

## Overview - Classification of Benchmark Points

Overall feature	Signature	Benchmark Points
<b>I. Exotic decay of Higgses</b>		
<b>Neutral Higgs to neutral Higgs + Z</b>		
H->AZ	bbll, tautau ll	BP1_D, BP2_2, BP2_3, BP2_4
A->HZ	bbll, tautau ll, WWZ, ZZZ	BP2_1, BP2_8, BP3_A1, BP3_A2, BP3_B1, BP3_B2
A->hZ	bbll, tautau ll, gagall, WWll, ZZll	BP1_B, BP2_9, BP2_10
	<i>comment</i>	The heavy CP-even Higgs H being the 125 GeV SM-like Higgs or non-alignment
h->ZA	Zmumu, Ztautau, Zbb	BP4_ABCD
	<i>comment</i>	SM Higgs decay
<b>Neutral Higgs to neutral Higgs + neutral Higgs</b>		
H->AA	bbbb, 4tau, bbtatau, bbgaga	BP2_3, BP2_3, BP2_5
H->hh	bbbb, bbtatau, bbWW, bbZZ, bbgaga	BP1_A, BP2_9
	<i>comment</i>	The heavy CP-even Higgs H being the 125 GeV SM-like Higgs or non-alignment
<b>Neutral Higgs to Hpm Wmp</b>		
H->Hpm Wmp	tblnu	BP1_D, BP2_6, BP2_8
A->Hpm Wmp	tblnu, taunulnu	BP1_D, BP2_6, BP2_7, BP3_A2, BP3_B2
<b>Neutral Higgs to H+H-</b>		
H->H+H-	ttbb	BP2_8
<b>Hpm to neutral Higgs + Wpm, Hpm produced with tbHpm channel</b>		
Hpm->AW	bbbbWW, tautau bbWW	BP1_D, BP2_2, BP2_3, BP2_4, BP2_5
Hpm->HW	bbbbWW, tautau bbWW	BP2_1
Hpm->hW	bbbbWW, tautau bbWW, bbZZWW, bbWWWW, bbgagaWW	BP2_9, BP2_10
	<i>comment</i>	The heavy CP-even Higgs H being the 125 GeV SM-like Higgs
<b>Long cascade</b>		
Hpm->AW->HZW	bbWZ, tautau WZ	BP1_E
A->Hpm Wmp ->WWH	bbWW, tautau WW	BP1_E
	<i>comment</i>	Small branching fraction, <5%
<b>II. Decay of Higgses to WW, ZZ, gaga, bb, tautau</b>		
<b>Fermiophobic heavy H, produced via H+H-, HA, H+A, H+H</b>		
H+->HW, A->HZ	H->WW, ZZ, multigauge boson final states	BP6
	<i>comment</i>	Small production cross section, difficult to search, a rather light, yet

		very elusive, non-SM scalar.
<b>Non-alignment/H being the SM-like 125 GeV Higgs/mA~mh~125/flipped Yukawa/MSSM-like</b>		
H/h to SM final states	usual SM-like Higgs search channel, higher mass	BP1_A, BP1_B, BP1_C, BP1_F, BP1_G
<b>III. One neutral Higgs being MET</b>		
<b>H in the Inert Doublet Model, produced via H+H-, HA, H+A, H+H</b>		
H+→HW (or AW), A→HZ	W/Z/WW/WZ+MET final states	BP5
	<i>comment</i>	Small production cross section for some benchmarks [masses > 300 GeV], H is dark matter candidate [mass > 50 GeV], unique signal of MET. W,Z decays as in SM.. SM gauge couplings and kinematics determine production cross sections and decays

## 2HDM Benchmarks

This is the working page for the discussion on CP-conserving 2HDM benchmarks. Note that the list of submitted proposals below is not necessarily (yet) complete.

### **BP1:** *Howard Haber, Oscar Stål*

Phenomenological benchmarks for the CP-conserving 2HDM with softly-broken  $Z_2$ -symmetry.

[https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHWG3Benchmarks2HDM/HH\\_OS\\_2HDM\\_Benchmarks.pdf](https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHWG3Benchmarks2HDM/HH_OS_2HDM_Benchmarks.pdf)

### **BP2:** *Felix Kling, Shufang Su*

Benchmark points for exotic Higgs decays.

[https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHWG3Benchmarks2HDM/Exotic\\_Benchmarks.pdf](https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHWG3Benchmarks2HDM/Exotic_Benchmarks.pdf)

### **BP3:** *Glauber Dorsch, Stephan Huber, Ken Mimasu, Jose Miguel No*

We attach our 2HDM benchmarks for LHC searches, based on our recent work 1405.5537, together with some discussion on their salient features and motivation.

[https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHWG3Benchmarks2HDM/2HDM\\_Cosmic\\_Benchmarks.pdf](https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHWG3Benchmarks2HDM/2HDM_Cosmic_Benchmarks.pdf)

### **BP4:** *Robin Aggleton, Daniele Barducci, Alexandre Nikitenko, Stefano Moretti, Claire Shepherd-Themistocleous*

Here in attach a brief note explaining the benchmark scenarios we chose (.pdf and .tex), together with a file with the definition of the benchmarks in terms of 2HDM parameter. We are still working on other benchmark scenarios mentioned in a previous mail (higgs-to-2-Higgs topologies) and we will provide them shortly.

[https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHWG3Benchmarks2HDM/2HDM\\_WG-final.pdf](https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHWG3Benchmarks2HDM/2HDM_WG-final.pdf)

### **BP5:** *Agnieszka Ilnicka, Maria Krawczyk, Tania Robens*

Please find attached a short writeup containing benchmarks for the IDM. This note should be seen as a preview of a full publication [NEW: arXiv:1508.01671] which should then be used as a reference.

[https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHWG3Benchmarks2HDM/IDM\\_benchmarks.pdf](https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHWG3Benchmarks2HDM/IDM_benchmarks.pdf)

### **BP6:** *David Lopez-Val*

Following your call for 2HDM benchmark suggestions, I'd like to contribute with one of the scenarios we devised for our Higgs pair study [arXiv:1407.0281]. Please find attached all the details, hopefully complying with the indications given in your email.

<https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHWG3Benchmarks2HDM/fermiophobic.pdf>

## Description of Benchmark Points

### BP1: Authors: Howard Haber, Oscar Stal, "New LHC Benchmarks for the CP-conserving Two-Higgs-Doublet Model"

1507.04281: Detailed description of 2HDM benchmarks.

### BP2: Authors: Felix Kling, Shufang Su, "Benchmark points for exotic Higgs decays"

BP2_P1	
<i>Main Features</i>	Type II 2HDM, exotic decay of non-SM Higgses
<i>Spectrum/input parameters</i>	mh (SM-like) = 125 GeV, mH=200 GeV, mA=350 GeV, mHpm=400 GeV, SBA=1, TB=2, m12=0 GeV
<i>Signatures/Rates</i>	
$\sigma(\text{gg} \rightarrow \text{A}) \cdot \text{Br}(\text{A} \rightarrow \text{HZ})$	$\sigma(\text{ggA}) \cdot 0.776$
$\sigma(\text{tbHpm}) \cdot \text{Br}(\text{Hpm} \rightarrow \text{HW})$	$\sigma(\text{tbHpm}) \cdot 0.617$
$\text{Br}(\text{H} \rightarrow \text{bb})$	0.877
$\text{Br}(\text{H} \rightarrow \text{tautau})$	0.093
$\text{Br}(\text{H} \rightarrow \text{gaga})$	0.0000412
$\text{Br}(\text{H} \rightarrow \text{mumu})$	0.000332
<i>comment</i>	More to come. Plan to extend those ten benchmark points to benchmark planes.

### BP3: Authors: Glauber Dorsch, Stephan Huber, Ken Mimasu, Jose Miguel No, "EW Cosmology Benchmarks for A -> HZ decays"

BP3_A1	
<i>Main Features</i>	Type I-II 2HDM in alignment limit, decay of non-SM Higgses: A -> HZ, Hpm -> HW
<i>Spectrum/input parameters</i>	mh (SM-like) = 125 GeV, mH=180 GeV, mA=420 GeV, mHpm=420 GeV, SBA=1, TB=3, m12=100 GeV
$\sigma(\text{gg} \rightarrow \text{A}) \cdot \text{Br}(\text{A} \rightarrow \text{HZ})$	Type I: $2.795 \cdot 0.843$ [pb] Type II: $2.837 \cdot 0.838$ [pb]
$\sigma(\text{tbHpm}) \cdot \text{Br}(\text{Hpm} \rightarrow \text{HW})$	Type I: $\sigma(\text{tbHpm}) \cdot 0.857$ Type II: $\sigma(\text{tbHpm}) \cdot 0.854$
<i>Relevant H decay branching fraction(s)</i>	Type I: $\text{Br}(\text{H} \rightarrow \text{bb}) = 0.711$ Type II: $\text{Br}(\text{H} \rightarrow \text{bb}) = 0.899$
<i>comment</i>	
BP3_A1_Bis	
<i>Main Features</i>	Type I-II 2HDM in alignment limit, decay of non-SM Higgses: A -> HZ
<i>Spectrum/input parameters</i>	mh (SM-like) = 125 GeV, mH=400 GeV, mA=550 GeV, mHpm=550 GeV, SBA=1, TB=3, m12=210 GeV
$\sigma(\text{gg} \rightarrow \text{A}) \cdot \text{Br}(\text{A} \rightarrow \text{HZ})$	Type I: $0.657 \cdot 0.498$ [pb] Type II: $0.684 \cdot 0.486$ [pb]
<i>Relevant H decay branching fraction(s)</i>	Type I: $\text{Br}(\text{H} \rightarrow \text{tt}) = 0.992$ Type II: $\text{Br}(\text{H} \rightarrow \text{tt}) = 0.866$ , $\text{Br}(\text{H} \rightarrow \text{bb}) = 0.115$
<i>comment</i>	Benchmark similar to BP3_A1 (sizable A-H mass splitting), but higher mH
	Dominant H -> tt makes H discovery challenging via direct (ggH) production
	Width_H < 1 GeV
BP3_B1	

<i>Main Features</i>	Type I 2HDM away from alignment, decay of non-SM Higgses: $A \rightarrow HZ$
<i>Spectrum/input parameters</i>	$m_h$ (SM-like) = 125 GeV, $m_H$ =180 GeV, $m_A$ =400 GeV, $m_{Hpm}$ =400 GeV, $SBA$ =0.95, $TB$ =2, $m_{12}$ =100 GeV
$\sigma(\text{gg} \rightarrow A) \cdot \text{Br}(A \rightarrow HZ)$	$8.158 \cdot 0.584$ [pb]
<i>Relevant H decay branching fraction(s)</i>	Type I: $\text{Br}(H \rightarrow WW) = 0.715$ Type II: $\text{Br}(H \rightarrow ZZ) = 0.285$
<i>comment</i>	Multilepton (2,3,4) Final State
	Direct H Production (ggH) suppressed for $CBA > 0$
	4-lepton Final State: $m_{4l}$ does not reconstruct $m_H \rightarrow$ Heavy Higgs di-boson searches not as sensitive

**BP4: Authors: R. Aggleton, D. Barducci, S. Moretti, A. Nikitenko and C. Shepherd-Themistocleous, "Benchmark points for Exotic decays of SM-like Higgs"**

BP4_A	
<i>Main Features</i>	Type I 2HDM, Decay of SM Higgses into Z boson and light $A=20$ GeV
<i>Spectrum/input parameters(A)</i>	$m_h$ (SM-like) = 125.97 GeV, $m_H$ =165.50 GeV, $m_A$ =20.25 GeV, $m_{Hpm}$ =444.72 GeV, $SBA$ =-0.99, $TB$ =1.86, $m_{12}$ =62.38 GeV
$\sigma(\text{gg} \rightarrow h_1) \cdot \text{Br}(h_1 \rightarrow ZA)$	$38.82 \cdot 0.0971$ [pb]
$\text{Br}(A \rightarrow \mu\mu)$	0.0002101
$\text{Br}(A \rightarrow \tau\tau)$	0.0585
$\text{Br}(A \rightarrow b\bar{b})$	0.8496
BP4_B	
<i>Main Features</i>	Type I 2HDM, Decay of SM Higgses into Z boson and light $A=63$ GeV
<i>Spectrum/input parameters(A)</i>	$m_h$ (SM-like) = 125.93 GeV, $m_H$ =153.37 GeV, $m_A$ =63.42 GeV, $m_{Hpm}$ =444.72 GeV, $SBA$ =-0.85, $TB$ =6.20, $m_{12}$ =52.85 GeV
$\sigma(\text{gg} \rightarrow h_1) \cdot \text{Br}(h_1 \rightarrow ZA)$	$26.59 \cdot 0.0268$ [pb]
$\text{Br}(A \rightarrow \mu\mu)$	0.0002318
$\text{Br}(A \rightarrow \tau\tau)$	0.0655
$\text{Br}(A \rightarrow b\bar{b})$	0.7908
BP4_C	
<i>Main Features</i>	Type II 2HDM, Decay of SM Higgses into Z boson and light $A=6$ GeV
<i>Spectrum/input parameters(A)</i>	$m_h$ (SM-like) = 125.85 GeV, $m_H$ =263.67 GeV, $m_A$ =6.28 GeV, $m_{Hpm}$ =308.25 GeV, $SBA$ =0.99, $TB$ =1.89, $m_{12}$ =52.32 GeV
$\sigma(\text{gg} \rightarrow h_1) \cdot \text{Br}(h_1 \rightarrow ZA)$	$52.32 \cdot 0.3063$ [pb]
$\text{Br}(A \rightarrow \mu\mu)$	0.003348
$\text{Br}(A \rightarrow \tau\tau)$	0.7813
$\text{Br}(A \rightarrow b\bar{b})$	0
BP4_D	
<i>Main Features</i>	Type II 2HDM, Decay of SM Higgses into Z boson and light $A=25$ GeV
<i>Spectrum/input parameters(A)</i>	$m_h$ (SM-like) = 126.27 GeV, $m_H$ =227.08 GeV, $m_A$ =24.71 GeV, $m_{Hpm}$ =226.80 GeV, $SBA$ =0.99, $TB$ =1.76, $m_{12}$ =58.37 GeV
$\sigma(\text{gg} \rightarrow h_1) \cdot \text{Br}(h_1 \rightarrow ZA)$	$52.46 \cdot 0.1526$ [pb]
$\text{Br}(A \rightarrow \mu\mu)$	0.000224
$\text{Br}(A \rightarrow \tau\tau)$	0.0627
$\text{Br}(A \rightarrow b\bar{b})$	0.9175
BP4_E	
<i>Main Features</i>	Type II 2HDM, Decay of SM Higgses into Z boson and light $A=63$ GeV

<i>Spectrum/input parameters(A)</i>	mh (SM-like) = 125.19 GeV, mH=210.20 GeV, mA=63.06 GeV, mHpm=333.50 GeV, SBA=0.78, TB=2.38, m12=69.22 GeV
$\sigma(\text{gg}\rightarrow\text{h1})\cdot\text{Br}(\text{h1}\rightarrow\text{ZA})$	53.46*0.03818 [pb]
$\text{Br}(\text{A}\rightarrow\text{mumu})$	0.000265
$\text{Br}(\text{A}\rightarrow\text{tautau})$	0.0747
$\text{Br}(\text{A}\rightarrow\text{bb})$	0.9191

## BP5: Authors: Agnieszka Ilnicka, Maria Krawczyk, Tania Robens, "Benchmark planes for Inert Doublet Model"

BP5	
<i>Main Features</i>	IDM, Two Higgs doublet model with dark matter candidate (labelled H)
Benchmark planes	
<i>Floating parameters</i>	masses of scalars mH,mA, mH+ mH > 50 GeV, mass degeneracy (see plots)
<i>Fixed parameters</i>	mh=125 GeV
<i>Irrelevant parameters</i>	lambda2; lambda345 (if kept within allowed ranges, ~ [0.02;0.02])
BR (A -> ZH)	1
BR (H+ -> W+ H)	dominant
<i>comment</i>	only pair-production of H,A,H+ possible signature: always missing ET from HH in final states Z,W decay as in SM production and decay modes determined by SM gauge couplings and kinematics for mH < mh/2: lam345 becomes important; parameter space extremely constrained
BP5_A	
<i>Main Features</i>	Low mass H [mH < mh/2]
<i>Spectrum/input parameters</i>	mh (SM-like) = 125.1 GeV, mH=57.5 GeV, mA=113.0 GeV, mH+=123.0 GeV, abs(lambda345) in [0.002,0.015]
$\sigma(\text{pp}\rightarrow\text{HA})$	0.371(4) [pb]
$\sigma(\text{pp}\rightarrow\text{H+H-})$	0.097(1) [pb]
$\text{Br}(\text{H+}\rightarrow\text{W+H})$	>0.99
$\text{Br}(\text{H+}\rightarrow\text{W+A})$	<0.01
BP5_B	
<i>Main Features</i>	Low mass H [mh/2 < mH < mh]
<i>Spectrum/input parameters</i>	mh (SM-like) = 125.1 GeV, mH=85.5 GeV, mA=111.0 GeV, mH+=140.0 GeV, abs(lambda345) < 0.015
$\sigma(\text{pp}\rightarrow\text{HA})$	0.226(2) [pb]
$\sigma(\text{pp}\rightarrow\text{H+H-})$	0.0605(9) [pb]
$\text{Br}(\text{H+}\rightarrow\text{W+H})$	~0.96
$\text{Br}(\text{H+}\rightarrow\text{W+A})$	~0.04
BP5_C	
<i>Main Features</i>	Intermediate mass H [mH ~ mh]
<i>Spectrum/input parameters</i>	mh (SM-like) = 125.1 GeV, mH=128.0 GeV, mA=134.0 GeV, mH+=176.0 GeV, abs(lambda345) < 0.05
$\sigma(\text{pp}\rightarrow\text{HA})$	0.0765(7) [pb]
$\sigma(\text{pp}\rightarrow\text{H+H-})$	0.0259(3) [pb]
$\text{Br}(\text{H+}\rightarrow\text{W+H})$	~0.66
$\text{Br}(\text{H+}\rightarrow\text{W+A})$	~0.34
BP5_D	
<i>Main Features</i>	High mass H [mH>mh]; degeneracy

<i>Spectrum/input parameters</i>	mh (SM-like) = 125.1 GeV, mH=363.0 GeV, mA=374.0 GeV, mH+=374.0 GeV, abs(lambda345) <0.25]
sigma(pp->HA)	0.00122(1) [pb]
sigma(pp->H+H-)	0.00124(1) [pb]
Br(H+->W+H)	1.0
BP5_E	
<i>Main Features</i>	High mass H [mH>mh]
<i>Spectrum/input parameters</i>	mh (SM-like) = 125.1 GeV, mH=311.0 GeV, mA=415.0 GeV, mHpm=447.0 GeV, abs(lambda345) <0.19
sigma(pp->HA)	0.00129(1) [pb]
sigma(pp->H+H-)	0.000553(7) [pb]
Br(H+->W+H)	>0.99
Br(H+->W+A)	<0.01

- XSecHA\_MM.pdf: cross sections in pb for HA production at a 13 TeV LHC, for points surviving all bounds, in the MH MA mass plane
- XSecHpm\_MM.pdf: cross sections in pb for H+ H- production at a 13 TeV LHC, for points surviving all bounds, in the MH MH+ mass plane
- outBRHp.pdf: BRs for H+ > H W+

production cross sections produced using Madgraph5 with a manually inserted ggh vertex in the EFT description [UFO model from <http://arxiv.org/abs/1303.3010>]

decay widths from 2HDMC

## BP6: Authors: David Lopez-Val (CP3-Univ. catholique de Louvain), "Fermiophobic heavy Higgs"

BP6	
<i>Main Features</i>	Fermiophobic heavy Higgs
Reference point	
<i>Spectrum/input parameters</i>	mh0 (SM-like) = 125 GeV, MHH=200 GeV, MA0=500 GeV, MHp=500 GeV, SA = 0, TB=20, m12=2000 GeV
<i>Leading Signatures/Rates</i>	
sigma(pp->HA)*Br(H->VV)	sigma(HA) = 1.91 fb
sigma(pp->Hpm H)*Br(H->VV)	sigma(Hpm H) = 0.88 fb
GammaH	3.39 E-03 GeV
Br(H -> ZZ)	0.742
Br(H -> WW)	0.258
Br(H -> gaga)	< 10 <sup>-4</sup>
Br(H -> ga Z)	< 10 <sup>-4</sup>
Br(H -> ff)	0
<i>comment</i>	Sharp resonance into WW/ZZ
	Relatively light, yet very elusive Higgs companion
	Warning sign: lack of signal should not rule out the model too early
Benchmark planes	
<i>Floating parameters</i>	CP--even heavy Higgs mass [MHH], Mass splitting [DeltaM]
<i>Fixed parameters</i>	Neutral Higgs mixing SA=0 (by construction)

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	CP--odd Higgs mass $MA_0 = M_{HH} + \Delta M$
	Charged Higgs mass $M_{Hp} = MA_0 + \Delta M$
	Z2 Soft-breaking mass $m_{12}^2 = M_{HH}^2 / \tan[b]$
<i>Fiducial TB choices</i>	(by increasing departure from alignment)
	TB=40 (small departure)
	TB=20 (moderate departure)
	TB=10 (large departure)
<i>comment</i>	fermiophobic.pdf: Detailed description of parameter plane.

ShufangSu - 2015-07-16

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