Phenomenology of the Two-Real-Singlet Model

Robens, Stefaniak, and JW 1908.08554

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Annual Meeting of the Terascale Alliance

LHC Signatures of Extended Scalar Sectors

Measurements of h_{125}

$$pp \to \left\{ \begin{array}{l} h_{125} \\ Vh_{125} \\ t\bar{t}h_{125} \end{array} \right\} \to \left\{ \begin{array}{l} ZZ \\ W^+W^- \\ \gamma\gamma \\ \tau^+\tau^- \\ b\bar{b} \\ (\mu^+\mu^-) \\ (c\bar{c}) \end{array} \right.$$

Neutral BSM scalar searches

$$pp \to \phi \to VV, \gamma\gamma$$
$$pp \to \phi \to \tau^+\tau^-, t\bar{t}$$

$$pp \to \phi_1 \to \phi_2 Z$$
$$pp \to Z\phi \to Z(\text{invisible})$$

$$pp \to \phi \to h_{125}h_{125}$$
$$pp \to h_{125} \to \phi\phi$$

$$pp \to \ldots$$

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Singlet Extensions of the SM

Singlet fields can only couple to SM gauge bosons and fermions through mixing with the SM Higgs field, *e.g.* for a real singlet field s

$$h_1 = \cos\alpha\, h_{\mathrm{SM}} + \sin\alpha\, s\,, \quad h_2 = -\sin\alpha\, h_{\mathrm{SM}} + \cos\alpha\, s\,.$$

Singlet Extensions of the SM

Singlet fields can only couple to SM gauge bosons and fermions through mixing with the SM Higgs field, *e.g.* for a real singlet field s

$$h_1 = \kappa_1 h_{\text{SM}} + \sin\alpha\, s\,, \quad h_2 = \kappa_2 h_{\text{SM}} + \cos\alpha\, s\,.$$

Couplings of h_a to SM particles

- rescaled universally by κ_a
- sum rule $\sum_a {\kappa_a}^2 = 1$ from orthogonality

Multi-h Couplings

- depend on all model parameters
- can be very different from the SM Higgs self coupling

Universal scaling by κ_a

$$\Gamma(h_a \to \text{SM}) = \kappa_a^2 \Gamma(h_{\text{SM}} \to \text{SM})$$
$$\sigma(\text{SM} \to h_a) = \kappa_a^2 \sigma(\text{SM} \to h_{\text{SM}})$$

New physics decays $\text{BR}(h_a \to \text{NP})$

$$\Gamma_{\text{tot}}(h_a) = \frac{\kappa_a^2 \Gamma_{\text{tot}}(h_{\text{SM}})}{1 - \text{BR}(h_a \to \text{NP})}$$
$$\frac{\text{BR}(h_a \to \text{SM})}{\text{BR}(h_{\text{SM}} \to \text{SM})} = 1 - \text{BR}(h_a \to \text{NP})$$

- production cross sections are the SM-like cross sections rescaled by $\kappa_a^2 < 1$
- if $\text{BR}(h_a \to \text{NP}) = 0$ the BRs of h_a are SM-like
- signal rates in all $pp \to h_a \to SM$ channels scaled as $\kappa_a^2(1 - \text{BR}(h_a \to \text{NP}))$
- holds to all orders in QCD

The Two-Real-Singlet Model (TRSM)

Extension of the SM by two real scalar singlet fields S and X with the $\mathbb{Z}_2$ symmetries $S \to -S$ and $X \to -X$.

$$V = \mu_\Phi^2|\Phi|^2 + \lambda_\Phi|\Phi|^4 + \mu_S^2 S^2 + \lambda_S S^4 + \mu_X^2 X^2 + \lambda_X X^4 + \lambda_{\Phi S}|\Phi|^2 S^2 + \lambda_{\Phi X}|\Phi|^2 X^2 + \lambda_{XS} S^2 X^2 \,,$$

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \,, \quad \langle S \rangle = \frac{v_S}{\sqrt{2}} \,, \quad \langle X \rangle = \frac{v_X}{\sqrt{2}} \,.$$

Dark Phase: v_S **or** $v_X = 0$

- unbroken $\mathbb{Z}_2$ symmetry
- scalar dark matter candidate(s)

Broken Phase: $v_S, v_X \neq 0$

- three mixing scalar fields
- mass eigenstates $h_{1,2,3}$ with $M_1 < M_2 < M_3$

Properties of h_{125}

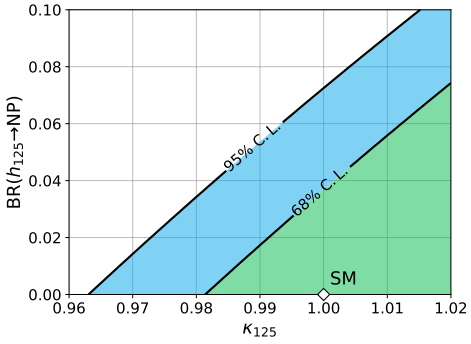
Any of the $h_{1,2,3}$ can be h_{125}

$$\frac{\mathrm{BR}(h_{125} \to \mathrm{SM})}{\mathrm{BR}(h_{SM} \to \mathrm{SM})} = 1 - \mathrm{BR}(h_{125} \to \mathrm{NP})$$

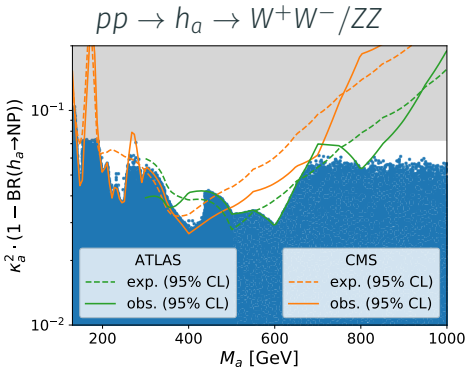
$$\frac{\sigma(h_{125})}{\sigma(h_{\mathrm{SM}})} = \kappa_{125}^2$$

Fit to h_{125} measurements using `HiggsSignals`.

[Bechtle et al. 2014b,c]



Searches for Additional Higgs Bosons



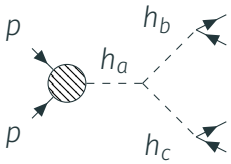
[ATLAS 1808.02380; CMS 1804.01939]

$$\frac{\sigma_{pp\to h_a\to VV}}{\sigma_{pp\to h_{\mathrm{SM}}\to VV}} = \kappa_a^2(1 - \mathrm{BR}(h_a \to \mathrm{NP}))$$

- Points fulfill all theoretical and experimental constraints.
- Indirect constraint through the sum rule: $\kappa_a^2 \leq 1 - \kappa_{125}^2 \lesssim 0.071$.

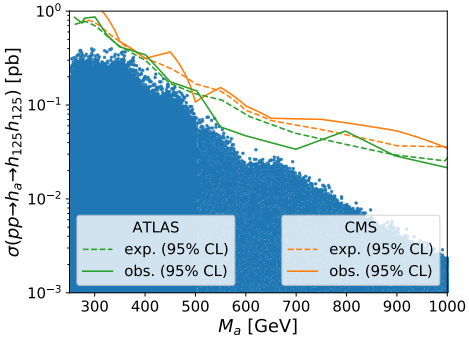
Implemented in the tool `HiggsBounds` [Bechtle et al. 2010, 2011, 2012, 2014a, 2015]

Resonant Multiscalar Production at the LHC



Currently studied processes:

- $pp \to h_{125} \to h_a h_a$
- $pp \to h_a \to h_{125} h_{125}$

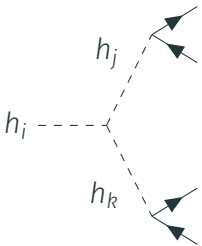


[ATLAS 1906.02025; CMS 1811.09689]

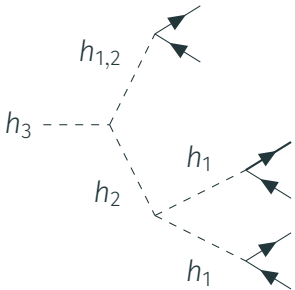
Signatures with $b \neq c$ or without h_{125} not covered.

Cascade Decays

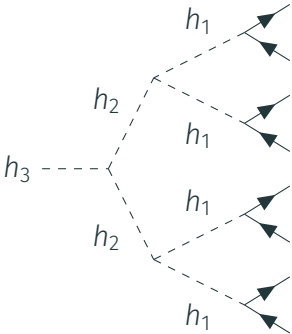
direct decay



single cascade



double cascade



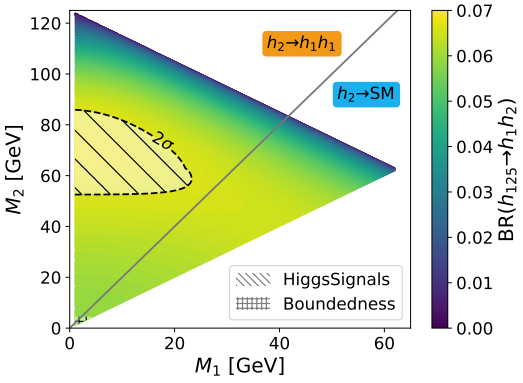
Benchmark Scenarios for Novel Multi-Scalar Signatures — Overview

	h_{125}	target signature	possible cascade decays
BP1	h_3	$h_{125} \to h_1 h_2$	$h_2 \to h_1 h_1$ if $M_2 > 2M_1$
BP2	h_2	$h_3 \to h_1 h_{125}$	—
BP3	h_1	$h_3 \to h_{125} h_2$	$h_2 \to h_{125} h_{125}$ if $M_2 > 250\,\text{GeV}$
BP4	h_3	$h_2 \to h_1 h_1$	—
BP5	h_2	$h_3 \to h_1 h_1$	—
BP6	h_1	$h_3 \to h_2 h_2$	$h_2 \to h_{125} h_{125}$ if $M_2 > 250\,\text{GeV}$

Proposed to the LHC-HXSWG HH subgroup and published [Robens, Stefaniak, and JW 1908.08554]

Benchmark Scenarios for Novel Multi-Scalar Signatures — BP1

$pp \to h_{125} \to h_1 h_2$



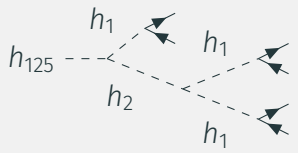
$\sigma(pp \to h_{125}) \sim 42\,\text{pb}$

$M_2 < 2M_1$

- $h_1, h_2 \to \text{SM}$

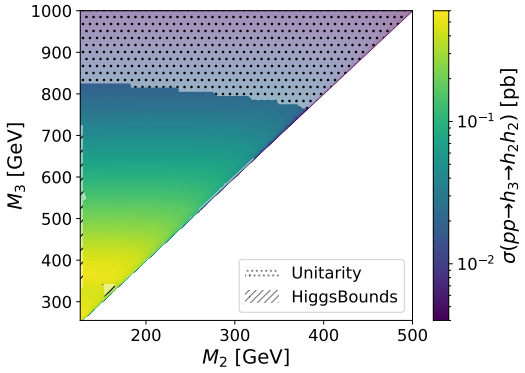
$M_2 > 2M_1$

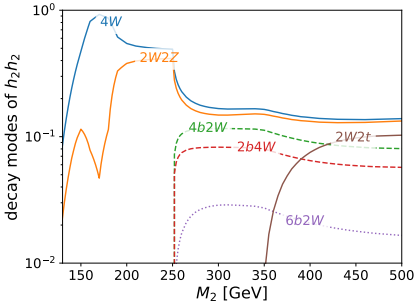
- $\text{BR}(h_2 \to h_1 h_1) \sim 1$



Benchmark Scenarios for Novel Multi-Scalar Signatures — BP6

$pp \to h_3 \to h_2 h_2$ with $h_{125} \equiv h_1$





first search in $4W$ [ATLAS 1811.11028]

Summary

- Many unprobed final states remain in the search for new resonances.
- Singlet extensions are excellent models to study resonant multi-scalar production.
- Benchmark scenarios in the TRSM for asymmetric and fully BSM multi-Higgs signatures.
- Cascade decays in the Higgs sector are another intriguing possibility to probe in the future.

Thank You!