Measuring the 2HDM potential: $hH$ associated production

Andrea Peterson
University of Wisconsin-Madison

with V. Barger, L. Everett, C. Jackson, and G. Shaughnessy
arXiv:1405.xxxx

May 6th, 2014 – Pheno 2014 – Pittsburgh, PA
Higgs pair production

- Higgs pair production provides insight into scalar sector and potential new physics
- Production through gluon fusion
- Contributions from box and triangle diagrams interfere

⇒ Implement $ggH$, $ggH$, and $gghH$ vertices in MadGraph5, including NNLO K-factor

see also V. Barger, L. Everett, C. Jackson, and G. Shaughnessy, arXiv:1311.2931
Potential includes three triscalar terms among CP-even Higgs bosons.

Couplings probed by multiple processes:

<table>
<thead>
<tr>
<th>Process</th>
<th>$\lambda^{hhh}$</th>
<th>$\lambda^{hhH}$</th>
<th>$\lambda^{hHH}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \rightarrow hh$ (continuum)</td>
<td>✓</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>$pp \rightarrow H \rightarrow hh$</td>
<td>✓</td>
<td>✓</td>
<td>×</td>
</tr>
<tr>
<td>$pp \rightarrow h^<em>/H^</em> \rightarrow hH$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Leave out for CP-odd Higgs for now, but $hA$ is also an interesting channel.
In Type-II 2HDM, triscalar (and Yukawa) couplings are set by model parameters ($M_H$, $M/M_H$, $\tan \beta$, $\cos(\beta - \alpha)$):

$$\lambda_{hhH} = \frac{\cos(\beta - \alpha) M^2 (\sin 2\beta - 3 \sin 2\alpha) + (2M_h^2 + M_H^2) \sin 2\alpha}{\sin 2\beta \frac{v}{\sin 2\beta}}$$

$$\approx \cos(\beta - \alpha) \frac{4M^2 - 2M_h^2 - M_H^2}{v} + O(\cos^2(\beta - \alpha))$$

$$\lambda_{hHH} = \frac{\sin(\beta - \alpha) M^2 (\sin 2\beta + 3 \sin 2\alpha) - (M_h^2 + 2M_H^2) \sin 2\alpha}{\sin 2\beta \frac{v}{\sin 2\beta}}$$

$$\approx \frac{-2M^2 + M_h^2 + 2M_H^2}{v} + O(\cos(\beta - \alpha))$$
Constraints

- Perturbative unitarity
- Bounded scalar potential
- Direct search for heavy Higgs

Fix $M/M_H = 0.8$, scan over $\tan \beta$, $\cos(\beta - \alpha)$, and $M_H$

Preliminary

grey = unitarity violated, pink = potential unstable
Let $h \rightarrow \gamma \gamma$ – low backgrounds

Consider two decay channels for $H$: $b\bar{b}$ and $hh \rightarrow 4b$
- Large branching fractions
- Sensitivity in different regions of $M_H$
- Ability to fully reconstruct events

Preliminary
The $b\bar{b}\gamma\gamma$ channel

- **Irreducible backgrounds:**
  - continuum $b\bar{b}\gamma\gamma$
  - $b\bar{b}h$, with $h \to \gamma\gamma$
  - $Zh$, with $Z \to bb$, $h \to \gamma\gamma$ (negligible for $M_{bb} > 100$ GeV)

- **Reducible backgrounds:**
  - $b\bar{b}e^+e^-$
  - $b\bar{b}j\gamma$
  - $b\bar{b}jj$
  - $jj\gamma\gamma$
  - $3j + \gamma$
  - $4j$ (negligible)

- Include tagging efficiencies and mistag rates for $e^\pm \to \gamma$, $j \to \gamma$, and $j \to b$
Substantial improvement in significance using MVA

Define MVA discriminant

\[ D = \frac{\prod_{i=1}^{N} \delta_i S(O_i)}{\prod_{i=1}^{N} \delta_i S(O_i) + \prod_{i=1}^{N} \delta_i B(O_i)} \]

Cut on \( D \) to isolate high-signal sample

Compute significance:

\[ S = 2 \left( \sqrt{S + B} - \sqrt{B} \right) \]

Bartsch and Quast, CERN-CMS-NOTE-2005-004
Multivariate Analysis

- Can toggle over included observables to maximize significance
- Best observable set for this channel:

\[ \mathcal{O} = \{ M_{b\bar{b}}, M_{\gamma\gamma}, p_T(b\bar{b}), p_T(\gamma\gamma) \} \]
The \( hh\gamma\gamma \rightarrow 4b + \gamma\gamma \) channel

- Only two important backgrounds:
  - continuum \( 4b + \gamma\gamma \)
  - \( b\bar{b}jj\gamma\gamma \)

- Total background very small
  - about 3 events at 3 \( ab^{-1} \)!
- MVA provides no advantage; cut based analysis best
- Cut on diphoton invariant mass eliminates most of the background

- Event reconstruction more complicated than \( b\bar{b}\gamma\gamma \) case
  - Daughters of heavy Higgs cluster together – cut on \( \Delta R(h_i; h_j) \)
LHC will be able to probe significant portion of parameter space

Sensitivity is best for small $\cos(\beta - \alpha)$ – a test of the decoupling limit!

$H \rightarrow b\bar{b}$ channel sensitive for small $M_H$, $H \rightarrow hh$ channel for $2M_h < M_H < 2m_t$
Measuring scalar couplings is an essential part of understanding the Higgs sector and testing for new physics.

$hH$ production directly probes couplings other processes don’t.

LHC can attain good reach, especially near the decoupling limit!
Backup: Effect of interference

The 2HDM: $hH$ associated production

\[ y_t^H = y_t^{SM} \]
\[ y_t^H = - y_t^{SM} \]

LHC 14 TeV

\[ \lambda_{hhH} = \lambda_{hHH} \text{ (GeV)} \]

\[ \sigma \text{ (pb)} \]

A. Peterson
The 2HDM: $hH$ associated production
Backup: Higgs identification

A. Peterson

The 2HDM: $hH$ associated production