Benchmarks for hh, hS, SS

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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

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Singlet Extensions of SM

- Consider two extensions of the SM:
  - Real singlet scalar.
  - Complex singlet scalar.
- Only couple to Higgs doublet at the renormalizable level.
- Useful laboratory to learn what Higgs physics can tell us about BSM, without showing up anywhere else.
- Can give a strong first order electroweak phase transition. See for example JHEP 1708 (2017) 098 for importance of hS and SS production to probe the electroweak phase transition.

Real Singlet Extension

- Based on C-Y. Chen, S. Dawson, **I. Lewis** PRD91 (2015) 035015; **I. Lewis**, M. Sullivan PRD96 (2017) 035037
- Extend the SM with a real, gauge singlet scalar S.
- Two largely studies scenarios:
  - Z_2 symmetric: impose $S \to -S$ symmetry. See Robens, Stefaniak EPJC76 (2016) 268; EPJC75 (2015) 104; etc.
  - No additional Z_2.
- We study the case with no additional Z_2. Most general renormalizable scalar potential:

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

  - Free to choose $\langle S \rangle = 0$.
- Rotate to into mass eigenstates h_1, h_2 with masses $m_1 = 125$ GeV and m_2, respectively:

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

Real Singlet Extension

- Parameter counting:
  - 8 parameters in Lagrangian.
  - 5 "physical" parameters:

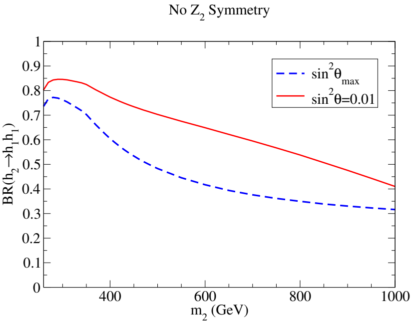
$$m_1 = 125 \text{ GeV}, m_2, \theta, v = 246 \text{ GeV}, \langle S \rangle = 0$$

  - 3 leftover "free" parameters:

$$a_2, b_3, b_4.$$

- In Z_2 symmetric limit: $a_1 = b_1 = b_3 = 0$.
  - 5 parameters in Lagrangian and 5 "physical" parameters. Fully determined.
- Vacuum structure is more complicated without Z_2.
  - Places constraints on how large $\text{BR}(h_2 \to h_1 h_1)$ can be.
- Relevant theoretical constraints:
  - Make sure the global minimum is $(v, \langle S \rangle) = (246 \text{ GeV}, 0)$.
  - Checked that $2 \to 2$ scalar scattering obeys perturbative unitarity.
  - Potential is bounded from below.

Real Singlet Model-Benchmarks for $S \to hh$



- Maximum allow branching ratio for $h_2 \to h_1 h_1$
- From Higgs precision: $\sin\theta_{max} = 0.22$ for $m_2 < 650$ GeV.
- From W-mass constraints: $\sin\theta_{max} = 0.21$ for $m_2 > 650$ GeV
  López-Val, Robens PRD90 (2014) 114018
- Production rates:

$$\sigma(pp \to h_1) = \cos^2\theta\, \sigma_{SM}(pp \to h_1)$$
$$\sigma(pp \to h_2) = \sin^2\theta\, \sigma_{SM}(pp \to h_2)$$

Complex Singlet Model

- Much more complicated. The potential with no additional symmetries:

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

  - Complex scalar singlet: $S_c = (S_0 + iA)/\sqrt{2}$.
  - Can choose $\langle S_c \rangle = 0$.
  - $a_1, b_1, e_2, e_2, \delta_1, \delta_3, d_1, d_3$ are complex parameters.
  - See Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy PRD79 (2009) 015018; Coimbra, Sampaio, Santos, EPJC73 (2013) 248; Gonderinger, Lim, Ramsey-Musolf PRD86 (2012) 043511; Costa, Mülleitner, Sampaio, Santos JHEP06 (2016) 034 for analysis when additional symmetries are imposed upon S_c.

Complex Singlet Model

- Three CP-even scalar bosons: h, S_0, A.
- In principle have to mix all three according to SO(3).
  - Three mixing angles: $\theta_1, \theta_2, \theta_3$.
- θ_3 is the mixing between S_0, A.
  - Equivalent to a phase rotation of $S_c = (S_0 + iA)/\sqrt{2}$.
  - Can be absorbed into the compelx parameters.
- Left over rotation matrix:

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

- h_1, h_2, h_3 are mass eigenstates with masses $m_1 = 125$ GeV$, m_2, m_3$, respectively.

Complex Singlet Model

- Left over rotation matrix:

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

- In the limit $\theta_2 \to 0$:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} \cos\theta_1 & -\sin\theta_1 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} h \\ S_0 \\ A \end{pmatrix}$$

- h_3 inherits its couplings to fermions and gauge bosons from the SM Higgs.
  - If $\theta \to 0$ no mixing with SM Higgs, hence no couplings to fermions or gauge bosons.
  - h_3 can only be produced from h_2 or h_1.
  - If $m_2 > 2m_3$ and $m_2 > m_1 + m_3$ then major discovery mode sof h_3 are:

$$h_2 \to h_3 h_3 \text{ and } h_2 \to h_1 h_3.$$

  - Why this is an interesting benchmark.

Complex Singlet Model

- Major theory constraints:
  - Make sure the global minimum is $(v, \langle S_c \rangle) = (246\ \text{GeV}, 0 + i0)$.
  - Checked that $2 \to 2$ scalar scattering obeys perturbative unitarity.
  - Potential is bounded from below.
- The width of h_2 can be very large, comparable to the mass of h_2
  S. Dawson, M. Sullivan PRD97 (2018) 015022
  - We demand that h_2 be narrow and fix:

$$\Gamma(h_2)/m_2 = 10\%$$

- Find benchmarks by maximizing the branching ratios of $h_2 \to h_3 h_3$ or $h_2 \to h_1 h_3$ with the above constraints.
- Production rate of h_2:

$$\sigma(pp \to h_2) = \sin^2\theta_1 \sigma_{SM}(pp \to h_2)$$

- Constraints on θ_1 are the same as the constraints on θ in the real singlet model.

Complex Singlet-Benchmarks for hS production

$\sin\theta_1$	m_2 (GeV)	BR$(h_2 \to h_1 h_3)$	Parameters
0.22	400	0.966	δ_2 = 0.962, δ_3=0.289-0.488 i, e_1/v =-2.94+23 i, e_2/v =-9.15+4.42 i
0.22	500	0.938	δ_2 = 4.15, δ_3=-1.06+2.82 i, e_1/v =-1.91+40.9 i, e_2/v =-8.21-3.43 i
0.22	600	0.909	δ_2 = 5.16, δ_3=2.84+3.77 i, e_1/v =2.38+44.8 i, e_2/v =6.02+7.45 i
0.22	700	0.876	δ_2 = 8.07, δ_3=1.78+5.04 i, e_1/v =2.24+55 i, e_2/v =3.71+2.23 i
0.1	400	0.993	δ_2 = 6.47, δ_3=-2.77-3.22 i, e_1/v =2.41+38.8 i, e_2/v =5.27-7.42 i
0.1	500	0.987	δ_2 = 4.02, δ_3=0.125-2.14 i, e_1/v =-1.63+52.4 i, e_2/v =-5.71+6.19 i
0.1	600	0.981	δ_2 = 16.3, δ_3=-9.45+9 i, e_1/v =2.39+141 i, e_2/v =1.70+7.81 i
0.1	700	0.974	δ_2 = 8.03, δ_3=1.5+1.5 i, e_1/v =3.31+106 i, e_2/v =8.55-9.68 i

Table: Benchmark points in the complex singlet model with large BR$(h_2 \to h_1 h_3)$ for $m_3 = 130$ GeV and $\Gamma_2/m_2 = 0.1$. Other parameters are set to $\theta_2 = 0$, $d_1 = 0.1 + 0.1\,i$, $d_2 = 0.4$, and $d_3 = 0.1 + 0.1\,i$.

Complex Singlet-Benchmarks for SS production

$\sin\theta_1$	m_2 (GeV)	$\mathrm{BR}(h_2 \to h_3 h_3)$	Parameters
0.22	400	0.966	δ_2 =0.42 , δ_3=-0.356-0.0186,i, e_1/v =-11.5+2.63 i, e_2/v =-9.71-8.05 i
0.22	500	0.938	δ_2 = 11, δ_3=-5.76+8.87 i, e_1/v =-4.63+27.2 i, e_2/v =7.47-2.35 i
0.22	600	0.909	δ_2 = 7.92 , δ_3=1.49+7.57 i, e_1/v =13.5+23.8 i, e_2/v =3.75-3.81 i
0.22	700	0.876	δ_2 = 7.44, δ_3=0.277+5.54 i, e_1/v =-10.5+17.6 i, e_2/v =3.20-3.42 i
0.1	400	0.993	δ_2 = 4.4, δ_3=-2.39+3.05 i, e_1/v =-10.1+21.7 i, e_2/v =-6.59-1.36 i
0.1	500	0.987	δ_2 = 2.83, δ_3=2.08-1.91 i, e_1/v =8.54-13.6 i, e_2/v =-4.09+0.887 i
0.1	600	0.981	δ_2 =12.4 , δ_3=-4.54-5.99 i, e_1/v =14.3-42.6 i, e_2/v =4.98+2.76 i
0.1	700	0.974	δ_2 = 11.9, δ_3=-4.71+10.3 i, e_1/v =-14.2+73 i, e_2/v =-6.77-3.94 i

Table: Benchmark points in the complex singlet model with large $\mathrm{BR}(h_2 \to h_3 h_3)$ for $m_3 = 130$ GeV and $\Gamma_2/m_2 = 0.1$. Other parameters are set to $\theta_2 = 0$, $d_1 = 0.1 + 0.1\,i$, $d_2 = 0.4$, and $d_3 = 0.1 + 0.1\,i$.

Thank You