Multi-scalar final states in the $\mathbb{Z}_2 \otimes \mathbb{Z}_2'$ two real singlet extension

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based on recent work with
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HH Subgroup Meeting

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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*.

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

Constraints

- **Theory**:
  boundedness from below for potential,
  perturbative unitarity;
- **Experiment:**
  electroweak precision via S, T, U;
  agreement with measurements of 125 GeV scalar;
  agreement with null-results for additional searches;

  also tested: $W-$mass as precision observable [à la Lopez-Val, TR, Phys. Rev. D 90, 114018]

Tools which were used:

`HiggsBounds`*, `HiggsSignals`, `ScannerS`*

[*: private updated version]

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]

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: $\sim$ 1.4 pb; h_1^3 final states: $\sim$ 30 fb

AS **BP3:** $h_3 \to h_1 h_2$ $(h_1 = h_{125})$ [see also Ians talk]

(a) SM-like decays for both scalars $\sim$ 0.7 pb; **(b)** h_1^3 **final states:** $\sim$ 0.25 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

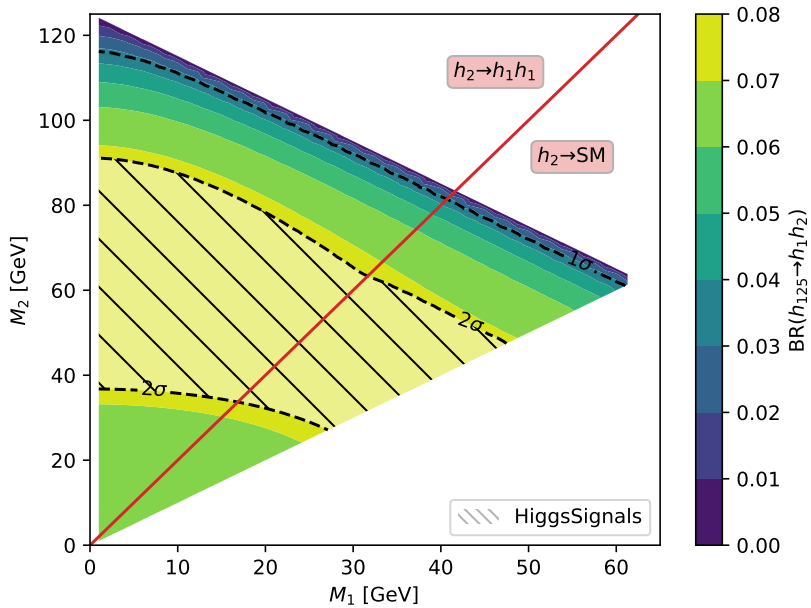
S **BP6:** $h_3 \to h_2 h_2$ $(h_1 = h_{125})$ [see also Ians talk]

SM-like decays: up to 0.4 pb; h_1^4 **final states: around 6 fb**

BP1: $h_3 \to h_1 h_2$ $(h_3 = h_{125})$ [up to 3.5 pb]

Example: $h_3 \simeq h_{\rm SM}$ at 125 GeV

$\sigma(pp \to h_3) \simeq \sigma(pp \to h_{\rm SM}) \sim 50$ pb,
$\mathrm{BR}(\mathrm{h_3} \to \mathrm{h_1 h_2})$ up to $7-8\%$,
if $M_2 > 2M_1$
$\Rightarrow \mathrm{BR}(\mathrm{h_2} \to \mathrm{h_1 h_1}) \approx 100\%$,
$(\to$ 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

$[\kappa_3 = 0.99976]$

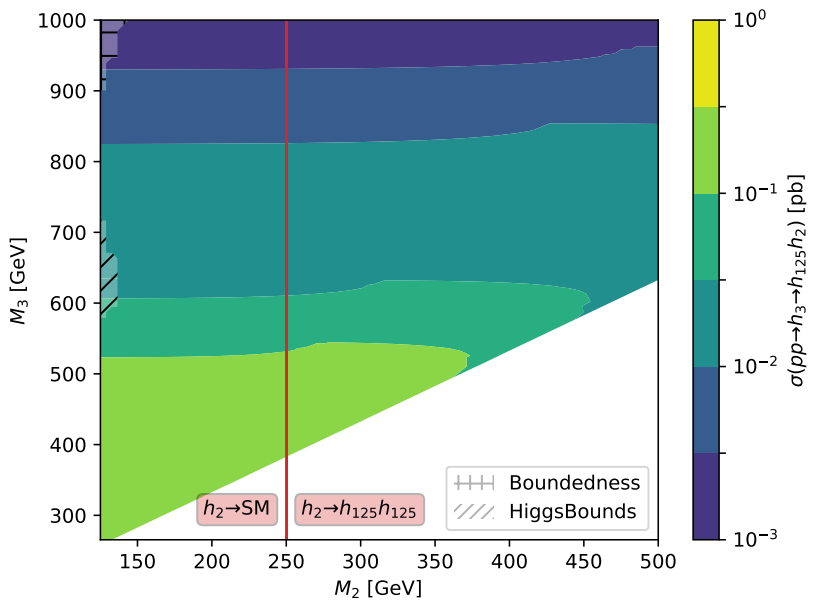
BP3b: $h_3 \to h_1 h_2$ $(h_1 = h_{125})$ [up to 0.25 pb]

Example: $h_1 \simeq h_{\rm SM}$ at 125 GeV

$\sigma(pp \to h_3) \simeq 0.04 \cdot \sigma(pp \to h_{SM})|_{m=M_3}$
$\mathrm{BR}(\mathrm{h_3} \to \mathrm{h_{125} h_2})$ always $\gtrsim 60\%$.
if $M_2 < 250\,\mathrm{GeV}$: $\Rightarrow$ $h_2 \to$ SM particles.
if $M_2 > 250\,\mathrm{GeV}$:
$\Rightarrow \mathrm{BR}(\mathrm{h_2} \to \mathrm{h_{125} h_{125}}) \approx 100\%$,

$\Rightarrow$ spectacular triple-Higgs signature

[maximal close to thresholds]



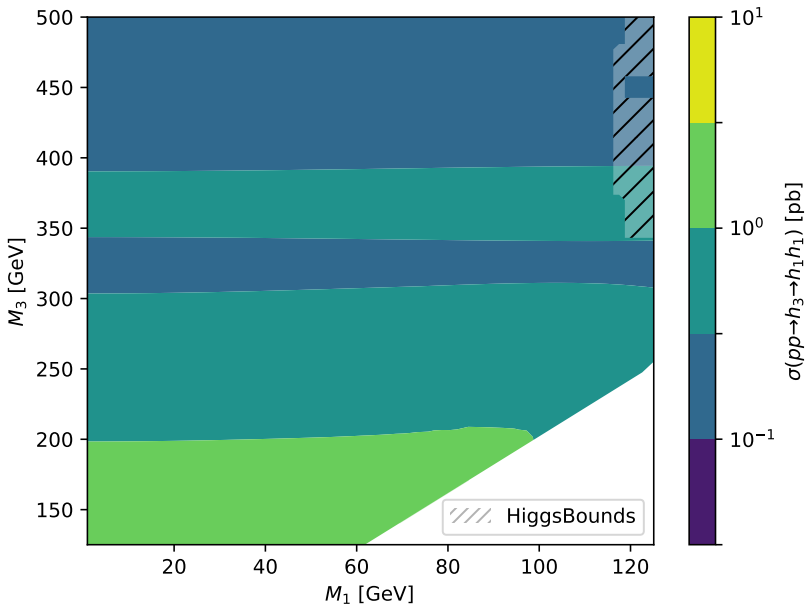
$[\kappa_3 = 0.21]$ $[\Gamma_3/M_3 \leq 0.1$ for $M_3 \lesssim 800\,\mathrm{GeV}]$

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

Example: $h_2 \simeq h_{\rm SM}$ at 125 GeV

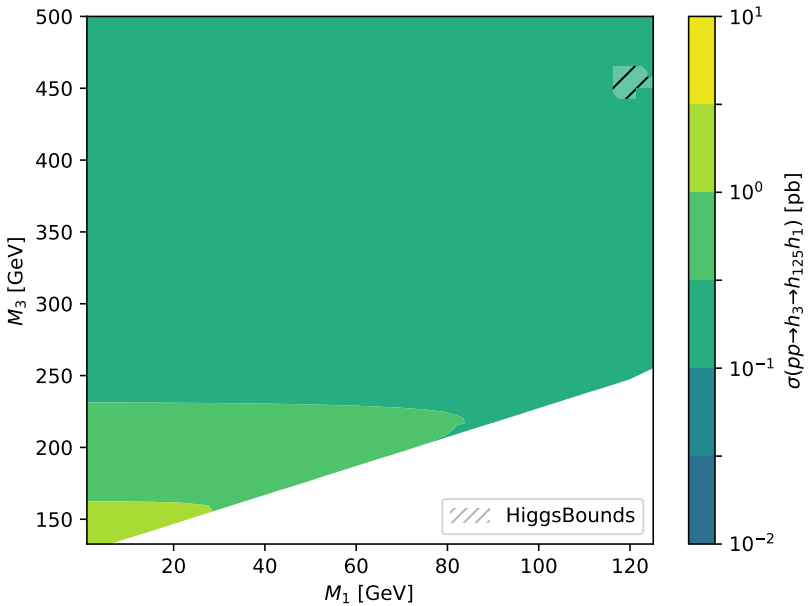
$\sigma(pp \to h_3) \simeq 0.06 \cdot \sigma(pp \to h_{SM})|_{M_3}$
$\mathrm{BR}(\mathrm{h_3} \to \mathrm{h_1 h_1})$ always $\gtrsim 75\%$.
h_1 decays to SM particles
($\to$ e.g., two pairings $m_{bb} \simeq M_1$),
at large M_3, the h_1's become boosted.

$[\kappa_3 = -0.25]$



two light scalars reconstructing to M_3

BP2: $h_3 \to h_1 h_2$ $(h_2 = h_{125})$ [1.4 pb]; BP4: $h_2 \to h_1 h_1$ $(h_3 = h_{125})$ [60 pb]

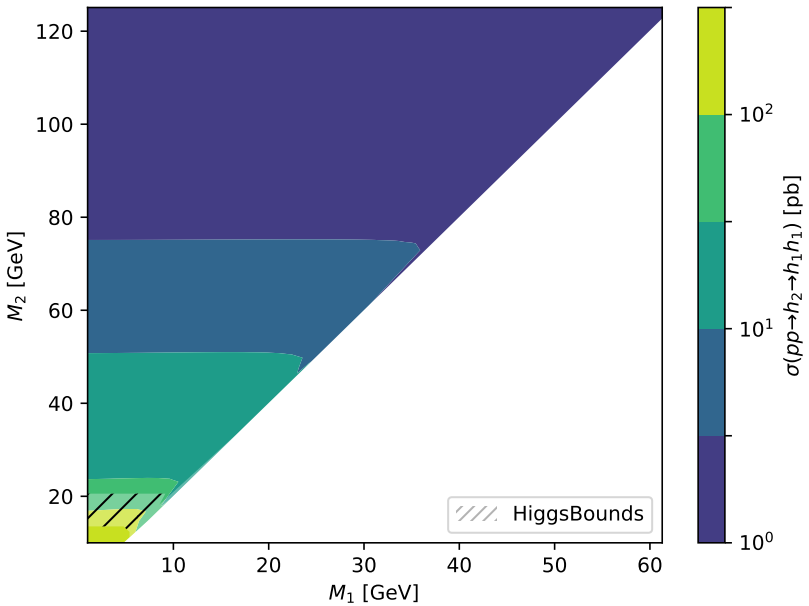


BP2

$[\mathrm{BR}_{h_2 \to h_1\, h_1} \leq 7\%]$

two scalars decaying as in SM at mass $M_{1,2}$,

reconstructing to M_3; $[\kappa_3 = -0.2]$



BP4

two lights scalars decaying as in SM at mass M_1,

reconstructing to M_2; $[\kappa_2 = 0.22]$

Please consult our note for many more details !!

Comparison to complex singlet from Ian [last minute...]

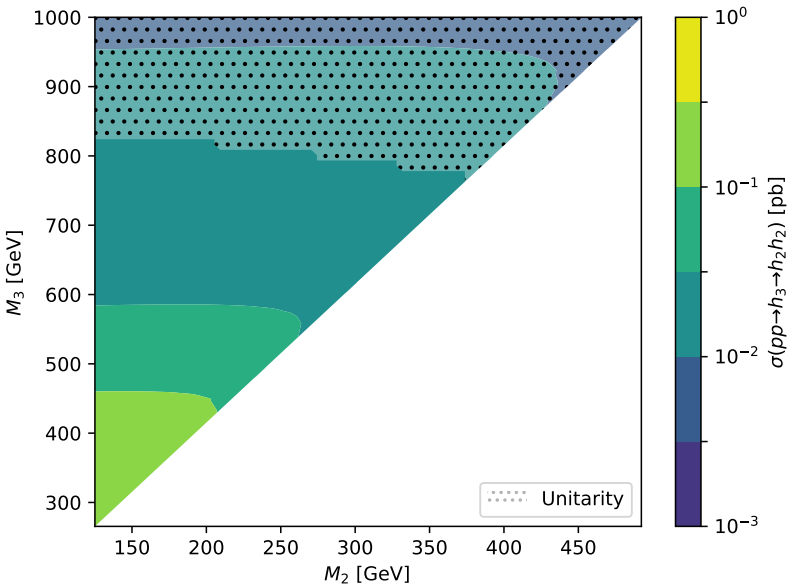
- we impose **additional symmetry**
  $\Rightarrow$ **smaller number of free parameters**

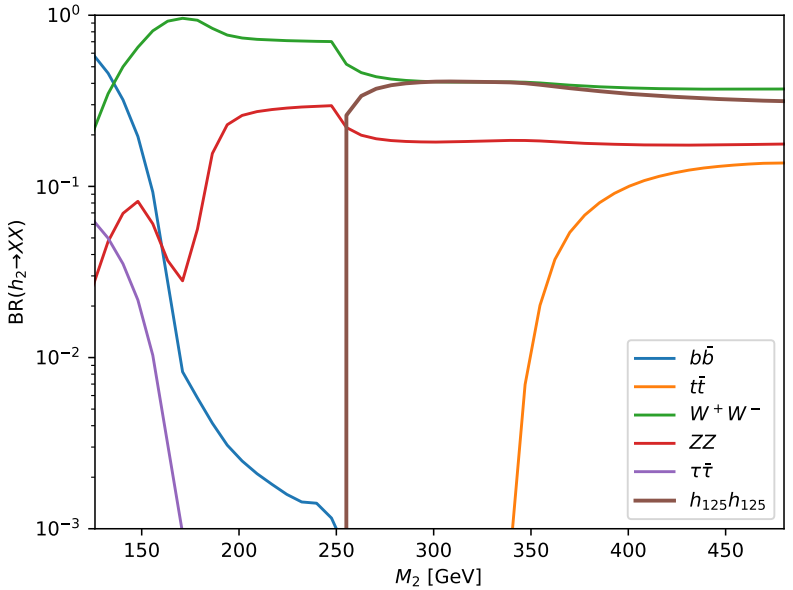
  [after setting of Higgs mass and vev: 7]
- **BPs 3,6: similar kinematical configuration** [in certain limits]
- **however**, we allow for **mixing of all states** $\Rightarrow$ **also** h_2 **decays to SM particles**
- in addition, also consider 125 GeV state to be heaviest (BPs 1,4) and intermediate (BPs 2,5) state

$\Rightarrow$ in general, **different decay topologies**

Plots I could not show for time reasons (Appendix)

BP6: $h_3 \to h_2 h_2$ $(h_1 = h_{125})$ [0.4 pb]



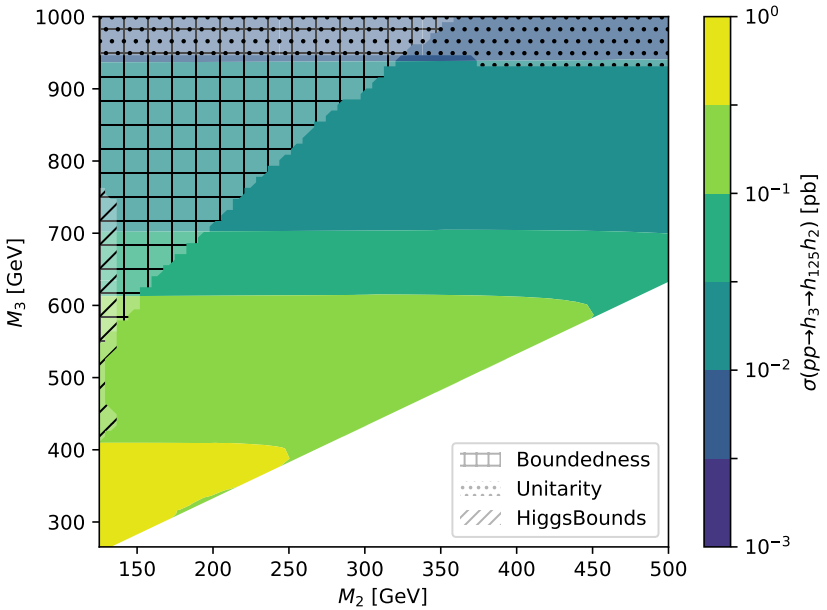


h_1^4 can be up to 6.5 fb;

$[\kappa_3 = 0.25][\Gamma_3/M_3 \leq 0.1 \text{ for } M_3 \lesssim 700\,\text{GeV}]$

[BR $h_3 \to h_2\, h_2 \geq 0.6$]

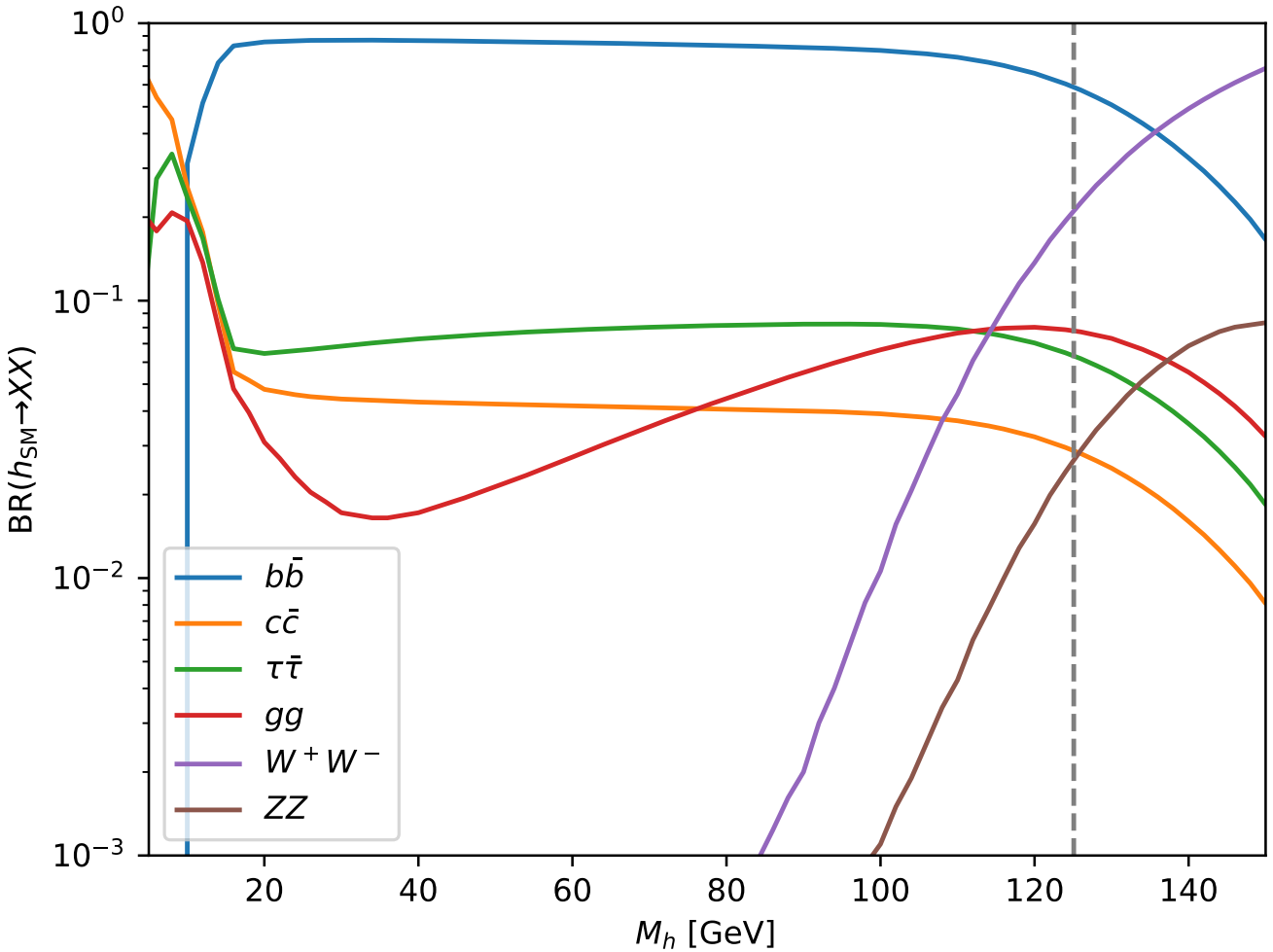
BP3a: $h_3 \to h_1 h_2$ $(h_1 = h_{125})$ [0.7 pb]



h_2 decays dominantly into SM;
2 scalars h_1, h_2 decaying into SM final states

$[\kappa_3 = 0.25]$ $[\Gamma_3/M_3 \leq 0.1$ for $M_3 \lesssim 600\,\mathrm{GeV}]$

Decays of light SM-like scalars



[from YREP 4/ HDecay]

W mass bounds

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

SM-like decays for both scalars: $\sim$ 1.4 pb; h_1^3 final states: $\sim$ 30 fb

excluded for $M_3 \geq 400\,\mathrm{GeV}$ [no problem]

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

(a) SM-like decays for both scalars $\sim$ 0.7 pb; **(b)** h_1^3 **final states:** $\sim$ 0.25 pb

excluded

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

up to 2.5 pb

excluded for $M_3 \geq 300\,\mathrm{GeV}$ [no problem]

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

SM-like decays: up to 0.4 pb; h_1^4 **final states: around 6 fb**

excluded for $M_3 \geq 270\,\mathrm{GeV}$