Overview on BSM scenarios with enhancements in [HH and] HHH

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based on work with

TR, T. Stefaniak, J. Wittbrodt, Eur.Phys.J.C 80 (2020) 2, 151; A. Papaefstathiou, TR, G. Tetlalmatzi-Xolocotzi, JHEP 2105 (2021) 193; TR, Symmetry 15 (2023) 27; TR, arXiv:2305.08595

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HHH Workshop
Dubrovnik
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Special role of the scalar sector

- **Higgs potential in the SM**

$$V = -\mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2, \quad \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$\Rightarrow$ **mass** for Higgs Boson and Gauge Bosons

$$m_h^2 = 2\lambda v^2,\ m_W = g\frac{v}{2},\ m_Z = \sqrt{g^2 + (g')^2}\frac{v}{2}$$

where v: Vacuum expectation value of the Higgs field, g, g'': couplings in $SU(2) \times U(1)$

$\Rightarrow$ **everything determined in terms of gauge couplings, v, and λ**

> **form of potential determines minimum,**
> **electroweak vacuum structure**

$\Rightarrow$ stability of the Universe, electroweak phase transition, etc

- **full test requires checks of *hhh*, *hhhh* couplings**

$\Rightarrow$ **so far: only limits; possible only at future machines** [HL-LHC: constraints on *hhhh*]

Models

- new scalars $\Rightarrow$ **models with scalar extensions**
- many possibilites: introduce new $SU(2) \times U(1)$ **singlets, doublets, triplets, ...**
- unitarity $\Rightarrow$ important **sum rule***

$$\sum_i g_i^2\,(h_i) = g_{SM}^2$$

for coupling g to vector bosons

- many scenarios $\Rightarrow$ **signal strength poses strong constraints**

* modified in presence e.g. of doubly charged scalars, see Gunion, Haber, Wudka, PRD 43 (1991) 904-912.

What about extensions ?

- in principle: **no limit**

can add more singlets/ doublets/ triplets/ ...

⇒ consequence: **will enhance particle content**

additional (pseudo)scalar neutral, additional charged, doubly charged, etc particles

- common feature:

new scalar states, which can now also be produced/ decay into each other/ etc

Particle content

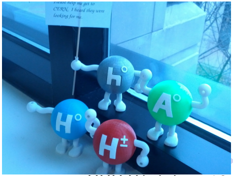
typical content:
singlet extensions ⇒ additional CP-even/ odd mass eigenstates
2HDMs, 3HDMs: add additional charged scalars

- e.g. 2 real scalars ⇒ **3 CP-even neutral scalars**
- 2HDM → **2 CP-even, one CP odd neutral scalar, and charged scalars**
- ...

Other possible extensions

- A priori: **no limit to extend scalar sector**
- **make sure you**
  - have a **suitable ew breaking mechanism**, including a **Higgs candidate at** $\sim 125\,\mathrm{GeV}$
  - can explain **current measurements**
  - are **not excluded by current searches** and precision observables
- **nice add ons:**
  - can **push vacuum breakdown to higher scales**
  - can **explain additional features**, e.g. dark matter, or hierarchies in quark mass sector
  - ...
- Multitude of models out there
- adding ew gauge singlets/ doublets/ triplets...

  ⇒ **new scalar states** ⇐



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)

Limited time $\Rightarrow$ next slides highly selective...

[long list of models, see e.g. https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG3]

tools used: `HiggsBounds`, `HiggsSignals`, `2HDMC`, `micrOMEGAs`, ...

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*.

[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]

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**

What is new

- **updated constraints using HiggsTools**
  (supersedes HiggsBounds and HiggsSignals)

  [H. Bahl, T. Biekoetter, S. Heinemeyer, C. Li, S. Paasch, G. Weiglein, J. Wittbrodt, arXiv:2210.09332]
- also slightly changed definition of strongest constraint

Most important new searches$^{(*)}$

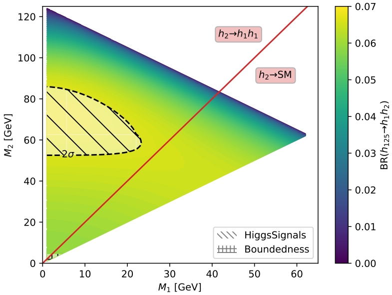
- $H_{\mathbf{BSM}} \rightarrow Z\,Z$, **ATLAS, Run II** [Eur.Phys.J.C 81 (2021) 4, 332]
- $H_{\mathbf{BSM}} \rightarrow h_{125}\,h_{\mathbf{BSM}}$, **CMS, Run II** [JHEP 11 (2021) 057]

[$^{(*)}$ as implemented in HiggsTools]

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

BP1

$\sigma(pp \to h_3) \simeq \sigma(pp \to h_{\rm SM}) \sim 50$ pb,
$\mathrm{BR}(\mathrm{h_3} \to \mathrm{h_1 h_2})$ up to 7%, 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 $m_{bb}^{(2)} \simeq M_2$)

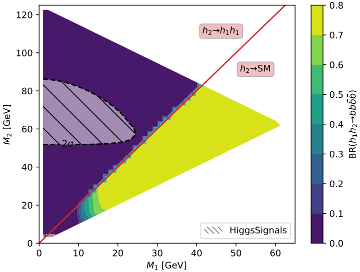


$\Rightarrow$ $h_1 h_1 h_1$ final states: reconstructing to M_3, with one pair reconstructing to M_2

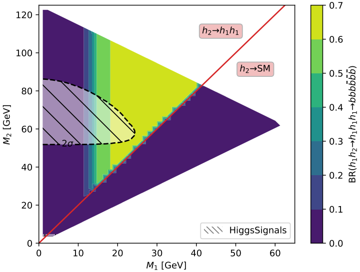
$\Rightarrow$ both scalars as in SM: 2 light scalars reconstructing to M_3

$[|\kappa_3| = 0.9965]$

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

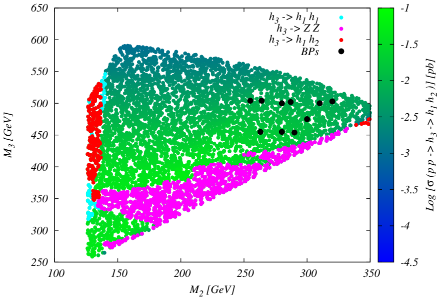
BP3: $h_3 \to h_1 h_2$ $(h_1 = h_{125})$ [up to 0.3 pb]

BP3

$\sigma(pp \to h_3) \simeq 0.06 \cdot \sigma(pp \to h_{SM})|_{m=M_3}$
$\mathrm{BR}(\mathrm{h}_3 \to \mathrm{h}_{125}\mathrm{h}_2)$ mostly $\sim 50\%$.
if $M_2 < 250\,\mathrm{GeV}$: $\Rightarrow h_2 \to$ SM particles.
if $M_2 > 250\,\mathrm{GeV}$:
$\Rightarrow \mathrm{BR}(\mathrm{h}_2 \to \mathrm{h}_{125}\mathrm{h}_{125}) \sim 70\%$,

$\Rightarrow$ spectacular triple-Higgs signature

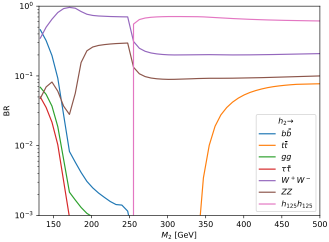
[up to 140 fb; maximal close to thresholds]

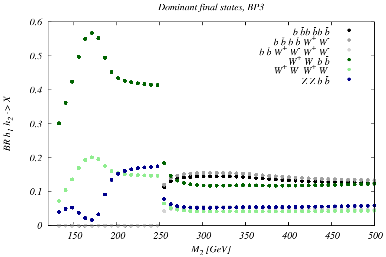


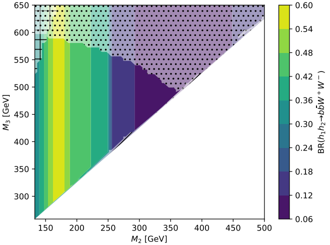
$[\kappa_3 = 0.24]$ $[\Gamma_3/M_3 \leq 0.05]$

bounds from $p\,p \to h_3 \to h_1\,h_2$ [CMS, Run II, JHEP 11 (2021) 057]

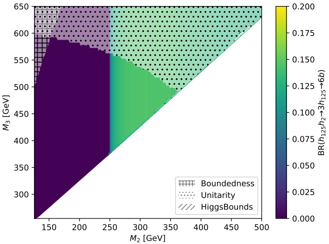
BP3: $h_3 \to h_1 h_2$ ($h_1 = h_{125}$) [up to 0.3 pb]





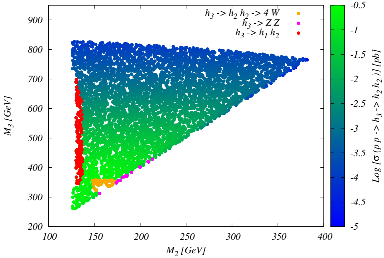


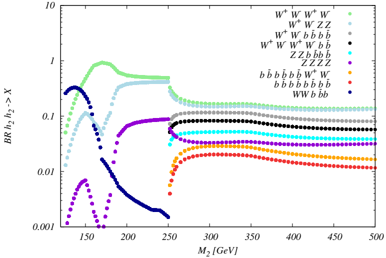
up to 0.18 pb



up to 30 fb

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**

! ATLAS WWWW search [36 fb^{-1}] **sensitive !** **[JHEP 05 (2019) 124]**

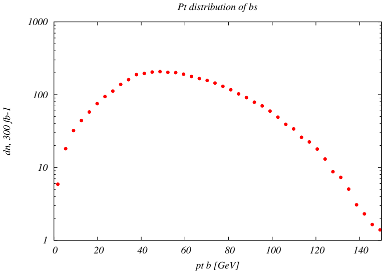
Sample distribution, $W^+W^-b\bar{b}b\bar{b}$ final state

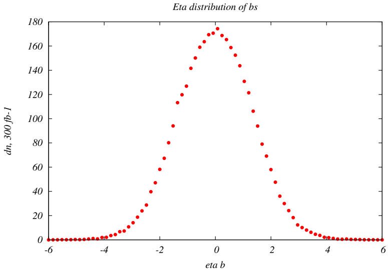
$$M_1 \sim 125\,\mathrm{GeV}, \quad M_2 \sim 279\,\mathrm{GeV}, \quad M_3 \sim 583\,\mathrm{GeV};$$

$$\sigma_{h_1 h_2} \sim 185\,\mathrm{fb};$$

$$\mathbf{BR}_{h_2 \to W^+ W^-} \sim 0.43, \quad \mathbf{BR}_{h_2 \to h_1 h_1} \sim 0.39, \quad \mathbf{BR}_{h_1 \to b\,\bar{b}} \sim 0.83;$$

$$\sigma_{W^+W^-b\bar{b}b\bar{b}} \sim 21\,\mathrm{fb}$$





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

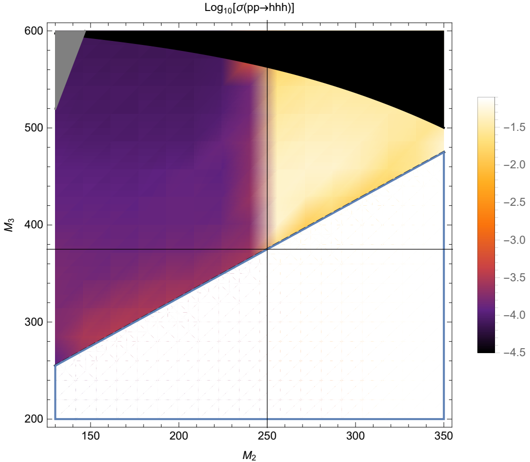
concentrate on
$$p\,p \;\rightarrow\; h_3 \;\rightarrow\; h_2\,h_1 \;\rightarrow\; h_1\,h_1\,h_1 \;\rightarrow\; b\,\bar{b}\,b\,\bar{b}\,b\,\bar{b}$$

$\Rightarrow$ **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]

$h_1 h_1 h_1$ production cross sections, leading order [pb], BP3



[using interpolation]

highest values: $\sim 50\text{fb}$ **for** $M_2 \sim 250\,\text{GeV},\, M_3 \sim 400 - 450\text{GeV}$

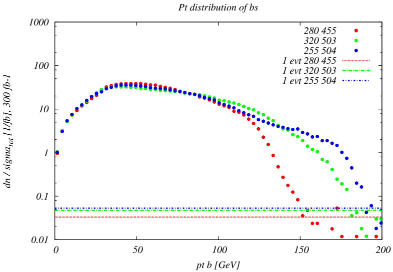
Benchmark points and results

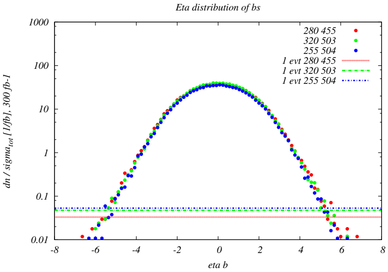
(M_2, M_3) [GeV]	$\sigma(pp \to h_1 h_1 h_1)$ [fb]	$\sigma(pp \to 3b\bar{b})$ [fb]	$\text{sig}\vert_{300\text{fb}^{-1}}$	$\text{sig}\vert_{3000\text{fb}^{-1}}$
(255, 504)	32.40	6.40	2.92	9.23
(263, 455)	50.36	9.95	4.78	15.11
(287, 502)	39.61	7.82	4.01	12.68
(290, 454)	49.00	9.68	5.02	15.86
(320, 503)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

⇒ at HL-LHC, all points within reach ⇐

Some *b*- distributions [preliminary]





Other work...

- in principle:

any model that gives additional scalar states works !

- additional singlets, 2HDMs, 3HDMs, ...
- always important:

constraints from signal strength [and direct searches]

$\Rightarrow$ **large number of models e.g. implemented in ScannerS**
[M. Muhlleitner ea, Eur.Phys.J.C 82 (2022) 3, 198]

Similar proposal

[H. Abouabid, A. Arhrib, D. Azevedo, J. El Falaki, P. M. Ferreira, M. Muhlleitner, R. Santos, JHEP 09 (2022) 011]

- consider **various BSM scenarios with extended scalar sectors**, leading to at least 3 additional scalars
- emphasize on $h_{125} h_{125}$ **and** $h_{125} \Phi$ **production modes**
- final states for the latter: $b\,\bar{b} b\,\bar{b} / WW / t\,\bar{t}$ (up to 2 pb for 4 bs)
- also **6 b and 8 b final states**; rates up to 100/ 1.4 fb
- typically not very boosted, but maximal production around thresholds

Multi-Higgs final states

In non-minimal Higgs models like the C2HDM, N2HDM, and NMSSM we can have multi-Higgs final states from cascade Higgs-to-Higgs decays. SM-like plus non-SM-like Higgs final state, $H_{SM}\Phi$ - both the Higgs-to-Higgs decay of the SM-like Higgs or the non-SM-like one can lead to substantial final state rates (largest NLO rates above 10 fb). Ordering f particles with regards to their decay chains is maintained, so that it is clear which Higgs boson decays into which Higgs pair. We give the rates in the (6b) final state as they lead to the largest cross sections for all shown scenarios.

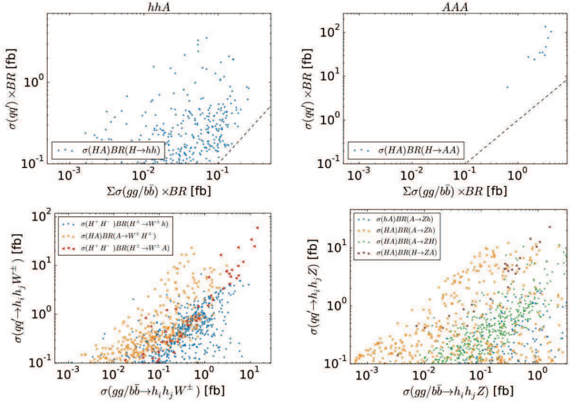
Model	Mixed Higgs State	m_{Φ_1} [GeV]	m_{Φ_2} [GeV]	Rate [fb]	K-factor
N2HDM-I	$H_2H_3(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	98	41	15	1.95
	$H_2H_1(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	282	-	40	1.96
	$H_2H_1(\equiv H_{SM}) \to AA(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	157	73	33	2.05
	$H_1H_2(\equiv H_{SM}) \to (b\bar{b})H_1H_1 \to (b\bar{b})(b\bar{b})(b\bar{b})$	54	-	111	2.09
	$H_3H_2(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	212	83	8	1.93
N2HDM-II	$H_2H_1(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	271	-	3	1.87
NMSSM	$H_2H_1(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	319	-	11	1.90
	$H_2H_1(\equiv H_{SM}) \to A_1A_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	253	116	26	1.92

Model	Mixed Higgs State	$m_{res.}$ [GeV]	res. rate [fb]
N2HDM-I	$H_2H_3(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	—	—
	$H_2H_1(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	441	39
	$H_2H_1(\equiv H_{SM}) \to AA(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	294	37
	$H_1H_2(\equiv H_{SM}) \to (b\bar{b})H_1H_1 \to (b\bar{b})(b\bar{b})(b\bar{b})$	229	119
	$H_3H_2(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	—	—
N2HDM-II	$H_2H_1(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	615	2
NMSSM	$H_2H_1(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	560	11
	$H_2H_1(\equiv H_{SM}) \to A_1A_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	518	26

Table 31: Upper: Maximum rates for multi-Higgs final states given at NLO QCD. The K-factor is given in the last column. In the third and fourth column we also give the mass values m_{Φ_1} and m_{Φ_2} of the non-SM-like Higgs bosons involved in the process, in the order of their appearance. Lower: In case of resonantly enhanced production the mass of the resonantly produced Higgs boson is given together with the NNLO QCD production rate. More details on these points can be provided on request.

R. Santos, Higgs Pairs Workshop, 1 June 2022

Enberg ea, Eur.Phys.J.C 79 (2019) 6, 512: Neutral Scalar States



[R. Enberg, W. Klemm, S. Moretti, SM, 1812.08623]

Summary

- **TRSM: 3 CP-even neutral scalars**
- allows for **many interesting decay chains** including scalars
- some searches already sensitive

Room for more

- New physics scenarios:
  discussed in **Extended Scalar Subgroup of Higgs WG**

egroup: lhc-higgs-neutral-extended-scalars

Appendix

Decay patterns

- **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**

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

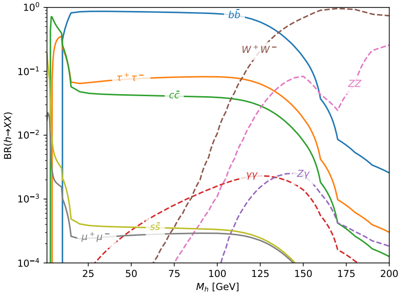
(whenever kinematically feasible)

$\Rightarrow$

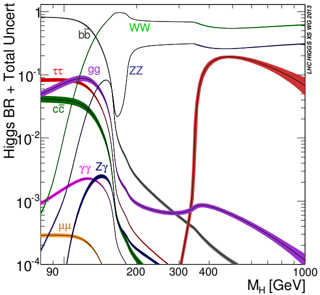
$$\text{BR}_{h_i \to \text{SM}}(M_i) = \frac{\kappa_i^2\, \Gamma^{\text{SM}}_{h_i \to \text{SM}}(M_i)}{\kappa_i^2\, \Gamma^{\text{SM}}_{h_i \to \text{SM}}(M_i) + \sum_{j,k} \Gamma_{h_i \to h_j\, h_k}}$$

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

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

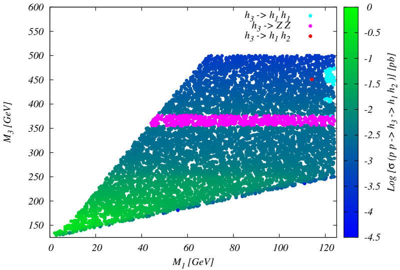


(using HDecay, courtesy J.Wittbrodt)



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

BP2: $h_3 \to h_1 h_2$ $(h_2 = h_{125})$ [up to 0.6 pb]



[upper left: excluded from boundedness from below]

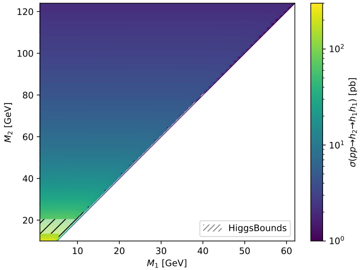
- $|\kappa_3| \sim 0.2$

$$\sigma_{gg \to h_3}(M_3) \sim 0.04\, \sigma^{SM}_{gg \to h_3}(M_3)$$

[$BR_{h_3 \to h_1 h_2}$ up to 50 %]

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

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



- $|\kappa_2| \sim 0.2$

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

[$BR_{h_2\to h_1 h_1} \gtrsim 0.9$ for $M_1 \gtrsim 40\,\mathrm{GeV}$]

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

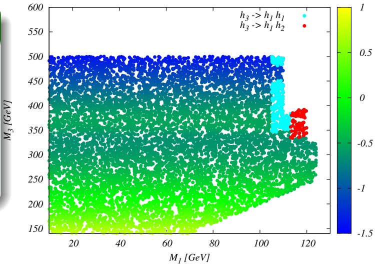
[exclusion from LEP combination, Phys.Lett.B 565 (2003) 61-75]

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

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

recast enhanced search: exclusion for
$M_3 \geq 350\,\mathrm{GeV}$, $M_1 \geq 60\,\mathrm{GeV}$

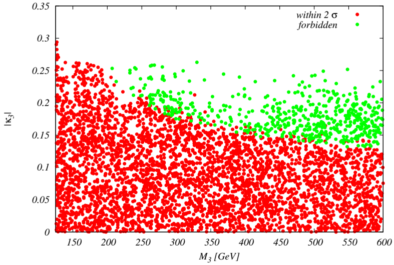
[TR, Symmetry 15 (2023) 27, using Barducci ea, JHEP 02 (2020) 002]

What about W-mass ?

- D. Lopez-Val, TR, Phys.Rev.D 90 (2014) 114018: need low-mass second scalar to drive mass up to measured value

  $\Rightarrow$ **conflict with signal strength measurements** $\Leftarrow$

- TRSM: extend to contributions of 2 additional scalars



2 σ from PDG value, $M_W = (80.377 \pm 0.012)\,\mathrm{GeV}$

highest value: $M_W \sim 80.361\,\mathrm{GeV}$;

$M_1 \sim 4\,\mathrm{GeV},\ M_3 \sim 494\,\mathrm{GeV},\ \kappa_1 \sim 0.24,\ \kappa_3 \sim 0.016$

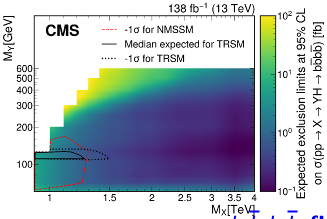
What about LHC search interpretations ?

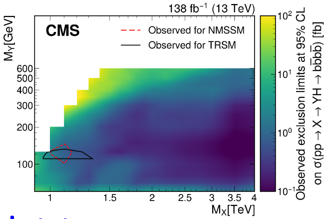
- so far: **2 searches (by CMS) with public results and TRSM interpretations**
- both target $p\,p \to X \to Y\,h$
- final states: $b\,\bar{b}\,b\,\bar{b}$ [2204.12413], $b\,\bar{b}\,\gamma\,\gamma$ [CMS-PAS-HIG-21-011]
- compares to **maximal rates** in TRSM and NMSSM

[TRSM rates available from https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG3EX]

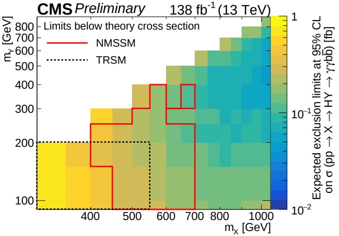
Results

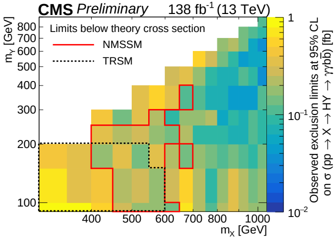
expected | **observed**





$b\,\bar{b}\,b\,\bar{b}$ final states





$b\,\bar{b}\,\gamma\,\gamma$ final states

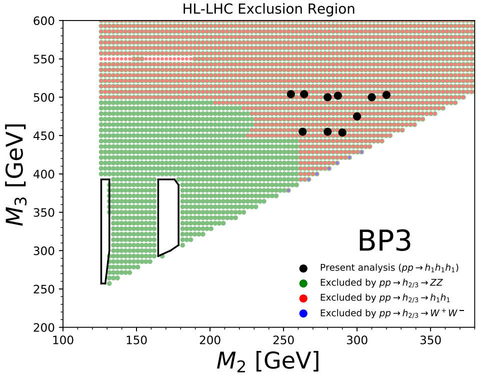
Cut selection

Label	(M_2, M_3) [GeV]	$< P_{T,b}$ [GeV]	$\chi^{2,(4)} <$ [GeV^2]	$\chi^{2,(6)} <$ [GeV^2]	$m_{4b}^{\rm inv} <$ [GeV]	$m_{6b}^{\rm inv} <$ [GeV]
A	(255, 504)	34.0	10	20	-	525
B	(263, 455)	34.0	10	20	450	470
C	(287, 502)	34.0	10	50	454	525
D	(290, 454)	27.25	25	20	369	475
E	(320, 503)	27.25	10	20	403	525
F	(264, 504)	34.0	10	40	454	525
G	(280, 455)	26.5	25	20	335	475
H	(300, 475)	26.5	15	20	352	500
I	(310, 500)	26.5	15	20	386	525
J	(280, 500)	34.0	10	40	454	525

Table : $|\eta|_b < 2.35$, $\Delta m_{\rm min,\ med,\ max} < [15, 14, 20]$ GeV, $p_T(h_1^i) > [50, 50, 0]$ GeV, $\Delta R(h_1^i, h_1^j) < 3.5$ and $\Delta R_{bb}(h_1) < 3.5$.

χ^2s: variables used in h_1 reconstruction

What about other channels ?



[extrapolation of 36 fb^{-1} and HL projections]

⇒ model can be tested from various angles ⇐

[Phys. Rev. Lett. 122 (2019) 121803; Phys. Lett. B800 (2020) 135103; JHEP 06 (2018) 127; CERN Yellow Rep. Monogr. 7 (2019) 221; Eur. Phys. J. C78 (2018) 24; ATL-PHYS-PUB-2018-022]

Relevant channels from HiggsTools

excluding points previously allowed

- $H_{\mathbf{BSM}} \rightarrow h_{125}\, h_{125} \rightarrow 4b$, **CMS, early Run II** [JHEP 08 (2018) 152]
- $H_{\mathbf{BSM}} \rightarrow h_{125}\, h_{125}$ **combination, CMS, early Run II** [Phys.Rev.Lett. 122 (2019) 12, 121803]
- $H_{\mathbf{BSM}} \rightarrow H'_{\mathbf{BSM}}\, H'_{\mathbf{BSM}} \rightarrow 4\,W$, **ATLAS, early Run II** [JHEP 05 (2021) 193]
- $H_{\mathbf{BSM}} \rightarrow h_{125}\, h_{125}$ **combination, ATLAS, early Run II** [Phys. Lett. B 800 (2020) 135103]
- $H_{\mathbf{BSM}} \rightarrow Z\,Z$, **ATLAS, Run II** [Eur.Phys.J.C 81 (2021) 4, 332]
- $H_{\mathbf{BSM}} \rightarrow h_{125}\, h_{\mathbf{BSM}}$, **CMS, Run II** [JHEP 11 (2021) 057]

Non-SM-like Higgs Search: Di-Higgs beats Single Higgs

N2HDM-I and NMSSM - 3 SM-like Higgs bosons (H1). NLO rates above 10 fb. Di-Higgs states larger/ comparable with direct production.

Reason: non-SM-like Higgs is singlet-like (suppressed couplings to SM-like particles) and/or is more down- than up-type like (suppressed direct production).

m_{H_1} [GeV]	m_{H_2} [GeV]	m_{H_3} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan\beta$
125.09	281.54	441.25	386.98	421.81	1.990
α_1	α_2	α_3	v_s [GeV]	$\mathrm{Re}(m_{12}^2)$ [GeV^2]	
1.153	0.159	0.989	9639	29769	

$$\sigma^{\rm NLO}_{H_1H_2} \times \mathrm{BR}(H_2 \to H_1H_1) \times \mathrm{BR}(H_1 \to b\bar{b})^3 = 509 \cdot 0.37 \cdot 0.60^3 \text{ fb} = 40 \text{ fb}$$

$$\sigma^{\rm NNLO}(H_2) \times \mathrm{BR}(H_2 \to H_1H_1) \times \mathrm{BR}(H_1 \to b\bar{b})^2 = 161 \cdot 0.37 \cdot 0.60^2 \text{ fb} = 21 \text{ fb}$$

$$\sigma^{\rm NNLO}(H_2) \times \mathrm{BR}(H_2 \to WW) = 161 \cdot 0.44 \text{ fb} = 71 \text{ fb}$$

H2 BR to bb tiny.

Non-SM- like H2 has better chances of being discovered in di-Higgs than in single Higgs channels (W bosons still have to decay).