Singlet Extension III: Resonant di-Higgs production

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Why go big?

- At high energy pp colliders, we can
  - Discover new particles
  - Precision measurement of Higgs self couplings (using double Higgs production)
- Address one of most fundamental issues, origin of electroweak symmetry breaking.
- Better understanding of the structure of the scalar potential
- Connection to electroweak baryogenesis
Goals

- Focus on collider study in a model with an additional **singlet** scalar
- In which part of parameter space can we have **big** enhancement of di-Higgs rate?
- Current constraints (both experimental and theoretical) on model parameters
Di-Higgs production in SM

\[ \sigma (pp \to HH + X) \text{ [fb]} \]

\[ M_H = 125 \text{ GeV} \]

\[ \sqrt{s} \text{ [TeV]} \]

[Baglio et al, 1212.5581]
Di-Higgs production in SM

- Dominant channel: Gluon fusion

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\[ gg \rightarrow HH \]

\[ qq' \rightarrow HHqq' \]

\[ qq'/gg \rightarrow t\bar{t}HH \]

\[ q\bar{q}' \rightarrow WHH \]

\[ q\bar{q} \rightarrow ZHH \]

[Baglio et al, 1212.5581]
Di-Higgs production in SM

- **Dominant channel:** Gluon fusion

![Diagram of Higgs production](image)

\[ \lambda_{hhh} \]

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Di-Higgs production in SM

- **Dominant channel:** Gluon fusion

1. How do they interfere?

2. Which diagram dominates?

![Graph showing production cross-sections](image)

\[ \sigma(pp \rightarrow HH + X) \text{ [fb]} \]

- \(M_H = 125 \text{ GeV}\)

- \(\sqrt{s} \text{ [TeV]}\)

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Di-Higgs production in SM

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1. How do they interfere? Ans: Destructive
2. Which diagram dominates? Ans: Box diagram

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14 TeV, cross section 40 fb

[Baglio et al, 1212.5581]
Di-Higgs production in SM

- Dominant channel: Gluon fusion

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   Ans: Box diagram

100 TeV, cross section ~ 1 pb

[Baglio et al, 1212.5581]
Collider study: di-Higgs production

- Using $\gamma\gamma b\bar{b}$ channel.
- Statistical significance: 1.3 sigma (ATLAS) with 3/ab at 14 TeV. 15 sigma (snowmass) with 3/ab at 100 TeV.
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- Higgs triple coupling can be measured with 15% statistical accuracy with 3/ab at 100 TeV (snowmass).
  
  [conference talk at HKUST by Yao, 2015]
- Barr et. al. 1412.7154: 40% with 3/ab at 100 TeV
- Azatov et. al. 1502.00539: 30% with 3/ab at 100 TeV
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- Barr et. al. 1412.7154: 40% with 3/ab at 100 TeV
- Azatov et. al. 1502.00539: 30% with 3/ab at 100 TeV
- Depending on efficiencies, background estimates, and approximations, etc.
Production cross section of di-Higgs can be enhanced due to the decay of heavy resonances in many new physics scenarios.

**BSM Models**

- **SM + Singlet**

[Liu, Wang and Zhu, 1310.3634]
[No and Ramsey-Musolf, 1310.6035]
[CC, Dawson and Lewis, 1410.5488]
Resonant di-Higgs production

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- BSM Models
  - SM + Singlet

  \[ h_1 \]

  Observed Higgs

  \[ \lambda_{111} \]

  [Liu, Wang and Zhu, 1310.3634]
  [No and Ramsey-Musolf, 1310.6035]
  Study \( b\bar{b}\tau^+\tau^- \) final state, discovery of the \( h_2 \) at the LHC may be achieved with \( \sim 100 \text{ fb}^{-1} \) at LHC14 for parameter points relevant to cosmology

  [CC, Dawson and Lewis, 1410.5488]
SM + Singlet

- SM Higgs doublet $H$ mixed with an additional singlet $S$. The singlet doesn’t couple to SM fermions and gauge bosons.

$$V = V_H + V_{HS} + V_S,$$
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\[
V_H(H) = -\mu^2 H^\dagger H + \lambda(H^\dagger H)^2
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$$V = V_H + V_{HS} + V_S, \quad V_H(H) = -\mu^2 H^\dagger H + \lambda(H^\dagger H)^2$$

$$V_S(S) = b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$
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*Keep it general.*

*No $\mathbb{Z}_2$ symmetry!*
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$Z_2$ symmetry: $S \rightarrow -S$
SM + Singlet

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$$V_H(H) = -\mu^2 H^\dagger H + \lambda(H^\dagger H)^2$$

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- Keep it general.
- No $Z_2$ symmetry!

- Mass eigenstates and mixing angle:

$$h_1 = h \cos \theta + S \sin \theta$$

$$h_2 = -h \sin \theta + S \cos \theta$$

- $h_1$ : the Higgs we observed; its couplings to fermions and gauge bosons are universally suppressed by a factor of $\cos \theta$.

- $h_2$ : Heavy Higgs; its couplings to fermions and gauge bosons are universally suppressed by a factor of $\sin \theta$. 
Shift invariance

A shift of the singlet field by $S \rightarrow S + \Delta S$ is just a redefinition of the parameters and does not change the physics.

The minimum of the potential is obtained by requiring

$$\frac{\partial V(v, x)}{\partial v} = 0 \text{ and } \frac{\partial V(v, x)}{\partial x} = 0$$

$$\frac{v}{\sqrt{2}} (-2\mu^2 + 2\lambda v^2 + a_1 x + a_2 x^2) = 0,$$

$$x(b_2 + b_3 x + b_4 x^2 + \frac{v^2}{2} a_2 x) + b_1 + \frac{v^2}{4} a_1 = 0.$$ 

It is always possible to choose a solution $(v, x) = (\sqrt{\frac{\mu^2}{\lambda}}, 0)$ provided $b_1 = -\frac{v^2}{4} a_1$. 

Couplings

- Higgs self potential in terms of mass eigenstates:

\[ V_{\text{self}} = \frac{\lambda_{111}}{3!} h_1^3 + \frac{\lambda_{211}}{2!} h_2 h_1^2 + \frac{\lambda_{221}}{2!} h_2^2 h_1 + \frac{\lambda_{222}}{3!} h_2^3 + \frac{\lambda_{1111}}{4!} h_1^4 + \frac{\lambda_{2111}}{3!} h_2 h_1^3 + \frac{\lambda_{2211}}{4} h_2^2 h_1^2 + \frac{\lambda_{2221}}{3!} h_2^3 h_1 + \frac{\lambda_{2222}}{4!} h_2^4. \]

\[
\begin{align*}
\lambda_{111} &= 2s^3b_3 + \frac{3a_1}{2}sc^2 + 3a_2s^2cv + 6c^3\lambda_v, \\
\lambda_{211} &= 2s^2cb_3 + \frac{a_1}{2}c(c^2 - 2s^2) + (2c^2 - s^2)sva_2 - 6\lambda sc^2v, \\
\lambda_{221} &= 2c^2sb_3 + \frac{a_1}{2}s(s^2 - 2c^2) - (2s^2 - c^2)cv a_2 + 6\lambda cs^2v, \\
\lambda_{222} &= 2c^3b_3 + \frac{3a_1}{2}cs^2 - 3a_2c^2sv - 6s^3\lambda_v,
\end{align*}
\]

- Relevant for di-Higgs resonant production

- One can increase the cross section of the di-Higgs production by tuning the value of \( b_3 \).

- Quartic couplings are not sensitive to EWPT, too small
Trilinear couplings

- Higgs self potential in terms of mass eigenstates:

\[
\begin{align*}
\lambda_{111} &= 2s^3b_3 + \frac{3a_1}{2}sc^2 + 3a_2s^2cv + 6c^3\lambda v, \\
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\lambda_{222} &= 2c^3b_3 + \frac{3a_1}{2}cs^2 - 3a_2c^2sv - 6s^3\lambda v,
\end{align*}
\]

Small angle approximation

\[
\begin{align*}
\lambda_{111} &\to 6\lambda v + \frac{3}{2}a_1s + 3vs^2(a_2 - 3\lambda) \quad &\text{sin }\theta \to 0 \\
\lambda_{211} &\to \frac{a_1}{2} + sv(-6\lambda + 2a_2) + \frac{s^2}{4}(8b_3 - 7a_1) \quad &0 \\
\lambda_{221} &\to 2sb_3 - a_1s + (1 - \frac{7}{2}s^2)va_2 + 6\lambda s^2v \quad &a_2v \\
\lambda_{222} &\to (2 - 3s^2)b_3 + \frac{3a_1}{2}s^2 - 3a_2sv, \quad &2b_3
\end{align*}
\]

- Trilinear couplings can potentially be sensitive to EWPT

\[
(a_1 = \frac{m_1^2 - m_2^2}{v_{EW}} \sin 2\theta)
\]
Counting parameters

❖ Model parameters:

\[ \mu, \lambda, a_1, a_2, b_1, b_2, b_3, \text{ and } b_4 \]

❖ Phenomenological parameters:

\[ m_1 = 126 \text{ GeV}, \ m_2, \ \theta, \ v_{EW} = 246 \text{ GeV}, \ x = 0, \ a_2, \ b_3, \ b_4 \]
Constraints on mixing angle

- **Light Higgs coupling** measurements:
  - Combined $h \to \gamma\gamma, ZZ^*, WW^*, \tau\tau, b\bar{b}$
  - Independent of branching ratios of new decay channels
  - $\sin^2 \theta < 0.12$

- **Heavy Higgs** searches:
  - Depend on branching ratios of new decay channels
  - Choose $B_{\text{new}} = 0$, $\sin^2 \theta < 0.2$ for $200 < m_{h_2} < 600 \text{ GeV}$

ATLAS-CONF-2014-010

arXiv: 1504.00936, CMS
Unitarity bound on $b_4$:

- relevant coupling:

$$\lambda_{2222} = 6(s^2 c^2 a_2 + c^4 b_4 + \lambda s^4)$$

High energy scattering of $h_2 h_2 \rightarrow h_2 h_2$. The $J = 0$ partial wave is

$$|\text{Re} \ a_0(h_2 h_2 \rightarrow h_2 h_2)| < \frac{1}{2}$$

$$|\text{Re} \ a_0(h_2 h_2 \rightarrow h_2 h_2)| \xrightarrow{s \gg m_2^2} \frac{3b_4}{8\pi}$$

$b_4 < 4.2$
Vacuum stability

- Vacuum stability requires the scalar potential to be positive definite as $h$ and $S$ become large.

\[ \lambda \text{ and } b_4 \text{ are positive definite} \]

- For $a_2 > 0$
  \[ \lambda h^4 + a_2 h^2 S^2 + b_4 S^4 > 0 \]
  \[ a_2 < \infty \]

- For $a_2 < 0$
  \[ (\sqrt{\frac{\lambda h^2}{2\lambda}} + \frac{a_2}{2\sqrt{\lambda}} S^2)^2 + (b_4 - \frac{a_2^2}{4\lambda}) S^4 > 0 \]
  \[ -4\lambda b_4 < a_2 \]
- Requiring that the global minimum is at \((v,x) = (246,0) \text{GeV}\), for \(m_2 = 270, 370, \text{ and } 500 \text{ GeV}\)
- Provides upper limits for \(a_2\) for a given value of \(b_3\)

\[
\begin{align*}
    b_4 &= 1 \\
    \cos \theta &= 0.94 \\
    m_1 &= 126 \text{ GeV}
\end{align*}
\]
Collider constraints on cross section at 8 TeV

![Graph showing cross section of di-Higgs production in the singlet model relative to the SM prediction at leading order.]

- Production cross section of di-Higgs in the singlet model relative to the SM prediction at leading order.
Collider constraints on cross section at 14 TeV

- Projected bounds based on expected 95%CL limits from ATLAS and CMS.
- Rule out the allowed region for $b_4=1$ and $a_2=-1$ (magenta) using CMS results.
Looking for big enhancement

$\sum_{\text{singlet}}$, $\sum_{\text{SM}}$

$b_4 = 1$, $a_2 = 0$,
$\cos \theta = 0.94$
$m_1 = 126$ GeV

Dashed line: Excluded by the EW minimum is the global minimum.
Solid line: Allowed range.
Differential cross section distributions

- Kinematic threshold $\sqrt{s} > 2m_h$
- Peak at $m_2$ due to resonance decay
- Cancellations occur near $2m_t$
- Pronounced peaks are useful for discovery of the heavy resonances.
**Take home messages**

- In the model with an additional singlet, the double Higgs rate could increase up to \(~20\) times of the SM prediction.
- LHC Run 2 can rule out large part of parameter space that is allowed by theoretical constraints.
- The coupling $b_3$ plays an important role in the enhancement of di-Higgs rate
- The Higgs self couplings in the singlet model can potentially be measured due to the large enhancement.
THANK YOU!
BACKUP SLIDES
The scalar mass matrix can be written as

\[ V_{\text{mass}} = \frac{1}{2} U M^2 U^T, \text{ where } U = \begin{pmatrix} h & S \end{pmatrix} \]

\[ M^2 = \begin{pmatrix} M_{11}^2 & M_{12}^2 \\ M_{12}^2 & M_{22}^2 \end{pmatrix} = \begin{pmatrix} 3\lambda v^2 - \mu^2 + x(a_1 + a_2 x)/2 & a_1 v/2 + a_2 v x \\ a_1 v/2 + a_2 v x & b_2 + a_2 v^2/2 + x(2b_3 + 3b_4 x) \end{pmatrix} \]

\[ \tan 2\theta = \frac{2M_{12}^2}{M_{11}^2 - M_{22}^2} \]

Diagonalize the mass matrix to obtain the mass eigenstates \( m_1 \) and \( m_2 \), and mixing angle \( \theta \)

Using \( m_1, m_2, \) and \( \theta \) as input parameters instead of \( \lambda, a_1, \) and \( b_2 \)
Branching ratios

- Assuming SM couplings: dominant decay channels of heavy Higgs are $WW$, $ZZ$ and $t\bar{t}$ (if $m_H > 350$ GeV)

$$\Gamma(H \rightarrow VV) \sim m_H^3$$
$$\Gamma(H \rightarrow f \bar{f}) \sim m_f^2$$

- If $Hhh$ coupling is large enough, $BR(H \rightarrow hh)$ can also be significant.
\[ \lambda_{211} = \sin \theta \left[ -\frac{2m_1^2 + m_2^2}{v_{EW}} \cos^2 \theta - a_2v_{EW} \left( 1 - 3 \cos^2 \theta \right) + b_3 \sin(2\theta) \right] \]

**BR**\( (h_2 \rightarrow h_1 h_1) \) v.s. \( b_3 \)
Collider constraints at 8 TeV

**ATLAS, 1406.5053**

- ATLAS $\gamma\gamma b\bar{b}$ channel.
Collider constraints at 8 TeV

- 4 b channel gives a better constraint for m_2 above 400 GeV.
Di-Higgs production: variation of triple coupling

- Competition between the triangle and box diagrams.

- Box diagram dominant
- Destructive interference between two diagrams
- Minimum occurs at $\lambda_{hhh} = 2.45 \times \lambda_{SM}^{hhh}$

\[ b_4 = 1 \]
\[ \cos \theta = 0.94 \]
\[ m_1 = 126 \text{ GeV} \]

\[ m_2 = 370 \text{ GeV} \]

\[ a_2 \]

\[ b_4 = 3 \]

\[ b_4 = 1 \]

- Constraint becomes weaker when increasing \( b_4 \).
## SENSITIVITY

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