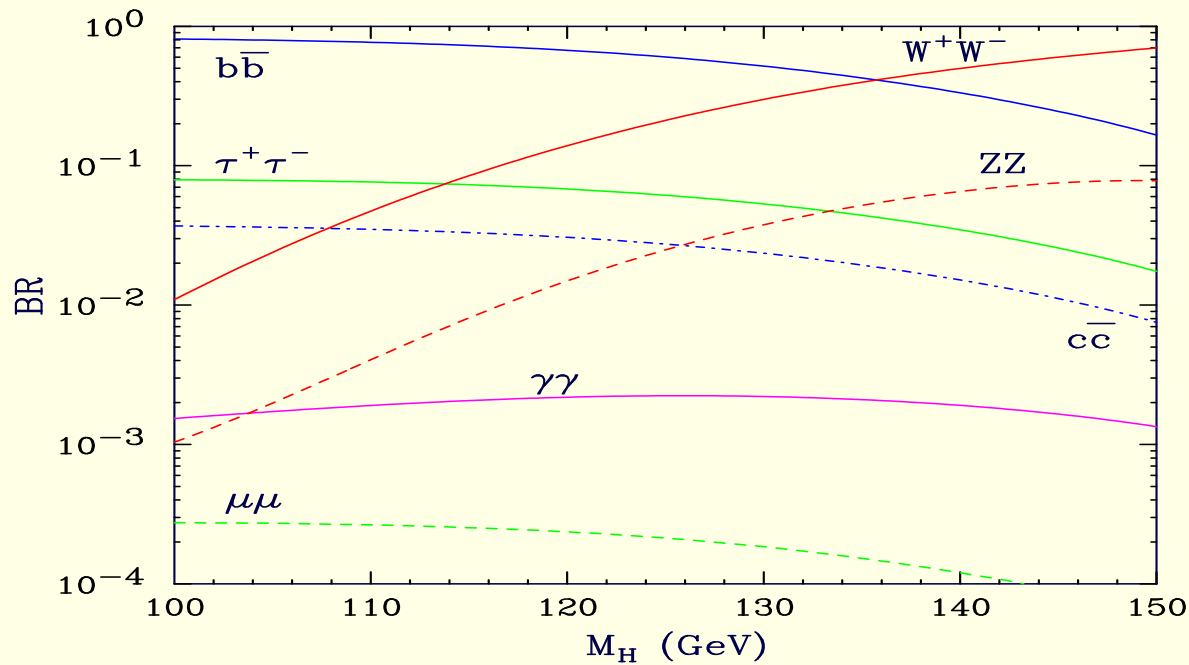


Figure 2: SM Higgs branching ratios.

$\sqrt{S}$ [TeV]	$M_H$ [GeV]	$\sigma_H$ [fb]	$\sigma_Z^{\text{ew}}$ [fb]	$\sigma_Z^{\text{QCD}}$ [fb]	$S/B$	significance $\sigma$	$\Delta\sigma/\sigma$	$\mathcal{L}_{5\sigma}$ [fb $^{-1}$ ]
14	115	0.25	3.57	0.40	1/9.1	1.7	60%	2600
14	120	0.22	2.60	0.33	1/7.5	1.8	60%	2300
14	130	0.17	1.61	0.24	1/6.5	1.7	65%	2700
14	140	0.10	1.11	0.19	1/7.5	1.2	85%	4900
40	115	0.56	4.52	1.03	1/6.2	3.2	35%	750
40	120	0.52	3.32	0.79	1/5.3	3.3	35%	700
40	130	0.39	2.11	0.53	1/4.3	3.2	35%	750
40	140	0.25	1.51	0.41	1/5.0	2.4	50%	1400
200	115	2.57	39.6	5.3	1/10.1	5.3	20%	270
200	120	2.36	29.2	4.0	1/8.0	5.7	20%	230
200	130	1.80	18.7	2.7	1/6.9	5.3	20%	260
200	140	1.14	13.4	2.0	1/7.9	4.0	27%	500

Table 1: Final results of the  $pp \rightarrow qqWW$  with  $WW \rightarrow h_{\text{SM}} \rightarrow \mu^+ \mu^-$  analysis. T. Plehn and D. L. Rainwater, Phys. Lett. B **520**, 108 (2001) [arXiv:hep-ph/0107180].

# Motivations for going beyond the SM

The motivation is to make a light Higgs (as desired for precision electroweak consistency) natural without making it too light, *i.e.* below LEP limits.

## Naturalness

The dominant quadratic divergence arises from a virtual top quark loop,

$$\delta m_{h_{\text{SM}}}^2 = -\frac{3}{4\pi^2} \frac{m_t^2}{v^2} \Lambda_t^2, \quad (1)$$

where  $\Lambda_t$  is the high energy cutoff and  $v = 176$  GeV.

This creates the hierarchy/fine-tuning issue in that the SM Higgs mass is very sensitive to the cutoff  $\Lambda_t$ . A formal definition of fine tuning with respect to  $\Lambda_t$  is (for numerics, we take  $m_t \sim v \sim 174$  GeV)

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

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

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

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

### The Alternatives

1. Introduce new physics: supersymmetry, little Higgs, .... of a dramatic new kind at  $\Lambda_t \lesssim 1 \text{ TeV}$ .
2. Alter the Higgs sector so as to raise  $\Lambda_t$ , thereby postponing the need for truly new physics.

Instead of looking for SUSY, ..., you would look for the extra Higgs phenomena in the sub- TeV region.

# Extensions of the SM involving only the Higgs sector

There is significant motivation and many possibilities!

- Additional Singlets

One possible 'worst' case is the addition of **many** singlets. ( J. R. Espinosa and J. F. Gunion, Phys. Rev. Lett. 82, 1084 (1999) [arXiv:hep-ph/9807275].)

In the worst case, we imagine that the singlets mix with the  $h_{SM}$  so that the resulting eigenstates,  $h_i$  share all the  $WW$ ,  $ZZ$ ,  $f\bar{f}$  couplings according to their overlap fraction  $f_i$ :  $h_i = f_i h_{SM} + \dots$ , where  $\sum_i f_i^2 = 1$  is required.

In terms of precision electroweak, one crudely ends up with ( 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)

$$T = \sum_i f_i^2 T_{SM}(m_{h_i}), \quad S = \sum_i f_i^2 S_{SM}(m_{h_i}). \quad (4)$$



Recalling that the  $T_{SM}$  and  $S_{SM}$  functions are basically logarithmic, we end up with a requirement for consistency with  $m_{EW} \sim 100$  GeV (central) or  $m_{EW} \sim 200$  GeV (95% cL) in the SM case of the form  $\log m_{EW} = \sum_i f_i^2 \log m_i$  or

$$m_{EW} = \prod_i m_i^{f_i^2}. \quad (5)$$

An appropriate  $m_{EW}$  is maintained if all the  $f_i^2$  are equal and the  $m_i$  are not too widely separated. Or, if they are widely separated, the larger  $m_i$  should have smaller  $f_i^2$ .

Meanwhile, each  $h_i$  has top quark loop scaled by  $f_i^2$  and thus

$$F_t^i = f_i^2 F_t(m_i) = c f_i^2 \frac{\Lambda_t^2}{m_i^2} \quad (6)$$

*i.e.* significantly reduced. (Note that smaller  $f_i$  for larger  $m_i$  keeps all  $F_t^i$  of similar size.)

**Thus, multiple mixed Higgs allow a much larger  $\Lambda_t$  for a given maximum**

acceptable common  $F_t^i$ . Also, large  $\Lambda_t$  implies significant corrections to low- $E$  phenomenology from  $\Lambda_t$ -scale physics less likely.

Consider for example, one doublet plus 4 complex singlets. This leads to 5 mixed CP-even states  $h_i$  and 4 CP-odd states  $a_k$ .

Using  $f_i^2 = 1/5$  and  $F_t^i \leq 10$  for each of the  $h_i$ ,  $\Lambda_t \sim 5$  TeV is the new requirement if the  $m_i$  are spread out in the vicinity of 100 GeV.

Meanwhile, the signal for each  $h_i$  can be much more difficult than before. There are two sources of difficulty:

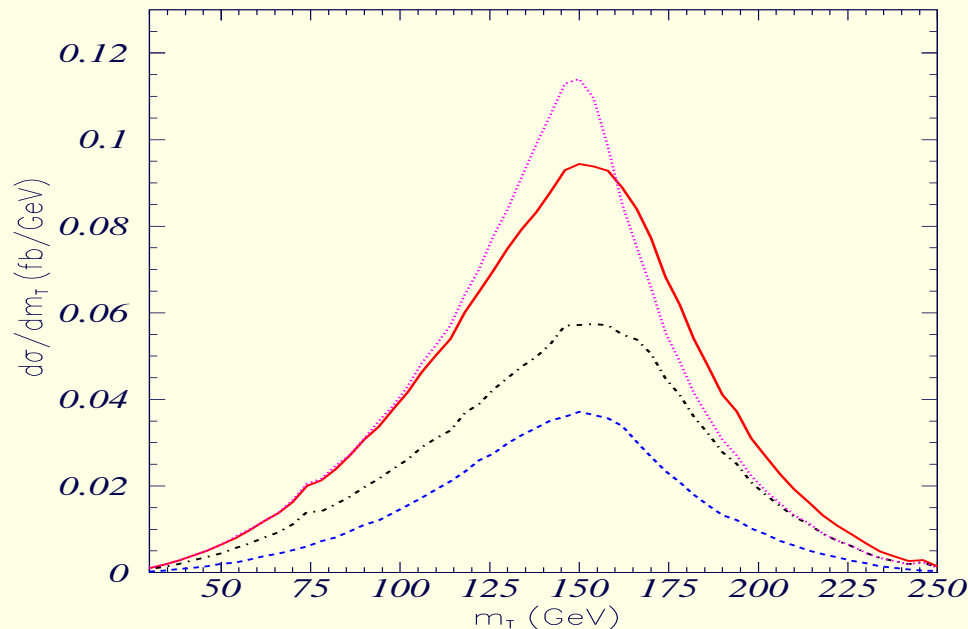
- We can spread out the  $m_i$  every 10 GeV or thereabouts, so that all but the  $4\ell$  signal and  $\gamma\gamma$  signal overlap in mass resolution (no peak), and the  $4\ell$  and  $\gamma\gamma$  signal rates are reduced to  $1/5$  of the SM value.
- There can be Higgs to Higgs decays by virtue of the presence of light  $a_k$ 's leading to  $h_i \rightarrow a_k a_l$  and we could also have enough  $m_i$  spread for  $h_i \rightarrow h_j h_k$ .

If one were lucky in that there were no Higgs to Higgs decays, there is one signal that does not care so very much about the multiple Higgs scenario: that is  $WW$  fusion,  $WW \rightarrow h_i \rightarrow WW \rightarrow \ell^+ \ell^- \nu \bar{\nu}$ . This is because one does not reconstruct the Higgs mass in this channel anyway but rather

looks for a peak in the  $m_T$  distribution where

$$m_T^2 \equiv m_{T,WW}^2 = \left( \sqrt{\vec{p}_{\ell\ell,T}^2 + m_{\ell\ell}^2} + \sqrt{\vec{p}_{\nu\nu,T}^2 + m_{\nu\nu}^2} \right)^2 - (\vec{p}_{\ell\ell,T} + \vec{p}_{\nu\nu,T})^2, \quad (7)$$

For a more or less constant spectrum of equally weighted Higgs bosons with equal vevs, a signal survives.



**Figure 3:** Transverse mass  $m_T$  spectrum for the continuum model signal (dashed), background (dash-dotted), and continuum signal plus background (solid). For comparison we also show the  $m_h = 155$  GeV SM signal plus background case, normalized to have the same signal cross section as the continuum model. A. Alves, O. Eboli, T. Plehn and D. L. Rainwater, *Phys. Rev. D* **69**, 075005 (2004) [arXiv:hep-ph/0309042].

With  $\lesssim 100 \text{ fb}^{-1}$ , one gets a  $5\sigma$  signal. But the peak relies on having a reasonable weight for Higgs with masses near  $2m_W$ . If you shift the spectrum of masses to deemphasize this region, the situation rapidly worsens.

However, Higgs to Higgs decays are very likely to be present. In order to get mixing of the type imagined, we need self couplings of the Higgs which will lead to **Higgs**  $\rightarrow$  **Higgs-pair** and **Higgs**  $\rightarrow$  **Higgs** +  $W, Z$  decays — e.g. any quartic potential term leads to a Higgs-Higgs-Higgs Feynman rule when one of the Higgs fields is replaced by its vev.

The importance of such decays has been emphasized by J. F. Gunion, H. E. Haber and T. Moroi, Snowmass 1996, [arXiv:hep-ph/9610337], and B. A. Dobrescu and K. T. Matchev, JHEP 0009, 031 (2000) [arXiv:hep-ph/0008192] and B. A. Dobrescu, G. Landsberg and K. T. Matchev, Phys. Rev. D 63, 075003 (2001) [arXiv:hep-ph/0005308].

The basic expressions for the decays make the reason clear.

$$\Gamma(h_i^0 \rightarrow h_j^0 h_k^0) = \frac{1}{1 + \delta_{jk}} \frac{g_{h_i^0 h_j^0 h_k^0}^2}{16\pi m_{h_i^0}} \lambda(1, m_{h_j^0}^2/m_{h_i^0}^2, m_{h_k^0}^2/m_{h_i^0}^2),$$

where  $h_i^0 \rightarrow h_j^0 h_k^0$  formula also applies for  $a_j^0 a_k^0$  final state. Similar expressions apply for  $h_i^0 \rightarrow h_j^+ h_k^- + h_j^- h_k^+$ ,  $h_i^0 \rightarrow a_k^0 Z$ , and  $h_i^0 \rightarrow h_j^+ W^- + h_j^- W^+$ .

These are all potentially dominant or at least prominent when allowed. For example, typically,  $g_{h_i^0 h_j^0 h_k^0} = c \frac{g m_{h_i^0}^2}{2m_W}$ . If  $c = 1$  (as can be the case if  $h_i^0$  is SM-like), and if we ignore phase space suppression and take  $j = k$ , this gives

$$\Gamma(h_i^0 \rightarrow h_j^0 h_j^0) = \frac{g^2 m_{h_i^0}^3}{128\pi m_W^2} \sim 0.17 \text{ GeV} \left( \frac{m_{h_i^0}}{100 \text{ GeV}} \right)^3 \quad vs. \quad (8)$$

$$\Gamma(h_i^0 \rightarrow b\bar{b}) \sim 0.003 \text{ GeV} \left( \frac{m_{h_i^0}}{100 \text{ GeV}} \right) \quad and \quad (9)$$

$$\Gamma(h_i^0 \rightarrow ZZ) = \frac{1}{2} \Gamma(h_i^0 \rightarrow WW) = \frac{g^2 m_{h_i^0}^3}{128\pi m_W^2}. \quad (10)$$

where the latter assumes that  $h_i^0$  carries all the vev for giving  $W$ 's and  $Z$ 's mass.  $c \sim 0.13$  makes the  $h_j^0 h_k^0$  or  $a_j^0 a_k^0$  mode equal to the  $b\bar{b}$  mode, and such  $c$ 's are common in models. Thus, Higgs pair modes will dominate until we pass above the  $WW$  threshold.

For  $m_{h_i^0} \gg m_W, m_Z, m_{h_j^0}$ ,  $B(h_i^0 \rightarrow a_j^0 a_j^0) = \frac{1}{4}$ .

Scaling  $c$  and all other couplings down to a fraction  $f_i$  reduces cross sections by  $f_i^2$ , but does not change the branching ratios.

**Summary:** Higgs to Higgs decays can be dominant when  $WW$ ,  $ZZ$  channels are not open and can still be substantial even when they are.

**Bottom Line:** No guarantee for observing a Higgs at the LHC and simultaneously no guarantee of new physics until the many TeV scale.

- **One-Singlet Models**

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

1. 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 a SM doublet of form

$$\mathcal{L} \ni \frac{c'}{2} a^2 |H|^2 \quad \Rightarrow \quad g_{haa} = \frac{c'v}{\sqrt{2}}, \quad (11)$$

and

$$\Gamma(h \rightarrow aa) = \frac{c'^2 v^2}{16\pi m_h} \lambda^{1/2}(\dots). \quad (12)$$

Not much  $c'$  is needed to make this decay dominant for a light  $h$ ;  $c' > 0.04$  will allow a  $m_h \sim 100$  GeV Higgs to escape detection so long as the  $a \rightarrow b\bar{b}$  decay is not dominant.

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  $m_h > 114$  GeV is required by LEP.

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

$$\mathcal{L} \ni \bar{\psi}(M + i\gamma_5 \lambda a)\psi \quad (13)$$

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

$$B(h \rightarrow 4\gamma) \sim 1.4 \times 10^{-5}, \quad B(h \rightarrow 2g2\gamma) \sim 7.6 \times 10^{-3}. \quad (14)$$

The one loop generation of these  $a$  couplings imply the possibility of

non-prompt  $a$  decay:

$$c\tau_a \sim \frac{1}{\Gamma_{a \rightarrow gg}} = 1 \text{ cm} \left( \frac{30 \text{ GeV}}{m_a} \right)^3 \left( \frac{M}{450 \text{ TeV}} \right)^2 \left( \frac{0.1}{\lambda b_3} \right)^2 \quad (15)$$

This would enhance Higgs discovery prospects.

2. 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.

Here the philosophy differs.

They introduce a scalar  $\Phi$  with

$$\mathcal{L} \ni \eta |\Phi|^2 |H|^2 \quad (16)$$

which causes eigenstate mixing, leading to eigenstates  $h$  and  $H$ .

- In one scenario, the heavier  $H$  is mainly doublet and the  $h$  mainly singlet.

Once again,  $H \rightarrow hh$  decays are possibly dominant if  $H$  is not heavier than  $2m_W$ .

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.

If there is a substantial hidden sector connected to the  $h$ , then it could be that  $h$  will decay mainly invisibly.

- In another scenario (the 2nd paper),  $H$  is mainly singlet and  $h$  mainly doublet. In this case, they have considered a few scenarios:

	Point A	Point B	Point C
$\sin^2 \omega$	0.40	0.31	0.1
$m_h$ (GeV)	143	115	120
$m_H$ (GeV)	1100	1140	1100
$\Gamma(H \rightarrow hh)$ (GeV)	14.6	4.9	10
$BR(H \rightarrow hh)$	0.036	0.015	0.095

**Table 2:** *Points illustrating parameters of trans-TeV mass Higgs boson.*

For the above A,B,C cases, the  $H$  will have large enough  $B(H \rightarrow WW)$  that the  $\ell\nu jj$  final state will show a high effective mass peak; and similar for  $H \rightarrow ZZ \rightarrow \ell\ell jj$ .

The large mass separation implies somewhat weak,  $H \rightarrow hh$  decays, but they still might be observable.

Alternatively, it is easy to lower  $m_H$  and get large  $B(H \rightarrow hh)$ .

	Point 1	Point 2	Point 3
$\sin^2 \omega$	0.5	0.5	0.5
$m_h$ (GeV)	115	175	225
$m_H$ (GeV)	300	500	500
$\Gamma(H \rightarrow hh)$ (GeV)	2.1	17	17
$BR(H \rightarrow hh)$	0.33	0.33	0.33

**Table 3:** Points illustrating parameters that allow large branching fractions of  $H \rightarrow hh$ .

$\Gamma(H \rightarrow hh)$  for points 1, 2, 3 are obtained based on the assumption that the branching ratio  $B(H \rightarrow hh) = 1/3$ . To see this decay, they suggest the  $\gamma\gamma b\bar{b}$  final state.

These scenarios tend to push the PEW constraints, but they argue that additional physics of the hidden sector can fix this up if it is a problem.

### 3. M. J. Strassler, arXiv:hep-ph/0607160.

In the 1st half of the paper, his discussion is quite similar to various aspects of the previous 2 works.

He in particular emphasizes the fact that  $a$  decay vertices could be displaced.

He also considers his hidden-valley models. 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,

$$h \rightarrow VV \rightarrow Z'Z' \rightarrow b\bar{b}b\bar{b}$$

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  $V \rightarrow b\bar{b}, \dots$  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.

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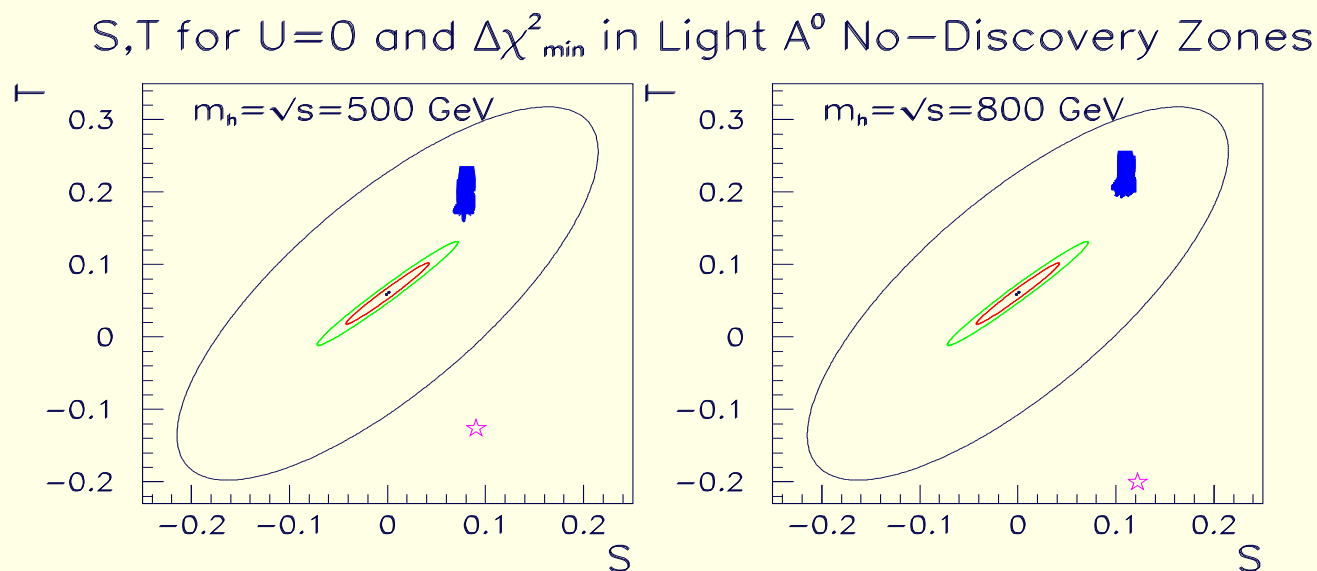
### Additional Doublets

A lot of work has been done in the two-doublet model context. I can only provide a sample. (Recall: multi-doublet models preserve  $\rho_{tree} = 1$ .)

#### Approach #1

One approach (T. Farris, J. F. Gunion and H. E. Logan, Snowmass 2001, P121, [arXiv:hep-ph/0202087]) is a two-doublet model with a light (possibly

very light)  $A^0$ , a possibly heavy SM-like  $h^0$  and quite heavy  $H^\pm$  and  $H^0$  which are almost (but not quite degenerate — need small  $m_{H^\pm} - m_{H^0}$  to generate large  $\Delta T > 0$ ).



**Figure 4:** Outer ellipses = current 90% CL region for  $U = 0$  and  $m_{h_{\text{SM}}} = 115$  GeV. Blobs =  $S, T$  predictions for 2HDM models with  $m_{H^\pm} - m_{H^0}$  for correct  $\Delta T > 0$ . Innermost (middle) ellipse = 90% (99.9%) CL region for  $m_{h_{\text{SM}}} = 115$  GeV after Giga-Z and a  $\Delta m_W \lesssim 6$  MeV threshold scan measurement. Stars = SM  $S, T$  prediction if  $m_{h_{\text{SM}}} = 500$  or 800 GeV.

**This model for relaxing the precision electroweak constraints on  $m_{h_{\text{SM}}}$  is a special case of a more general approach to allow for heavy  $h_{\text{SM}}$  (Peskin, Wells).**

In any case,  $m_{h^0} = 2m_W$  (800 GeV) would allow  $\Lambda_t \gtrsim 1.5$  TeV (9 TeV) if  $F_t = 10$  is 'ok'.

You would then only need supersymmetry or little Higgs or ... above 1.5 – 1.7 TeV (9 – 10 TeV). Even so, Higgs phenomenology would change greatly. In particular, in this model  $c = 1$  and the  $h_{\text{SM}} \rightarrow A^0 A^0$  mode would be dominant (important) for  $m_{h_{\text{SM}}} < 2m_W$  ( $m_{h_{\text{SM}}} > 2m_W$ ).

## Approach #2

More recently, R. Barbieri and L. J. Hall, arXiv:hep-ph/0510243, have used the  $m_{EW}$  game as follows.

They allow only the heavier  $m_+$  Higgs of the two-doublet model to couple to top quarks, so that if  $m_+$  is large enough  $\Lambda_t$  can be quite large. Meanwhile, precision electroweak data requires

$$m_+ < m_- \left( \frac{m_{EW}}{m_-} \right)^{\frac{1}{\sin^2 \beta}} \quad (17)$$

where, in their the model,  $f_+^2 \sim \sin^2 \beta$  and  $f_-^2 \sim \cos^2 \beta$ . By taking  $\sin^2 \beta = 1/2$ , say,  $m_{EW} = 200$  GeV and  $m_- = 115$  GeV,  $m_+ = 300$  GeV,

and hence large  $\Lambda_t$  (which only knows about  $m_+$ ) at 3 TeV is 'ok'. For,  $m_{EW} = 100$  GeV, this game runs into conflict with LEP limits.

In this model, LHC Higgs discovery will be more challenging

– for the  $h_-$

Since the  $h_-$  has little  $t\bar{t}$  coupling,  $gg \rightarrow h_-$  will be greatly suppressed which jeopardizes the  $\gamma\gamma$  signal for the light Higgs.

Also,  $t\bar{t}h_-$  associated production is highly suppressed.

$WW \rightarrow h_- \rightarrow \tau^+\tau^-$  will be suppressed by reduced  $WW h_-$  coupling, but might still be ok.

– for the  $h_+$

If  $m_+ > 2m_W$ ,  $h_+ \rightarrow h_-h_-$  decays will be present but not dominant, while  $gg \rightarrow h_+$  production will be full strength  $\Rightarrow h_+ \rightarrow ZZ \rightarrow 4\ell$  will be quite ok, you just will need to find the  $h_-$  to understand precision electroweak data.

If  $m_+ < 2m_W$ , you will not have raised  $\Lambda_t$  all that much, and the  $h_+ \rightarrow h_-h_-$  decays, if present, could wipe out all normal signals.

Well, I have not really done a careful study. Perhaps it is worth pursuing the phenomenology in more detail.

- **Adding triplets**

There are too very distinct possibilities:

1. The neutral triplet vevs are zero.

$\rho = 1$  remains a **prediction**.

2. There is one or more non-zero neutral triplet vev.

$m_W$  and  $m_Z$  must be separately input as part of the renormalization program.

This is far too complicated a subject for this short presentation. I simply remind you that if there is a  $Y = \pm 1$  triplet it will contain  $H^{\pm\pm}$  states that could easily have their decays dominated by  $\ell^{\pm}\ell^{\pm}$ .

These are very clean signals, and limits on doubly-charged Higgs are already available that exceed LEP limits.

A full exposition of triplet phenomenology is given in the CPNSH report: E. Accomando *et al.*, arXiv:hep-ph/0608079 — the triplet section was authored by JFG and C. Hayes.

# The Standard Model in Extra Dimensions

- There are two canonical models.
  - Non-curved and wrapped up  $\delta$  extra dimensions (ADD).
  - Randall-Sundrum warped 5th dimension model.

Both can cause big change in Higgs phenomenology even if the Higgs sector remains that of the SM one-doublet.

- **ADD**

The possible complication for Higgs phenomenology here comes if the Higgs mixes with the graviscalars of the theory (which propagate in the extra dimensions and are therefore invisible). The net result is **Invisible Higgs Decays**.

In ADD models, there is an interaction between the Higgs complex doublet field  $H$  and the Ricci scalar curvature  $R$  of the induced 4-dimensional metric  $g_{ind}$ . After the usual shift  $H = (\frac{v+h}{\sqrt{2}}, 0)$ , this interaction leads to



the mixing term (Giudice, Wells, Ratazzi)

$$\mathcal{L}_{\text{mix}} = \epsilon h \sum_{\vec{n} > 0} s_{\vec{n}} \quad (18)$$

with

$$\epsilon = -\frac{2\sqrt{2}}{M_{\text{P}}} \xi v m_h^2 \sqrt{\frac{3(\delta - 1)}{\delta + 2}}. \quad (19)$$

Above,  $M_{\text{P}} = (8\pi G_N)^{-1/2}$  is the reduced Planck mass and  $s_{\vec{n}}$  is a graviscalar KK excitation with mass  $m_{\vec{n}}^2 = 4\pi^2 \vec{n}^2 / L^2$ ,  $L$  being the size of each of the extra dimensions.

The invisible mixing width is given by

$$\begin{aligned} \Gamma_{h_{\text{eff}} \rightarrow \text{graviscalar}} &= 2\pi \xi^2 v^2 \frac{3(\delta - 1)}{\delta + 2} \frac{m_h^{1+\delta}}{M_D^{2+\delta}} S_{\delta-1} \\ &\sim (16 \text{ MeV}) 20^{2-\delta} \xi^2 S_{\delta-1} \frac{3(\delta - 1)}{\delta + 2} \left( \frac{m_h}{150 \text{ GeV}} \right)^{1+\delta} \\ &\quad \times \left( \frac{3 \text{ TeV}}{M_D} \right)^{2+\delta}. \end{aligned} \quad (20)$$

A typical result is that invisible decays dominate if the  $m_h < 2m_W$ . For example, for  $\delta = 2$ ,  $M_D = 500$  GeV and  $m_h = 120$  GeV,  $\Gamma_{h_{eff} \rightarrow graviscalar}$  is of order 50 GeV already by  $\xi \sim 1$ , *i.e.* far larger than the SM prediction of 3.6 MeV.

- RS Scenario

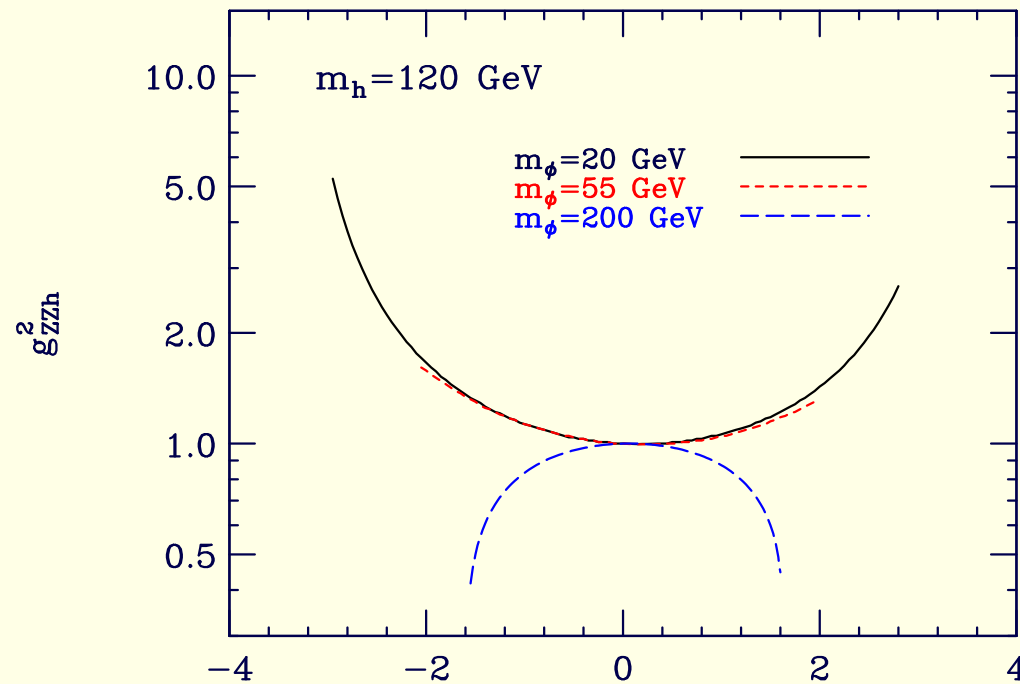
Here, there is again mixing, this time between the Higgs and the radion. Big changes in Higgs phenomenology are possible, since such mixing causes Higgs couplings to change and the radion will come into play as an observable Higgs-like object. (You may not even know which is which without a lot of detailed analysis.) Remarks here based on: D. Dominici, B. Grzadkowski, J. F. Gunion and M. Toharia, Nucl. Phys. B 671, 243 (2003) [arXiv:hep-ph/0206192]; M. Battaglia, S. De Curtis, A. De Roeck, D. Dominici and J. F. Gunion, Phys. Lett. B 568, 92 (2003) [arXiv:hep-ph/0304245]. See also, J. L. Hewett and T. G. Rizzo, JHEP 0308, 028 (2003) [arXiv:hep-ph/0202155].

– We begin with

$$S_\xi = \xi \int d^4x \sqrt{g_{\text{vis}}} R(g_{\text{vis}}) \widehat{H}^\dagger \widehat{H}, \quad (21)$$

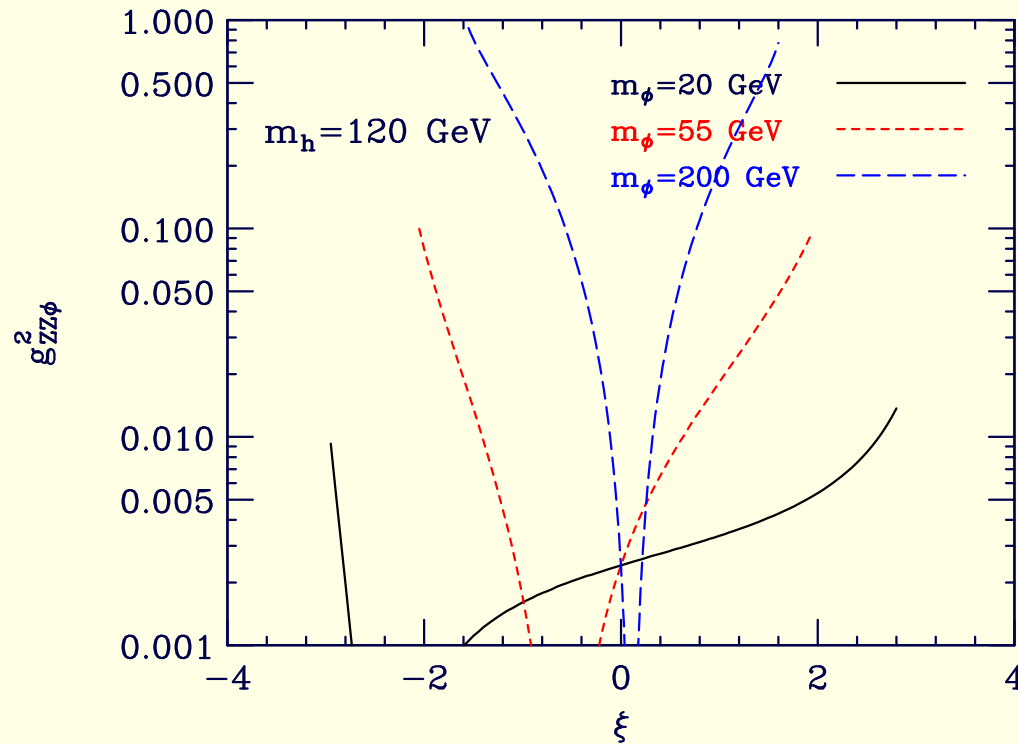
where  $R(g_{\text{vis}})$  is the Ricci scalar for the metric induced on the visible brane.

- An example of altered couplings is



**Figure 5:**  $g_{ZZh}^2/g_{ZZh_{SM}}^2 = g_{f\bar{f}h}^2/g_{f\bar{f}h_{SM}}^2$  as a function of  $\xi$  for several  $m_\phi$  values.

The couplings of the  $\phi$  are very rapidly varying:



**Figure 6:**  $g^2_{ZZ\phi}/g^2_{ZZh_{SM}} = g^2_{f\bar{f}\phi}/g^2_{f\bar{f}h_{SM}}$  as a function of  $\xi$  for several  $m_\phi$  values.

All of this can effect branching ratios and production rates in either desirable or undesirable ways.

New decays open up. Especially likely to be important is  $\phi \rightarrow hh$ , since  $\phi$  couplings to SM particles can easily be greatly suppressed and there is a significant  $\phi hh$  coupling.

When  $m_h \sim 100$  GeV (PEW preferred) this decay will lead to  $\phi \rightarrow 4b$  final

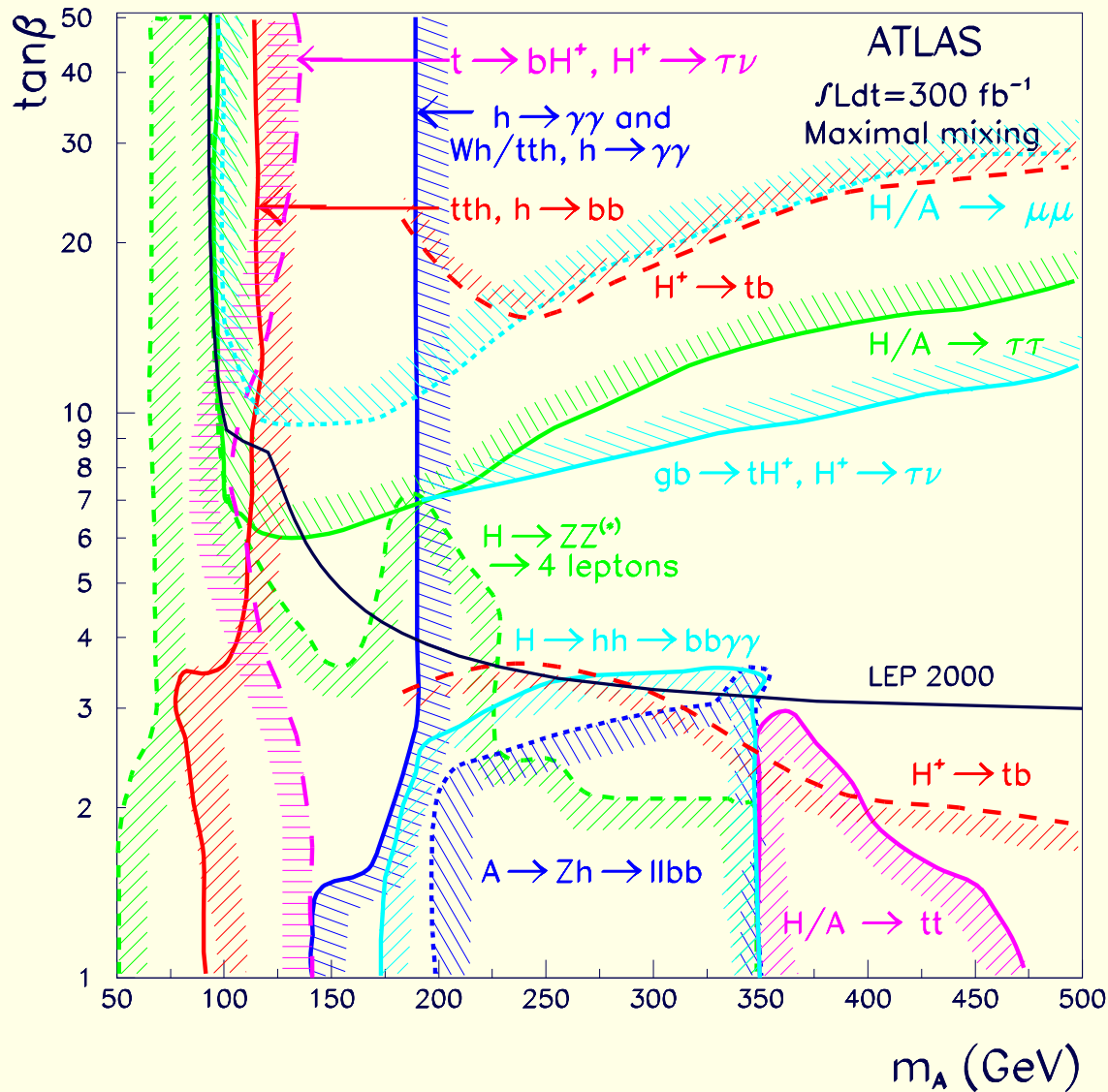
states (also  $2b2\tau$ ). The latter channel has been investigated by various combinations of Ellwanger, JFG, Hugonie, Moretti, Munir, Poulouose and D. Zerwas. The most recent paper on this mode is S. Moretti, S. Munir and P. Poulouose, Phys. Lett. B 644, 241 (2007), but with focus on lower masses for the secondary  $h$  and primary  $\phi$ . (More later.)

# New Physics A: Supersymmetry

- **The MSSM** is a well-known and well-studied model and I will not give details. All the standard signals are well known and are summarized in plots such as shown on the next page.

The signals rely on the fact that  $m_{h^0}$  is limited to  $< 130$  GeV or so and on the fact that the  $A^0$  and  $H^0$  have  $\tan\beta$  enhanced  $bb, \tau\tau$  couplings and  $1/\tan\beta$  suppressed  $tt$  coupling. Recall also the decoupling limit of large  $m_{A^0} \sim m_{H^0} \sim m_{H^\pm}$  in which  $h^0$  is SM-like. We have:

1.  $gg \rightarrow h^0 \rightarrow \gamma\gamma$  (good in decoupling large  $m_{A^0}$  region)
2.  $gg \rightarrow b\bar{b}H^0, b\bar{b}A^0$  (large  $\tan\beta$ ) with  $H^0, A^0 \rightarrow \tau\tau$
3.  $gg \rightarrow t\bar{b}H^- + b\bar{t}H^+$  (large  $\tan\beta$ ) with  $H^\pm \rightarrow \tau^p m\nu$
4.  $t \rightarrow bH^+$  (away from decoupling region, *i.e.* low  $m_{A^0}$ )
5.  $A^0 \rightarrow Zh^0$  (largish  $m_{A^0}$ , but small  $\tan\beta$ ) with  $h^0 \rightarrow b\bar{b}$
6. the  $h^0$ -only moderate  $\tan\beta$  wedge, wherein precision  $h^0$  measurements might be the only way to ascertain that the Higgs is not the simple SM Higgs.



**Figure 7:**  $5\sigma$  discovery contours for MSSM Higgs boson detection in various channels are shown in the  $[m_{A0}, \tan \beta]$  parameter plane, assuming maximal mixing and an integrated luminosity of  $L = 300 \text{ fb}^{-1}$  for the ATLAS detector. This figure is not up to date

- However, the MSSM has two really significant problems.

1. Lack of a convincing source for the  $\mu$  term of the superpotential, where  $\mu$  should be of order 1 TeV (rather the natural values of 0 or  $M_P$ ).
2. Substantial fine-tuning with respect to GUT scale parameters.

The latter cannot be ignored since coupling unification suggests we should consider the model all the way up to the GUT scale.

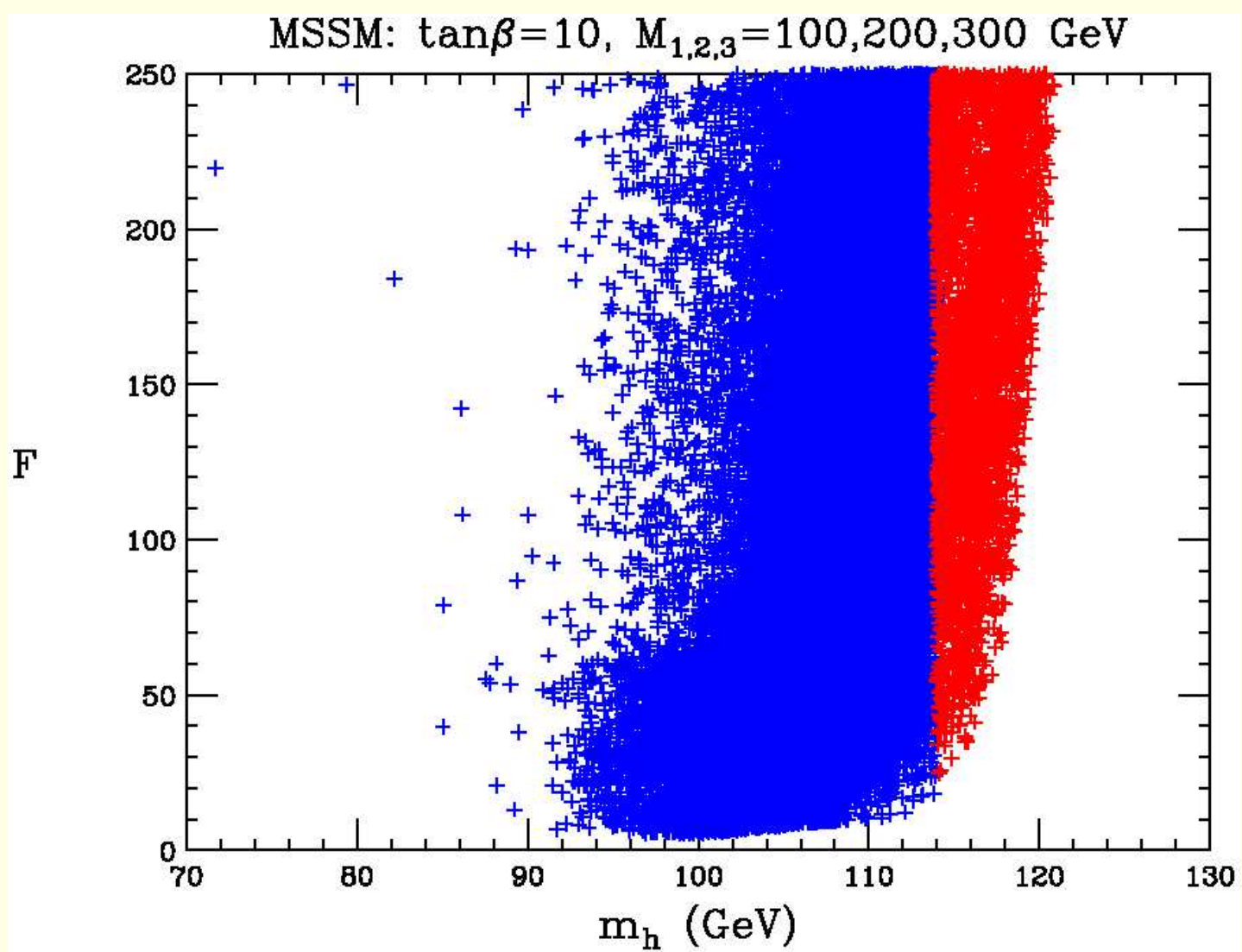
Here, the important fine-tuning is how precisely GUT-scale parameters must be tuned in order to get the correct  $m_Z$  after RGE evolution:

$$F \equiv \text{Max}_p \left| \frac{\partial \log m_Z}{\partial \log p} \right|, \quad (22)$$

where  $p$  are the GUT scale parameters (e.g.  $\mu$ ,  $M_3$ ,  $m_{H_u}^2$ ,  $A_t$ , to name the usually critical ones).

The lowest  $F$  ( $\sim 25$ ) with  $m_{h^0}$  above the 114 GeV LEP limit (assuming  $m_{A^0} > 100$  GeV) is achieved in the maximal mixing scenario when  $A_t \sim -500$  GeV (rather precisely).





**Figure 8:**  $F$  vs.  $m_{h^0}$  in the MSSM for  $\tan\beta = 10$ ,  $M_{1,2,3}(m_Z) = 100, 200, 300$  GeV. Blue '+'s have  $m_{h_1} < 114$  GeV and are excluded by LEP data. From R. Dermisek and J. F. Gunion, *Phys. Rev. D* **73**, 111701 (2006) [arXiv:hep-ph/0510322]; *Phys. Rev. Lett.* **95**, 041801 (2005) [arXiv:hep-ph/0502105]; and in preparation.

**Wouldn't it have been nice if  $m_{h^0} \sim 100$  GeV were LEP-allowed?**

- **The NMSSM** allows you to have your cake and eat it too.

Recall that the NMSSM introduces a singlet superfield that leads to an extra CP-even Higgs and an extra CP-odd Higgs: we end up with the mixed states  $h_{1,2,3}$  and  $a_{1,2}$ .

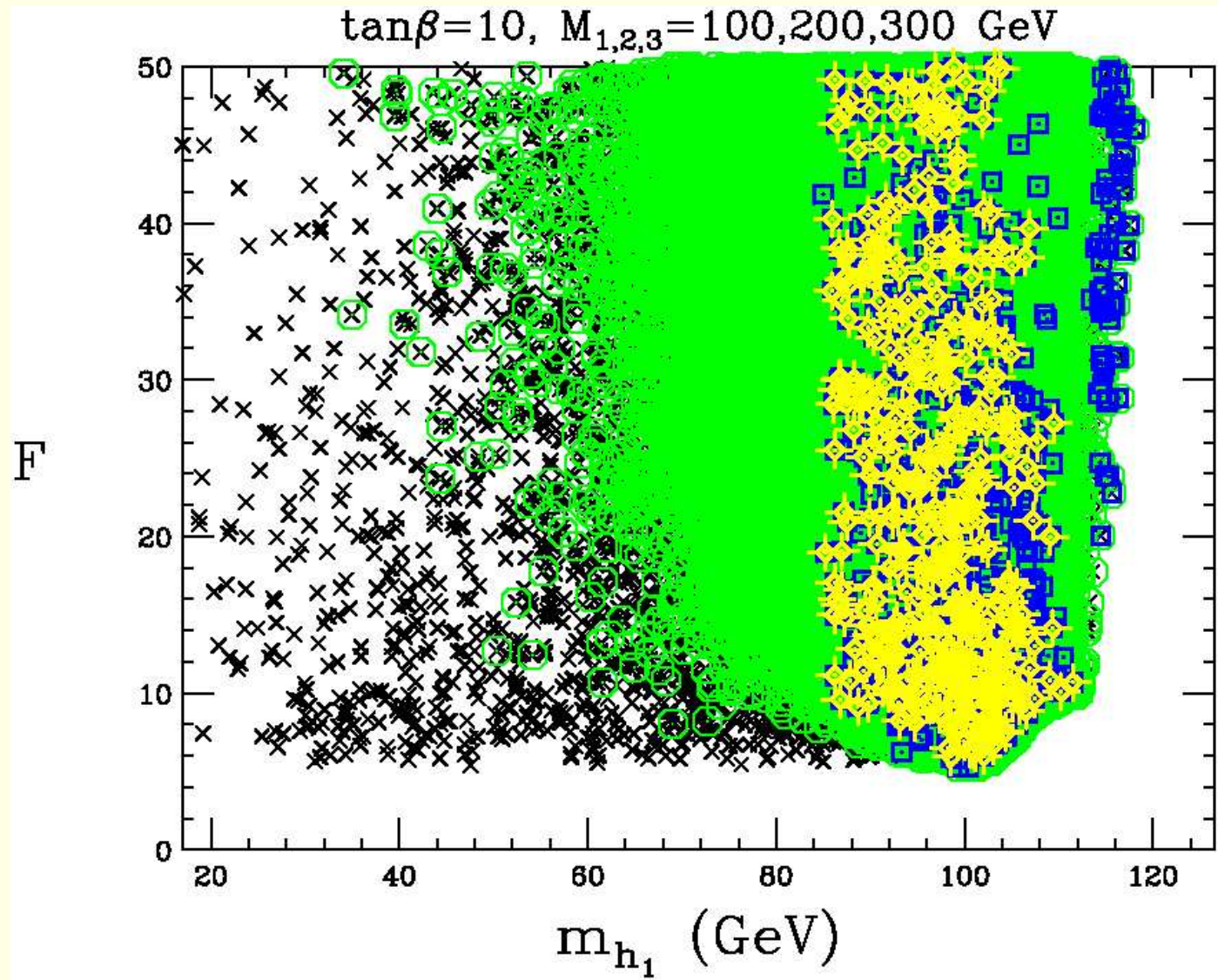
The NMSSM has the following wonderful properties:

- Gauge coupling unification is preserved under singlet addition.
- RGE breaking of electroweak symmetry is preserved.
- An effective  $\mu \widehat{H}_d \widehat{H}_u$  superpotential term is automatically from the  $\lambda \widehat{S} \widehat{H}_d \widehat{H}_u$  NMSSM superpotential term:  $\mu_{\text{eff}} = \lambda \langle S \rangle$ .

There is also a  $\frac{1}{3} \kappa \widehat{S}^3$  superpotential term.

- Once again minimal fine-tuning is achieved for a SM-like  $h_1$  with  $m_{h_1} \sim 100$  GeV, but now this is LEP allowed provided  $h_1 \rightarrow a_1 a_1$  with  $m_{a_1} < 2m_b$  is the dominant decay. If  $m_{a_1} > 2m_b$ , then  $h_1 \rightarrow a_1 a_1$  also feeds the  $Z + b'$ s channel that is strongly constrained by LEP data.

In fact, large  $B(h_1 \rightarrow a_1 a_1)$  with small  $m_{a_1}$  can be arranged without significant tuning of the  $A_\lambda$  and  $A_\kappa$  soft parameters. Some preference is shown for  $m_{a_1} > 2m_\tau$  for this. (R. Dermisek and J. F. Gunion, arXiv:hep-ph/0611142.)



**Figure 9:**  $F$  vs.  $m_{h_0}$  in the NMSSM for  $\tan\beta = 10$ ,  $M_{1,2,3}(m_Z) = 100, 200, 300 \text{ GeV}$ . Large yellow crosses are fully consistent with LEP constraints. See earlier Dermisek + JFG refs.

– A large majority of the yellow crosses have  $B(h_1 \rightarrow b\bar{b}) \sim 0.1$  or so

which perfectly explains the long known  $2.3\sigma$  LEP excess at  $\sim 98$  GeV. Philip Bechtle used the full LHWG code to check this for a number of these points.

–  $m_{h_1} \sim 100$  GeV is also perfect for precision electroweak.

– **Higgs Signals**

1. We have assessed all the standard MSSM Higgs signals for these preferred low- $F$  points (including signals for the heavy Higgs) and find a maximum signal of  $2.5\sigma$  after  $300 \text{ fb}^{-1}$ .

2.  $\Rightarrow$  We must tackle the  $h_1 \rightarrow a_1 a_1 \rightarrow 4\tau$  or  $4j$  final state.

There is some hope for  $WW$  fusion:  $WW \rightarrow h_1 \rightarrow 4\tau$ .

There is some hope for  $t\bar{t}h_1$  with  $h_1 \rightarrow 4\tau$ .

The only guaranteed approach is diffractive Higgs production:  $pp \rightarrow pp h_1$  where we don't care how  $h_1$  decays (**except that we must be able to trigger on the decay** since the TOTEM detectors are so far downstream that they can't be used to trigger these events.

Estimated event rate (Dino agrees I think) is about 3 events for  $30 \text{ fb}^{-1}$ .

If we can use high luminosity in the face of triggering necessity, then  $300 \text{ fb}^{-1}$  would give  $\sim 30$  events.

But, even a small handful of background events might be enough.

3. However, even if you see one of the above signals, it is going to be a bit amorphous/uncertain/... For example, the  $pp \rightarrow pp h_1$  signal is

independent of whether the  $h_1$  has SM-like  $WW, ZZ$  couplings.

It will be crucial to check perturbativity of  $WW \rightarrow WW$  scattering to verify that some Higgs-like object is present at low mass. (This is, of course, true for all scenarios where the Higgs is hard to see or its properties hard to verify.)

4. Searches for  $\Upsilon(1S) \rightarrow \gamma a_1$  could reveal the  $a_1$  so long as its mass is not too close to  $M_\Upsilon$ .

In fact, there is a lower bound on the branching ratio that results from the requirement of large enough  $B(h_1 \rightarrow a_1 a_1)$ .

One finds that  $B(\Upsilon(1S) \rightarrow \gamma a_1) \gtrsim 10^{-7}$  ranging up to the current limits of *few*  $\times 10^{-4}$  at  $\tan\beta = 10$  for  $m_{a_1} < 9.2$  GeV.

Could the  $\zeta(8.3)$  been a lucky observation of some events from this small branching ratio that were then overwhelmed by statistics?

**Pushing down these limits is something that the  $B$ -factories can and must do!**

- Of course, if you are willing to accept somewhat higher  $F \sim 15 - 20$ , then  $m_{h_1} > 114$  GeV points that automatically evade all LEP constraints are present.

These need not have dominant  $h_1 \rightarrow a_1 a_1$  decays, **but many do!**

Generally, almost any  $B(h_1 \rightarrow a_1 a_1)$  is possible.

However,  $m_{a_1} < 2m_b$  is no longer required, but it is allowed.

Thus, we must look for all of the following:

$$h_1 \rightarrow b\bar{b}$$

$$h_1 \rightarrow 4j,$$

$$h_1 \rightarrow 2j2\tau,$$

$$h_1 \rightarrow 4\tau,$$

$$h_1 \rightarrow 2b2\tau,$$

$$h_1 \rightarrow 4b.$$

As stated earlier, there has been substantial work on the  $2b2\tau$  channel, but I regard its status as uncertain at the moment.

Particularly difficult might be models where  $B(h_1 \rightarrow a_1 a_1) \sim 1/2$ , so that neither the usual  $\gamma\gamma$  signal is very strong nor the  $2b2\tau$  signal strong enough.

**We really need to get a handle on the Higgs pair final state!**

- MSSM with a singlet S. Chang, P. J. Fox and N. Weiner, JHEP 0608, 068 (2006) [arXiv:hep-ph/0511250].

This is the supersymmetric version of the paper discussed previously.

Aside from the usual NMSSM type of scenarios, they add some possible operators into the MSSM plus extra singlet superfield scenario that would

cause a light somewhat singlet  $s$  and  $a$ , with a fairly normal SM-like  $h$ .  
The additional operators lead to:

$$h \rightarrow ss \rightarrow aaaa \rightarrow 8g, 8\tau, 4g, 4\tau, 8b, \dots$$

$$h \rightarrow sa \rightarrow aaaa \rightarrow 6g, 6\tau, 6b, \dots$$

Obviously,  $h$  discovery is getting to be challenging. But you haven't seen anything yet.

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

This model has an extra  $U(1)'$  gauge group added to the MSSM along with a singlet  $S$  as well as 3 other  $S_{1,2,3}$ ; all are charged under the  $U(1)'$ , but not under the SM groups.  $S$  gives the  $\mu$  parameter as in the NMSSM.

The model has some attractive features, but also a lot of complexity.

Some problems and features are:

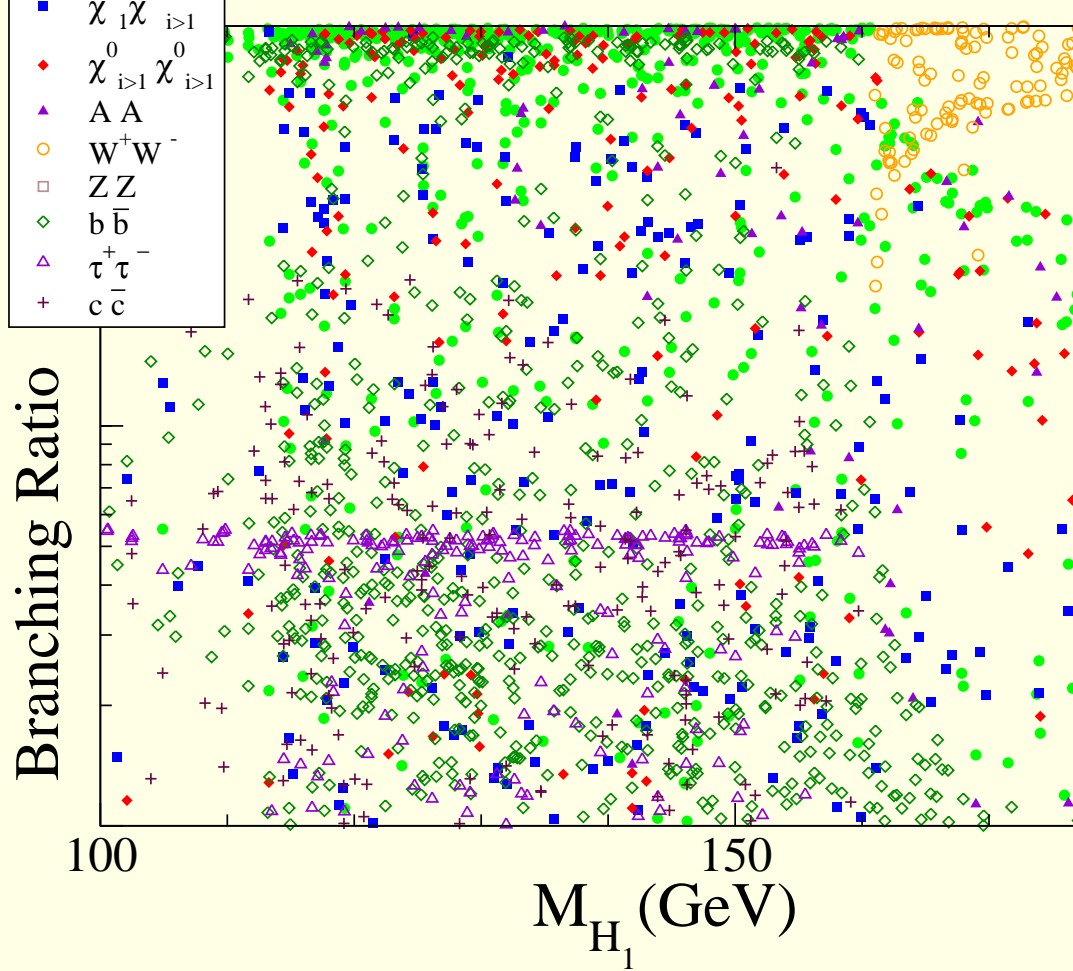
- The lightest Higgs with  $WW$  couplings can be heavy because of extra  $D$ -term contributions to its mass.

Problem: precision electroweak likes a low mass.

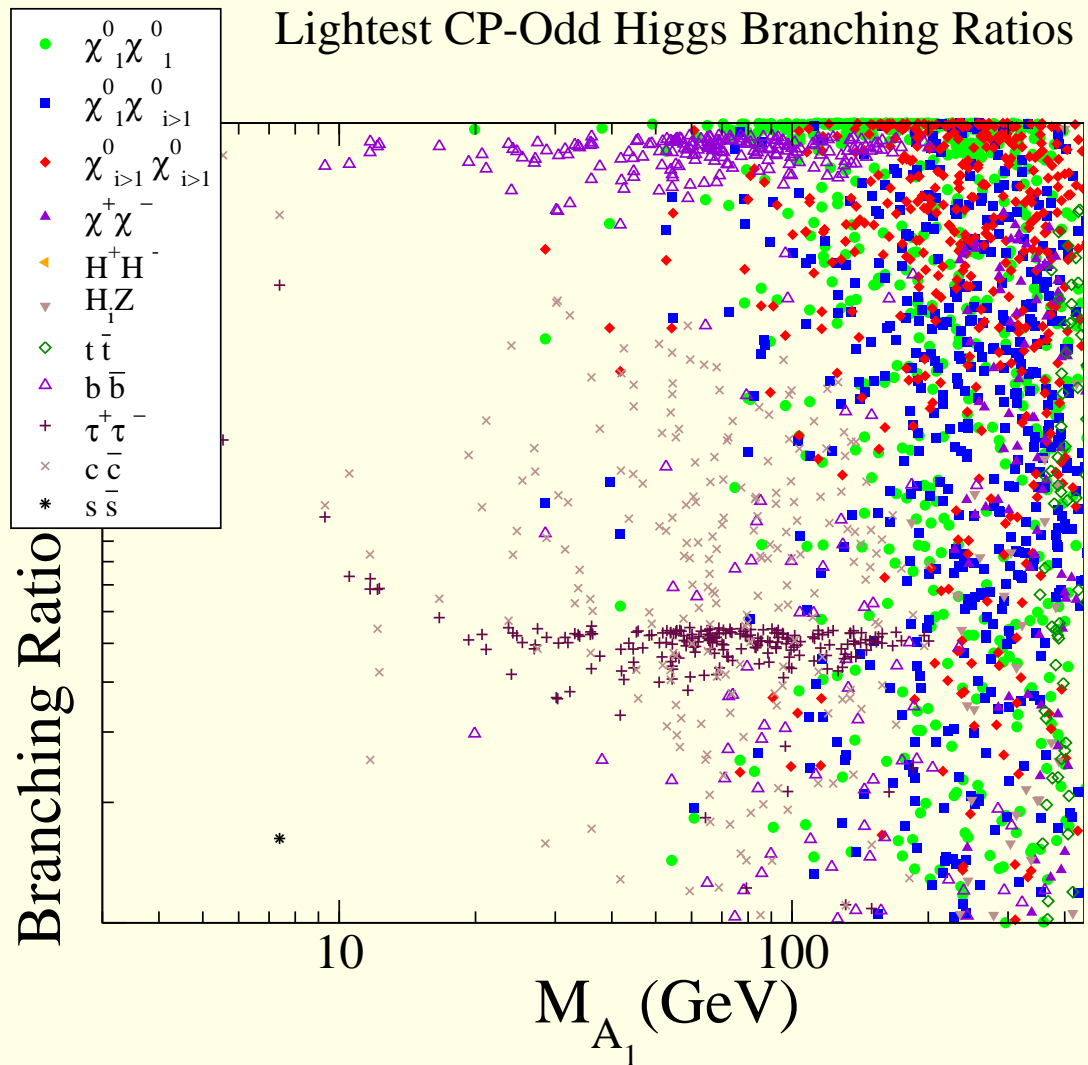
Question: if you raise the Higgs mass, why not raise the SUSY scale to the point where quadratic fine-tuning becomes problematical.

- The lightest Higgs need not have  $WW$  couplings. If it doesn't, then it is usually somewhat singlet in nature.
- Gauge coupling unification would appear to require significant extra matter at high scales.
- A more complete model would be required to assess fine-tuning with respect to GUT-scale parameters.
- There are 4 light  $a_k^0$ 's and these are definitely important in Higgs decays, especially for a light singlet-like Higgs with suppressed couplings to SM particles, but also for the heavier SM-like Higgs if it has mass below  $2m_W$ .
- There many neutralinos, some of which are singlet-like and very light, but coupled to the Higgs so that  $h_i \rightarrow \tilde{\chi}_j^0 \tilde{\chi}_k^0$  is often a dominant or at least important channel, again especially for the lighter singlet-like Higgs boson.
- The decays of the lightest  $a_1$  can be dominated by neutralino pairs.





**Figure 10:** Branching ratios for the somewhat heavy lightest Higgs with substantial  $WW$  coupling.



**Figure 11:** Branching ratios for the lightest CP-odd  $A_1$ . Note the presence of some  $\tilde{\chi}_{k>1}^0$ 's in the  $A_1$  decays.

- **Decay Channels** Examples only.

$$H_1 \rightarrow A_1 A_1 \rightarrow 4\tilde{\chi}'s \rightarrow \text{visible} + \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

$$H_1 \rightarrow 2\tilde{\chi}'s \rightarrow \text{visible} + \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

The above will contain a mixture of visible and invisible energy and not have a reconstructable mass peak.

$$H_1 \rightarrow A_1 A_1 \rightarrow \text{all the NMSSM channels}$$

Probably, the most likely result is a mixture of all possibilities.

I hope we will not have to contend with such a complex model, but one should keep in mind that string theory can easily produce models of this type.

- The E(6)MSSM S. F. King, S. Moretti and R. Nevzorov, Phys. Rev. D 73, 035009 (2006) [arXiv:hep-ph/0510419];

This is an example where the  $Z'$  eats up the extra  $a$  and the remaining  $A$  is heavy. So, if I have understood this correctly, there will no  $h \rightarrow AA$  decays.

There are two more sets of two Higgs doublets, but these are chosen to decouple. Also the singlinos are chosen to decouple.

A different limit of the model might lead to a lot of complexity.

- **MSSM with  $R$ -parity Violation**

I will mention two models of this type. Both are designed to allow the PEW preferred value of  $m_{h^0} \sim 100$  GeV, which you have also seen is preferred by fine-tuning in the MSSM, while escaping LEP limits through unusual decays, much in the spirit of  $h_1 \rightarrow a_1 a_1$ .

1. First there is the model of M. Carena, S. Heinemeyer, C. E. M. Wagner and G. Weiglein, Phys. Rev. Lett. 86, 4463 (2001) [arXiv:hep-ph/0008023]. Here, they argue in favor of a light sbottom quark of mass about 7.5 GeV. The Higgs boson would decay mainly into  $\tilde{b}\tilde{b}$ .

Normally,  $\tilde{b} \rightarrow b\tilde{\chi}_1^0$ , in which case  $h^0 \rightarrow 2b + \cancel{E}_T$ . Would this have been picked by LEP search?

With baryonic  $R$ -parity violation  $\tilde{b} \rightarrow 2j$  is possible, and the Higgs signal is  $h^0 \rightarrow 4j$  with no missing energy. LEP would have missed this signal for  $m_{h^0} \sim 100$  GeV.

2. The second model I mention is that of L. M. Carpenter, D. E. Kaplan and E. J. Rhee, arXiv:hep-ph/0607204.

They find parts of MSSM parameter space in which  $m_{h^0} \sim 100$  GeV and  $h^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$  is dominant.

If  $R$ -parity is conserved this is equivalent to  $h^0 \rightarrow invisible$  and LEP excludes this channel at such a low  $m_{h^0}$ .

However, if there is baryonic  $R$ -parity violation, then  $\tilde{\chi}_1^0 \rightarrow 3j$  and therefore  $h^0 \rightarrow 6j$ . This channel not excluded by LEP for  $m_{h^0} \sim 100$  GeV.

The  $\tilde{\chi}_1^0$  decays could be slightly non-prompt and still have effectively the same LEP signal. In this case, one would want to search for  $6j$  events with a somewhat displaced vertex.

# New Physics B, C, D, . . . : Little Higgs, Twin Higgs, Higgsless, ...

No time. My apologies.

## Conclusions

My bias:

The combination of:

1. the precision electroweak preference for a SM-like Higgs with  $m_h \sim 100$  GeV,
2. the old LEP excess (at reduced rate) at this mass in the  $b\bar{b}$  channel,
3. the fact that supersymmetric models evolved to the GUT scale have minimal fine-tuning for such a mass

all combine to suggest that  $h \rightarrow pp$  where  $p$  then decays in some way that evades the LEP  $m_h > 114$  GeV bound may be what LHC should be looking for.

There are many possibilities for  $p$  and how it decays with  $p =$  a pseudoscalar and  $p =$  a neutralino or other light SUSY particle being prominent on the list.

$p$  decays can be constructed in both cases to avoid LEP limits and make LHC discovery very difficult.

Incidentally, for  $\tan\beta = 50$  our NMSSM scan gives a  $F = 8$  point with very nearly the correct properties to explain the CDF enhancement (the  $a_2$  and  $h_2$  masses are nearer 200 GeV, but we don't see why we can't find similarly good points with somewhat lower masses). The  $h_1$  mass is at exactly 98 GeV, the LEP excess location.

Don't forget the importance of checking for perturbative  $WW$  scattering if you have trouble seeing the Higgs bosons.