Extra/Exotic Higgs Decays:
A Proliferation of Known Unknowns

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Outline

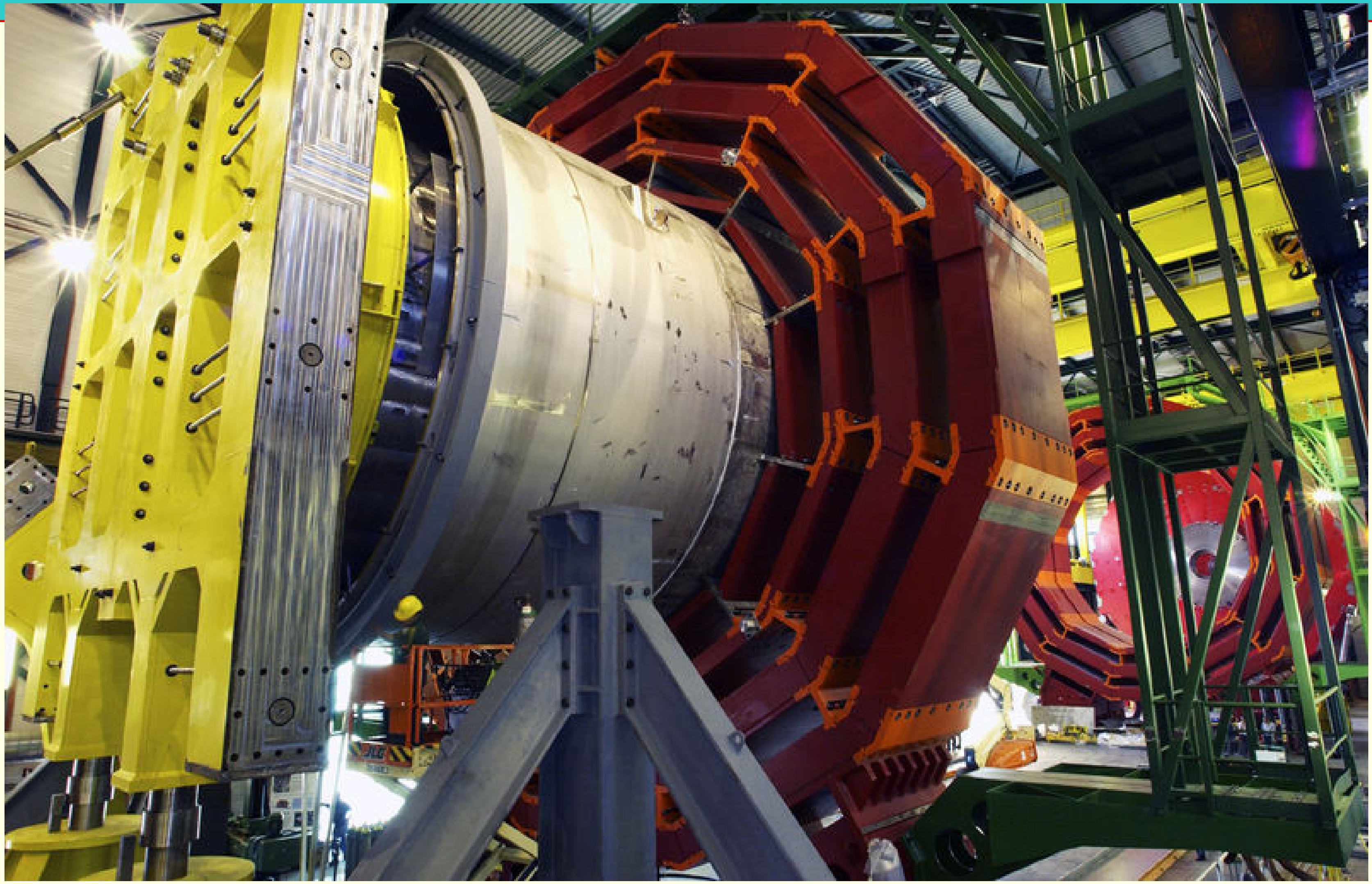
1. The LHC is coming, but even if there is a Higgs boson sector how will we see it?

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. I will focus entirely on 'standard' Higgs bosons, broadly defined as CP-even or CP-odd spin zero states, but not including Little Higgs Models and such.

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 main channels for the $h_{\rm SM}$ decays yield all the usual LHC signals.**

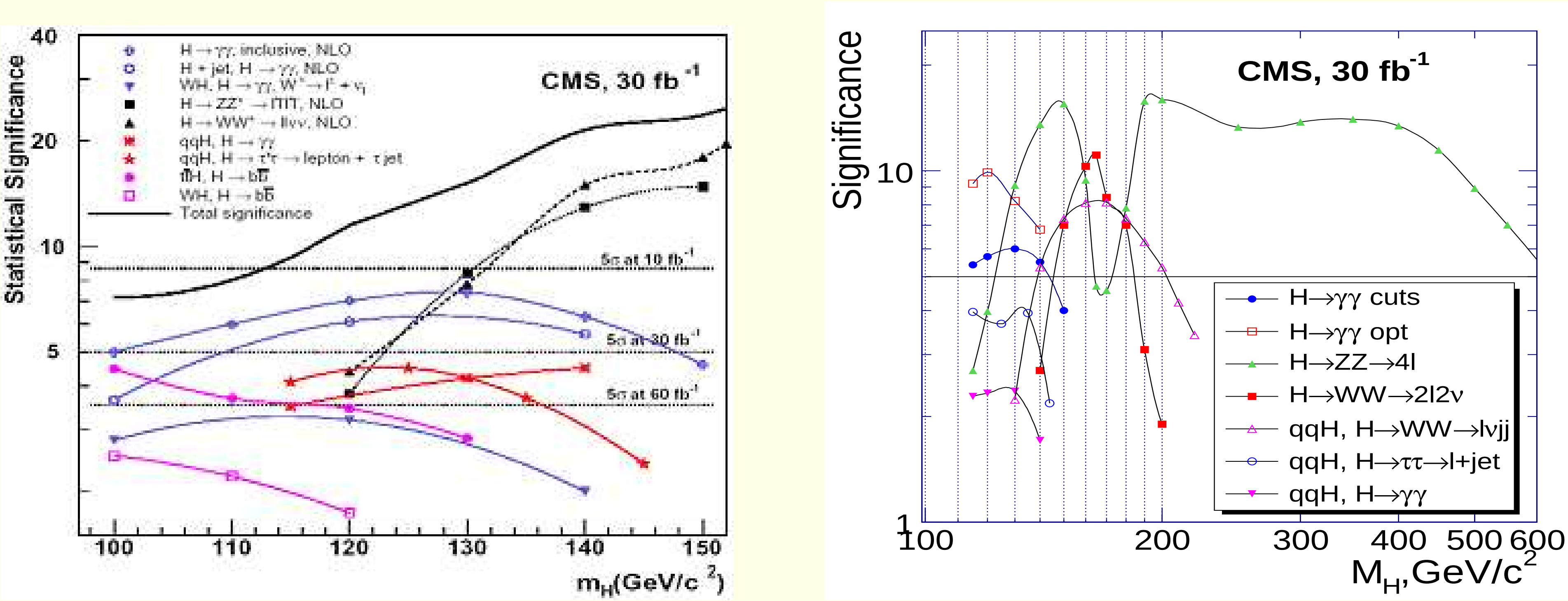


Figure 1: *SM Higgs signal significance as function of the Higgs boson mass. The curves show the signal significance for an integrated luminosity of 30 fb^{-1} for* ATLAS *(left) and* CMS *(right).*

Roughly the 5σ lines at $30~{\rm fb}^{-1}$ are the 3σ lines for $10~{\rm fb}^{-1}$ $\Rightarrow$ 3σ sensitivity in some mode or other.

Another perspective is luminosity needed for discovery.

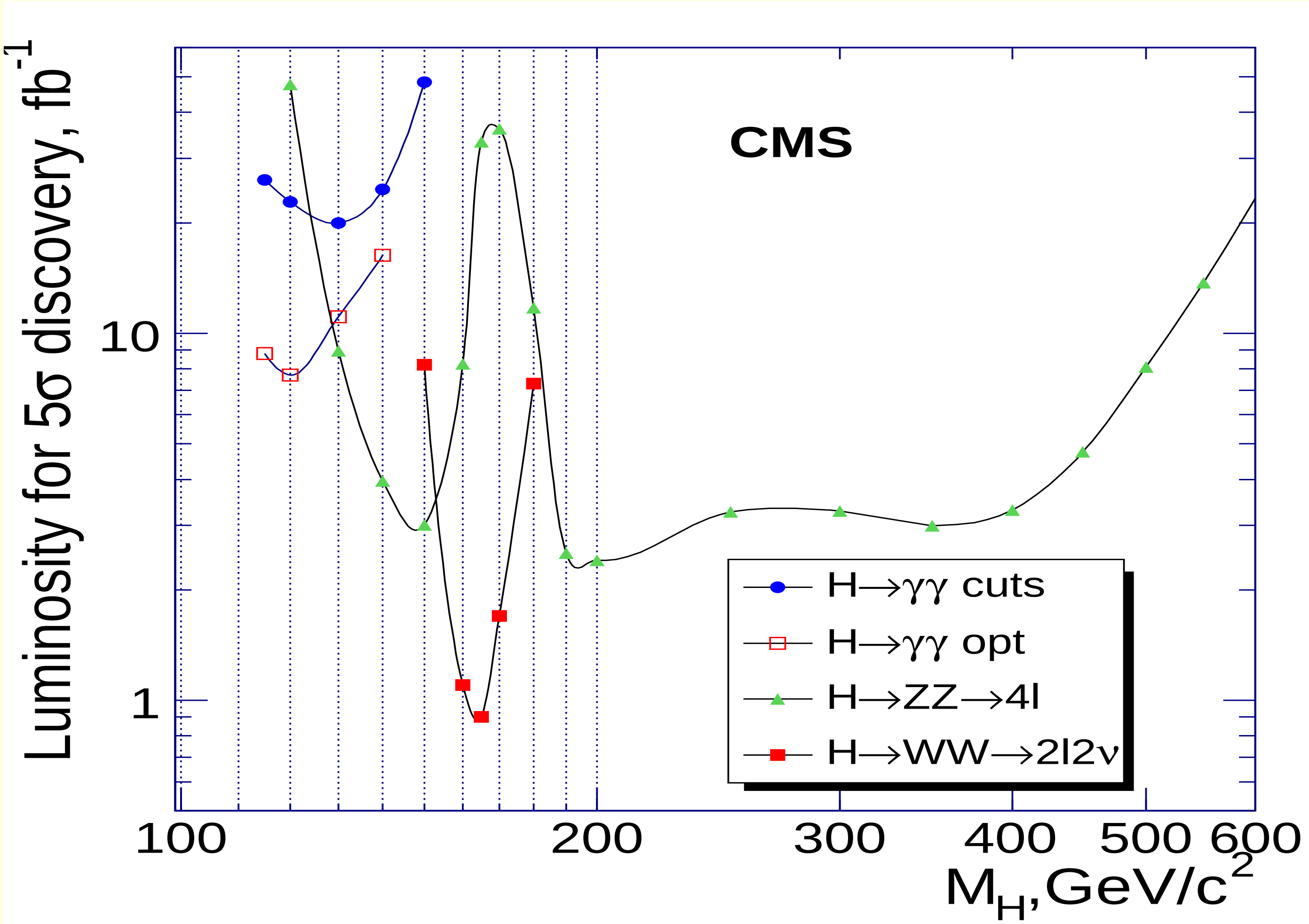


Figure 2: *Luminosity needed for 5σ discovery of SM Higgs at CMS.*

We see that with $\mathcal{L} = 10~\mathrm{fb}^{-1}$ we are not far from 5σ discovery in at least one mode. It would seem that 3σ exclusion of a SM Higgs will certainly be achieved with $\mathcal{L} = 10~\mathrm{fb}^{-1}$.

Motivations for going beyond the SM

Precision Electroweak

Allow a light Higgs boson with mass near $100\ \mathrm{GeV}$ (as desired for precision electroweak consistency) while escaping LEP limits.

Naturalness

Make a light Higgs boson 'natural'.

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

$$\delta m^2_{h_{\rm SM}} = -\frac{3}{4\pi^2}\frac{m_t^2}{v^2}\Lambda_t^2\,, \tag{1}$$

where Λ_t is the high energy cutoff and $v = 176\ \mathrm{GeV}$.

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

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

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

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

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

Note: In this simple context, to delay new physics you need a heavy Higgs which is maybe not consistent with precision electroweak.

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 Λ_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.

We begin with the 2nd possibility, but there is a tendency for these two things to fit together (NMSSM).

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]. 'Rediscovered' recently by O. Bahat-Treidel, Y. Grossman and Y. Rozen, arXiv:hep-ph/0611162.)

In the worst case, we imagine that the singlets mix with the $h_{\rm SM}$ so that the resulting eigenstates, h_i share all the WW, ZZ, $f\overline{f}$ couplings according to their overlap fraction f_i: $h_i = f_i h_{\rm SM} + \ldots$, 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)

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

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

$$m_{EW} = \prod_i m_i^{f_i^2} \,. \tag{5}$$

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

$$F_t^i = f_i^2 F_t(m_i) = \frac{3}{4\pi^2} f_i^2 \frac{\Lambda_t^2}{m_i^2} \tag{6}$$

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 Λ_t for a given maximum acceptable common F_t^i. Also, large Λ_t implies significant corrections to low-E phenomenology from Λ_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, $\Lambda_t \sim 5~\mathrm{TeV}$ is the new requirement if the m_i are spread out in the vicinity of $100~\mathrm{GeV}$.

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 $10~\mathrm{GeV}$ or thereabouts, so that all but the 4ℓ signal and $\gamma\gamma$ signal overlap in mass resolution (no peak), and the 4ℓ 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 $h_i \to a_k a_l$ and we could also have enough m_i spread for $h_i \to h_j h_k$.

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, $WW \to h_i \to WW \to \ell^+\ell^-\nu\overline{\nu}$. 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.

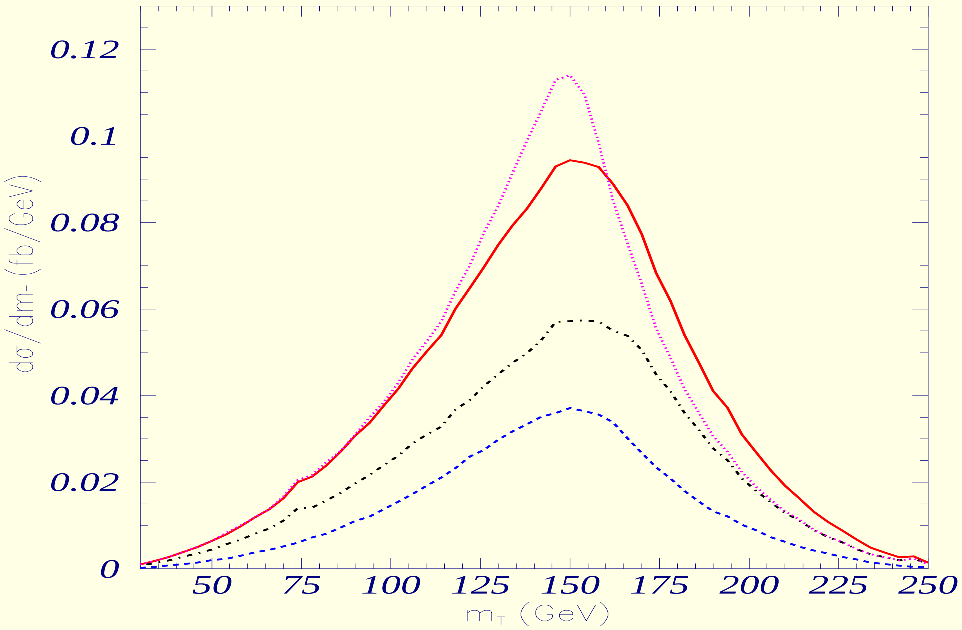


Figure 3: *Transverse mass m_T spectrum for the continuum model signal (dashed), background (dash-dotted), and continuum signal plus background (solid). For comparison we also show the $m_h = 155$ GeV SM signal plus background case, normalized to have the same signal cross section as the continuum model.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

With $\lesssim 100~\mathrm{fb}^{-1}$, one gets a 5σ 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 was first emphasized by J. F. Gunion, H. E. Haber and T. Moroi, Snowmass 1996, [arXiv:hep-ph/9610337], followed by 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].

Further exploration of such decays appeared in a number of works by JFG, Hugonie, Ellwanger and Moretti, beginning with JFG+Hugonie+Ellwanger, hep-ph/0111179. And, now, it has become quite popular as we shall see.

The basic expressions for the decays make the reason why such $h \rightarrow aa$

decays can dominate quite clear.

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

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

These are all potentially dominant or at least prominent when allowed. For example, typically, $g_{h_i^0 h_j^0 h_k^0} = c \frac{g m^2_{h_i^0}}{2 m_W}$. 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

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

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

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

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 $b\overline{b}$ mode, and such c's are common in models. Thus, Higgs pair modes will dominate until we pass above the WW threshold.

Even for $m_{h_i^0} \gg m_W, m_Z, m_{h_j^0}$, if $c \sim \mathcal{O}(1)$ then $B(h_i^0 \to a_j^0 a_j^0) \sim \frac{1}{4}$.

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. It also illustrates nicely some basic points about what kinds of $\mathcal{L}$ one might wish to consider.

Very generally, if even one singlet s is added, the Lagrangian can be such that it mixes with the SM $h_{\rm SM}$ and acquires SM style fermion couplings.

The two simplest Lagrangian forms are (H=doublet, s=singlet, and before mixing H contains the SM Higgs, $h_{\rm SM}$)

$$H^\dagger H s \quad \text{and} \quad H^\dagger H s^2 \,. \tag{11}$$

The first form leads to $h_{\rm SM} - s$ mixing when a vev is introduced for one of the H fields, and would also directly lead to $h \to ss$ decays, where the h is mainly $h_{\rm SM}$ and s now refers to the mass eigenstate. However, the trilinear form must come with a dimensionful coupling, which typically has its own problems.

Note that the trilinear form can be naturally forbidden by requiring symmetry of $\mathcal{L}$ under $s \to -s$.

The **second form** leads to $h_{\rm SM} - s$ mixing if both H and s acquire vevs. Were there no vev for the s, the s would not mix with the $h_{\rm SM}$ and would then have no couplings to SM particles and could be stable. Assigning a vev to one of the H or $H^\dagger$ leads to $h_{\rm SM} \to ss$ decays, which would then be invisible. Also, the s could be dark matter in this case.

If $\mathcal{L}$ has no $m_s^2 s^2$ and s^4 terms (a simple possibility, but both must be present for the H) then the s will not acquire a vev. For it to decay would then require an external source of Z_2 symmetry breaking. One possibility will be discussed later

Whether or not there is mixing, it is easy to arrange for one of the Higgs to be fairly SM-like (for which I retain h as the notation) with regard to its couplings to SM particles and yet have it decay primarily via $h \to ss$, especially if $m_h < 2m_W$.

With even very small mixing, s would decay in canonical fashion: e.g. for $m_s > 2m_b$ one finds $B(s \to b\bar{b}) \sim 0.9$ and $B(s \to \tau^+\tau^-) \sim 0.08$. One would search for $h \to ss \to 4b, 2b2\tau, 4\tau$, all of which are challenging.

In this case, it is important to note that LEP limits on the $Zh \to (Z + 2b) + (Z + 4b)$ channels exclude this scenario if $m_h \lesssim 110~\mathrm{GeV}$.

A few studies

1. Exploration of the scenario with $h \to ss$ with $h \sim h_{\rm SM}$ and s decaying 'normally' was the focus of the JFG, Hugonie, Ellwanger and Moretti works of hep-ph/0305109 and hep-ph/0401228. Higgs discovery is, at best, very challenging. (These works actually considered the case of a light pseudoscalar a, but the results apply equally here.)
   Assuming $L = 300~\rm fb^{-1}$, a fairly sophisticated simulation shows that the WW fusion production mode

$$pp \to W^* W^* \to h \to ss \to b\bar{b}\tau^+\tau^- \tag{12}$$

   provides a significant Higgs peak in the reconstructed $jj\tau^+\tau^-$ mass distribution on the tail of a steeply falling mass spectrum from the $t\bar{t}$ background. However, experimental studies (D. Zerwas and S. Baffioni) suggest that further refinement of the procedures we employed may be needed.
   The production modes $pp \to W^\pm h$ and $pp \to t\bar{t}h$ (with $h \to ss$) can be significant and should probably be added to the mix. (Moretti, Munir, Poulose, hep-ph/0608233 explore this in the similar NMSSM case). They could help to improve the signal significance. However, background simulations are lacking in these cases.

2. S. Chang, P. J. Fox and N. Weiner, arXiv:hep-ph/0608310.
Here, they simply add to the SM a singlet s and restrict the $\mathcal{L}$ to the form (in my notation)

$$\mathcal{L} \ni \frac{c'}{2} s^2 |H|^2 \quad \Rightarrow \quad g_{h_{\rm SM} ss} = \frac{c' v}{\sqrt{2}}, \tag{13}$$

and

$$\Gamma(h_{\rm SM} \to ss) = \frac{c'^2 v^2}{16\pi m_{h_{\rm SM}}} \lambda^{1/2}(\ldots) \,. \tag{14}$$

Not much c' is needed to make this decay dominant for a light $h_{\rm SM}$; $c' > 0.04$ will allow a $m_{h_{\rm SM}} \sim 100~{\rm GeV}$ Higgs to escape detection in the normal $h_{\rm SM} \to b\bar{b}$ channel.

So, how *will* the s decay? If there is no explicit Z_2 breaking and no spontaneous Z_2 breaking, as assumed since the $\mathcal{L}$ does not give s a vev, then the s would be totally stable and therefore invisible in the detector. LEP limits would then imply $m_{h_{\rm SM}} > 114~{\rm GeV}$.
They introduce explicit Z_2 breaking via interactions of the s with a heavy vector-like colored quark of form:

$$\mathcal{L} \ni \overline{\psi}(M + i\gamma_5 \lambda s)\psi \tag{15}$$

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

$$B(h_{\rm SM} \to 4\gamma) \sim 1.4 \times 10^{-5}\,, \quad B(h_{\rm SM} \to 2g2\gamma) \sim 7.6 \times 10^{-3}\,. \tag{16}$$

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

$$c\tau_s \sim \frac{1}{\Gamma_{s\to gg}} = 1\,{\rm cm}\left(\frac{30\ \ {\rm GeV}}{m_s}\right)^3\left(\frac{M}{450\ \ {\rm TeV}}\right)^2\left(\frac{0.1}{\lambda\, b_3}\right)^2 \tag{17}$$

This would enhance Higgs discovery prospects. Without such non-prompt decays, things are a bit tough:

(a) $h_{\rm SM} \to ss \to 4g$ **has huge QCD background.**

(b) $h_{\rm SM} \to ss \to 4\gamma$ **has too small a rate (maybe SLHC?).**

(c) Only $h_{\rm SM} \to ss \to 2g2\gamma$ **could have a chance. For** $m_{h_{\rm SM}} \sim 100$ GeV **and** $L = 300~{\rm fb}^{-1}$, 5σ **is achieved for** $B(h_{\rm SM} \to 2\gamma 2g) > 0.04$ **(which is above the nominal value quoted above) for** $20 \lesssim m_a \lesssim 45$ GeV. **(A. Martin, hep-ph/0703247)**

3. 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 Φ as well as the doublet Φ_{SM} with

$$\mathcal{L} \ni -\eta|\Phi|^2|\Phi_{SM}|^2 + m^2_{\Phi_{SM}}|\Phi_{SM}|^2 + m^2_{\Phi}|\Phi|^2 - \lambda|\Phi_{SM}|^4 - \rho|\Phi|^4 \quad (18)$$

   which causes both Φ_{SM} and Φ to acquire a vev. This, in turn, leads to eigenstate mixing, which results in two mass eigenstates denoted by H and h. (Sorry for notation switch, but ...)

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

     Once again, $H \to hh$ 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
$\Gamma(H \to hh)$ (GeV)	14.6	4.9	10
$BR(H \to hh)$	0.036	0.015	0.095

Table 1: *Points illustrating parameters of trans-TeV mass Higgs boson.*

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

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

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

	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
$\Gamma(H \to hh)$ (GeV)	2.1	17	17
$BR(H \to hh)$	0.33	0.33	0.33

Table 2: *Points illustrating parameters that allow large branching fractions of $H \longrightarrow hh$.*

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

4. **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, but he focuses on a CP-odd state a, with $h \to aa$ being an important decay.

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,

$h \to VV \to Z'Z' \to b\overline{b}b\overline{b}$

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 $V \to b\overline{b}, \ldots$ 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.

- **Additional Doublets**

Multi-doublet models have the nice property that they preserve $\rho_{tree} = 1$ (as did the singlet-addition models).

A lot of work has been done in the two-doublet model context. I can only provide a sample.

My notation in the two-doublet context for the Higgs mass eigenstates is: h^0 and H^0 for the light and heavy CP-even scalars; A^0 for the single CP-odd state; and $H^\pm$ for the charged Higgs pair.

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 $\Delta T > 0$).

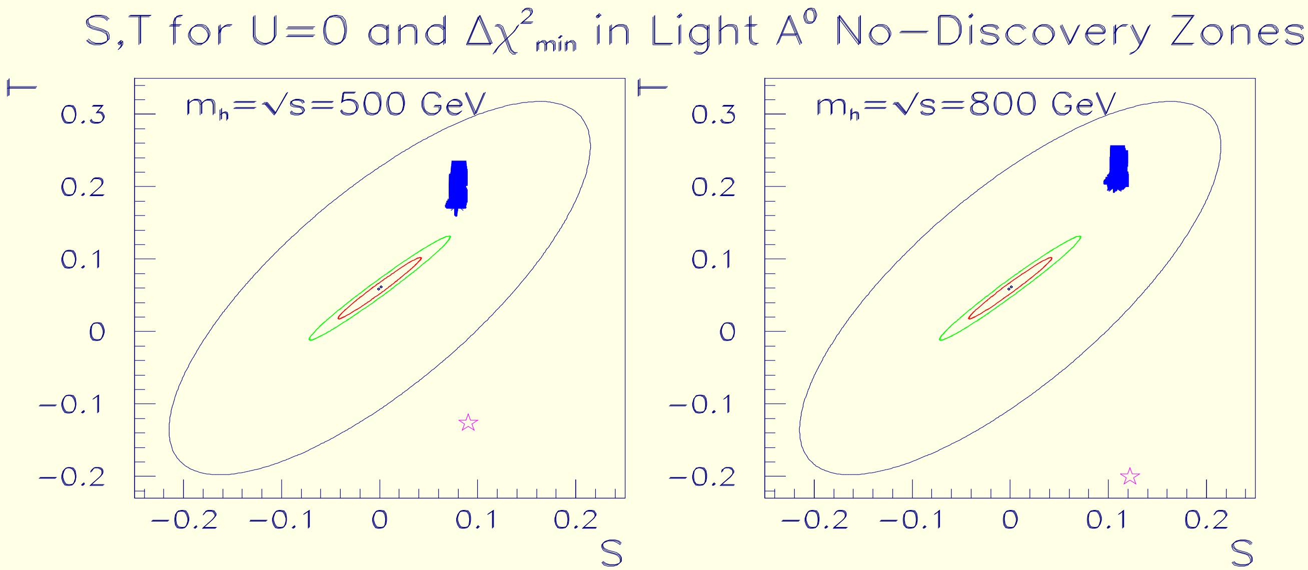


Figure 4: *Outer ellipses = current 90% CL region for* $U=0$ *and* $m_{h_{\rm SM}}=115$ *GeV. Blobs =* S,T *predictions for 2HDM models with* $m_{H^\pm}-m_{H^0}$ *for correct* $\Delta T>0$*. Innermost (middle) ellipse = 90% (99.9%) CL region for* $m_{h_{\rm SM}}=115$ *GeV after Giga-*Z *and a* $\Delta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

This model for relaxing the precision electroweak constraints on $m_{h_{\rm SM}}$ is a special case of a more general approach to allow for heavy $h_{\rm SM}$ (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 $h_{\rm SM} \to A^0 A^0$ mode would be dominant (important) for $m_{h_{\rm SM}} < 2m_W$ ($m_{h_{\rm SM}} > 2m_W$).

The A's would decay in canonical fashion, e.g. $A \to b\bar{b}$ is dominant for $m_A > 2m_b$.

If the h^0 is on the heavy side, then the A decay products would be extremely collinear, which might lead to some special problems for detecting that channel.

This scenario actually arises by imposing a new kind of symmetry on the general two-Higgs-doublet model (JFG various talks, JFG + Haber, J.-M. Gerard and M. Herquet, hep-ph/0703051 — the latter authors refer to the symmetry as 'twisted custodial symmetry').

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 Λ_t can be quite large.

Meanwhile, precision electroweak data requires

$$m_+ < m_- \left(\frac{m_{EW}}{m_-}\right)^{\frac{1}{\sin^2\beta}} \tag{19}$$

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, $m_{EW} = 200~\mathrm{GeV}$ and $m_- = 115~\mathrm{GeV}$, $m_+ = 300~\mathrm{GeV}$, and hence large Λ_t (which only knows about m_+) at $3~\mathrm{TeV}$ is 'ok'. For, $m_{EW} = 100~\mathrm{GeV}$, 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, $gg \to h_-$ will be greatly suppressed which jeopardizes the $\gamma\gamma$ signal for the light Higgs.
Also, $t\bar{t}h_-$ associated production is highly suppressed.
$WW \to h_- \to \tau^+\tau^-$ will be suppressed by reduced WWh_- coupling, but might still be ok.

– **for the h_+**

If $m_+ > 2m_W$, $h_+ \to h_-h_-$ decays will be present but not dominant, while $gg \to h_+$ production will be full strength $\Rightarrow h_+ \to ZZ \to 4\ell$ 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 Λ_t all that much, and the $h_+ \to h_- h_-$ 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 two 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 $\ell^\pm \ell^\pm$.

$pp \to H^{++}H^{--}$ production (via Drell-Yan) with $H^{\pm\pm} \to \ell^\pm \ell^\pm$ provides 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.

Summary

Simply adding to the Higgs sector is almost certain to give rise to $Higgs \to Higgs + Higgs$ and $Higgs \to Higgs + V$ decays that will generally make Higgs detection far more difficult than in the case of the SM.

The Standard Model in Extra Dimensions

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

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

- $\boxed{\textbf{ADD}}$

  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)

$$\mathcal{L}_{\rm mix} = \epsilon h \sum_{\vec{n}>0} s_{\vec{n}} \tag{20}$$

with

$$\epsilon = -\frac{2\sqrt{2}}{M_{\rm P}} \xi v m_h^2 \sqrt{\frac{3(\delta-1)}{\delta+2}}\,. \tag{21}$$

Above, $M_{\rm P} = (8\pi G_N)^{-1/2}$ 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

$$\begin{aligned}
\Gamma_{h_{eff}\to graviscalar} &= 2\pi\xi^2 v^2 \frac{3(\delta-1)}{\delta+2} \frac{m_h^{1+\delta}}{M_D^{2+\delta}} S_{\delta-1} \\
&\sim (16\,MeV) 20^{2-\delta} \xi^2 S_{\delta-1} \frac{3(\delta-1)}{\delta+2} \left(\frac{m_h}{150\,GeV}\right)^{1+\delta} \\
&\quad \times \left(\frac{3\,TeV}{M_D}\right)^{2+\delta}\,.
\end{aligned} \tag{22}$$

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

- **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 are 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

$$S_\xi = \xi \int d^4x \sqrt{g_{\rm vis}} R(g_{\rm vis}) \widehat{H}^\dagger \widehat{H}\,, \tag{23}$$

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

– An example of altered couplings is

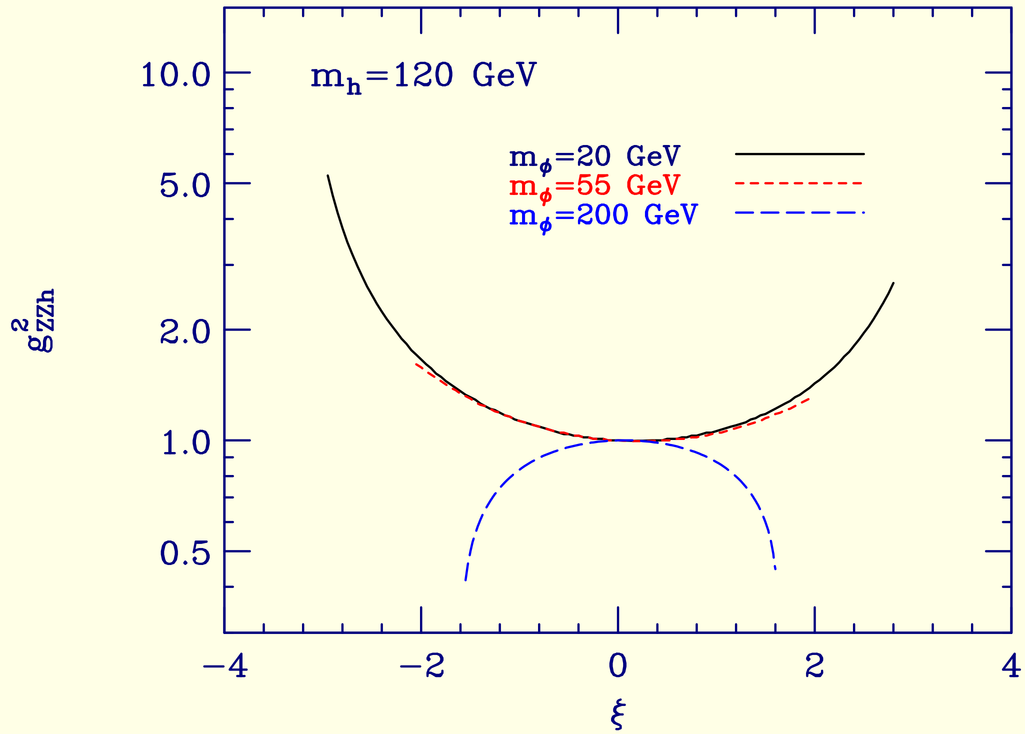


Figure 5: $g^2_{ZZh}/g^2_{ZZh_{\rm SM}} = g^2_{f\overline{f}h}/g^2_{f\overline{f}h_{\rm SM}}$ *as a function of* ξ *for several* m_ϕ *values.*

The couplings of the ϕ are very rapidly varying:

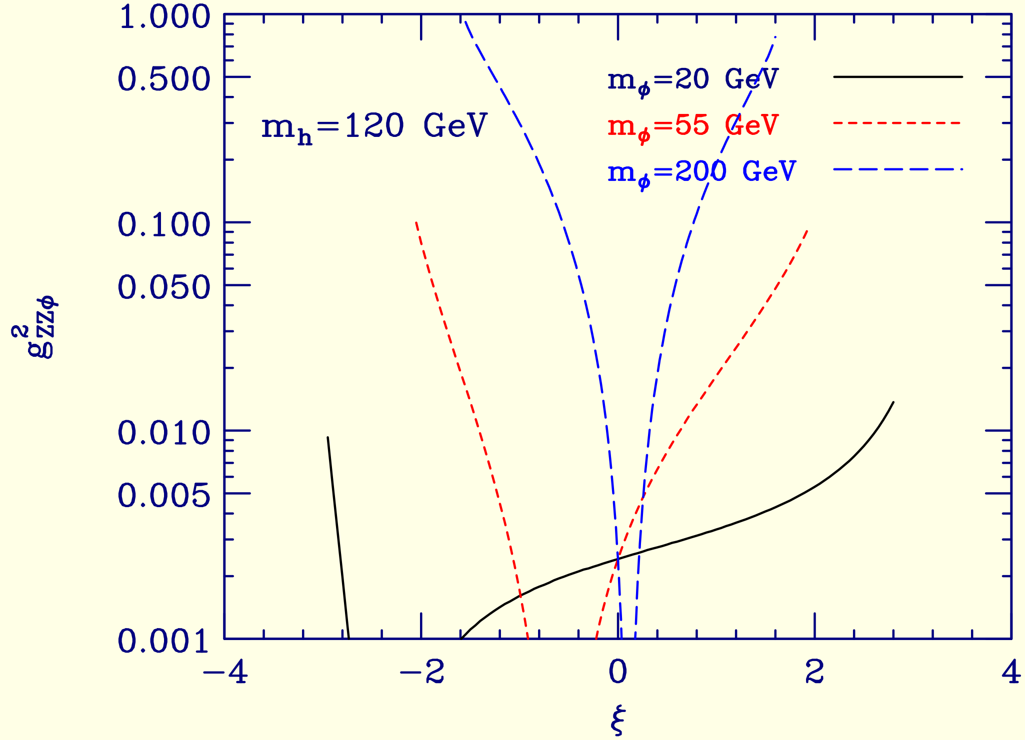


Figure 6: $g^2_{ZZ\phi}/g^2_{ZZh_{\rm SM}} = g^2_{f\overline{f}\phi}/g^2_{f\overline{f}h_{\rm SM}}$ *as a function of* ξ *for several* m_ϕ *values.*

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 $\phi \to hh$, since ϕ couplings to SM particles can easily be greatly suppressed and there is a significant ϕhh coupling.

When $m_h \sim 100~{\rm GeV}$ (PEW preferred) this decay will lead to $\phi \to 4b$

final states (also $2b2\tau$). As discussed earlier, the latter channel has been investigated by various combinations of Ellwanger, JFG, Hugonie, Moretti, Munir, Poulose and D. Zerwas.

New Physics A: Supersymmetry

- $\boxed{\text{The MSSM}}$ 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 $< 130~\mathrm{GeV}$ 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. $gg \to h^0 \to \gamma\gamma$ (good in decoupling large m_{A^0} region)
2. $gg \to b\bar{b}H^0, b\bar{b}A^0$ (large $\tan\beta$) with $H^0, A^0 \to \tau\tau$
3. $gg \to t\bar{b}H^- + b\bar{t}H^+$ (large $\tan\beta$) with $H^\pm \to \tau^p m\nu$
4. $t \to bH^+$ (away from decoupling region, *i.e.* low m_{A^0}
5. $A^0 \to Zh^0$ (largish m_{A^0}, but small $\tan\beta$) with $h^0 \to b\bar{b}$
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.

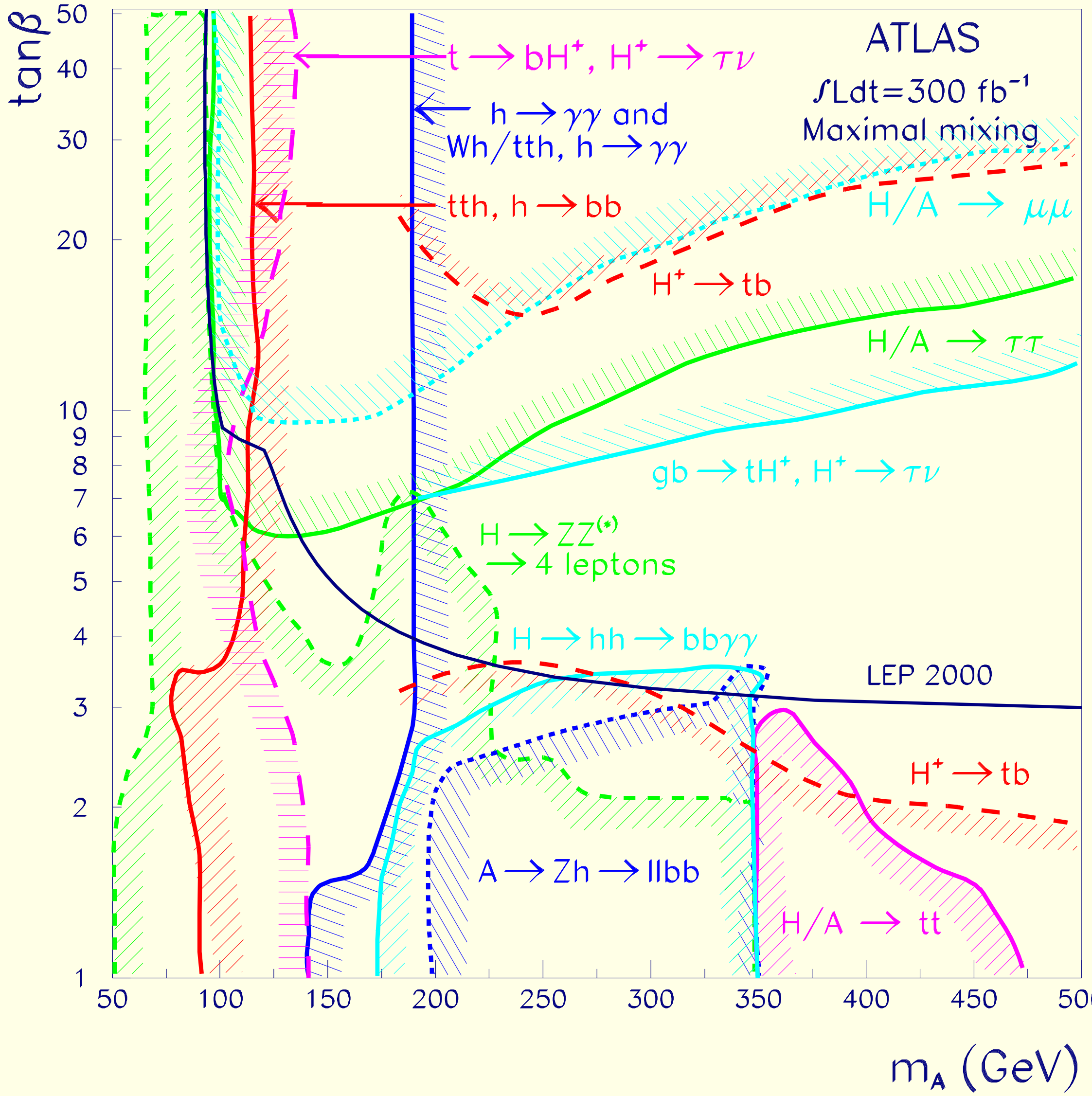


Figure 7: 5σ *discovery contours for MSSM Higgs boson detection in various channels are shown in the* $[m_{A^0}, \tan\beta]$ *parameter plane, assuming maximal mixing and an integrated luminosity of* $L = 300~\mathrm{fb}^{-1}$ *for the ATLAS detector. This figure is not up to date*

- **However, the MSSM has two really significant problems.**

1. **Lack of a convincing source for the μ term of the superpotential, where μ should be of order $1~\mathrm{TeV}$ (rather the natural values of 0 or M_{P}).**
2. **Substantial fine-tuning with respect to GUT scale parameters.**
   The latter should not 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:

$$F \equiv \mathrm{Max}_p \left| \frac{\partial \log m_Z}{\partial \log p} \right| , \tag{24}$$

   where p are the GUT scale parameters (e.g. μ, M_3, $m^2_{H_u}$, A_t, to name the usually critical ones).
   The lowest F (~ 25) with m_{h^0} above the $114~\mathrm{GeV}$ LEP limit (assuming $m_{A^0} > 100~\mathrm{GeV}$) is achieved in the maximal mixing scenario when $A_t \sim -500~\mathrm{GeV}$ (rather precisely).

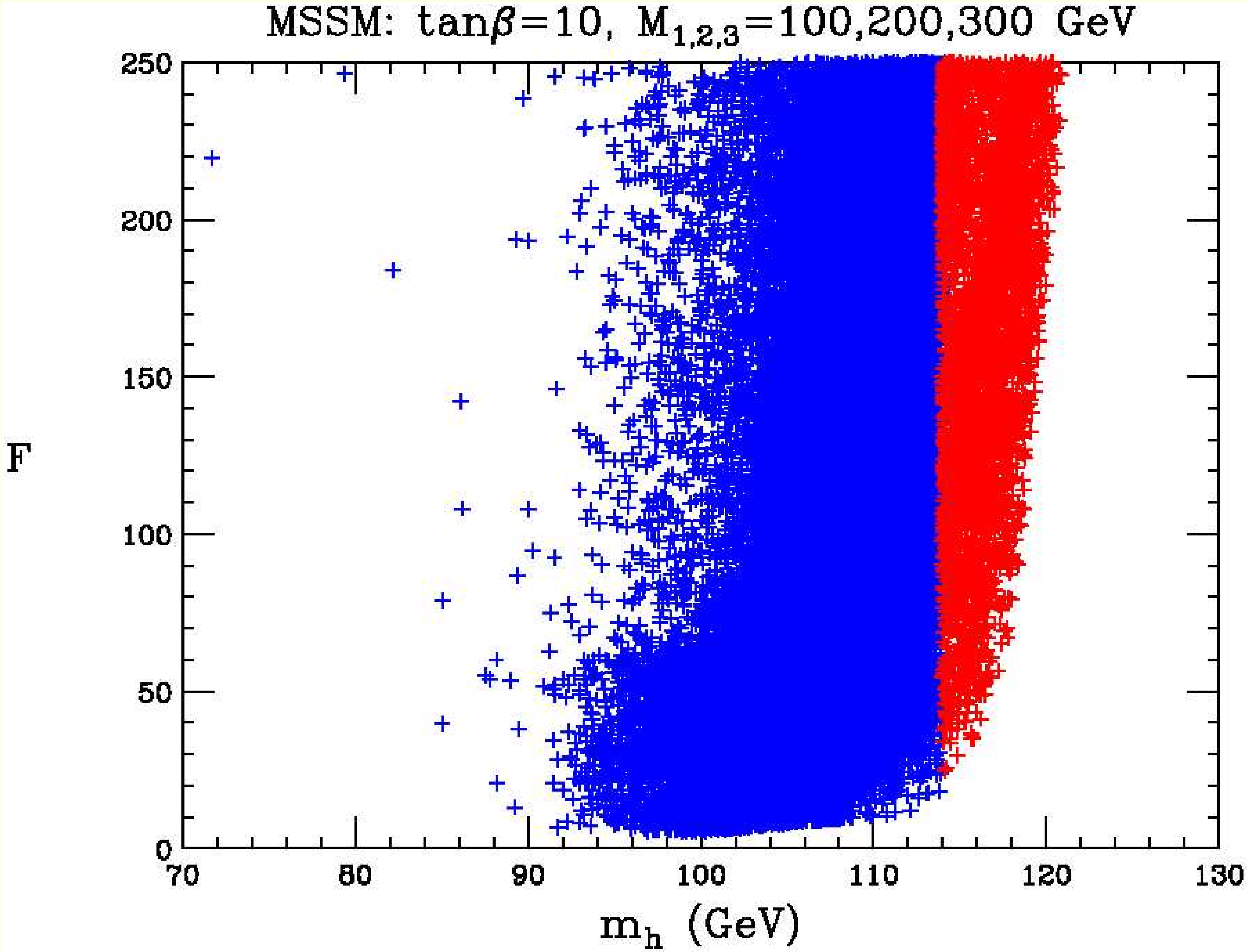


Figure 8: *F vs. m_{h^0} in the MSSM for $\tan\beta = 10$, $M_{1,2,3}(m_Z) = 100, 200, 300\ \mathrm{GeV}$. Blue $+$'s have $m_{h_1} < 114\ \mathrm{GeV}$ and are excluded by LEP data. From R. Dermisek and J. F. Gunion, Phys. Rev. D* **73***, 111701 (2006) [arXiv:hep-ph/0510322]; Phys. Rev. Lett.* **95***,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

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

- $\boxed{\text{The NMSSM}}$ 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 generated from the $\lambda\widehat{S}\widehat{H}_d\widehat{H}_u$ NMSSM superpotential term: $\mu_{\rm eff} = \lambda\langle S\rangle$.
    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 $m_{h_1} \sim 100~{\rm GeV}$, but now this is LEP allowed provided that $h_1 \to a_1a_1$ is the dominant decay *and* $m_{a_1} < 2m_b$. If $m_{a_1} > 2m_b$, then $h_1 \to a_1a_1$ also feeds the $Z + b's$ channel that is strongly constrained by LEP data.
    In fact, large $B(h_1 \to a_1a_1)$ with small m_{a_1} can be arranged without significant tuning of the A_λ and A_κ soft parameters. Some preference is shown for $m_{a_1} > 2m_\tau$ for this. (R. Dermisek and J. F. Gunion, arXiv:hep-ph/0611142.)

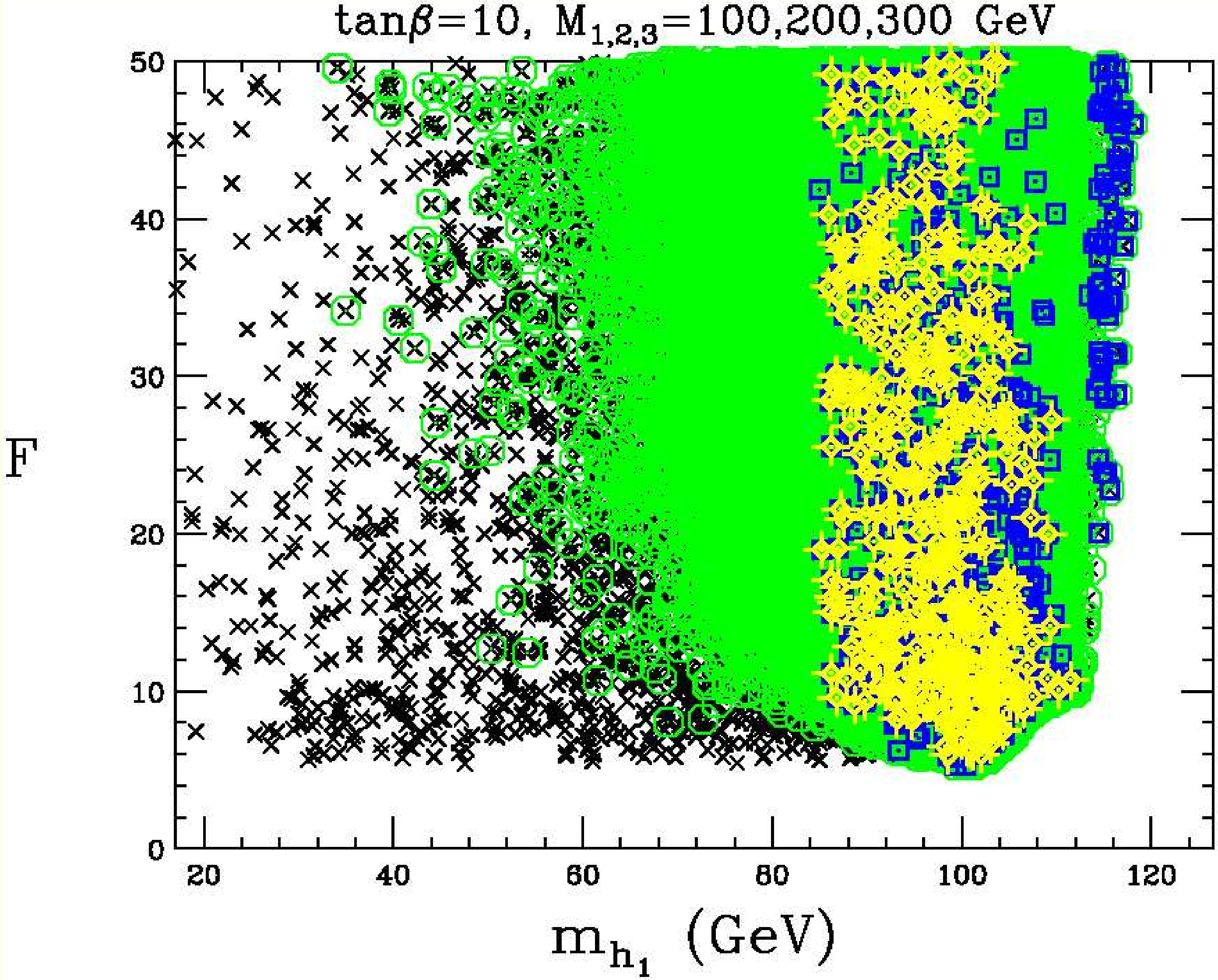


Figure 9: *F vs. m_{h^0} in the NMSSM for $\tan\beta = 10$, $M_{1,2,3}(m_Z) = 100, 200, 300$ GeV. Large yellow crosses are fully consistent with LEP constraints. See earlier Dermisek + JFG refs.*

- **A large majority of the yellow crosses have $B(h_1 \to b\bar{b}) \sim 0.1$ or so** which perfectly explains the long known 2.3σ LEP excess at ~ 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 2.5σ after $300\ \mathrm{fb}^{-1}$.
2. $\Rightarrow$ We must tackle the $h_1 \to a_1 a_1 \to 4\tau$ or $4j$ final state.
   * There is some hope for WW fusion: $WW \to h_1 \to 4\tau$.
   * There is some hope for $t\bar{t}h_1$ with $h_1 \to 4\tau$.
   * A very interesting possibility is diffractive Higgs production: $pp \to pph_1$ 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 down stream that they can't be used to trigger these events).

     The estimated event rate after some cuts is about 5 events for $30\ \mathrm{fb}^{-1}$. If we can use high luminosity in the face of triggering necessity, then $300\ \mathrm{fb}^{-1}$ would give ~ 50 events.

     But, even a small handful of background-free 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 $pp \to pph_1$ signal is independent of whether the h_1 has SM-like WW, ZZ couplings.

It will be crucial to check perturbativity of $WW \to WW$ 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 $\Upsilon(1S) \to \gamma a_1$ could reveal the a_1 so long as its mass is not too close to M_Υ.

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

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

   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 $m_{h_1} > 114~\mathrm{GeV}$ points that automatically evade all LEP constraints are present.

  These need not have dominant $h_1 \to a_1 a_1$ decays, but many do! Generally speaking, almost any $B(h_1 \to a_1 a_1)$ is possible.

However, if $m_{h_1} > 114~\mathrm{GeV}$ then $m_{a_1} < 2m_b$ is no longer required, but it is allowed.

Thus, we must look for all of the following:

$h_1 \to b\bar{b}$

$h_1 \to 4j$,

$h_1 \to 2j2\tau$,

$h_1 \to 4\tau$,

$h_1 \to 2b2\tau$,

$h_1 \to 4b$.

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 $B(h_1 \to a_1a_1) \sim 1/2$, 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!

- $\boxed{\text{MSSM with a singlet}}$ 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:

$h \to ss \to aaaa \to 8g, 8\tau, 4g, 4\tau, 8b, \ldots$

$h \to sa \to aaaa \to 6g, 6\tau, 6b, \ldots$

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

- $\boxed{U(1)' \text{ Extended MSSM}}$ 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 μ 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 $h_i \to \widetilde\chi_j^0 \widetilde\chi_k^0$ 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.

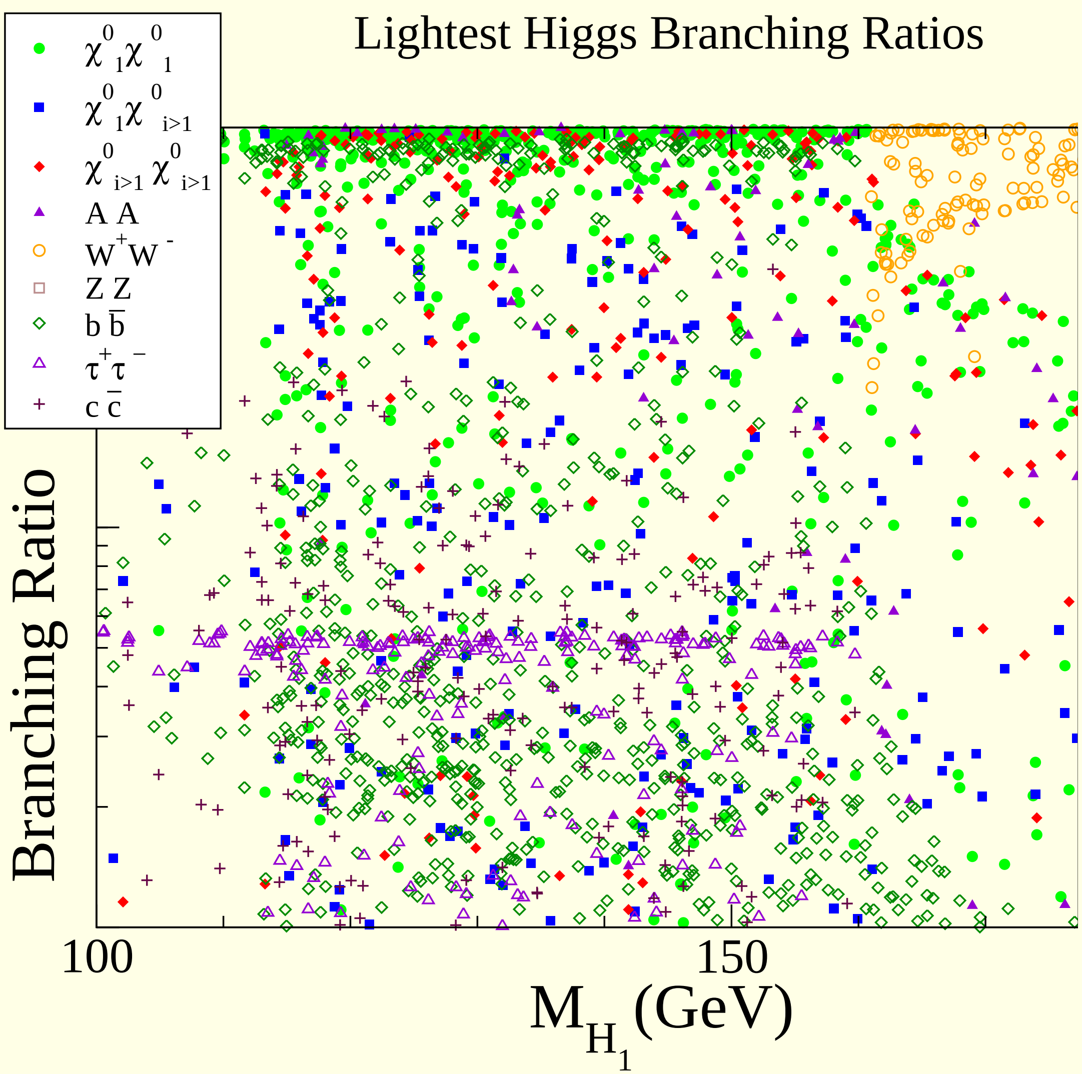


Figure 10: *Branching ratios for the somewhat heavy lightest Higgs with substantial $\boldsymbol{WW}$ coupling.*

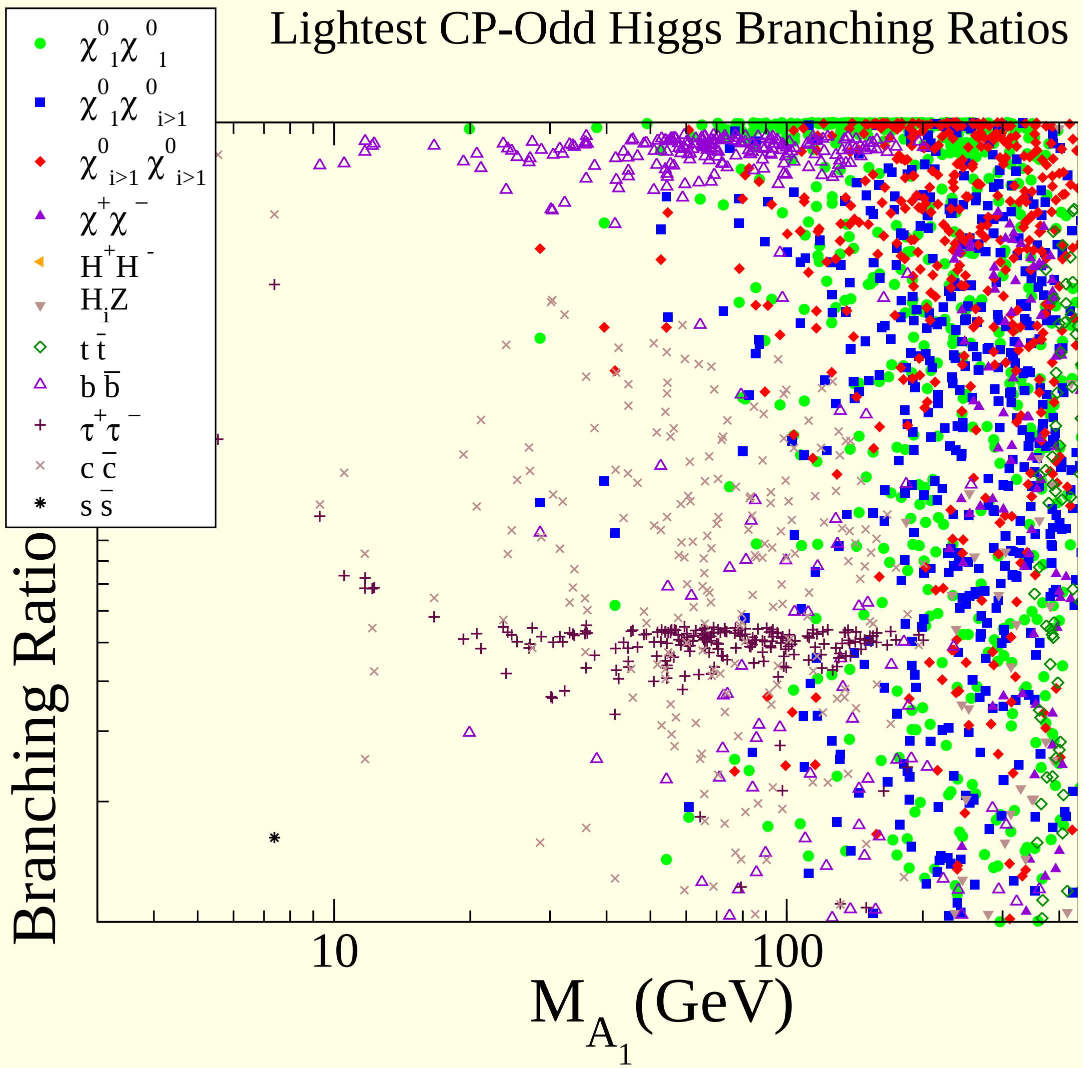


Figure 11: *Branching ratios for the lightest CP-odd A_1.*

Note the presence of some $\widetilde{\chi}^0_{k>1}$'s in the A_1 decays.

- **Decay Channels** Examples only.

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

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

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

  $H_1 \rightarrow A_1 A_1 \rightarrow$ 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.

- $\boxed{\text{The E(6)MSSM}}$ 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.

- $\boxed{\text{MSSM with } R\text{-parity Violation}}$

I will mention two models of this type. Both are designed to allow the PEW preferred value of $m_{h^0} \sim 100~\mathrm{GeV}$, 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 $h_1 \to a_1 a_1$.

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 $7.5~\mathrm{GeV}$. The Higgs boson would decay mainly into $\widetilde{b}\widetilde{b}$.
   Normally, $\widetilde{b} \to b\widetilde{\chi}_1^0$, in which case $h^0 \to 2b + \not{E}_T$. Would this have been picked by LEP search?
   With baryonic R-parity violation $\widetilde{b} \to 2j$ is possible, and the Higgs signal is $h^0 \to 4j$ with no missing energy. LEP would have missed this signal for $m_{h^0} \sim 100~\mathrm{GeV}$.

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 $m_{h^0} \sim 100~\mathrm{GeV}$ and $h^0 \to \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$ is dominant.

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

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

   The $\widetilde{\chi}_1^0$ 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, ...

Covered in other talks. In general there is some motivation from issues of naturalness and so forth.

However, it is also possible for new physics from a totally unrelated sector to have a strong impact on Higgs physics. A recent example is that investigated by M. Graesser (hep-ph/0704.0438). He points out that if the 'heavy' right-handed neutrinos (N here) for the see-saw mechanism are actually fairly light, then they can appear in Higgs decays.

In this model, the whole see-saw scale is pushed down and the couplings λ_ν appearing in

$$\mathcal{L} = \frac{1}{2} M_R N N + \lambda_\nu \widetilde{H} N L + \ldots \quad (\widetilde{H} = i\tau_2 H^*) \tag{25}$$

must be very small compared to M_R/v if the see-saw is to operate:

$$\lambda_\nu \sim 7 \times 10^{-7} \left(\frac{m_L}{0.5 \text{ eV}} \right)^{1/2} \left(\frac{M}{30 \text{ GeV}} \right)^{1/2} \tag{26}$$

in order for the Dirac mass, $m_D = \lambda_\nu v/\sqrt{2}$, to be small compared to M.

Still, some new physics connecting the Higgs to the N sector must be introduced for this to have an impact. One possibility is

$$\mathcal{L} \ni \frac{c}{\Lambda} H^\dagger H N N \tag{27}$$

(what else!), where Λ is a new physics scale required by dimensional analysis. This coupling will lead to $h \to NN$.

$$\frac{\Gamma(h \to NN)}{\Gamma(h \to b\bar{b})} = \frac{2c_1^2}{3} \frac{v^4}{m_b^2 \Lambda^2} \beta^3 \,. \tag{28}$$

For $c_1 \sim \mathcal{O}(1)$, the NN modes wins if $\Lambda \lesssim 20~\mathrm{TeV}$.

The dominant decay of the N is via its couplings Wl and $Z\nu$, which are suppressed by $1/M$. The result is 3-body final states for each of the N's, which means that the h will not be easy to see, unless, as quite possible in this model the lifetime of the N is long and one has displaced vertices.

A theoretical issue: why is $M \ll \Lambda$?

Conclusions

My bias:

The combination of:

1. the precision electroweak preference for a SM-like Higgs with $m_h \sim 100 \text{ GeV}$,
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 the LHC may have to find the Higgs boson by looking for $h \to pp$ where p then decays in some way that evades the LEP $m_h > 114 \text{ GeV}$ bound.

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.

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