Unexplored signatures in the IDM and TRSM

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based on work with

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Rudjer Boskovic Institute

LHC Higgs Working Group WG3 (BSM)
Extended Higgs Sector subgroup meeting
6.7.21

IDM and TRSM - mini-introduction

- both models **extend scalar sector of SM, lead to novel particle states and non-SM signatures**
- **IDM: Inert Doublet Model**, Two-Higgs-Doublet Model with an exact Z_2 symmetry $\Rightarrow$ $H, A, H^\pm$ **states**, one of these is dark matter
- **signatures: electroweak gauge bosons and** $\not{E}_\perp$
- **TRSM: model introducing 2 real scalar fields**, mixing $\Rightarrow$ **3 scalar states** $h_{1,2,3}$ (one $=$ h_{125})
- **signatures: many**, including multiscalar production and decays $p\,p\,\rightarrow\,h_i\,\rightarrow\,h_j\,h_k,\;i,j,k\,\in\{1,2,3\},\,\ldots$
- **can lead to** $h_1\,h_1\,h_1$ **and** $h_1\,h_1\,h_1\,h_1$ **final 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)

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

Models with dark matter candidates: Inert Doublet Model

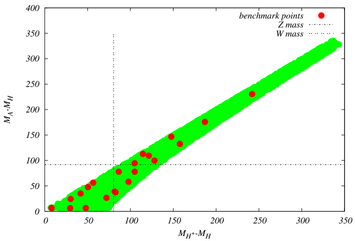
2 Higgs Doublet Model: 4 new scalars $H, A, H^{\pm}$

Z_2 symmetry $\rightarrow$ **DM candidate(s)** (here: choose H)

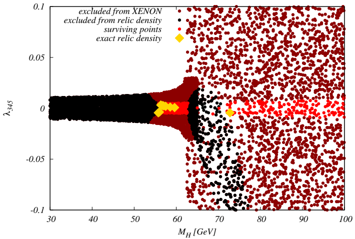
free parameters: **masses,** λ_2, λ_{345} (couplings in V)

signatures: EW gauge boson(s) + MET

$\Rightarrow$ **so far: no LHC analysis** $\Leftarrow$



Masses highly constrained from electroweak precision [Kalinowski, Kotlarski, TR, Sokolowska, Zarnecki, JHEP 1812 (2018)]



... and also from signal strength and astrophysical constraints ...
[Ilnicka, TR, Stefaniak, Mod.Phys.Lett. A33 (2018) no.10n11, 1830007]

Production and decay

- Z_2 symmetry:

only pair-production of dark scalars $H, A, H^{\pm}$

- production modes:

$$\mathbf{p\,p} \to \mathbf{HA},\, \mathbf{HH^{\pm}},\, \mathbf{AH^{\pm}},\, \mathbf{H^{+}H^{-}}$$

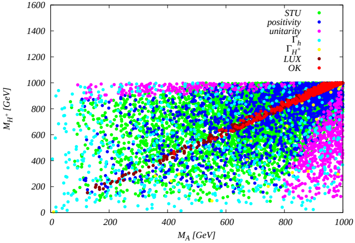
$+$ dijet: VBF-type production

- decays:

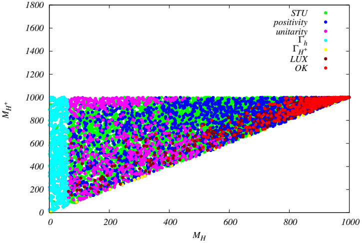
$$\mathbf{A} \to \mathbf{Z\,H} :\ \mathbf{100\%},\ \mathbf{H^{\pm}} \to \mathbf{W^{\pm}H} :\ \text{dominant}$$

signature: **electroweak gauge boson(s) + MET**

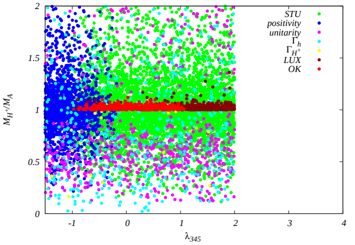
Results of generic scan [Phys.Rev.D 93 (2016) 5, 055026; JHEP 12 (2018) 081]



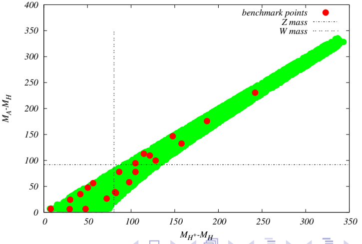
M_A vs $M_{H\pm}$



M_H vs $M_{H\pm}$



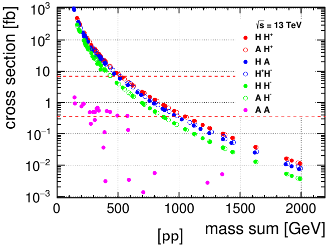
λ_{345} vs $M_{H\pm}/M_A$

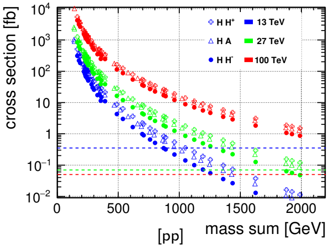


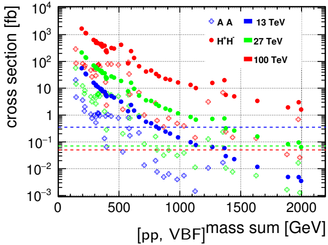
mass differences

Production cross sections [Symmetry 13 (2021) 6, 991]

lines: 1000 events for design luminosity





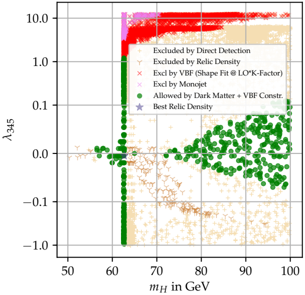


IDM at LHC

(in collaboration w D. Dercks, Eur.Phys.J.C 79 (2019) 11, 924)

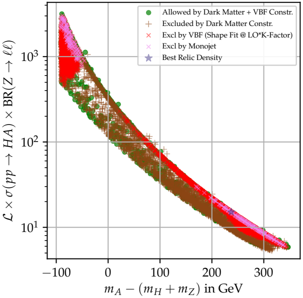
VBF recast; test of dilepton sensitivity

Search for invisible decays of a Higgs boson produced through vector boson fusion in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$, CMS, arXiv:1809.05937 [$35.9\mathrm{fb}^{-1}$]



Recast of 13 TeV VBF $h \to$ invisible search

important constraints in offshell regime !

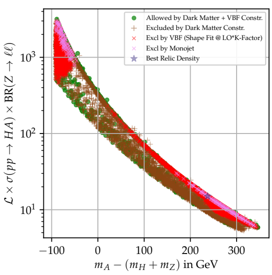


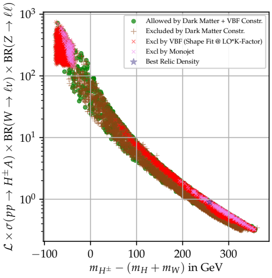
example for $\not{E}_\perp$ vs rate

high rates $\Longleftrightarrow$ low $\not{E}_\perp$ cuts

current searches at LHC need to be modified

Brief comments on null-results for other channels





- **high** $\not{E}_\perp \Rightarrow$ **low** σ and vice versa

experiments need to venture into low $\not{E}_\perp$ region

(first discussions: The 15th Workshop of the LHC Higgs Cross Section Working Group, CERN, 12/18; cf e.g. summary talk by D. Sperka)

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]

Benchmark points/ planes [ASymmetric/ Symmetric]

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

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

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

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

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

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

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

up to 60 pb

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

up to 2.5 pb

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

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

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

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

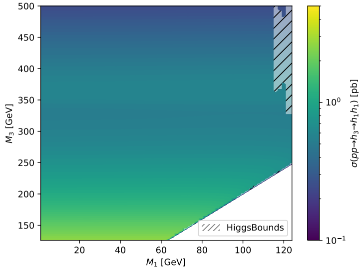
(M_2, M_3) [GeV]	$\sigma(pp \to h_1 h_1 h_1)$ [fb]	$\sigma(pp \to 3b\bar{b})$ [fb]	$\text{sig}\vert_{300\text{fb}^{-1}}$	$\text{sig}\vert_{3000\text{fb}^{-1}}$
$(255, 504)$	32.40	6.40	2.92	9.23
$(263, 455)$	50.36	9.95	4.78	15.11
$(287, 502)$	39.61	7.82	4.01	12.68
$(290, 454)$	49.00	9.68	5.02	15.86
$(320,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

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

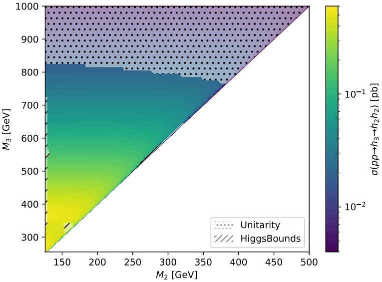
BP5 recast: $h_3 \to h_1 h_1 \to b\bar{b}b\bar{b}$

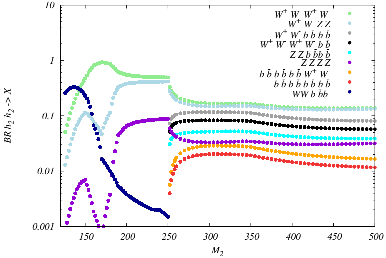
Enlarging the scope of resonant di-Higgs searches: Hunting for Higgs-to-Higgs cascades in 4b final states at the LHC and future colliders [Barducci, Mimasu, No, Vernieri, Zurita; JHEP 2002 (2020) 00]



$\Rightarrow$ 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

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)**

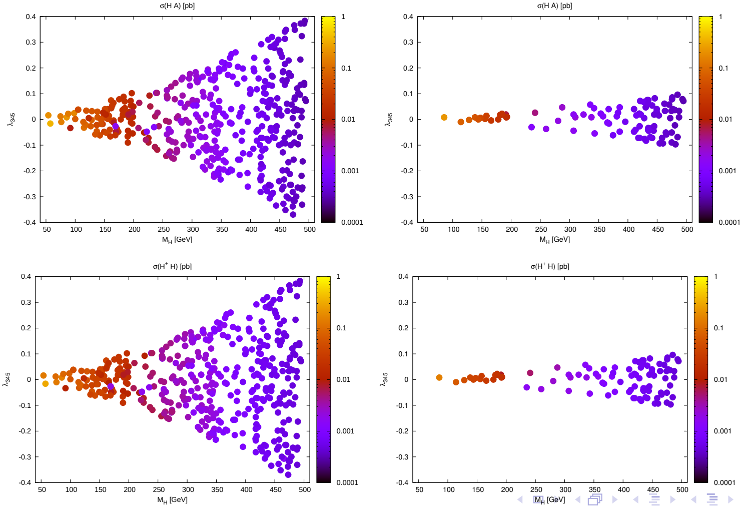
- interesting **multi-scalar final states** ($h_1 h_1 h_1$, $h_1 h_1 h_1 h_1$)
- decays typically involve $b\bar{b}$, $W^+ W^-$, $\tau^+\tau^-$ pairs that reconstruct to scalars

Stay tuned...

Appendix

Updated constraints [XENON1T] [Phys.Rev.Lett. 121 (2018) no.11, 111302]

LUX **XENON**



Recast of LHC Run II results

(in collaboration w D. Dercks, Eur.Phys.J.C 79 (2019) 11, 924)

- so far:

  no dedicated searches at the LHC

- however, dominant final states:

  jet(s) + MET, EW gauge boson(s) + MET

  $\Rightarrow$ **same final states appear in other BSM searches** $\Leftarrow$

- idea: **use recasting methods** to give (preliminary) exclusion limits if feasible
- many tools around; here: **CheckMATE** [Drees ea '13, Dercks ea '16]

IDM recast

- considered a long list of processes at 13 TeV
- most sensitive:

VBF + invisible Higgs decay (by far), Monojet

⇒ implemented in CheckMATE [currently: private version]

⇒ applied to IDM

VBF: *Search for invisible decays of a Higgs boson produced through vector boson fusion in proton-proton collisions at* $\sqrt{s} = 13\,\mathrm{TeV}$, CMS, arXiv:1809.05937 [$35.9\mathrm{fb}^{-1}$]

Monojet: *Search for dark matter and other new phenomena in events with an energetic jet and large missing transverse momentum using the ATLAS detector*, ATLAS, ATLAS-CONF-2017-060 [$36.1\mathrm{fb}^{-1}$]

Backup slide

Low mass IDM benchmark points

No.	M_H	M_A	$M_{H\pm}$	λ_2	λ_{345}	$\Omega_c h^2$
BP1	72.77	107.8	114.6	1.445	-0.004407	0.1201
BP2	65	71.53	112.8	0.7791	0.0004	0.07081
BP3	67.07	73.22	96.73	0	0.00738	0.06162
BP4	73.68	100.1	145.7	2.086	-0.004407	0.08925
BP5	55.34	115.4	146.6	0.01257	0.0052	0.1196
BP6	72.14	109.5	154.8	0.01257	-0.00234	0.1171
BP7	76.55	134.6	174.4	1.948	0.0044	0.0314
BP8	70.91	148.7	175.9	0.4398	0.0051	0.124
BP9	56.78	166.2	178.2	0.5027	0.00338	0.08127
BP10	76.69	154.6	163	3.921	0.0096	0.02814
BP11	98.88	155	155.4	1.181	-0.0628	0.002737
BP12	58.31	171.1	173	0.5404	0.00762	0.00641
BP13	99.65	138.5	181.3	2.463	0.0532	0.001255
BP14	71.03	165.6	176	0.3393	0.00596	0.1184
BP15	71.03	217.7	218.7	0.7665	0.00214	0.1222
BP16	71.33	203.8	229.1	1.03	-0.00122	0.1221
BP17	55.46	241.1	244.9	0.289	-0.00484	0.1202
BP18	147	194.6	197.4	0.387	-0.018	0.001772
BP19	165.8	190.1	196	2.768	-0.004	0.002841
BP20	191.8	198.4	199.7	1.508	0.008	0.008494
BP21	57.48	288	299.5	0.9299	0.00192	0.1195
BP22	71.42	247.2	258.4	1.043	-0.00406	0.1243
BP23	62.69	162.4	190.8	2.639	0.0056	0.06404

Backup slide

High mass IDM benchmark points

No.	M_H	M_A	$M_{H\pm}$	λ_2	λ_{345}	$\Omega_c h^2$
HP1	176	291.4	312	1.49	-0.1035	0.0007216
HP2	557	562.3	565.4	4.045	-0.1385	0.07209
HP3	560	616.3	633.5	3.38	-0.0895	0.001129
HP4	571	676.5	682.5	1.98	-0.471	0.0005635
HP5	671	688.1	688.4	1.377	-0.1455	0.02447
HP6	713	716.4	723	2.88	0.2885	0.03515
HP7	807	813.4	818	3.667	0.299	0.03239
HP8	933	940	943.8	2.974	-0.2435	0.09639
HP9	935	986.2	988	2.484	-0.5795	0.002796
HP10	990	992.4	998.1	3.334	-0.051	0.1248
HP11	250.5	265.5	287.2	3.908	-0.1501	0.00535
HP12	286.1	294.6	332.5	3.292	0.1121	0.00277
HP13	336	353.3	360.6	2.488	-0.1064	0.00937
HP14	326.6	331.9	381.8	0.02513	-0.06267	0.00356
HP15	357.6	400	402.6	2.061	-0.2375	0.00346
HP16	387.8	406.1	413.5	0.8168	-0.2083	0.0116
HP17	430.9	433.2	440.6	3.003	0.08299	0.0327
HP18	428.2	454	459.7	3.87	-0.2812	0.00858
HP19	467.9	488.6	492.3	4.122	-0.252	0.0139
HP20	505.2	516.6	543.8	2.538	-0.354	0.00887

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

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

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

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

- **additional onshell decays**

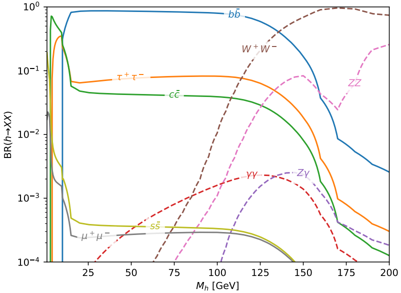
$$h_3 \rightarrow h_1\, h_2,\ h_3 \rightarrow h_1\, h_1,\ h_3 \rightarrow h_2\, h_2,\ h_2 \rightarrow h_1\, h_1$$

(whenever kinematically feasible)

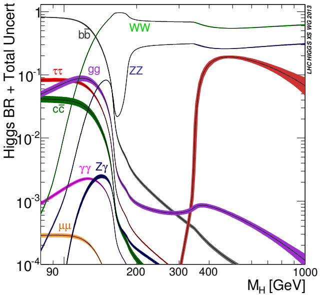
$\Rightarrow$ **relative ratio for SM final states as in SM at mass M_i**

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

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



(using HDecay, courtesy J.Wittbrodt)



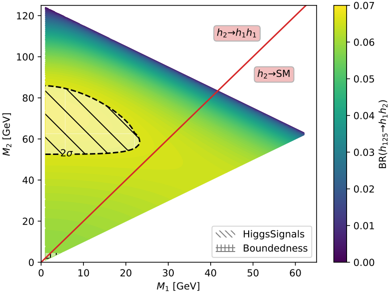
(https://twiki.cern.ch/twiki/bin/view/LHCPhysics

/LHCHXSWGCrossSectionsFigures)

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

BP1

$\sigma(pp \to h_3) \simeq \sigma(pp \to h_{SM}) \sim 50$ pb,
$\mathrm{BR}(h_3 \to h_1 h_2)$ up to 7%, if
$M_2 > 2M_1$
$\Rightarrow \mathrm{BR}(h_2 \to h_1 h_1) \approx 100\%$,
(→ e.g., three pairings $m_{bb} \simeq M_1$)
if $M_2 < 2M_1 \Rightarrow h_2 \to$ SM particles.
(→ e.g., $m_{bb}^{(1)} \simeq M_1$ and $m_{bb}^{(2)} \simeq M_2$)

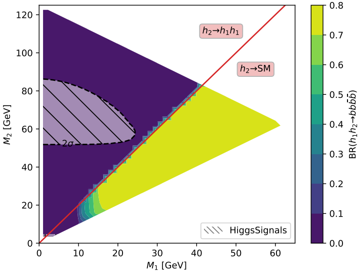


⇒ $h_1 h_1 h_1$ final states: reconstructing to M_3, with one pair reconstructing to M_2

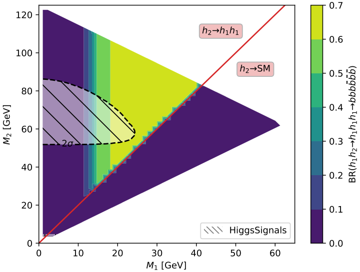
⇒ both scalars as in SM: 2 light scalars reconstructing to M_3

$[|\kappa_3| = 0.9965]$

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, arXiv:2101.00037]

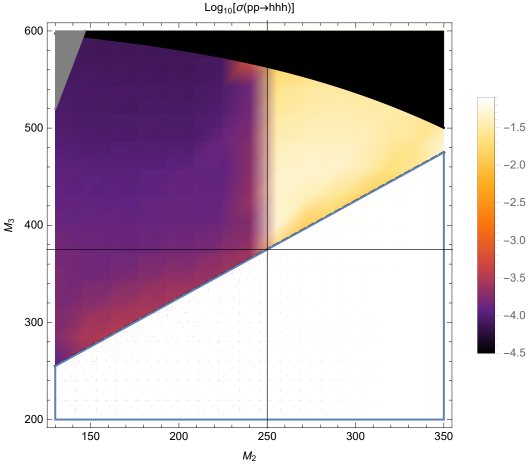
concentrate on $p\,p \;\rightarrow\; h_1\, h_1\, h_1 \;\rightarrow\; b\,\bar{b}\,b\,\bar{b}\,b\,\bar{b}$

$\Rightarrow$ **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]

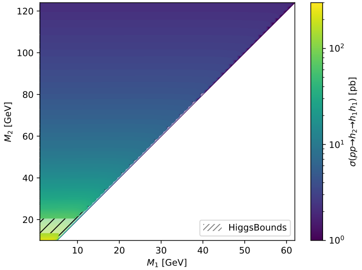
$h_1 h_1 h_1$ production cross sections, leading order [pb]



[using interpolation]

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

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



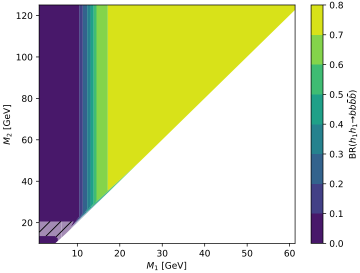
- $|\kappa_2| \sim 0.2$

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

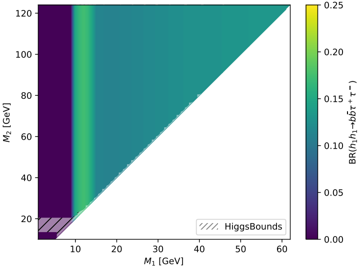
[$\text{BR}_{h_2 \rightarrow h_1 h_1} \gtrsim 0.9$ for $M_1 \gtrsim 40\,\text{GeV}$]

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

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 $H \to h_{125}\, h_{125} \to b\bar{b}b\bar{b}$**

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

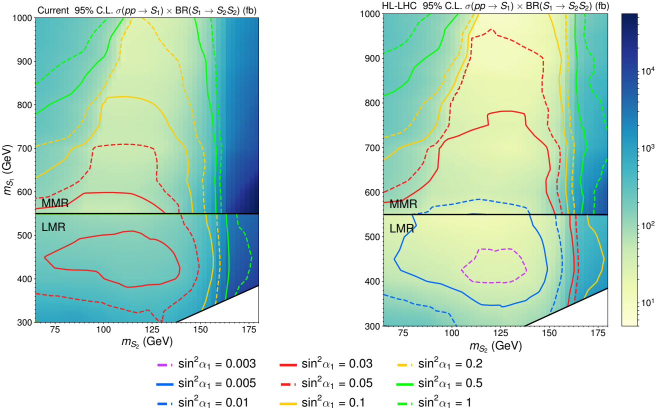
$\Rightarrow$ **reinterpret/ adjust for resonances and decay products in a wider mass range $h_2 \to h_1\, h_1$**

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

(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

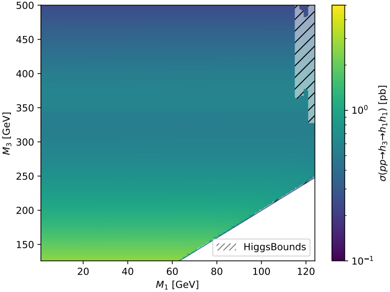


BP5: $h_3 \to h_1 h_1$ $(h_2 = h_{125})$ [up to 2.5 pb]

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.

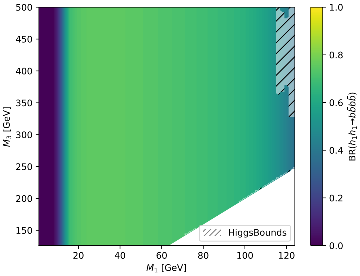
$[\kappa_3 = -0.25, \Gamma_3/M_3 \leq 0.08]$



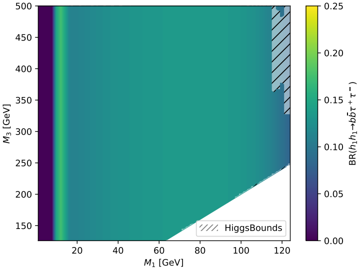
two light scalars reconstructing to M_3

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]



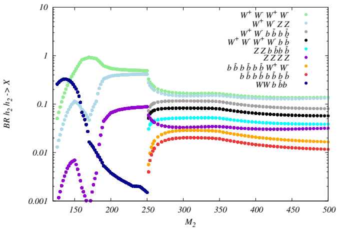
$h_3 \to h_1\, h_1 \to b\bar{b}b\bar{b}$

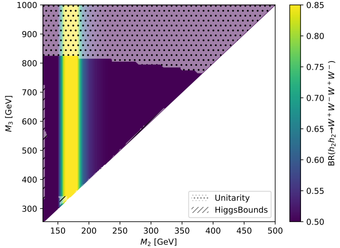


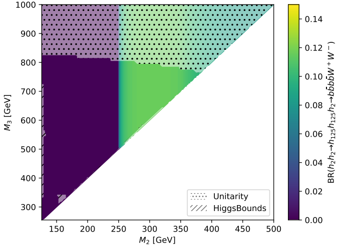
$h_3 \to h_1\, h_1 \to b\bar{b}\tau^+\tau^-$

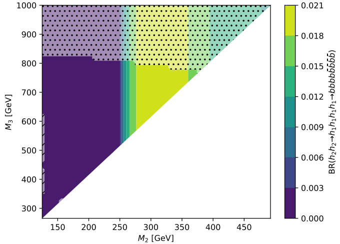
reaching $\sim 2/0.3\,\mathrm{pb}$**, max for** $M_1 > 20\,\mathrm{GeV}, M_3 \sim 140\,\mathrm{GeV}$

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)