HIGGS LOOK-ALIKES AT THE LHC

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• Alvaro De Rujula, J.L., Maurizio Pierini, Chris Rogan, Maria Spiropulu, arXiv:1001.5300
• Ian Low and J.L., arXiv:1005.0872
• +500 other papers going back 30 years
Higgs look-alikes

• Suppose your favorite LHC experiment sees a resonant signal with ~10 to 100 signal events

• How do we determine that this is the neutral CP-even spin 0 component of a \((2_L, 2_R)\) of \(SU(2)_L \times SU(2)_R\) predicted by the Standard Model, or a look-alike?

• How many Higgs look-alike candidates can you eliminate at or around the time of discovery?
The post-discovery LHC Higgs challenge

- Note that answering this question comes before the eventual precision extraction of the parameters of the Higgs sector (see talks by Tilman Plehn and Tao Han)

- A simpler question: How many Higgs look-alike candidates can you eliminate at or around the time of discovery by looking at distributions and correlations in the 4 lepton final state?
Factorizing the problem

- Distributions and correlations in the 4 lepton final state
- Production (gluon fusion, VBF, ...)
- Correlations with signals (or lack of signals) in other channels
  (see talk by Ian Low)
The golden Higgs channel at the LHC

- The leptonic decay $h \rightarrow ZZ \rightarrow 4\ell$ has a small branching fraction but provides a (relatively) clean and fully-reconstructable final state.
- The Z bosons don’t have to be on shell!
- Relevant for SM Higgs mass above about $\sim 130$ GeV.
ATLAS and CMS can measure the 4-lepton final state with exquisite precision

So you can choose any basis you want for your 12 observables without losing experimental realism
The 12 observables of the fully reconstructed event

- To get from the lab frame to the Higgs rest frame, I need to specify a boost and the direction of the boost, which is given by two angles:
  \[ \gamma_h, \theta_h, \phi_h \]

- I need to specify the reconstructed Higgs mass
  \[ M_h \]

- In the Higgs rest frame, by convention, take the positive z-axis to be along the direction of motion of \( Z_2 \), then use two angles to specify the direction of one of the incoming partons (note 2-fold ambiguity)
  \[ \Theta, \Phi \]

- Z decay involves another pair of angles measured in the Z rest frame, with the polar angle measured wrt the z-axis defined above. We also need the two boosts from the Higgs rest frame to the Z rest frames, \( \gamma_1, \gamma_2 \), which is equivalent to specifying the (possibly off-shell) Z masses:
  \[ m_1, \theta_1, \phi_1, \quad m_2, \theta_2, \phi_2 \]
8 angles!

• In the spirit of factorization, we will (for now) ignore the two production angles $\theta_h$, $\phi_h$

• If the resonance is a spin 0 particle, the signal distribution will be isotropic (i.e. flat) in the $h \to ZZ$ angles $\Theta$, $\Phi$

• Twenty-year-old common wisdom says that therefore we should ignore these angles as well

• Is this reasonable?
No!

- If we want to test that the Higgs is a Higgs, and not a higher spin look-alike, then we should use the $h \rightarrow ZZ$ angles $\Theta, \Phi$ as discriminators.

- Furthermore, even for the spin 0 case, it is NOT TRUE that the distributions are flat in these angles, after we take into account realistic detector effects:
Detector phase space sculpting is important

- They create non-flat distributions from flat ones, create asymmetries, and distort the underlying parton-level distributions

\[ p_T > 10 \text{ GeV} \]

\[ |\eta| < 2.3 \]
Correlations are important

$m_H = 200 \text{ GeV}$
Example of an unexpected correlation in the off-shell case: the Rogan flip for spin 1

\[ m_H = 200 \, \text{GeV} \]

\[ m_H = 145 \, \text{GeV} \]
Example of an unexpected correlation in the off-shell case: the Rogan flip for spin 1

- the full decay amplitude is of course symmetric under interchange of the two Z bosons:

\[ 2m_Z^2 \sin^2 \theta_1 + 2m_1^2 \sin^2 \theta_2 - (m_1^2 + m_2^2) \sin \theta_1 \sin \theta_2 \]

- but if one Z is on shell and the other is far off shell, it is more appropriate to write the above as:

\[ 2m_Z^2 (\sin^2 \theta_1 + \sin^2 \theta_2 - \sin^2 \theta_1 \sin^2 \theta_2) - (m_2^2 - m_1^2) \sin \theta_1 (2 - \sin^2 \theta_2) \]

- for \( m_2 < 49 \text{ GeV} \) the negative piece wins and you get the Rogan flip
Phase space sculpting also creates correlations

\[ m_H = 145 \text{ GeV} \]  

flat matrix element
What about the backgrounds?

- Although there is a fairly large irreducible background from ZZ production, this can be “subtracted” using a fit+weighting scheme called sPlots.
General couplings of Higgs Look-alikes to ZZ

• Allow couplings up to dimension 6

• Allow spin 0, 1, 2, and all possible C and P

• Note includes derivative couplings as would occur e.g. from expanding the form factor of a composite spin 0

\[ L^0_{\mu\nu} = X g_{\mu\nu} - (Y + iZ) \frac{p^h_{\mu} p^h_{\nu}}{M^2_Z} + (P + iQ) \epsilon_{\mu\nu\rho\sigma} \frac{p_1^\rho p_2^\sigma}{M^2_Z} \]

\[ L^1_{\mu\nu\rho} = X (g^{\mu\nu} p_1^\rho + g^{\mu\rho} p_2^\nu) + (P + iQ) \epsilon_{\mu\nu\rho\sigma} (p_1^\sigma - p_2^\sigma) \]

\[ L^2_{\mu\nu\rho\sigma} = M^2 h X_0 g^{\mu\rho} g^{\nu\sigma} + (X_1 + iY_1) (p_1^\nu p_2^\rho g^{\sigma\mu} + p_2^\mu p_1^\rho g^{\sigma\nu}) \]
\[ + (X_2 + iY_2) g^{\mu\nu} p_1^\rho p_2^\sigma + (P + iQ) \epsilon_\alpha^{\rho\mu\nu} (p_1^\alpha p_2^\sigma - p_2^\alpha p_1^\sigma) \]
fully-differential decay widths

- **SM Higgs**

\[
\frac{d\Gamma[0^+]}{dc_1\, dc_2\, d\phi} \propto m_1^2 \, m_2^2 \, m_H^4 \left[ 1 + c_1^2 \, c_2^2 + (\gamma_b^2 + c^2) s_1^2 s_2^2 \right.
\]

\[
\left. + 2\gamma_a \, c \, s_1 \, s_2 \, c_1 \, c_2 + 2\eta^2 (c_1 \, c_2 + \gamma_a \, c \, s_1 \, s_2) \right].
\]

(14)

- **pure 1-**

\[
4m_1^2 m_2^2 \Sigma^2 \gamma_b^2 \left[ g_1 S_2^2 s_2^2 \left( 2\ell_0^2 m_d^2 - \ell^2 m_H^2 [m_1^2 \cos(2\varphi_1) + m_2^2 \cos(2\varphi_2)] \right) \right.
\]

\[
\left. + g_1 \ell^2 m_H^4 (1 + C^2) \left[ 2m_2^2 s_1^2 + 2m_1^2 s_2^2 - (m_1^2 + m_2^2) s_1^2 s_2^2 \right] + 4\ell_0 g_1 m_H m_d^2 C S \left[ m_1 c_1 s_1 s_2 \sin \varphi_1 - m_2 c_2 s_2 s_1 \sin \varphi_2 \right] - 2\ell^2 m_H^4 m_1 m_2 s_1 s_2 \left[ (1 + C^2)(g_1 c_1 c_2 - g_{\sigma \sigma}) \cos(\varphi_1 - \varphi_2) + S^2 (g_1 c_1 c_2 + g_{\sigma \sigma}) \cos(\varphi_1 + \varphi_2) \right] \right].
\]

- **pure 1+**

\[
P^2 \left[ \ell^2 g_1 m_H^2 S^2 s_1^2 s_2^2 \left[ M_2^4 m_1^2 \cos(2\varphi_1) + M_1^4 m_2^2 \cos(2\varphi_2) \right] \right.
\]

\[
\left. + 8\ell_0^2 m_1^2 m_2^2 m_d^4 S^2 \left[ g_1 (c_1^2 + c_2^2 + s_1^2 s_2^2 \sin(\varphi_1 - \varphi_2)^2) + 2g_{\sigma \sigma} c_1 c_2 \right] \right.
\]

\[
\left. + (1 + C^2) \ell^2 g_1 m_H^2 \left[ 2M_1^2 m_2^2 s_1^2 + 2M_2^2 m_1^2 s_2^2 - (M_1^2 m_1^2 + M_2^2 m_2^2) s_1^2 s_2^2 \right] \right.
\]

\[
\left. - 8\ell_0 m_H m_d^2 m_1 m_2 C S \left[ M_2^4 m_1 s_2 \left( g_1 c_2 s_1^2 \sin \varphi_1 \cos(\varphi_1 - \varphi_2) + c_1 (g_1 c_1 c_2 + g_{\sigma \sigma}) \sin \varphi_2 \right) \right. \right.
\]

\[
\left. - M_1^4 m_2 s_1 \left( g_1 c_1 s_2^2 \sin \varphi_2 \cos(\varphi_1 - \varphi_2) + c_2 (g_1 c_1 c_2 + g_{\sigma \sigma}) \sin \varphi_1 \right) \right] \right.
\]

\[
\left. + 2\ell^2 m_H^4 M_1^2 M_2^2 m_1 m_2 s_1 s_2 \left[ (1 + C^2)(g_1 c_1 c_2 - g_{\sigma \sigma}) \cos(\varphi_1 - \varphi_2) - S^2 (g_1 c_1 c_2 + g_{\sigma \sigma}) \cos(\varphi_1 + \varphi_2) \right] \right].
\]

Note for spin 1 we symmetrized over the quark vs antiquark directions in the initial state.
Hypothesis testing with likelihood ratios

\[ H_0 = 0^- \quad H_1 = 0^+ \quad \Lambda = \log (\mathcal{L}_{0^+} / \mathcal{L}_{0^-}) \]

Neyman-Pearson (NP) simple hypothesis test

Risk of the 1st type:

\[ \alpha = \int_{-\infty}^{\Lambda} P(\Lambda|H_0) d\Lambda \]

Risk of the 2nd type:

\[ \int_{-\infty}^{\Lambda} P(\Lambda|H_1) d\Lambda = \beta \]

Power of the test:

\[ 1 - \beta \]
Example of hypothesis testing: Higgs or no Higgs?
Example: $0^+ \text{ vs. } 0^-$

Consider the case when we are trying to distinguish between $0^+$ vs. $0^-$ resonances:

\[
\gamma_a = \frac{1}{2m_1 m_2} \left[ m_H^2 - m_1^2 - m_2^2 \right]
\]

\[
\cos \theta_i = c_i, \ \sin \varphi = s
\]

\[
\eta = \frac{2 c_v v_a}{(c_v^2 + c_a^2)} \approx 0.15
\]

The standard Higgs, $J^{PC} = 0^{++}$

\[
|\mathcal{M}[0^+]|^2 \equiv \frac{d\Gamma[0^+]}{dc_1 dc_2 d\varphi} \propto m_1^2 m_2^2
\]

\[
\{ 2 (c_1 c_2 + c s_1 s_2 \gamma_a) \eta^2 + s_1^2 s_2^2 \gamma_a^2 + \frac{1}{2} [(2 c^2 - 1) s_1^2 s_2^2 + (c_1^2 + 1) (c_2^2 + 1)] + 2 c c_1 c_2 s_1 s_2 \gamma_a \}
\]

A pure pseudoscalar, $J^{PC} = 0^{--}$

\[
|\mathcal{M}[0^-]|^2 \equiv \frac{d\Gamma[0^-]}{dc_1 dc_2 d\varphi} \propto m_1^4 m_2^4 \gamma_b^2
\]

\[
(c_1^2 c_2^2 + 2 \eta^2 c_1 c_2 - c^2 s_1^2 s_2^2 + 1)
\]
Simple hypothesis test results, 0+ versus 0-
What happens if you ignore the correlations or ignore one of the discriminating variables?
0+ versus a little bit of mixed CP

\[ L_{\mu \alpha} \propto \cos(\xi_{XP}) g_{\mu \alpha} + \sin(\xi_{XP}) \epsilon_{\mu \alpha p_1 p_2}/M_Z^2 \]

**how small an admixture can I exclude when in fact it is an SM Higgs?**

![Graph showing significance for excluding values of $\xi_{XP}$ in the CP-violating $J=0$ hypothesis in favor of the $0^+$ one, assumed to be correct, for $m_H=350$ GeV/c$^2$ and $N_S=50$. The dashed line corresponds to the median of the significance. The 1 and 2 $\sigma$ bands correspond to 68% and 95% confidence intervals centered on the median value.](image)

**how large does the admixture have to be before I will be able to exclude the SM?**

![Graph showing the significance for excluding a pure $0^+$ in favor of a CP-violating $HZZ$ coupling ($\xi_{XP} \neq 0$), assuming the latter to be correct, with $\xi_{XP}$ given by its x-axis values. Example for $N_S=50$, $m_H=350$ GeV/c$^2$. Dashed line and bands as in Fig. 37.](image)
0+ versus a little bit of mixed CP

$$\mathcal{L}_{\mu\alpha} \propto \cos(\xi_{XP}) g_{\mu\alpha} + \sin(\xi_{XP}) \epsilon_{\mu\alpha} p_1 p_2 / M_Z^2$$

how small an admixture can I exclude when in fact it is an SM Higgs? how large does the admixture have to be before I will be able to exclude the SM?
0+ versus any possible spin 1 look-alike

\[ \mathcal{L}^{\rho\mu\alpha} \propto \cos \xi (g^{\rho\mu} p_1^\alpha + g^{\rho\alpha} p_2^\mu) + e^{i\delta} \sin \xi \epsilon^{\rho\mu\alpha}(p_1 - p_2) \]

how well do I exclude arbitrary spin 1 when in fact I have a SM Higgs?

how well do I exclude an SM Higgs when in fact I have some arbitrary spin 1?

for SM Higgs masses (145, 200, 350) GeV we can exclude the general spin 1 hypothesis at 5 sigma with (60, 200, 85) signal events
discriminating Higgs look-alikes at the moment of discovery

- **number of signal events required for**
  (median expected ) 3 sigma discrimination:

<table>
<thead>
<tr>
<th>$H_0 \Downarrow H_1 \Rightarrow$</th>
<th>$0^+$</th>
<th>$0^-$</th>
<th>$1^-$</th>
<th>$1^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^+$</td>
<td>–</td>
<td>17</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>$0^-$</td>
<td>14</td>
<td>–</td>
<td>11</td>
<td>17</td>
</tr>
<tr>
<td>$1^-$</td>
<td>11</td>
<td>11</td>
<td>–</td>
<td>35</td>
</tr>
<tr>
<td>$1^+$</td>
<td>17</td>
<td>18</td>
<td>34</td>
<td>–</td>
</tr>
</tbody>
</table>

**TABLE I**: Minimum number of observed events such that the median significance for rejecting $H_0$ in favor of the hypothesis $H_1$ (assuming $H_1$ is right) exceeds $3 \sigma$ with $m_H=145 \text{ GeV}/c^2$.

<table>
<thead>
<tr>
<th>$H_0 \Downarrow H_1 \Rightarrow$</th>
<th>$0^+$</th>
<th>$0^-$</th>
<th>$1^-$</th>
<th>$1^+$</th>
<th>$2^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^+$</td>
<td>–</td>
<td>24</td>
<td>45</td>
<td>62</td>
<td>86</td>
</tr>
<tr>
<td>$0^-$</td>
<td>19</td>
<td>–</td>
<td>19</td>
<td>19</td>
<td>38</td>
</tr>
<tr>
<td>$1^-$</td>
<td>40</td>
<td>18</td>
<td>–</td>
<td>90</td>
<td>48</td>
</tr>
<tr>
<td>$1^+$</td>
<td>56</td>
<td>19</td>
<td>85</td>
<td>–</td>
<td>66</td>
</tr>
<tr>
<td>$2^+$</td>
<td>86</td>
<td>45</td>
<td>54</td>
<td>70</td>
<td>–</td>
</tr>
</tbody>
</table>

**TABLE III**: Minimum number of observed events such that the median significance for rejecting $H_0$ in favor of the hypothesis $H_1$ (assuming $H_1$ is right) exceeds $3 \sigma$ with $m_H=200 \text{ GeV}/c^2$. 

26
The importance of using all the information

- All angles+correlations
- All angles, no correlations
- Just the $ZZ \rightarrow \mu^- \mu^+ e^- e^+$ angles $\theta_1, \theta_2, \phi$
- Same as above, and integrating over the $h \rightarrow ZZ$ angles $\Theta, \Phi$
Higgs electroweak look-alikes

• OK so you discovered a neutral resonance and used the first 20 events in the ZZ golden mode to exclude higher spins, large CP admixtures, etc.

• But is this particle the SM Higgs of electroweak symmetry breaking?

• Can we pin down the electroweak properties of the neutral resonance by measuring its branching fractions into electroweak vector bosons?

\[ h \rightarrow W^+ W^-, \ ZZ, \ \gamma \gamma, \ Z\gamma \]

• what look-alikes should we worry about?

• do we need to measure all four branching fractions?

• see talk by Ian Low
Higgs electroweak look-alikes

\[ h \rightarrow W^+W^-, \ ZZ, \ \gamma\gamma, \ Z\gamma \]

• Can do a general analysis making one additional assumption: the look-alike electroweak sector still respects custodial symmetry

• Thus the only look-alikes we have to worry about transform like some \((N_L, N_R)\) under the global \(SU(2)_L \times SU(2)_R\) of which custodial \(SU(2)_C\) is the diagonal remnant after EWSB
what look-alikes should we worry about?

\[ h \rightarrow W^+W^-, ZZ, \gamma\gamma, Z\gamma \]

- \((1_L, 1_R)\) an electroweak singlet with dimension 5 couplings to VV
- \((2_L, 2_R)\) the SM case
- \((3_L, 3_R)\) the custodial symmetry preserving combination of a real and a complex \(SU(2)_L\) triplet
- \((4_L, 4_R)\) some weird thing nobody bothers to talk about

In the last three cases we have dimension 4 couplings to WW and ZZ

\[ g_{h_1^{0}WW} = g_{h_1^{0}ZZ} c_w^2 = \sqrt{\frac{N^2 - 1}{3}} g m_W \]
do we need to measure all four branching fractions?

\[ h \rightarrow W^+W^-, \ ZZ, \ \gamma\gamma, \ Z\gamma \]

Yes

<table>
<thead>
<tr>
<th>(m_S) (GeV)</th>
<th>(Br(\gamma\gamma/WW))</th>
<th>(Br(ZZ/WW))</th>
<th>(Br(Z\gamma/WW))</th>
</tr>
</thead>
<tbody>
<tr>
<td>115</td>
<td>(2.7 \times 10^{-2}) ((2.7 \times 10^{-2}))</td>
<td>(5.1 \times 10^{-2}) (0.11)</td>
<td>39 ((9.0 \times 10^{-3}))</td>
</tr>
<tr>
<td>120</td>
<td>(1.7 \times 10^{-2}) ((1.7 \times 10^{-2}))</td>
<td>(5.7 \times 10^{-2}) (0.11)</td>
<td>35 ((8.2 \times 10^{-3}))</td>
</tr>
<tr>
<td>130</td>
<td>(7.8 \times 10^{-3}) ((7.8 \times 10^{-3}))</td>
<td>(6.7 \times 10^{-2}) (0.13)</td>
<td>26 ((6.7 \times 10^{-3}))</td>
</tr>
<tr>
<td>140</td>
<td>(4.0 \times 10^{-3}) ((4.0 \times 10^{-3}))</td>
<td>(7.1 \times 10^{-2}) (0.14)</td>
<td>18 ((5.1 \times 10^{-3}))</td>
</tr>
<tr>
<td>150</td>
<td>(2.0 \times 10^{-3}) ((2.0 \times 10^{-3}))</td>
<td>(6.4 \times 10^{-2}) (0.12)</td>
<td>10 ((3.5 \times 10^{-3}))</td>
</tr>
<tr>
<td>170</td>
<td>(1.6 \times 10^{-4}) ((1.6 \times 10^{-4}))</td>
<td>(1.4 \times 10^{-2}) ((2.3 \times 10^{-2}))</td>
<td>0.81 ((4.1 \times 10^{-4}))</td>
</tr>
</tbody>
</table>

**TABLE II:** Ratios of branching fractions for an electroweak singlet scalar when \(Br(\gamma\gamma/WW)\) is tuned to the SM value. The value in the parenthesis is for the corresponding SM prediction.
Conclusion

• The LHC will (we hope) discover Higgs-like resonances

• We have powerful tools to figure out the identity of what we find

• Most of this does not require 1000 fb-1 or an ILC, but it will require
  ▶ more work to get ready
  ▶ multi-channel searches
  ▶ some cooperation from Nature