(1) LHC Benchmark scenarios in the TRSM

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based on

TR, T. Stefaniak, J. Wittbrodt, Eur.Phys.J.C 80 (2020) 2, 151; A. Papaefstathiou, TR, G. Tetlalmatzi-Xolocotzi, JHEP 05 (2021) 193; TR, arXiv:2205.14486

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(2) LHC: Multi scalar production modes

[TR, T. Stefaniak, J. Wittbrodt, Eur.Phys.J. C80 (2020) no.2, 151]

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]

(3) Possible production and decay patterns

$$M_1 \leq M_2 \leq M_3$$

Production modes at pp and decays

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

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

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

(4) Benchmark points/ planes (ASymmetric/ Symmetric)

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

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

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

SM-like decays for both scalars: $\sim 0.6\,\text{pb}$

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

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

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**

(5) LHC: Multi scalar production modes

[TR, T. Stefaniak, J. Wittbrodt, Eur.Phys.J. C80 (2020) no.2, 151]

2 real singlet extension $\Rightarrow$ 2 additional scalars ($M_1 \leq M_2 \leq M_3$; $M_i \in [0; 1\text{TeV}]$)

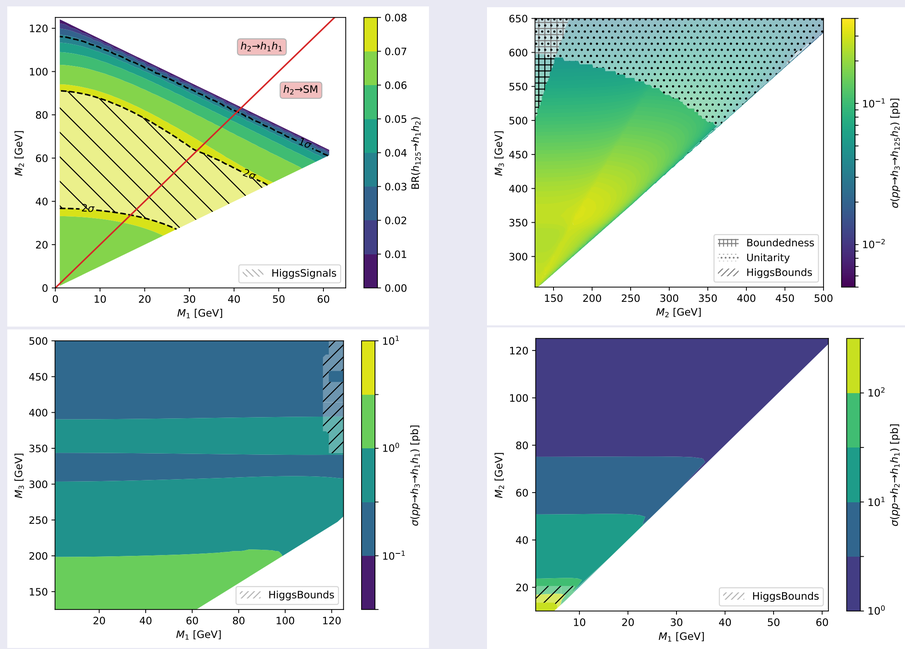
[1 mass always at 125 GeV, others free]

asymmetric, triple h_1

(3.5/ 0.25 pb)

symmetric, no h_{125} involved

(2.5/ 60 pb)



(6) Exploration of $h_1 h_1 h_1$ final state at HL-LHC

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

- 3 scalar states h_1, h_2, h_3 that mix

concentrate on

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

$\Rightarrow$ **select points** on BP3 which might be **accessible at HL-LHC**

$\Rightarrow$ perform detailed analysis including SM background, hadronization, ...

- tools: implementation using **full t, b mass dependence, leading order** [UFO/ Madgraph/ Herwig] [analysis: use K-factors]

(7) Benchmark points and results

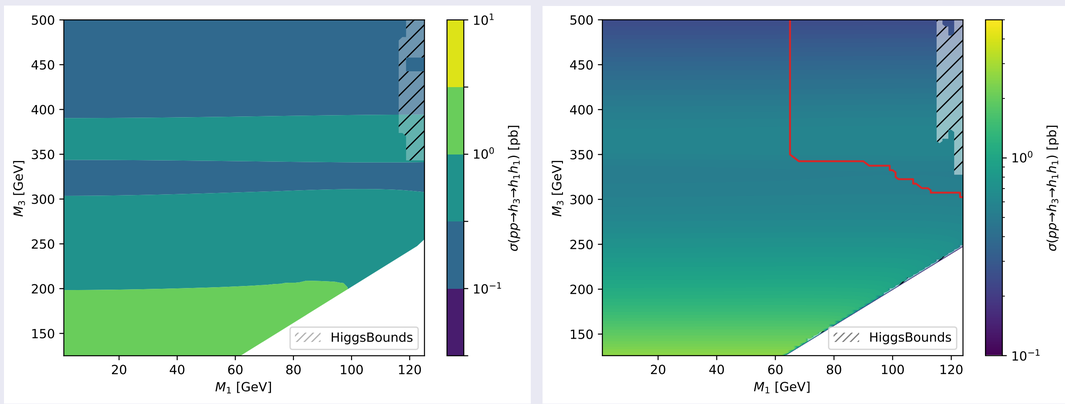
(M_2, M_3) [GeV]	$\sigma(pp \to h_1 h_1 h_1)$ [fb]	$\sigma(pp \to 3b\bar{b})$ [fb]	sig$\|_{300\text{fb}^{-1}}$	sig$\|_{3000\text{fb}^{-1}}$
(255, 504)	32.40	6.40	2.92	9.23
(263, 455)	50.36	9.95	4.78	15.11
(287, 502)	39.61	7.82	4.01	12.68
(290, 454)	49.00	9.68	5.02	15.86
(320, 503)	35.88	7.09	3.76	11.88
(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 $\Leftarrow$

(8) BP5 recast: $h_3 \to h_1 h_1 \to b\bar{b}b\bar{b}$

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