Benchmarks from the Two Real Singlet Extension

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based on work with

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Models with extended scalar sectors

Constraints

- **Theory**

  minimization of vacuum (tadpole equations), vacuum stability, positivity, perturbative unitarity, perturbativity of couplings

- **Experiment**

  provide viable candidate @ 125 GeV (coupling strength/ width/ ...);
  agree with null-results from additional searches and ew gauge boson measurements (widths);
  agree with electroweak precision tests (typically via S,T,U);
  agree with astrophysical observations (if feasible)

tools used: `HiggsBounds`, `HiggsSignals`, `ScannerS`, ...

LHC: Multi scalar production modes

[Eur.Phys.J. C80 (2020) no.2, 151; JHEP 05 (2021) 193]

Adding two real scalar singlets

Scalar potential (Φ: $SU(2)_L$ doublet, S, X: $SU(2)_L$ singlets)

$$\mathcal{V} = \mu_\Phi^2 \Phi^\dagger \Phi + \mu_S^2 S^2 + \mu_X^2 X^2 + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \lambda_S S^4 + + \lambda_X X^4 + \lambda_{\Phi S} \Phi^\dagger \Phi S^2 + \lambda_{\Phi X} \Phi^\dagger \Phi X^2 + \lambda_{SX} S^2 X^2.$$

Imposed $\mathbb{Z}_2 \times \mathbb{Z}_2'$ symmetry, which is spontaneously broken by singlet vevs.

$\Rightarrow$ three $\mathcal{CP}$-even neutral Higgs bosons: h_1, h_2, h_3

Two interesting cases:

Case (a): $\langle S \rangle \neq 0, \langle X \rangle = 0 \Rightarrow X$ is DM candidate;

Case (b): $\langle S \rangle \neq 0, \langle X \rangle \neq 0 \Rightarrow$ all scalar fields mix.

Again, Higgs couplings to SM fermions and bosons are *universally reduced by mixing*.

Tim Stefaniak (DESY) | BSM Higgs physics | ALPS 2019 | 27 April 2019 10

[some material stolen from T. Stefaniak, Talk at ALPS 2019, April '19]

singlet = singlet under SM gauge group

Possible production and decay patterns

$$M_1 \leq M_2 \leq M_3$$

Production modes at pp and decays

$$pp \to h_3 \to h_1\,h_1; \qquad pp \to h_3 \to h_2\,h_2;$$
$$pp \to h_2 \to h_1\,h_1; \qquad pp \to h_3 \to h_1\,h_2$$

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

$\Rightarrow$ two scalars with same or different mass decaying directly to SM, or $h_1\,h_1\,h_1$, or $h_1\,h_1\,h_1\,h_1$

[h_1 decays further into SM particles]

[BRs of h_i into $X_{\text{SM}} = \frac{\kappa_i \Gamma^{\text{SM}}_{h_i \to X}(M_i)}{\kappa_i \Gamma^{\text{SM}}_{\text{tot}}(M_i) + \sum_{j,k} \Gamma_{h_i \to h_j h_k}}$; κ_i: rescaling for h_i]

Benchmarks and decay patterns [Eur.Phys.J. C80 (2020) no.2, 151]

suggested benchmark points for symmetric $h_X \to h_Y\, h_Y$ and assymetric $h_3 \to h_1\, h_2$ scenarios
h_{125} can be either $h_1,\, h_2,\, h_3$

- **SM couplings inherited through mixing**, $\propto \kappa_i$, such that

$$g_{h_i \to X\,Y} = \kappa_i\, g^{\text{SM}}_{h_i \to X\,Y}.$$

- **additional onshell decays**

$$h_3 \to h_1\, h_2,\; h_3 \to h_1\, h_1,\; h_3 \to h_2\, h_2,\; h_2 \to h_1\, h_1$$

(whenever kinematically feasible)

$\Rightarrow$ **relative ratio for SM final states as in SM at mass M_i**

$$\text{BR}_{h_i \to \text{SM}}(M_i) = \frac{\kappa_i^2\, \Gamma^{\text{SM}}_{h_i \to \text{SM}}(M_i)}{\kappa_i^2\, \Gamma^{\text{SM}}_{h_i \to \text{SM}}(M_i) + \sum_{j,k} \Gamma_{h_i \to h_j\, h_k}}$$

Benchmark points/ planes [ASymmetric/ Symmetric]

AS **BP1:** $h_3 \to h_1 h_2$ $(h_3 = h_{125})$

SM-like decays for both scalars: $\sim$ 3 pb; h_1^3 final states: $\sim$ 3pb

AS **BP2:** $h_3 \to h_1 h_2$ $(h_2 = h_{125})$

SM-like decays for both scalars: $\sim$ 0.6 pb

AS **BP3:** $h_3 \to h_1 h_2$ $(h_1 = h_{125})$

(a) SM-like decays for both scalars $\sim$ 0.3 pb; **(b) h_1^3 final states:** $\sim$ 0.14 pb

S **BP4:** $h_2 \to h_1 h_1$ $(h_3 = h_{125})$

up to 60 pb

S **BP5:** $h_3 \to h_1 h_1$ $(h_2 = h_{125})$

up to 2.5 pb

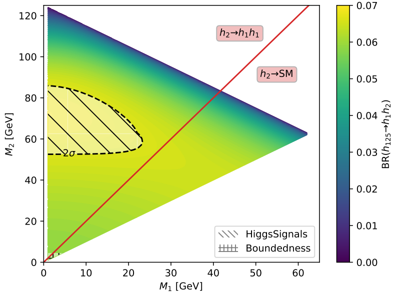
S **BP6:** $h_3 \to h_2 h_2$ $(h_1 = h_{125})$

SM-like decays: up to 0.5 pb; h_1^4 **final states: around 14 fb**

BP1: $h_3 \to h_1 h_2$ $(h_3 = h_{125})$ [up to 3 pb]

BP1

$\sigma(pp \to h_3) \simeq \sigma(pp \to h_{SM}) \sim 50\ \mathrm{pb}$, $\mathrm{BR}(\mathrm{h}_3 \to \mathrm{h}_1\mathrm{h}_2)$ up to 7%, if $M_2 > 2M_1$
$\Rightarrow \mathrm{BR}(\mathrm{h}_2 \to \mathrm{h}_1\mathrm{h}_1) \approx 100\%$,
($\to$ e.g., three pairings $m_{bb} \simeq M_1$)
if $M_2 < 2M_1 \Rightarrow h_2 \to$ SM particles.
($\to$ e.g., $m_{bb}^{(1)} \simeq M_1$ and $m_{bb}^{(2)} \simeq M_2$)

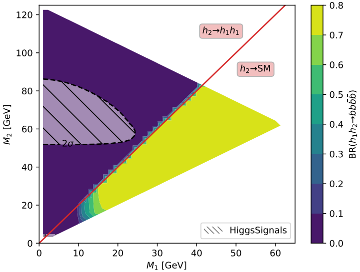


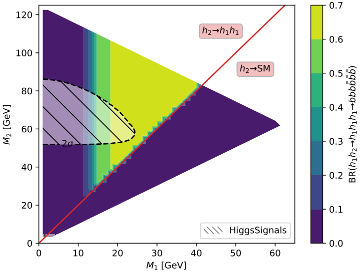
$\Rightarrow$ $h_1 h_1 h_1$ final states: reconstructing to M_3, with one pair reconstructing to M_2

$\Rightarrow$ both scalars as in SM: 2 light scalars reconstructing to M_3

$[|\kappa_3| = 0.9965]$

BP1: $h_3 \to h_1 h_2 \ (h_3 = h_{125})$ [up to 3 pb]





$h_3 \to h_1\ h_2 \to b\bar{b}b\bar{b}$

$h_3 \to h_1\ h_2 \to h_1\ h_1\ h_1 \to b\bar{b}b\bar{b}b\bar{b}$

reaching $\sim 2\,\mathrm{pb}$, depending on masses

BP3: Exploration of $h_1 h_1 h_1$ final state at HL-LHC

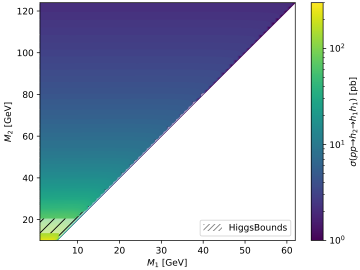
[A. Papaefstathiou, TR, G. Tetlalmatzi-Xolocotzi, JHEP 05 (2021) 193]

(M_2, M_3) [GeV]	$\sigma(pp \to h_1 h_1 h_1)$ [fb]	$\sigma(pp \to 3b\bar{b})$ [fb]	$\text{sig}\|_{300\text{fb}^{-1}}$	$\text{sig}\|_{3000\text{fb}^{-1}}$
$(255, 504)$	32.40	6.40	2.92	9.23
$(263, 455)$	50.36	9.95	4.78	15.11
$(287, 502)$	39.61	7.82	4.01	12.68
$(290, 454)$	49.00	9.68	5.02	15.86
$(320, 503)$	35.88	7.09	3.76	11.88
$(264, 504)$	37.67	7.44	3.56	11.27
$(280, 455)$	51.00	10.07	5.18	16.39
$(300, 475)$	43.92	8.68	4.64	14.68
$(310, 500)$	37.90	7.49	4.09	12.94
$(280, 500)$	40.26	7.95	4.00	12.65

discovery, exclusion

$\Rightarrow$ at HL-LHC, all points within reach $\Leftarrow$

BP4: $h_2 \to h_1 h_1$ $(h_3 = h_{125})$ [up to 60 pb]



- $|\kappa_2| \sim 0.2$

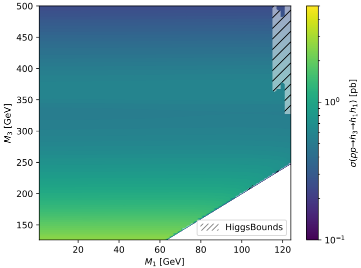
$$\sigma_{gg \to h_2}(M_2) \sim 0.04\, \sigma^{SM}_{gg \to h_2}(M_2)$$

[$\text{BR}_{h_2 \to h_1 h_1} \gtrsim 0.9$ for $M_1 \gtrsim 40\,\text{GeV}$]

dominant decays to $b\bar{b}b\bar{b}$ and $b\bar{b}\tau^+\tau^-$

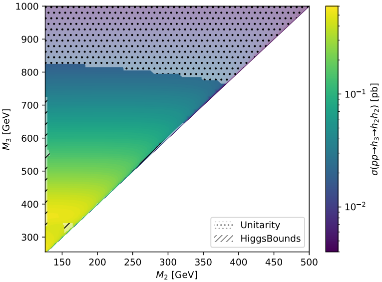
BP5 recast: $h_3 \to h_1\, h_1 \to b\bar{b}b\bar{b}$ $(h_2 = h_{125})$

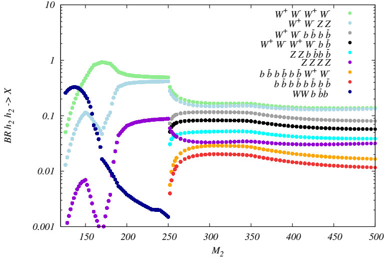
Enlarging the scope of resonant di-Higgs searches: Hunting for Higgs-to-Higgs cascades in 4b final states at the LHC and future colliders [Barducci, Mimasu, No, Vernieri, Zurita; JHEP 2002 (2020) 00]



$\Rightarrow$ region stemming from resonance searches (ATLAS, 36 fb^{-1}, Phys.Rev.Lett. 121 (2018) no.19, 191801; CMS, 36 fb^{-1}, Phys.Rev.Lett. 122 (2019) no.12, 121803) extended

BP6: $h_3 \to h_2 h_2$ $(h_1 = h_{125})$ [up to 0.5 pb]





- $|\kappa_3| \sim 0.25$ [$\Gamma_3/M_3 \lesssim 0.14$]

$$\sigma_{gg\to h_3}(M_3) \sim 0.06\, \sigma^{SM}_{gg\to h_3}(M_3)$$

$h_{125} h_{125} h_{125} h_{125}$ **up to 14 fb**

! $36\,\mathrm{fb}^{-1}$ searches start being sensitive [1811.11028] !

2 real singlets: Mini-summary

- **3 scalars with different masses:**

rich phenomenology

- either **asymmetric** $(h_1\,h_2)$ or **symmetric** $(h_x h_x)$ final states

$\Rightarrow$ production **cross sections up to 3 pb (AS)/ 60 pb (S)**

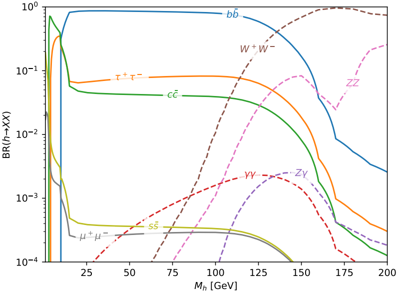
- interesting **multi-scalar final states** $(h_1 h_1 h_1,\; h_1 h_1 h_1 h_1)$
- decays typically involve $b\bar{b}$, $W^+ W^-$, $\tau^+\tau^-$ pairs that reconstruct to scalars

Stay tuned...

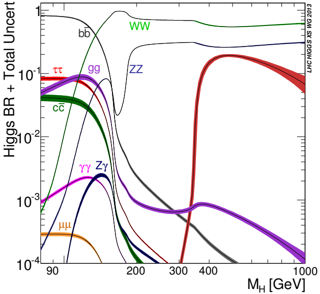
new CERN e-group: lhc-higgs-neutral-extended-scalars

Appendix

Reminder: decays of a SM-like Higgs of mass $M \neq 125\,\mathrm{GeV}$



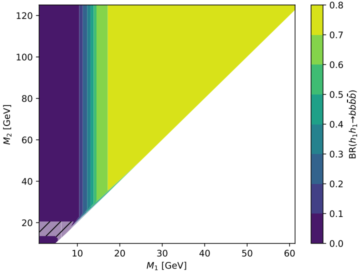
(using HDecay, courtesy J.Wittbrodt)



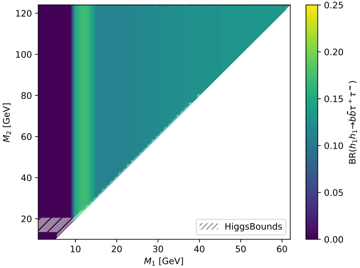
(https://twiki.cern.ch/twiki/bin/view/LHCPhysics

/LHCHXSWGCrossSectionsFigures)

BP4: $h_2 \to h_1 h_1$ $(h_3 = h_{125})$ [up to 60 pb]



$h_2 \to h_1\, h_1 \to b\bar{b}b\bar{b}$



$h_2 \to h_1\, h_1 \to b\bar{b}\tau^+\tau^-$

reaching $\sim 15/8\,\mathrm{pb}$**, max for** $M_1 \sim 15/10\,\mathrm{GeV}, M_2 \sim 2\,M_1$

[for lower masses: $c\bar{c}c\bar{c}$, $c\bar{c}\tau^+\tau^+$ also become sizeable]

Enlarging the scope of resonant di-Higgs searches: Hunting for Higgs-to-Higgs cascades in 4b final states at the LHC and future colliders

[Barducci, Mimasu, No, Vernieri, Zurita; JHEP 2002 (2020) 00]

- idea: **take search for $H \rightarrow h_{125}\, h_{125} \rightarrow b\bar{b}b\bar{b}$**

  (CMS, 36 fb^{-1}; JHEP 1808 (2018) 152)

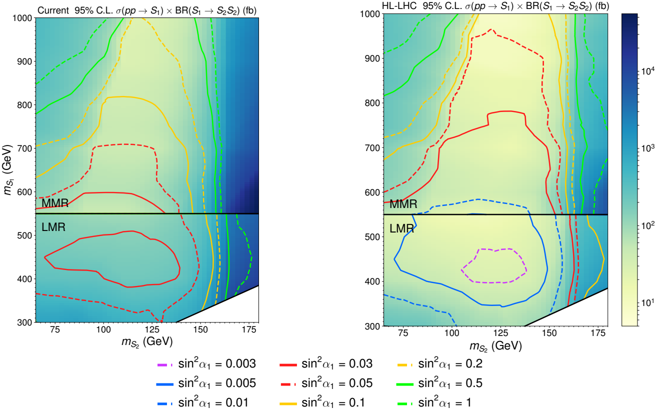
$\Rightarrow$ **reinterpret/ adjust for resonances and decay products in a wider mass range $h_2 \rightarrow h_1\, h_1$**

$$\mathbf{M_1} \in [\mathbf{65}; \mathbf{180}]\ \mathrm{GeV},\ \mathbf{M_2} \in [\mathbf{300}; \mathbf{1000}]\ \mathrm{GeV}$$

(includes detailed validation of procedure reproducing results in JHEP 1808 (2018) 152)

JHEP 2002 (2020) 00: Results for 2 real singlet

- low mass region, $M_2 \in [250\,\mathrm{GeV}; 650\,\mathrm{GeV}]$; medium mass region, $M_2 \in [550\,\mathrm{GeV}; 1200\,\mathrm{GeV}]$
- results contain some cut optimization with respect to CMS search

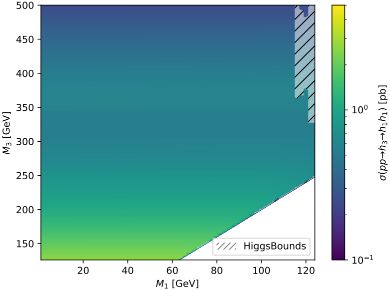


BP5: $h_3 \to h_1 h_1$ $(h_2 = h_{125})$ [up to 2.5 pb]

BP5

$\sigma(pp \to h_3) \simeq 0.06 \cdot \sigma(pp \to h_{SM})|_{M_3}$
$\mathrm{BR}(h_3 \to h_1 h_1)$ always $\gtrsim 75\%$.
h_1 decays to SM particles
($\to$ e.g., two pairings $m_{bb} \simeq M_1$),
at large M_3, the h_1's become boosted.

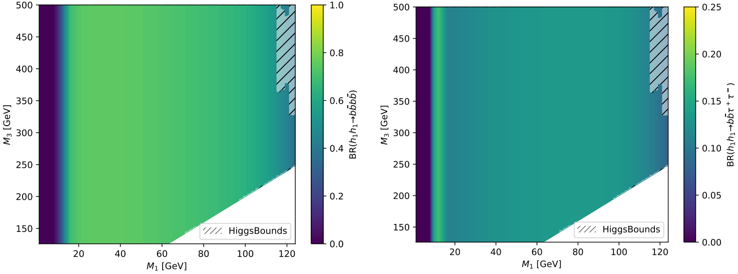
$[\kappa_3 = -0.25, \Gamma_3/M_3 \leq 0.08]$



two light scalars reconstructing to M_3

relevant searches: CMS and ATLAS combinations $X \to h_{125} h_{125}$

BP5: $h_3 \to h_1 h_1 \; (h_2 = h_{125})$ [up to 2.5 pb]

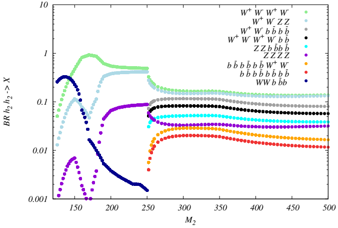


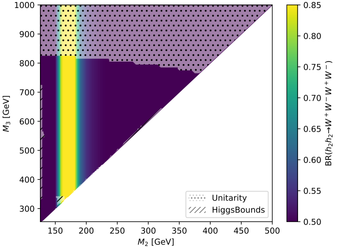
$h_3 \;\to\; h_1\, h_1 \;\to\; b\bar{b}b\bar{b}$

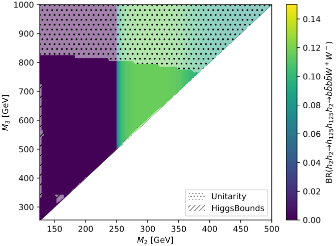
$h_3 \;\to\; h_1\, h_1 \;\to\; b\bar{b}\tau^+\tau^-$

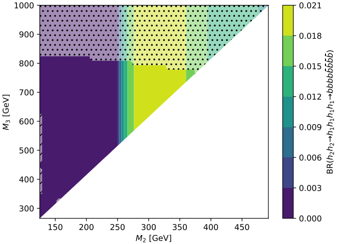
reaching $\sim 2/0.3\,\mathrm{pb}$**, max for** $M_1 > 20\,\mathrm{GeV},\, M_3 \sim 140\,\mathrm{GeV}$

BP6: $h_3 \to h_2 h_2 \; (h_1 = h_{125})$ [up to 0.5 pb]









$W^+W^-W^+W^-$: 0.45 pb for $M_2 \sim M_{top}$/ others: $\mathcal{O}$ (fb)