Resonant Double Higgs Production in the Singlet Extended Standard Model at the LHC

(arXiv:1701.08774, Ian M. Lewis, Matthew Sullivan; ongoing work with Sally Dawson)

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Outline

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

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

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
- Diagonalize quadratic terms in potential to get masses
- 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

The Model's Parameters

- The eight original parameters can be written more usefully as m_1, m_2, θ, v, x, and three remaining independent parameters
- x, the vev of S is actually irrelevant
  - No new terms are introduced to the potential when S is shifted
  - What's important is what the parameters are in terms of the shifted s
  - We can fix a parameter such that S never gets a vev in the first place without any physical consequences
- So seven physical parameters can be m_1, m_2, θ, v, a_2, b_3, b_4

Parameter Relationships

- We want relationships between our seven physical parameters and the terms in our potential
- To reproduce $(v, x) = (v_{EW}, 0)$ minima:

$$\mu^2 = \lambda v_{EW}^2$$

$$b_1 = -\frac{v_{EW}^2}{4} a_1.$$

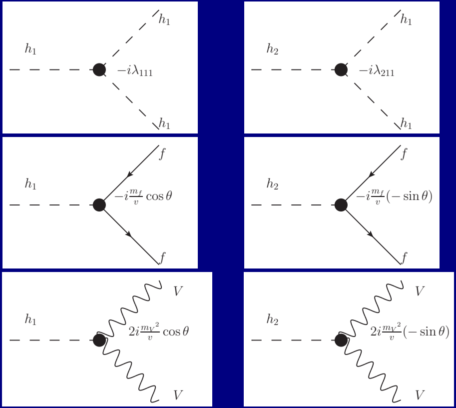
- To reproduce the masses and mixing angle:

$$a_1 = \frac{m_1^2 - m_2^2}{v_{EW}} \sin 2\theta$$

$$b_2 + \frac{a_2}{2} v_{EW}^2 = m_1^2 \sin^2\theta + m_2^2 \cos^2\theta$$

$$\lambda = \frac{m_1^2 \cos^2\theta + m_2^2 \sin^2\theta}{2 v_{EW}^2}.$$

Important Feynman Rules



- Trilinear and quartic couplings come from the potential
- Some trilinear couplings that will be relevant are λ_{211} and λ_{111}:

$$V(h_1, h_2) \supset \frac{\lambda_{111}}{3!} h_1^3 + \frac{\lambda_{211}}{2!} h_2 h_1^2$$

- Abbreviating $s = \sin\theta$, $c = \cos\theta$

$$\lambda_{111} = 2s^3 b_3 + \frac{3a_1}{2} sc^2 + 3a_2 s^2 cv + 6\lambda c^3 v$$

$$\lambda_{211} = 2s^2 cb_3 + \frac{a_1}{2} c(c^2 - 2s^2) + (2c^2 - s^2) sva_2 - 6\lambda sc^2 v$$

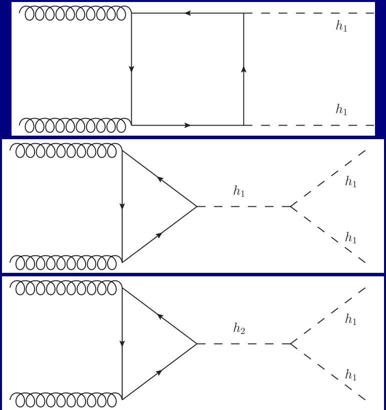
Theoretical Constraints

- Vacuum stability requires the potential to be bounded from below
  - $b_4 > 0$ is required
  - $\lambda > 0$ is required as well
    - Guaranteed as long as $m_2^2 > 0$ and $m_1^2 > 0$
  - $-2\sqrt{\lambda b_4} < a_2$ is also required
- Electroweak minimum should be the global minimum of the potential, not just an extremum
  - Need to check other extrema
- Requiring perturbative unitarity for $h_2 h_2 \to h_2 h_2$ at high energy places an upper bound on b_4

Experimental Constraints

- ATLAS 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 $\cos\theta$
- Constraints from direct searches for heavy resonance decays to ZZ and W^+W^- also must be satisfied, but these are weaker than the ATLAS bound

Resonant Double Higgs Production



- All three diagrams contribute to double Higgs production via gluon fusion
- Choosing $m_1 = 125$ GeV and $m_2 > 2m_1$, the third diagram 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

Maximization of Double Higgs Production

- Approximate resonant double Higgs production cross section:

$$\sigma(pp \to h_2)\mathrm{BR}(h_2 \to h_1 h_1)$$

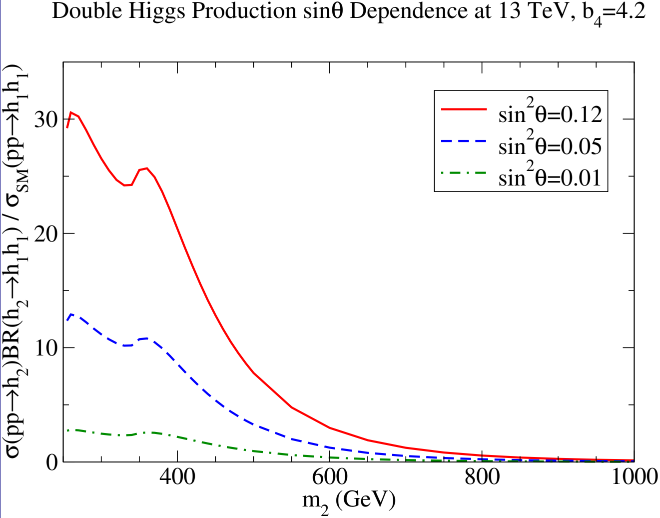
- All h_2 production cross sections and Standard Model-like decay widths are suppressed by $\sin^2\theta$ compared to a SM Higgs of the same mass
- Larger mixing angle increases production of h_2 but also increases width to SM particles
- Increased production wins out, and the largest resonant double higgs production occurs when $\sin^2\theta = 0.12$ at the ATLAS limit
- Problem reduces to maximizing the double Higgs branching ratio at the largest mixing angle

The Important Trilinear Coupling

$$\lambda_{211} = 2s^2cb_3 + \frac{a_1}{2}c(c^2 - 2s^2) + (2c^2 - s^2)sva_2 - 6\lambda sc^2v$$

- A larger magnitude of λ_{211} means a larger double Higgs partial width
- For fixed masses, vev, and mixing angle, the only free parameters are a_2, b_3, and b_4
- Only mass and mixing angle affect SM-like decay widths
- λ and a_1 don't depend on b_4
- The only free parameters that affect the trilinear coupling are b_3 and a_2
- Maximizing the partial width to double Higgs also maximized the branching ratio to double Higgs

Resonant Double Higgs Production for Different $\sin^2\theta$



$\sigma_{SM} = 32.91^{+13.6\%}_{-12.6\%}$ fb, NLO in QCD w/ full top mass effects

Preview of Complex Singlet Extended Standard Model

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

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 $S = (s + iA)/\sqrt{2} + x$ with x being the (complex) vev of S
- Diagonalize quadratic terms in potential to get three masses
- Mass eigenstates h_1, h_2, and h_3 are related to gauge eigenstates h, s, and A:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} \cos\theta_1 & -\cos\theta_3 \sin\theta_1 & -\sin\theta_1 \sin\theta_3 \\ \cos\theta_2 \sin\theta_1 & \cos\theta_1 \cos\theta_2 \cos\theta_3 - \sin\theta_2 \sin\theta_3 & \cos\theta_3 \sin\theta_2 + \cos\theta_1 \cos\theta_2 \sin\theta_3 \\ \sin\theta_1 \sin\theta_2 & \cos\theta_1 \cos\theta_3 \sin\theta_2 + \cos\theta_2 \sin\theta_3 & \cos\theta_1 \sin\theta_2 \sin\theta_3 - \cos\theta_2 \cos\theta_3 \end{pmatrix} \begin{pmatrix} h \\ s \\ A \end{pmatrix}$$

The Complex Model's Many Parameters

- There are originally 21 real parameters that be rewritten in a similar way to the real singlet
- S can be shifted like in the real case, removing the complex vev x by fixing 2 real parameters
- Unlike the real case, S can also be rotated by a phase arbitrarily, which can be used to eliminate the mixing angle θ_3
- Final parameters are 3 masses and 2 mixing angles, the vev v, plus all the quartic couplings (δ_2, δ_3, and all d parameters) and the S cubic couplings (the c parameters) remain free, just like the real singlet.
- With masses, mixings, and vev fixed, there are still 12 real parameters remaining

Simplified Mixing Matrix

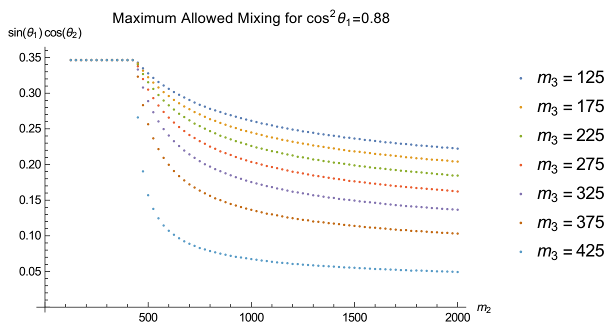
$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} \cos\theta_1 & -\sin\theta_1 & 0 \\ \cos\theta_2 \sin\theta_1 & \cos\theta_1 \cos\theta_2 & \sin\theta_2 \\ \sin\theta_1 \sin\theta_2 & \cos\theta_1 \sin\theta_2 & -\cos\theta_2 \end{pmatrix} \begin{pmatrix} h \\ s \\ A \end{pmatrix}$$

- θ_1 parametrizes how much the SM-like Higgs couplings of h_1 are suppressed
- θ_2 parametrizes how much the remaining SM-like Higgs couplings are spread between h_2 and h_3

Constraints for the Complex Singlet

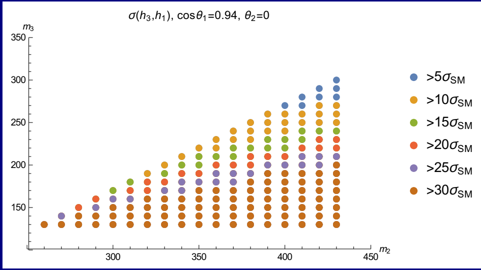
- Vacuum stability requires the potential to be bounded from below; closed form not known
- Electroweak minimum should be the global minimum of the potential, not just an extremum; closed form not nown
- Requiring perturbative unitarity for all 2 to 2 scattering processes involving scalars, including goldstones, at high energy places an upper bound on all quartics; closed form is in terms of roots of quartic equations
- ATLAS Higgs signal strengths lead to $\cos^2\theta_1 \geq 0.88$ or $\sin^2\theta_1 \leq 0.12$
- Constraints from direct searches for heavy resonance decays to ZZ and W^+W^- also must be satisfied
- We also require consistency with the oblique parameters at the 95% confidence level, calculated at one loop order

Masses and Mixings Allowed by Oblique Parameters



- Only interested in masses at least as heavy as the 125 GeV Higgs right now

Resonant Production of Higgs and a New Scalar at 13 TeV



- SM double Higgs cross section reference is roughly 13 fb
- If $m_2 > m_1 + m_3$, then we can get resonant production of h_1 and h_3
- Maximize the relevant trilinear for $h_3 h_2 h_1$ coupling
  - Without further constraints, the widths here can be 40% to 80% of the mass, and the resonance can be extremely wide
- Calculated at leading order with all relevant diagrams
  - $\theta_2 = 0$ means no box diagram in this case, though

Summary

- Standard Model double Higgs production is small, but resonant double Higgs production is more viable for observation at the LHC
- Best case scenario, 13 TeV double Higgs production cross section can be improved by around a factor of 30 over the Standard Model
- The parameter space of the real model can be reasonably probed at the LHC via resonant double Higgs production
- The complex model can lead to large resonant production for Higgs and a new scalar