Double Higgs Production in the Singlet Extended SM

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Higgs is Central

- Source of electroweak symmetry breaking in the Standard Model.
- Source of fundamental masses in the Standard Model.
- Completely predictive.
- Precision measurements of Higgs boson gives us insights into the nature of electroweak symmetry breaking.

Higgs decays at $m_H=125\text{GeV}$

![Graph showing Higgs decays at $m_H=125\text{GeV}$ with different decay channels and their respective fractions.]

- $WW$: 21%
- $gg$: 9%
- $\tau\tau$: 6%
- $cc$: 3%
- $ZZ$: 3%
- $bb$: 57%
- Other: 1%
Double Higgs Production

Double Higgs production depends on off-diagonal couplings. Single and double Higgs production depend on different couplings. Hope to change double Higgs rate substantially while keeping single Higgs rate the same as in SM.

What does bounding double Higgs rate tell us about new physics in loops?

In addition, sensitive to Higgs trilinear couplings.

- In SM, once Higgs mass known can completely solve for terms in potential.
- Need additional measurement to check the predictions.
- Directly measure shape of Higgs potential to determine origin of electroweak symmetry breaking.

$$V = -\mu^2 |\Phi|^2 + \lambda |\Phi|^4$$
Cross section of $\sim 36.8$ fb at 13 TeV at NNLO+NNLL de Florian, Mazzitelli PRL111 (2013) 201801, JHEP 1509 (2015) 053

Small rate due to strong destructive interference between triangle and box diagrams.

Most likely most sensitive final state is $gg \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$

Baur, Plehn, Rainwater, PRD69 (2004) 053004 Snowmass Higgs Working Group; Yao, 1308.6302:

<table>
<thead>
<tr>
<th>$S/\sqrt{B}$</th>
<th>14 TeV</th>
<th>33 TeV</th>
<th>100 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trilinear uncertainty</td>
<td>50%</td>
<td>20%</td>
<td>8%</td>
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</tbody>
</table>

ATLAS study showed sensitivity to $1.3\sigma$ and $-1.3 \lesssim \lambda/\lambda_{SM} \lesssim 8.7$ in $bb\gamma\gamma$ ATL-PHYS-PUB-2014-019

CMS showed $1.9\sigma$ evidence for $bb\gamma\gamma$, $bb\tau\tau$, $bbWW$ CMS PAS FTR-15-002
Singlet Scalar Extension
Introduce a real scalar $S$ singlet under SM gauge group.

Introduce $Z_2$ parity: $S \rightarrow -S$ and $SM \rightarrow SM$

Start with potential:

$$V(\Phi, S) = -\mu^2 \Phi^\dagger \Phi - m^2 S^2 + \lambda (\Phi^\dagger \Phi)^2 + \frac{a_2}{2} \Phi^\dagger \Phi S^2 + \frac{b_4}{4} S^4$$

- $\Phi$: SM Higgs doublet.

Two mass eigenstates:
- $h$ with mass $m_h = 125$ GeV.
- $H$ with mass $M_H > m_h$.

5 degrees of freedom:
- Masses of physical scalars: $m_h = 125$ GeV, $M_H$
- Mixing angle between scalars: $\theta$
  - $h = \cos \theta h_{SM} - \sin \theta s$
  - $H = \sin \theta h_{SM} + \cos \theta s$
- Vevs of the two scalars: $v = 246$ GeV, $\tan \beta = v/x$, where $\langle S \rangle = x/\sqrt{2}$
Relevant Feynman Rules in $Z_2$ Limit

- **Trilinear couplings:**

  \[ h h h - i \lambda_{hhh} \]

  \[ H h h - i \lambda_{Hhh} \]

- **Couplings to fermions:**

  \[ h t \bar{t} - i \cos \theta \frac{m_t}{v} \]

  \[ H t \bar{t} - i \sin \theta \frac{m_t}{v} \]

- **Couplings to gauge bosons:**

  \[ h V V i \cos \theta \frac{2m_V^2}{v} g_{\mu\nu} \]

  \[ H V V i \sin \theta \frac{2m_V^2}{v} g_{\mu\nu} \]

- Since couplings to gauge bosons and fermions proportional to SM couplings, heavy scalar produced through same mechanisms as SM-like scalar.
Branching Ratio Into Double Higgs

Dawson, IL PRD92 (2015) 094023

- **Black**: $\tan \beta = \sqrt{2} \frac{v}{\langle S \rangle} = 10$
- **Red**: $\tan \beta = \sqrt{2} \frac{v}{\langle S \rangle} = 1$

- Triple coupling: $\lambda_{Hhh} = \frac{m_h^2}{v} \sin 2\theta (\cos \theta + \sin \theta \tan \beta) \left( 1 + \frac{M_H^2}{2m_h^2} \right)$
Double Higgs Production

- 3-contributions:
  - Heavy resonance production (H-resonance).
  - Light off-shell resonance (h-resonance).
  - Box diagram.

- Refer to box diagram and h-resonance as "SM-like" contributions.
In limit $M_H \gg m_h$: $\lambda_{Hhh} \rightarrow \frac{M_H^2}{2v} \sin 2\theta (\cos \theta + \sin \theta \tan \beta)$

Hence, in limit $s, m_h^2 \ll M_H^2$, have $H$-propagator and coupling:

$$\frac{\lambda_{Hhh}v}{s - M_H^2 + i\Gamma_H M_H} \rightarrow -\frac{\sin 2\theta (\cos \theta + \sin \theta \tan \beta)}{2}$$

Production through $s$-channel $h$ and box diagrams have no explicit dependence on $M_H$. 

Dawson, IL PRD92 (2015) 094023
Total Contribution From Interference

- Fractional contribution from interference of $H$-resonance with other diagrams to total cross section.

- Fractional contribution of $H$-resonance to total cross sections.

Dawson, IL PRD92 (2015) 094023

Interference can make substantial contribution to total cross section and should be taken into account in experimental searches.
Can achieve significant enhancement over SM rate.
Enhancement to rate NLO very similar to enhancement at LO.
Narrow width approximation describes resonance very well, but not overall rate at high invariant masses.
Non $\mathbb{Z}_2$ Symmetric Case
More terms in potential:

\[ V(\Phi, S) = V_\Phi(\Phi) + V_{\Phi S}(\Phi, S) + V_S(S) \]

Higgs potential:

\[ V_\Phi(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \]

Scalar singlet potential:

\[ V_S(S) = b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4 \]

Mixing terms:

\[ V_{\Phi S}(\Phi, S) = \frac{a_1}{2} \Phi^\dagger \Phi S + \frac{a_2}{2} \Phi^\dagger \Phi S^2 \]

Additional terms complicate vacuum structure.

- Unlike $Z_2$ case, not all parameters solved in terms of masses, mixing, and vevs.
- Want to insure that $(\langle \Phi \rangle, \langle S \rangle) = (\nu/\sqrt{2}, 0)$ is the global minimum.
- $b_3$ and $b_4$ are completely free.
- Find a relationship between $b_2$ and $a_2$. 
Constraints from Global Minimum

Area inside curves have correct global minimum.

Effects phenomenology:

- Coupling between new heavy scalar and two light (observed) scalars:
  \[ \lambda_{Hhh} = \sin \theta \left[ -\frac{2m_1^2 + m_2^2}{v_{EW}} \cos^2 \theta - a_2 v_{EW} (1 - 3 \cos^2 \theta) + b_3 \sin(2\theta) \right] \]

- Limits how large BR\((H \rightarrow hh)\) can be.
Current Constraints

\[ \sqrt{S} = 8 \text{ TeV} \]

\[
\frac{\sigma^{\text{singlet}}}{\sigma_{\text{SM}}} \text{ (Ratio of rates)}
\]

- ATLAS observed 95% CL (\(\gamma\gamma b\bar{b}\))
- CMS observed 95% CL (\(\gamma\gamma b\bar{b}\))
- CMS observed 95% CL (\(b\bar{b}b\bar{b}\))

Allowed region for \(b_4=3, a_2=0\)

Allowed region for \(b_4=1, a_2=-1\)

\[ \chi^2 = 8 \text{ TeV}, L=20 \text{ fb}^{-1} \]

Experimental Bounds

Theoretical Bounds

Chen, Dawson, IL PRD91 (2015) 035015

BLACK: ATLAS \(\gamma\gamma b\bar{b}\)

RED: CMS \(b\bar{b}b\bar{b}\)

BLUE: CMS \(\gamma\gamma b\bar{b}\)

GREEN and MAGENTA: theory bounds.
Conclusions

- Discovered a Higgs boson with remarkably SM like properties.
  - Standard Model double Higgs very hard to measure.
    - Important for trilinear coupling measurement

In Singlet models, can get up to a factor of 20 increase over Standard Model double Higgs Production.

Interference effects between singlet resonance and SM-like contributions can be significant.

NLO QCD corrections increase rate by about a factor of two.

The ratio of the double Higgs rate in the Singlet model to the SM rate is insensitive to NLO corrections.
Total Contribution From Interference

- Fractional contribution from interference of $H$-resonance with other diagrams to total cross section.

- Fractional contribution of $H$-resonance to total cross sections.

Dawson, IL PRD92 (2015) 094023

Interference can make substantial contribution to total cross section and should be taken into account in experimental searches.
Comparison of Two Cases

Branching Ratio \( (h_2 \rightarrow h_1 h_1) \)

\( Z_2 \) Symmetric Model, \( \cos \theta = 0.94 \)

\[
\begin{align*}
\text{m}_2 &= 270 \text{ GeV} \\
\text{m}_2 &= 420 \text{ GeV} \\
\text{m}_2 &= 500 \text{ GeV}
\end{align*}
\]

\( Z_2 \) Symmetric Limit

\( Z_2 \) Nonsymmetric

\( a_2 = 0, b_4 = 1 \)

Chen, Dawson, IL PRD91 (2015) 035015

- Similar branching ratios, so similar conclusions.
Current Limits on Scalar Singlet

Limits from direct searches, $W$-mass, and Higgs measurements apply to non-$Z_2$.

Limits on $\tan \beta = \sqrt{2}v/\langle S \rangle$ come from perturbativity ($\sin \theta = 0.1$)\(^\text{104}^\text{104}$:

- for $M_H = 200$ GeV $\tan \beta \lesssim 1.5$
- for $M_H = 500$ GeV $\tan \beta \lesssim 0.5$.

See also Falkowski, Gross, Lebedev JHEP 1505 (2015) 057, Buttazzo, Sala, Tesi 1505.05488