Singlet Benchmarks for hh, hS, SS[1]

Matthew Sullivan

University of Kansas

June 25, 2019
LHCHXSWG

[1]Based on work by I. Lewis, M. Sullivan,
C-Y. Chen, S. Dawson, I. Lewis PRD91 (2015) 035015,
I. Lewis, M. Sullivan PRD96 (2017) 035037,
S. Dawson, M. Sullivan PRD97 (2018) 015022

Singlet Extensions of the Standard Model

- Can add a real or complex gauge singlet to the SM
- At the renormalizable level, only couples to the SM Higgs doublet
- Simple and useful BSM scenario for modifying the Higgs sector
  - Can result in a strong first order electroweak phase transition [2]
  - New scalar state(s) that can decay to SM states OR other scalar states when kinematically allowed

[2] see e.g. JHEP 1708 (2017) 098

Real Singlet Extension (no Z_2 symmetry)[3]

- The most general renormalizable potential:

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

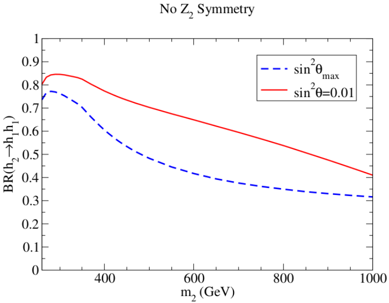
- Can choose $\langle S \rangle = 0$ with field redefinitions
- Obtain mass eigenstates h_1, h_2 with masses $m_1 = 125$ GeV and m_2 from mixing:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

- Want to satisfy global minimization of EW vacuum, perturbative unitarity, and vacuum stability

[3] based on C-Y. Chen, S. Dawson, I. Lewis PRD91 (2015) 035015, I. Lewis, M. Sullivan PRD96 (2017) 035037

$S \to hh$ Benchmarks for Real Singlet Model



- Maximum BR($h_2 \to h_1 h_1$) subjected to theoretical constraints
- Higgs precision gives $\sin\theta_{max} = 0.22$ for $m_2 < 650$ GeV
- W-mass constraints give $\sin\theta_{max} = 0.21$ for $m_2 > 650$ GeV

Complex Singlet Extension (no Z_2, $U(1)$ symmetries)[4]

- The most general renormalizable potential:

$$
\begin{aligned}
V(\Phi, S_c) = & \frac{\mu^2}{2}\Phi^\dagger\Phi + \frac{\lambda}{4}(\Phi^\dagger\Phi)^2 + \Big(\frac{1}{4}\delta_1\Phi^\dagger\Phi S_c + \frac{1}{4}\delta_3\Phi^\dagger\Phi S_c^2 \\
& + a_1 S_c + \frac{1}{4}b_1 S_c^2 + \frac{1}{6}e_1 S_c^3 + \frac{1}{6}e_2 S_c \mid S_c \mid^2 \\
& + \frac{1}{8}d_1 S_c^4 + \frac{1}{8}d_3 S_c^2 \mid S_c \mid^2 + h.c.\Big) \\
& + \frac{1}{4}d_2(\mid S_c \mid^2)^2 + \frac{\delta_2}{2}\Phi^\dagger\Phi \mid S_c \mid^2 + \frac{1}{2}b_2 \mid S_c \mid^2
\end{aligned}
$$

- Can choose $\langle S_c \rangle = 0 + 0i$ with field redefinitions
- Require perturbative unitarity, vacuum stability, and reproduction of the EW vacuum like the real case

[4]based on S. Dawson, M. Sullivan PRD97 (2018) 015022

Complex Singlet Mixing

- Expand the complex scalar into a real and imaginary part: $S_c = (S_0 + iA)/\sqrt{2}$
- The mass eigenstates h_1, h_2, and h_3 with masses $m_1 = 125$ GeV, m_2, and m_3 will in general be an arbitrary orthogonal mixture of the CP even gauge eigenstates h, S_0, and A
- A field redefinition to rotate S_c by a complex phase can remove one of the rotation angles

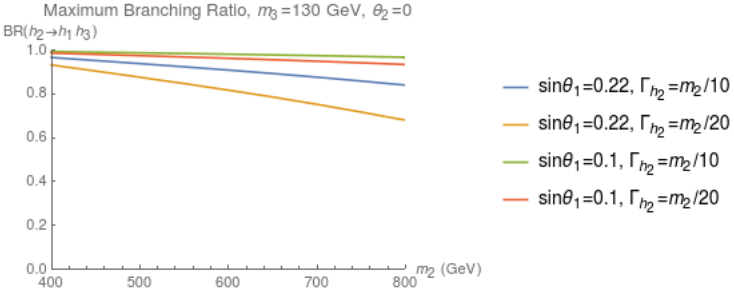
$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} \cos\theta_1 & -\sin\theta_1 & 0 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2 & \sin\theta_2 \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2 & -\cos\theta_2 \end{pmatrix} \begin{pmatrix} h \\ S_0 \\ A \end{pmatrix}$$

- The same constraints on θ in the real singlet model apply to θ_1 in this model

The $\theta_2 \to 0$ Limit

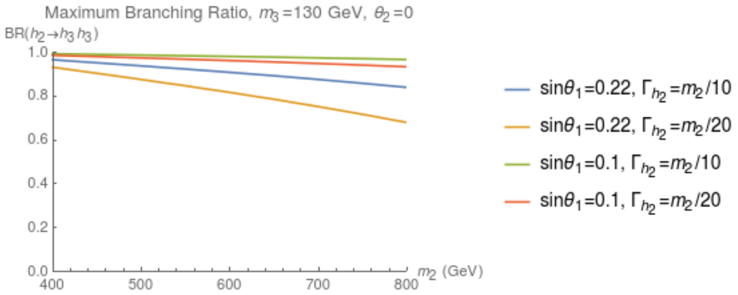
- In the $\theta_2 \to 0$ limit, SM gauge boson and fermion couplings of h_3 go to 0
- Thus single production of h_3 goes to 0
- Trilinears coupling h_3 to h_2 and h_1 will not generally go to 0
- Thus pair production of h_3 with another scalar will not generally go to 0
- This limit is interesting as it provides a benchmark scenario for hS and SS production where these channels would be the discovery channels for S

$S_heavy \to Sh$ Benchmarks for Complex Singlet Model



- Maximum BR($h_2 \to h_1 h_3$) subjected to theoretical constraints
- Enough freedom in trilinears that the constrained total width and inherited SM width are all that constrains the BR

$S_heavy \to SS$ Benchmarks for Complex Singlet Model

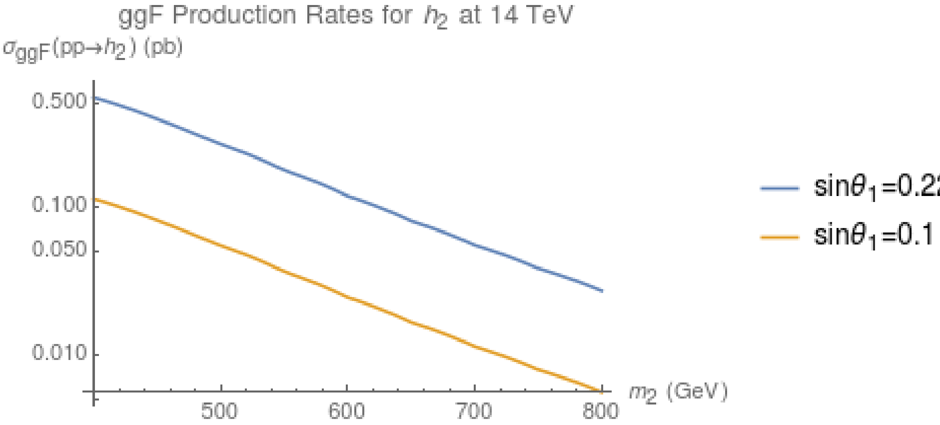


- Maximum BR($h_2 \to h_3 h_3$) subjected to theoretical constraints
- Reaches same upper limit as $h_1 h_3$ case

$S \rightarrow hh$ in Complex Singlet Model?

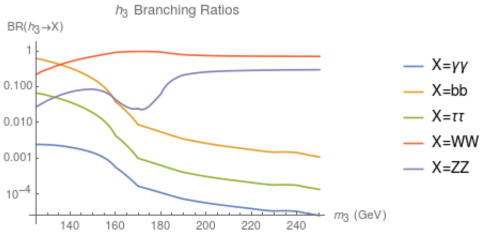
- Real singlet model with an extra decoupled scalar mode can be embedded in the complex singlet model
- General complex singlet model might give more freedom to the BR due to more parameters
- But nothing would be qualitatively different from real singlet hh production
- Complex singlet also bring many more parameters

h_2 Production Rates



- h_2 production is just SM-like rates suppressed by $\sin^2\theta_1 \cos\theta_2 \to \sin^2\theta_1$

h_3 Branching Ratios



- If $m_3 > 2m_1$ then one has to worry about on-shell decays to $h_1 h_1$
- Below $h_1 h_1$ threshold, as long as $\theta_2 = 0$ is only a rough approximation, h_3 will inherit SM-like BRs

Summary

- Singlet models are great, relatively simple benchmark models that affect only the Higgs
- The real singlet model is ideal for *hh* production benchmarks
- The complex singlet model in the $\theta_2 \to 0$ limit is ideal for *SS* and *hS* production benchmarks
- *hS* or *SS* production could be the discovery channel for light or intermediate mass scalars

Thank you

Any questions?