Is (are) the Higgs Boson (s) Hidden?

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For $m_h < 2m_W$, the main decay mode of the Higgs is to $b\bar{b}$ and $\Gamma_{h}^{\text{tot}}$ is very tiny. $h \rightarrow \gamma\gamma$ is an important discovery mode.
- Higgs cross section is dominated by $gg \rightarrow h$ until $m_h$ is large.

A reminder: the number of events in a given channel $X$ is given by

$$N_X = L \left( fb^{-1} \right) \times \sigma \left( fb \right) \times B(X),$$

(1)
where the integrated luminosity analyzed for ATLAS and CMS (each) is of order $1 - 2 \text{ fb}^{-1}$ depending upon the channel. Note: $1 \text{ pb} = 1000 \text{ fb}$, so for the $\sigma$ values from $gg$ fusion, we get lots of Higgs produced.

So, what do they see?

- In the $\gamma\gamma$ final state, there are some narrow excesses above the background.

- In the $\ell\nu\ell\nu$ case, there is a broad excess in

$$m_T = \sqrt{(E_T^{\ell\ell} + \not{E}_T)^2 - (\not{p}_T^{\ell\ell} + \not{p}_T)^2}$$

(2)

where

$$E_T^{\ell\ell} = \sqrt{(\not{p}_T^{\ell\ell})^2 + m_{\ell\ell}^2}, \quad \not{E}_T = |\not{p}_T|$$

(3)

that could be associated with a variety of Higgs masses.

- In the $ZZ \rightarrow 4\ell$ final state there are also some excesses.

Some sample plots from the CMS and ATLAS experiments will illustrate.
Data 2011, $\sqrt{s} = 7$ TeV, $\int L dt = 1.08$ fb⁻¹

ATLAS Preliminary

- Data
- MC $m_H = 120$ GeV, $5 \times SM$
- Total background (Fit)

$H \rightarrow \gamma \gamma$

Note scale factor of $5 \times SM$. 
ATLAS $H \rightarrow \gamma \gamma$

Data 2011, $\sqrt{s} = 7$ TeV

$\int Ldt = 1.08 \text{ fb}^{-1}$

CMS preliminary

$\sqrt{s} = 7$ TeV $L = 1.66 \text{ fb}^{-1}$

Observed CLs Limit
Observed Bayesian Limit
Median Expected CLs Limit
$\pm 1\sigma$ Expected CLs
$\pm 2\sigma$ Expected CLs

$\sigma(H \rightarrow \gamma \gamma)$ vs $m_H (\text{GeV/c}^2)$
Note scale factor of $1 \times SM$.

While the $\gamma\gamma$ and $\ell\nu\ell\nu$ are the channels with greatest sensitivity to the $h$, others also contribute.
Limits on a SM-like Higgs after combining all channels
CMS results for most probable $\mu = \sigma / \sigma_{SM}$. Could there be a SM Higgs at 120 GeV?

**Caveats**

- **In $\gamma\gamma$, inconsistency of CMS peak at $m_h = 140$ GeV vs. ATLAS peak at $m_h = 128$ GeV, with only small $\gamma\gamma$ excesses elsewhere, argues for statistical fluctuations being dominant.**

- **Excess in $WW^*$ for $m_h \sim 140$ GeV vicinity is consistent between experiments and might indicate a weak $\sim 0.3 - 0.5 \times SM$ signal.**
Seems quite possible that with more statistics and after combining CMS and ATLAS that the local $p$ values will fall below 1 “everywhere”.

This implies that we should certainly be taking seriously scenarios in which the Higgs has either reduced coupling to the important production modes or reduced branching ratio to the $WW$ and $\gamma\gamma$ final states.

In fact, an entirely reasonable expectation is a chameleon-like emergence from camouflage:
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This implies that we should certainly be taking seriously scenarios in which the Higgs has either reduced coupling to the important production modes or reduced branching ratio to the $WW$ and $\gamma\gamma$ final states.

In fact, an entirely reasonable expectation is a chameleon-like emergence from camouflage:
Indeed, there are at least 50 ways to hide the Higgs(es)\(^1\) for now (possibly forever at the LHC) in very reasonable and well-motivated (extreme) models.

Of course, in doing so we should not forget

![Graph](image)

**Figure 1:** LEP precision electroweak suggests a light Higgs with SM-like \(WW, ZZ\) couplings-squared. Or, many light Higgs which cumulatively have SM-like \(\sum_k g_{VV h_k}^2 = 1\).

\(^1\)“50 ways to leave your lover”, Paul Simon: [http://www.youtube.com/watch?v=298nld4Yfds](http://www.youtube.com/watch?v=298nld4Yfds)
If the $\gamma\gamma$ LHC signal “evaporates” a very attractive option is to have a light Higgs, $m_h \lesssim 100$ GeV, with SM-like $ZZ$, $WW$ couplings (for good PEW) that is “hidden” in that it does not appear in SM-like final states with more than a fraction of SM strength.

This is supported by the old LEP excess near $95 - 100$ GeV:

Figure 2: Preference is to retain a $e^+e^- \rightarrow Zb\bar{b}$ signal at about 20 – 30% of SM strength.
Such a scenario is not excluded by the weak LEP limits for model-independent decays of the $h$:

**Figure 3:** Limits on $\xi^2 = \sigma(e^+e^- \rightarrow Zh)/(e^+e^- \rightarrow Zh_{SM})$ from OPAL with no assumption about $h \rightarrow X$ decays. $m_h$ as small as 82 GeV is allowed.
General Considerations

Experimental

- Experiment measures
  \[ \sigma(pp \rightarrow h) B(h \rightarrow X) \]  
  \[ (4) \]

- \( \sigma(pp \rightarrow h) \) depends on initial state, e.g. \( gg \) or \( q\bar{q} \), with \( \mathcal{L}(gg)_{\text{eff}} \) increasing much more rapidly with increasing energy than \( \mathcal{L}(q\bar{q})_{\text{eff}} \).

- \( gg \rightarrow h \) is quite sensitive to what goes inside the loop.

- Branching ratios probe the partial width to total width ratio:
  \[ B(h \rightarrow X) = \frac{\Gamma(h \rightarrow X)}{\Gamma_{h}^{\text{tot}}} \]  
  \[ (5) \]

When \( \Gamma_{h}^{\text{tot}} \) is small, as for Higgs masses below \( 2m_{W}, 2m_{Z} \), it is very easy to modify branching ratios when a new channel is added — one is typically only competing with the \( b\bar{b} \) final state.
• If there is more than one Higgs and they mix or have special properties, their experimental signals can exhibit a great deal of variation.

• It will often be convenient to define

\[ \xi^2(X) = \frac{\sigma(pp \rightarrow h) B(h \rightarrow X)}{\sigma(pp \rightarrow h_{\text{SM}}) B(h_{\text{SM}} \rightarrow X)} \]  

(6)

where \( X \) is some final state. Usually, one production mechanism will be dominant for both \( \sigma(pp \rightarrow h) \) and \( \sigma(pp \rightarrow h_{\text{SM}}) \) for a given final state \( X \).

**Theoretical**

• In this talk, I will only discuss supersymmetric models. RS warped extra-dimension models also solve the hierarchy problem, but I have no time.

These are the only ones that provide a solution to the hierarchy problem and are a complete theory in the ultraviolet regime.

They already provide a plethora of examples of how the Higgs can hide.

• My apologies to all the other interesting ideas I cannot cover.
Supersymmetric Models

- Supersymmetry is well-motivated as a solution to the hierarchy problem.
- Gauge unification is successful.
- There is no little hierarchy problem if $m_{\tilde{t}_1} \lesssim 700$ GeV, and it is still reasonably acceptable to have $m_{\tilde{t}_1} \sim 1$ TeV.
- Very heavy first and second generation squarks are entirely acceptable and good for FCNC, ... and do not affect the little hierarchy issue.
- A light Higgs, perhaps as light as $100 - 110$ GeV for $m_{\tilde{t}_1} \lesssim 700$ GeV, is then very natural and certainly not yet excluded in the supersymmetric context which provides many escapes from LEP, Tevatron and LHC limits.
- Direct limits on $m_{\tilde{t}_1}$ are a priority.
1. The MSSM

In even the simplest version of the MSSM, with all sparticles at $\sim 1$ TeV, there is a general tendency for Higgs mixing to lead to increased $b\bar{b}$ width of the SM-like Higgs boson at smaller $m_A$. This suppresses the rates into the most relevant LHC discovery modes, such as $\gamma\gamma, WW^*$. 

Figure 4: Suppression for the $WW$ and $\gamma\gamma$ final states (Carena, Wagner, et al., arXiv:1107.4354)
There is no need for concern that we have not found the MSSM $h$ for $L$ analyzed so far. But, discovery should not be far off.

**Figure 5:** For $L = 15$ fb$^{-1}$ and minimal mixing (the hardest case), most of parameter space is covered at $3\sigma$ (left figure). Or (right figure) combine $L = 5$ fb$^{-1}$ LHC and $L = 10$ fb$^{-1}$ Tevatron and do even better. The Tevatron helps at low Higgs mass where the LHC is weak. Do not LHC limits excluding a light $H$ decaying to $\tau^+\tau^-$ for $\tan\beta \gtrsim 15$ eliminate the green “spike”.
2. Supersymmetry with Invisible Higgs decays

If $2m_{\tilde{\chi}^0_1} < m_h$ the Higgs can decay largely invisibly (assuming $R$ parity). For low $m_h$, the $M_1$ gaugino mass cannot obey the GUT relation $M_1 = \frac{1}{2}M_2$.

If $m_h > 114$ GeV, no experimental limit prevents $B(h \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1) = 1$.

Even $m_h < 114$ GeV is experimentally acceptable if there is a mixture of $h \rightarrow b\bar{b}$ and $h \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1$ decays.

Figure 6: LEP limits on $\xi^2(\text{inv}) \equiv [\sigma(Zh)/\sigma(Zh)_{SM}]B(h \rightarrow \text{invisible})$ — at $m_h = 112$ GeV, $\xi^2(\text{inv}) = 0.5$ would be ok. Meanwhile, $\xi^2(b\bar{b}) = 0.5$ would also fall under LEP and Tevatron limits. LHC $\gamma\gamma$ rate would be decreased by more than 50%.
The best LHC search channel for an invisibly decaying Higgs is $h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ using the $pp \rightarrow W^*W^* + 2j \rightarrow h + 2j \rightarrow \text{invisible} + 2j$ mode.

Figure 7: ATLAS-PHYS-PUB-2006-009 95% CL limits on $\xi^2(\text{inv}) \equiv \left[ g_{hWW}^2 / g_{h_{\text{SM}}WW}^2 \right] B(h \rightarrow \text{invisible})$ for $L = 30 \text{ fb}^{-1}$. Can probe $\xi^2(\text{inv}) \sim 0.25$ at low $m_h$.

Significant invisible decays will soon be visible.
3. Supersymmetry with Baryonic $R$ parity violation

If $B(h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0)$ is large and $\tilde{\chi}_1^0 \rightarrow 3j$ (or $5j$ in “collective” RPV) via baryonic $R$ parity violating term(s) in superpotential, $\Rightarrow$ very difficult Higgs detection scenario. (Carpenter, Kaplan, Rhee, arXiv:0804.1581) And, SUSY discovery hard!

Is detection possible in this case, given low $m_{\tilde{\chi}_1^0}$ and large QCD background for soft jets?

Could $WW$ fusion with 6 not very hard central jets and two forward jets be separated from background?

Could boosted $\tilde{\chi}_1^0$ analysis help in $gg \rightarrow h \rightarrow 3j + 3j$ when $m_{\tilde{\chi}_1^0}$ is not too close to $m_h/2$.

NB: in this scenario one loses the beautiful supersymmetry explanation for dark matter.

4. MSSM with Hidden Sector Decays of $\tilde{\chi}_1^0$ ($= \tilde{N}_1$)
• This is simply one more option. The idea (Falkowski et al., arXiv:1007.3496) is that there could be a “dark sector” that communicates with our visible sector via kinematic mixing in the Lagrangian. The resulting Higgs decay picture would be:

![Higgs decay diagram](image)

**Figure 8:** Picture of $h$ decay to dark sector photons and neutralinos and ultimate final state of two lepton jets. Most likely $m_{\gamma_d} > 2m_\mu$ and the leptons would be $\mu$’s.

• At SUSY, Wright showed this transparency which appears to eliminate possibility of muonic lepton jets – assumed $m_h \lesssim 150$ GeV, $m_{\gamma_d} \sim 300$ GeV and prompt decays (delayed decays a possibility in the model).
Dark Sector Decays

- One of several ways to hide a light Higgs from the LEP limits
  - Decays through neutralinos and dark sector “photons”
  - Falkowski et al arXiv:1002.2952
- Search for W/Z+H production, final state containing many soft leptons
- Exclude this particular benchmark scenario at 99.7% CL

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5. Higgs decay via a Hidden Valley

- Much similarity to the lepton jets proposal, but displaced vertices viewed as more likely.
- Since final states are more varied, there are no available limits.

6. MSSM with CPV Higgs sector

If one introduces CP-violation into the MSSM parameters, then CP Violation can be induced in the Higgs sector at the 1-loop level.

Mixing between the CP-even $h$ and $H$ Higgs and the CP-odd $A$ then occurs and one ends up with three neutral Higgs states, $h_1, h_2$ and $h_3$, plus the $H^\pm$.

LEP limits are much weaker when substantial CP-violation is present. Such a case is represented by the so-called CPX scenario (Carena, Ellis, Wagner, et al., hep-ph/0211467).
Figure 9: Exclusions from LEP at 95\% CL (light-green) and 99.7\% CL (dark-green) for the CPX scenario with $m_t = 179.3$ GeV. For lower $m_t$ excluded regions expand. Note that unexcluded $m_{h_1} < 2m_b$ cases appear for $m_{h_2} \sim 105$ GeV.

The main reason holes develop is that the channel $e^+e^- \rightarrow Zh_2 \rightarrow Zh_1h_1$ with $h_1 \rightarrow b\bar{b}$ (or possibly $\tau^+\tau^-$) becomes important (originally pointed out by Haber, Gunion, Moroi, hep-ph/9610337 In NMSSM context) and, further, the $h_2$ does not have full $ZZ$ coupling.
The combination of weakened $ZZh_2$ coupling and the weaker limits on the more complex and less constrained $Z + 4b$ final states lead to regions of parameter space for which LEP cannot exclude the scenario.

These same $h_2 \rightarrow h_1 h_1 \rightarrow 4b, 4\tau$ decays are considerably more difficult to detect at the LHC than the SM-like final states.

In the $4b$ case, multiple $b$-tagging is needed. A number of studies by theorists suggest that $10 - 30$ fb$^{-1}$ will suffice to reveal the $4b$ final states in $W + Higgs$ events (Kingman Cheung et al., hep-ph/0703149), but full simulations by ATLAS and CMS have not appeared to my knowledge.

Detection of $h_2 \rightarrow h_1 h_1 \rightarrow 4\tau$ at the LHC is problematical (see later).

7. The NMSSM: = MSSM + extra singlet superfield, $\hat{S}$

The many attractive features of the NMSSM are well known:

(a) Solves $\mu$ problem: $W \ni \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{3} \kappa \hat{S}^3 \Rightarrow \mu_{\text{eff}} = \lambda \langle S \rangle$.
(b) Preserves MSSM gauge coupling unification.
(c) Preserves radiative EWSB.
(d) Preserves dark matter (assuming $R$-parity is preserved).
(e) Like any SUSY model, solves quadratic divergence hierarchy problem.

The Higgs sector is expanded in the NMSSM to two CP-odd Higgs bosons $(a_1, a_2)$ and three CP-even Higgs bosons $(h_1, h_2, h_3)$, as well as the $H^\pm$.

In both sectors, the Higgs are typically a mixture of a singlet component and the doublet components. In particular, we write

$$a_1 = \cos \theta_A A_s + \sin \theta_A A_{MSSM}.$$  \hspace{1cm} (7)

This Higgs sector expansion leads to some new attractive possibilities:

In particular, a SM-like $h_1$ with $m_{h_1} \sim 90 - 105$ GeV can escape LEP limits because of $h_1 \rightarrow a_1 a_1$ decays with $m_{a_1} < 2m_b$ so that $a_1 \rightarrow \tau^+ \tau^-$ at large $\tan \beta$ or $a_1 \rightarrow gg, c\bar{c}, \ldots$ at low $\tan \beta$ (Dermisek, Gunion, hep-ph/0502105 and subsequent).

Typically, LEP escape scenarios correspond to small $|\cos \theta_A| \lesssim 0.1$ for $\tan \beta > 5$, but larger $|\cos \theta_A|$ is possible for small $\tan \beta$. 
In terms of the $Z + b\bar{b}$ LEP limits the picture becomes:

Figure 10: The excess at $M_{bb} \sim 100$ GeV is easily explained, and almost automatically so when small fine-tuning $F$ is required.

Such a situation has three very attractive features:
- Precision electroweak constraints are ideally satisfied.
- Fine-tuning for getting $m_Z$ (i.e. $v$) correct is small = reduced little hierarchy.
- An $a_1$ with large $B(h_1 \rightarrow a_1a_1)$ and $m_{a_1} < 2m_b$ corresponds to a natural symmetry limit of the NMSSM in which the $A_\lambda$ and $A_\kappa$ soft-SUSY breaking parameters ($V \ni A_\lambda S H_uH_d + \frac{1}{3}A_\kappa S^3$) are small.

This scenario is very hard to constrain/detect.

- ALEPH (Cranmer et al., arXiv:1003.0705) have looked at $Zh_1 \rightarrow Z4\tau$ and eliminated about 1/2 of the preferred points at large $\tan\beta$, but there are still plenty left.
- ALEPH is also looking at the more complicated $Zh_1 \rightarrow Z4j$ scenarios appropriate to low $\tan\beta$, but no results yet.
- At the Tevatron and LHC, one approach (Lisanti, Wacker, arXiv:0903.1377) is to look for $W, Z + h_1$ with $h_1 \rightarrow a_1a_1 \rightarrow 2\mu + 2\mu, 2\mu + 2\tau$, relying on the $0.3\%$ branching ratio for $a_1 \rightarrow \mu^+\mu^-$. Some not very constraining results were obtained (Has et al., arXiv:0905.3381).

LHC estimates by (Lisanti, Wacker, arXiv:0903.1377) in this same mode
suggested it was quite promising, but the study of (Balyaev et al., arXiv:1002.1956) suggests the backgrounds are much larger than anticipated.

- Forshaw, Gunion et al., arXiv:0712.3510 looked at $pp \rightarrow pp + h_1 \rightarrow pp + 4\tau$. Detection is possible, but requires very high $L > 100$ fb$^{-1}$.

- Many of the “ideal” scenarios have large enough $C_{a_1 b\bar{b}} = \tan \beta \cos \theta_A$ coupling that $gg \rightarrow a_1 \rightarrow \mu^+\mu^-$ would have a significant event rate (Gunion, Dermisek, arXiv:0911.2460). Detectability in this mode is being studied by both CMS and ATLAS, with some low $L$ results from ATLAS publicly available (Hal Evans et al.), but not very constraining yet.

Unfortunately, in the light of BaBar/Belle constraints from $\Upsilon(3S) \rightarrow \gamma a_1 \rightarrow \gamma \mu^+\mu^-, \gamma \tau^+\tau^-$ the preferred $m_{a_1}$ range lies within the $\Upsilon$ peaks, preferably fairly close to $2m_b$. This region will be hard.

Of course, we can easily imagine that LEP limits are avoided by simply choosing parameters so that $m_{h_1} > 114$ GeV.

This would still be quite good for PEW, but then

- $m_{a_1} > 2m_b$ would be entirely acceptable and one must also consider
scenarios with $h_1 \rightarrow a_1 a_1 \rightarrow 2b + 2b$ as the main decay channel.
This was a channel pointed out early in the NMSSM game (Haber, Gunion, Moroi, hep-ph/9610337; Ellwanger, Gunion, Hugonie; Moretti, hep-ph/0305109, hep-ph/0401228).

• As discussed already, while such a channel will eventually be probed in $W, Z + h_1, t\bar{t} + h_1$ and (at large $\tan \beta$) $b\bar{b} + h_2$ production (assuming $h_1$ is SM-like), it is likely to take more $L$ than will be available by the end of the current LHC run (see, in particular, studies by Almarashi, Moretti, arXiv:1105.4191).

8. The NNNN....MSSM: = MSSM + extra singlet superfields

• 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 $\tilde{\chi}$'s.
• This supersymmetry scenario is closely related to the “worst case” Higgs scenario (Espinosa, Gunion, hep-ph/9807275) in which there are many Higgs bosons reasonably closely spaced (or continuously spaced) with net $g_{ZZh_i}^2$
weight centered in the vicinity of the ideal PEW value of 100 GeV. See also, the van der Bij scenarios, arXiv:0804.3534 and references therein.

In general, the different \( h_i \) will have \( h_i \rightarrow h_k h_l \) decays so that final states will be complicated and overlapping.

- Estimates are that the LHC would not be able to detect the Higgs signal(s) directly.
  
  Only an ILC, preferably at modest \( \sqrt{s} \sim 250 - 350 \) GeV, could reveal the more or less continuum enhancement in the recoil \( M_X \) spectrum predicted in the \( e^+e^- \rightarrow Z + X \) channel.
  
  High \( L \) would certainly be needed.

9. Other NMSSM-related scenarios

One can construct SUSY models using a singlet superfield in which the \( a \rightarrow b\bar{b} \) decay partial width is suppressed and \( a \rightarrow gg \) is dominant with \( B(a \rightarrow \gamma\gamma) \sim 1\% \). (Bellazini et al., arXiv:0910.3210, Luty et al., arXiv 1012.21347)

In particular, the Luty et al. model extends the MSSM with two singlet Higgs fields, \( S \) and \( N \), as well as vector-like colored particles, \( X \). As
in the NMSSM, \( h \rightarrow aa \) is easily dominant. However, since the \( a \) is a pseudo-Nambu Goldstone boson of a new global \( U(1) \) symmetry, \( a \rightarrow b\bar{b} \) decays are suppressed and even if \( m_A > 2m_b \) the dominant \( a \) decay will be \( a \rightarrow gg \) (via \( X \) loops, leading to \( \Delta \mathcal{L} = \frac{1}{\Lambda} a \tilde{G}_{\mu\nu} G^{\mu\nu} \), where \( \Lambda \sim m_X \)). All interactions can be perturbative up to the GUT scale, and gauge coupling unification is preserved if the colored mediators come in complete GUT representations.

The potential, but very difficult, \( h \) discovery modes would employ \( h \rightarrow aa \rightarrow (gg)(gg) \) or \( (gg)(\gamma\gamma) \). The \( h \) could easily remain undiscovered at the LHC. (See, however, the claim by Falkowski \( \text{et al.} \), arXiv:1006.1650, that the \( 4g \) final state could yield \( 5\sigma \) for \( L = 100 \text{ fb}^{-1} \) and \( \sqrt{s} = 14 \text{ TeV} \) using jet substructure techniques in \( Zh \) and \( t\bar{t}h \) production with \( h \rightarrow 4g \).

Also, Luty \( \text{et al.} \) argue that the colored particles \( X \) must be below the TeV scale, and can therefore be produced at the LHC, so there would be some LHC signature for the model. \( m_X \sim \text{ TeV} \) is also mandated so that \( \Delta \mathcal{L} \) is not too small.
10. Other scenarios based on supersymmetry

There are many and there is no time to consider them here.
Thus, while the Higgs boson(s) may be buried, they could be alive and well just below the surface.

If anything, the failure to see a SM-like Higgs in the SM-like channels was “expected” by many of us.
Certainly, I will continue watching and waiting