A Higgs or Not a Higgs?

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This talk summarizes a method for analyzing the properties of any new scalar particle, which
is systematic in the sense that it minimizes apriori theoretical assumptions about the properties of
the scalar particle, leading to very model-independent results. This kind of analysis lends itself to
systematic survey through the terrain of candidate theories, which we find has vast unpopulated
areas. It is also useful for quantifying the comparison of the goodness of fit of competing descriptions
of data, should a new scalar be found.

I. MOTIVATION

This talk1 is a telegraphic summary of the much more detailed discussion of the physics of a new scalar presented
in ref. [1]. We encourage interested readers to look to this reference, which fills in the fine pencil work behind the
broad brush strokes presented here. (Lack of space also necessarily limits the number of papers we can cite, so please
see [1] for more extensive referencing.)

Much has been written about the properties of the Higgs boson, both in its Standard Model (SM) guise, or within
one of the more popular variant models, such as two doublet models (THDMs), left-right symmetric models (LRSMs)
or supersymmetric generalizations of these. [2,3] Considerable experimental effort also has gone into Higgs searches,
partly guided by the many detailed theoretical studies. The recent indications for a Higgs having a mass of order 115
GeV has led to an extension of LEP’s running time, and may yet bring news of a final discovery.

But if a new scalar is indeed found, how can we know if it is our friend the Higgs rather than some other kind of
scalar imposter? Ideally, this is answered by measuring all of the scalar’s couplings and comparing the results to the
well-known SM predictions. Unfortunately, the precision required to distinguish the SM Higgs from its popular close
cousins is not likely to be available soon after discovery.

This talk addresses what we can do in the meantime. Instead of being glum due to the cup being half-empty –
 i.e. over our likely inability to distinguish scalars coming from well-motivated, but closely related models – we would
like to rejoice at it being half-full: there will be numerous theories which predict scalars which are experimentally
distinguishable from the SM very early on. It was the purpose of Ref. [1] to provide the first systematic roadmap to
these dark and poorly explored corners of theory space.

II. THE FRAMEWORK

Of course any analysis must come with working assumptions, our goal is to minimize ours and to tie them closely to
physical questions. We assume that at first only a new scalar is discovered, and all other new particles are reasonably
heavy compared to it. E.g.: if the new scalar has mass 115 GeV, we imagine all other particles being much heavier
(say > 200 GeV). This assumption permits the analysis of the scalar’s properties within the effective theory obtained
by integrating out all other heavier particles. The lowest-dimensional effective couplings of such a scalar are the most
important at low energies. Up to dimension 4 the complete list of couplings is:

\[ \frac{m_h^2}{2} h^2 + \frac{\nu}{3!} h^3 + \frac{a_Z}{2} Z_\mu Z^\mu h + a_W W_\mu^* W^\mu h, \]

1Presented by C. Burgess to ICHEP XXX, Osaka, Japan, July/August 2000.
and
\[
\sum_{Q(f) = Q(f')} T(y_{ff'} + i\gamma_5 z_{ff'}) f' h + \frac{\lambda}{4!} h^4 + \left( \frac{b_Z}{4} Z_{\mu} Z^{\mu} + \frac{b_W}{2} W^*_\mu W^\mu \right) h^2
\]

Some dimension-five interactions can also be important:
\[
\begin{align*}
&c_g G_{\mu}^\alpha G^{\mu \alpha} h + \tilde{c}_g G_{\mu}^\alpha \tilde{G}^{\mu \alpha} h + c_\gamma F_{\mu \nu} F^{\mu \nu} h \\
&\tilde{c}_\gamma F_{\mu \nu} \tilde{F}^{\mu \nu} h + c_{Z\gamma} Z_{\mu \nu} F^{\mu \nu} h + \tilde{c}_{Z\gamma} Z_{\mu \nu} \tilde{F}^{\mu \nu} h.
\end{align*}
\]

Ref. [1] gives expressions for how observables depend on these couplings without making common theoretically-motivated assumptions (like \(y_{ff} \propto m_f/v \ll 1\)). It also collects current experimental limits on their size.

### III. CONSEQUENCES

1. **Map of Model Space**
   The kinds of experimental distinctions likely to be possible soon after discovery can be summarized by the answers provided to four questions. 
   (i) Q1: Are trilinear \(hWW\) and \(hZZ\) couplings of order electromagnetic in size (\(O(e)\) or larger)?
   (ii) Q2: Is the same true for Yukawa couplings?
   (iii) Q3: Are electromagnetic \(h\gamma\gamma\) couplings \(O(e^2/16\pi^2)\) or larger?
   (iv) Are gluonic \(hgg\) couplings \(O(g^2/16\pi^2)\) or larger?

   There are 12 possible combinations of answers to these 4 yes/no questions because a ‘yes’ answer to Q1 generally implies a ‘yes’ answer to Q3. Table 1 enumerates the 12 options, and places the most popular models. Three features emerge:

   1. The most popular models tend to cluster together, making them difficult to easily distinguish from one another.
   2. Models are not completely clustered so experiments can immediately provide some information about the viability of some popular models.
   3. Some categories are empty in Table 1, indicating a failure of theoretical imagination. Should experiments point us to the empty slots, theorists will fill them, so we must bear in mind they can exist.

   Similarly general statements may be made concerning the finer distinctions amongst models sharing one of the entries of the Table. For instance loop corrections to Yukawa couplings are known to distinguish supersymmetric models from some 2HDMs. We show how these arguments rely on an underlying chiral symmetry, and so apply more generally than to these two alternatives. Alternatively, by comparing general expressions for \(hWW\) and \(hZZ\) couplings in multi-Higgs models, we find general inequalities which these couplings must satisfy, depending on the electroweak representation filled out by the various Higgses.

### ACKNOWLEDGMENTS

Support from N.S.E.R.C. (Canada), F.C.A.R. (Québec), DoE Grant No. DE-FG02-94ER40823 (US), the Ambrose Monell Foundation and a Marie Curie EC grant (TMR-ERBFMBICT 972147) is gratefully acknowledged.

[2] Theoretical discussions may be found in the contributions of Klaus Desch and Jan Kalinowski to this volume.
<table>
<thead>
<tr>
<th>Class</th>
<th>Examples</th>
<th>Q1</th>
<th>Q2</th>
<th>Q3</th>
<th>Q4</th>
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<tr>
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<td>SM, 2HDM (+), LRSM (+), SUSY (+)</td>
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<td>Y</td>
<td>Y</td>
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<tr>
<td>II</td>
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<td>Y</td>
<td>Y</td>
<td>N</td>
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<td>Y</td>
<td>N</td>
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<td>Y</td>
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<tr>
<td>IV</td>
<td>TechniPGBs, LRSM ($-$), 2HDM ($-$), SUSY ($-$)</td>
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<td>Y</td>
<td>Y</td>
<td>Y</td>
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<tr>
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<td>Higher Representation (+)</td>
<td>Y</td>
<td>N</td>
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</table>

**Table I.** The twelve categories of models, based on the size of their effective couplings. The positions of some representative models are indicated, where CP conserving scalar couplings are assumed for simplicity. ($\pm$) denotes the CP quantum number of the observed light scalar state. A $\nu$ in brackets indicates that the large Yukawa coupling may be restricted to neutrinos only. Categories XIII through XVI are not listed because models having $O(e)$ couplings to the $W$ and $Z$ generally also have $O(\alpha/2\pi)$ effective couplings to photons. Triplet indicates a doublet-triplet model for which the observed light scalar is dominantly from the triplet component.