Di-Higgs in Singlet Extensions

(arXiv:1701.08774, Ian M. Lewis, Matthew Sullivan;
arXiv:1711.06683, Sally Dawson, Matthew Sullivan)

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Motivation for Singlet Models

- The cubic terms in the Higgs potential can be measured via di-Higgs production, but the Higgs potential in the Standard Model is completely determined
- Adding scalar singlets is one of the simplest things to do in order to change the Higgs potential
- Singlet models provide a benchmark for new scalar searches, including resonant di-Higgs searches
- Singlets models are fairly generic

Real Singlet Extended Standard Model

- Add a real scalar gauge singlet S to the Standard Model
- Allow for all renormalizable terms with no additional symmetry

$$
\begin{aligned}
V(H,S) = & -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 \\
& + \frac{a_1}{2} H^\dagger H S + \frac{a_2}{2} H^\dagger H S^2 \\
& + b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4
\end{aligned}
$$

- S has no direct coupling to other Standard Model fields

Masses, vevs, and Mixing

- vevs are given by minima of the potential
- Expand H as $H = \begin{pmatrix} 0 \\ (h+v)/\sqrt{2} \end{pmatrix}$ with v being the vev of H
- Expand S as $S = s + x$ with x being the vev of S
- Mass eigenstates h_1 and h_2 are related to gauge eigenstates h and s:
$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$
- h_1 has mass m_1, h_2 has mass m_2

Theoretical Constraints

- Vacuum stability requires the potential to be bounded from below
- Requiring perturbative unitarity for SS to SS scattering at high energy places an upper bound on the quartic couplings
- The vacuum structure for the real singlet model is complicated, and there are multiple minima. Since the singlet does not play any role in mass generation, electroweak symmetry breaking requires the 246 GeV Higgs vev to be the global minimum.
    - This places limits on how large the cubics can be

Experimental Constraints

- Higgs signal strengths places a constraint of $\cos^2\theta \geq 0.88$ or $\sin^2\theta \leq 0.12$
  - Each Standard Model coupling to the 125 GeV Higgs is suppressed by $\cos\theta$
- There are also constraints from direct searches for heavy resonance decays to ZZ and W^+W^- which are competitive for some mass regions

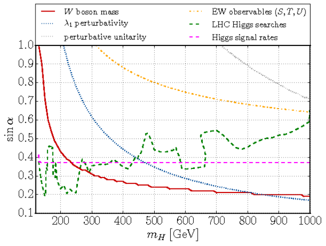
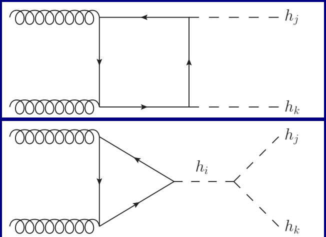


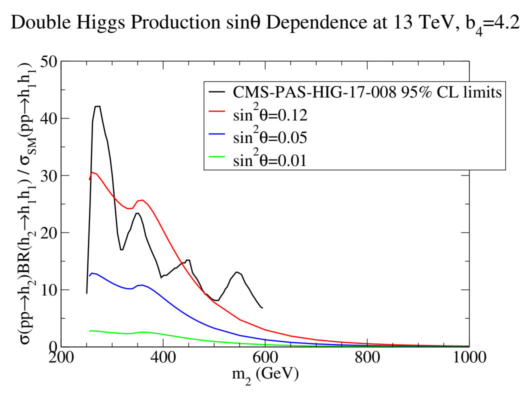
Figure from Ilnicka, Robens, and Stefaniak, 2018

Resonant Di-Higgs Production



- All diagrams contribute to di-Higgs production via gluon fusion
- Choosing $m_1 = 125$ GeV and $m_2 > 2m_1$, the triangle diagram with heavy scalar propagator leads to a resonant contribution
- With the narrow width approximation, we maximize the resonant production rate for different values of m_2 over the remaining parameters

Resonant Di-Higgs Production for Different $\sin^2\theta$ at 13 TeV



- $\sigma_{SM} = 32.91^{+13.6\%}_{-12.6\%}$ fb, NLO in QCD w/ full top mass effects
- Recent analysis (black) of 13 TeV constrains some regions
- At higher luminosity, θ will become more constrained

Complex Singlet Extended Standard Model

- Add a complex scalar gauge singlet S to the Standard Model
- Allow for all renormalizable terms with no additional symmetry

$$
\begin{aligned}
V(H,S) = {} & \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \left(\frac{\delta_1}{4} H^\dagger H S + c.c.\right) \\
& + \frac{\delta_2}{2} H^\dagger H |S|^2 + \left(\frac{\delta_3}{4} H^\dagger H S^2 + c.c.\right) \\
& + (a_1 S + c.c.) + \left(\frac{b_1}{4} S^2 + c.c.\right) + \frac{b_2}{2}|S|^2 \\
& + \left(\frac{c_1}{6} S^3 + c.c.\right) + \left(\frac{c_2}{6} S|S|^2 + c.c.\right) \\
& + \left(\frac{d_1}{8} S^4 + c.c.\right) + \left(\frac{d_3}{8} S^2|S|^2 + c.c.\right) + \frac{d_2}{4}|S|^4
\end{aligned}
$$

- Terms with $+c.c.$ have complex coefficients
- S has no direct coupling to other Standard Model fields

Masses, vevs, and Mixing in the Complex Model

- Expand H as $H = \begin{pmatrix} 0 \\ (h+v)/\sqrt{2} \end{pmatrix}$ with v being the vev of H
- Expand S as $S = (s + iA + x)/\sqrt{2}$ with x being the (complex) vev of S
- Mass eigenstates h_1, h_2, and h_3 are related to gauge eigenstates h, s, and A:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = V \begin{pmatrix} h \\ s \\ A \end{pmatrix} = \begin{pmatrix} \cos\theta_1 & -\sin\theta_1 & 0 \\ \sin\theta_1 \cos\theta_2 & \cos\theta_1 \cos\theta_2 & \sin\theta_2 \\ \sin\theta_1 \sin\theta_2 & \cos\theta_1 \sin\theta_2 & -\cos\theta_2 \end{pmatrix} \begin{pmatrix} h \\ s \\ A \end{pmatrix}$$

- θ_1 parametrizes how SM-like the h_1 state is
- θ_2 parametrizes how much the remaining SM-like Higgs couplings are spread between h_2 and h_3
- Note: all couplings to SM fields are Higgs-like, i.e. CP even

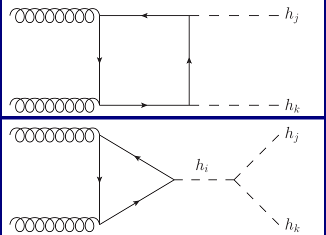
Theoretical Constraints for the Complex Singlet

- Vacuum stability requires the potential to be bounded from below
- Requiring perturbative unitarity for all 2 to 2 scattering processes involving scalars, including goldstones, at high energy places an upper bound on all quartics
- The vacuum structure for the complex singlet model is complicated, and there are several minima generically. Electroweak symmetry breaking requires the 246 GeV Higgs vev to be the global minimum.

Experimental Constraints for the Complex Singlet

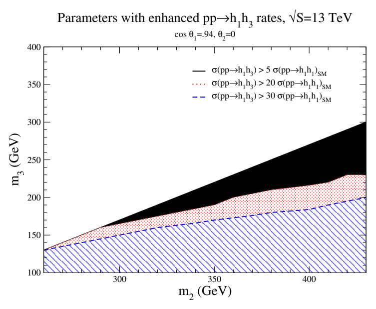
- Higgs signal strength measurements lead to $\cos^2\theta_1 \geq 0.88$ or $\sin^2\theta_1 \leq 0.12$
- We also calculated corrections to the oblique parameters at one loop order, and required consistency at the 95% confidence level
- There are again constraints from direct searches for heavy resonances decaying to ZZ and W^+W^-

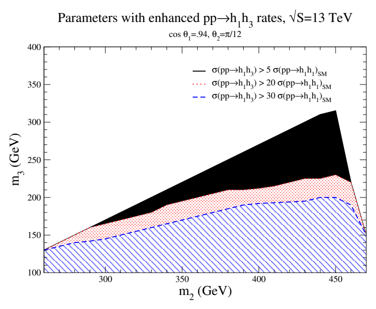
Which Resonant Di-Higgs Production Process?



- All diagrams with all scalars in the propagator of the triangle diagram contribute to di-Higgs production via gluon fusion, for any final state scalars
- With suitable masses, triangle diagrams with scalar propagator lead to resonant contributions
- Most interesting compared to the real singlet case is resonant production of two different scalars, e.g. $h_2 \rightarrow h_1 h_3$

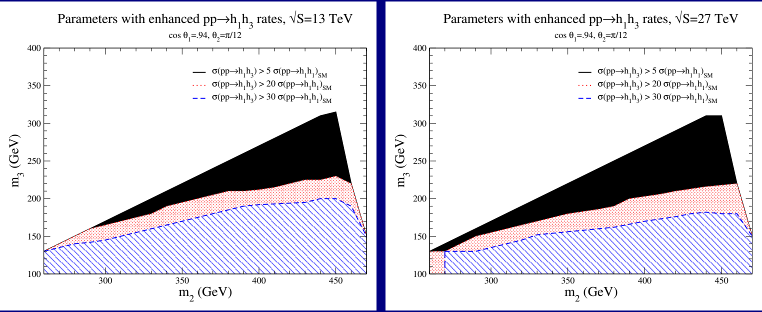
Resonant Production of Higgs and a New Scalar at 13 TeV





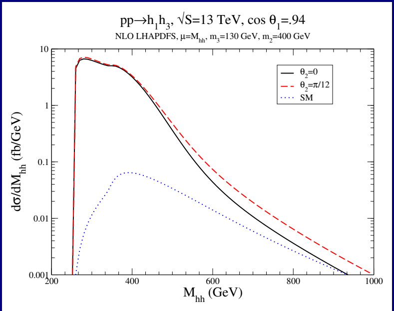
- Most interesting case is $\theta_2 \to 0$ where h_3 is not singly produced
- SM di-Higgs cross section reference is roughly 13 fb
- Calculated at leading order with all relevant diagrams

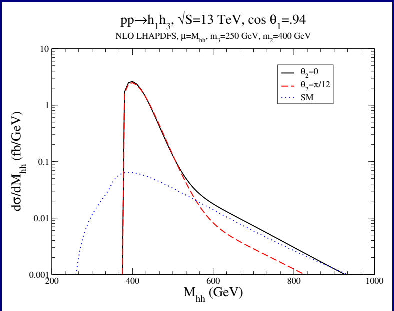
Comparison of 13 TeV and 27 TeV



- SM cross section is roughly 13 fb at 13 TeV, roughly 65 fb at 27 TeV
- Energy scaling is roughly the same for all parameter points, about a factor of 5 larger at 27 TeV

Some Invariant Mass Distributions





- Widths can be around 80% of the mass, so the resonances are wide

Decay of the h_3 into Standard Model States

- Couplings of h_3 to SM fermions and gauge bosons is Higgs-like with $\sin\theta_1 \sin\theta_2$ mixing suppression
- If $m_3 < 2m_1 = 250$ GeV:
  - h_3 would decay to Standard Model states like $b\bar{b}$ or W^+W^- with branching ratios like a SM-like Higgs boson of mass m_3, as long as the mixing is not extremely small
  - h_3 can be long lived when the mixing is small enough
  - If mixing is zero, off-shell decays to $h_1 h_1$ would be the main decay mode
- For $m_3 > 2m_1$, h_3 would be able to decay into $h_1 h_1$ on-shell, giving effectively tri-Higgs production

Summary

- Standard Model di-Higgs production is small, but resonant di-Higgs production is more viable for observation at the LHC
- The LHC is still sensitive to singlet models
- Real singlet model gives the chance for large resonant di-Higgs production enhancement of around a factor of 30
- Resonant production of 125 GeV Higgs and another scalar can be similarly large in complex singlet models
- New physics might only be seen in di-Higgs channels

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