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Single charged Higgs boson production at the LHC

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OUTLINE

INTRODUCTION

- Measurements of Higgs properties at run 1 and run 2 are in a good agreement with the SM, but ...
- Maybe other scalars waiting to be discovered ;
- In the SM, only one scalar isospin doublet field is introduced to break the electroweak gauge symmetry. This is just an assumption.
- Two Higgs Doublet Model
  - Larger scalar sector than SM
  - Rich collider phenomenology

GENERAL 2-HIGGS-DOUBLET MODEL

The most general scalar potential of the 2HDM :

$$\begin{aligned} V(\phi_1,\phi_2) \quad = \quad & m_{11}^2(\phi_1^\dagger\phi_1) + m_{22}^2(\phi_2^\dagger\phi_2) - [m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}] \\ & + \frac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) \\ & + \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}\right] + \left\{\left[\lambda_6(\phi_1^\dagger\phi_1) + \lambda_7(\phi_2^\dagger\phi_2)\right](\phi_1^\dagger\phi_2) + \text{h.c.}\right\}, \quad (1) \end{aligned}$$

Where,

$$\Phi_i = \begin{pmatrix} \Phi_i^+ \\ \Phi_i^0 \end{pmatrix}, < 0|\Phi_i|0 >= \begin{pmatrix} 0 \\ \frac{v_i}{\sqrt{2}} \end{pmatrix}, i = 1, 2 \qquad (2)$$

- $\Longrightarrow$ 8 degrees of freedom
- 5 physical Higgses : 2 CP-even h and H, 1 CP-odd A and 2 Charged Higgs $H^\pm$
- Avoid FCNC $\Longrightarrow$, $\mathcal{Z}_2$ symmetry($\lambda_6 = \lambda_7 = 0$)
- The CP-conserving of the potential $\Longrightarrow$ all parameter are real.
- 2 minimization conditions and the combination $v_1^2 + v_2^2 \Longrightarrow$ 7 free parameters : $m_h < m_H, m_H^\pm, m_A, \sin(\beta - \alpha), \tan\beta = \frac{v_2}{v_1}$ and m_{12}^2.

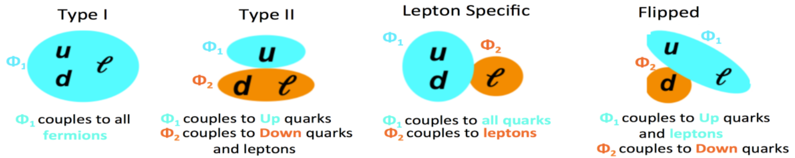
GENERAL 2-HIGGS-DOUBLET MODEL

YUKAWA COUPLINGS

The Yukawa Lagrangian, which describes the interactions between the Higgs sector and the fermion sector, is given as follows

$$\mathcal{L}_Y = \bar{Q'_L}(Y_1^u\tilde{\Phi}_1 + Y_2^u\tilde{\Phi}_2)U'_R + \tilde{Q}'_L(Y_1^d\Phi_1 + Y_2^d\Phi_2)d'_R + \bar{L'_L}(Y_1^l Q_1 + Y_2^l\Phi_2)l'_R + h.c \quad (3)$$

- $\mathcal{Z}_2$ Symmetry

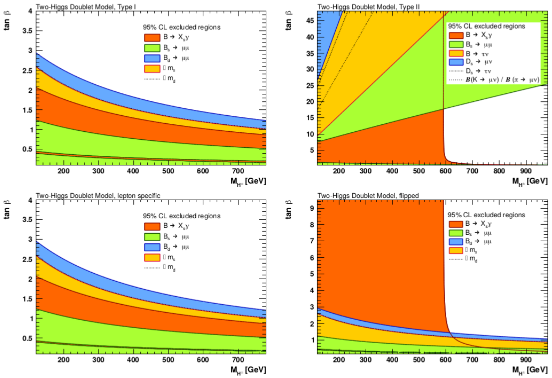


Type	ξ_u^h	ξ_d^h	ξ_l^h	ξ_u^H	ξ_d^H	ξ_l^H	ξ_u^A	ξ_d^A	ξ_l^A
I	c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β	ct_β	$-ct_\beta$	$-ct_\beta$
II	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	s_α/s_β	c_α/c_β	c_α/c_β	ct_β	t_β	t_β
X	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	s_α/s_β	s_α/s_β	c_α/c_β	ct_β	$-ct_\beta$	t_β
Y	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β	s_α/s_β	c_α/c_β	s_α/s_β	ct_β	t_β	$-ct_\beta$

GENERAL 2-HIGGS-DOUBLET MODEL

THEORETICAL AND EXPERIMENTAL CONSTRAINTS

- Unitarity, Perturbativity, Vacuum Stability.
- Exclusion limits at 95% Confidence Level (CL) from Higgs searches at colliders (LEP, Tevatron and LHC)
- Constraints from the Higgs boson signal strength measurements
- Constraints of flavour physics observables, namely, $B \to X_s\gamma$, $B_{s,d} \to \mu^+\mu^-$ and Δm_s.



CHARED HIGGS PRODUCTIONS AT LHC.

At hadron colliders, a charged Higgs boson can be produced through several channels:

- the $pp \to t\bar{t} \to b\bar{b}H^-H^+ + c.c$;process via the top decay $t \to bH^+$ (or the equivalent antitop mode).
- $pp \to H^{\pm}tb$: $g\bar{b} \to \bar{t}H^{\pm} + C.C$ and $gg \to tbH^+$
- Associated production with a $W^{\pm}$ gauge boson: $gg \to W^{\pm}H^{\mp}$ and $b\bar{b} \to W^{\pm}H^{\mp}$.
- Production in association with a bottom quark and a light-jet: $pp \to H^{\pm}bj$.
- Resonant production via $c\bar{s}, c\bar{b} \to H^+$
- Associate production with a neutral Higgs: $q\bar{q}' \to H^{\pm}\Phi_i$ where Φ_i denotes one of the three neutral Higgs bosons, $\Phi = h, H \ or \ A$
- Pair production: $gg \to H^+H^-$ and $q\bar{q} \to H^+H^-$.

Production through $pp \to H^{\pm}W^{\mp}$ & $pp \to H^{\pm}bj$

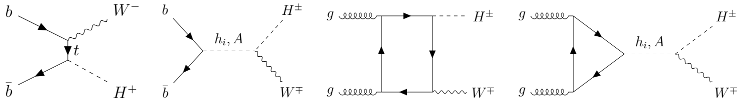


Figure: Feynman diagrams contributing to the $H^{\pm}W^{\mp}$ production.

- $b\bar{b}$-resonant channel is negligible since the Yukawa couplings are small.
- gg-resonant is only relevant when $M_H > M_{H^{\pm}} + M_W$ or $M_A > M_{H^{\pm}} + M_W$

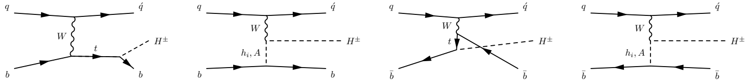


Figure: Feynman diagrams contributing to the $H^{\pm}bj$ production.

- $qb \to q^{'}bH^{\pm}$ (s and t-channel) and $q\bar{b} \to q^{'}bH^{\pm}$(u and t-channel)
- $M_{H^{\pm}} < m_t - m_b$, s-channel dominate, Other diagram contribute for $M_{H^{\pm}} > m_t - m_b$

RESULTS AND DISCUSSION

- We randomly scan the space parameter as set in bellow:

	M_h [GeV]	M_H [GeV]	M_A [GeV]	$M_{H^\pm}$ [GeV]	$\sin(\beta-\alpha)$	$\tan\beta$	m_{12}^2 [GeV^2]
NS	125.09	[126; 700]	[15; 700]	[80; 700]	[0.95; 1]	[2; 25]	[0; $m_H^2 \cos\beta \sin\beta$]
IS	[15; 120]	125.09	[15; 700]	[80; 700]	[−0.5; 0.5]	[2; 25]	[0; $m_h^2 \cos\beta \sin\beta$]

Table: 2HDM type-I and type-X input parameters.

- we concentrate on the following signatures:

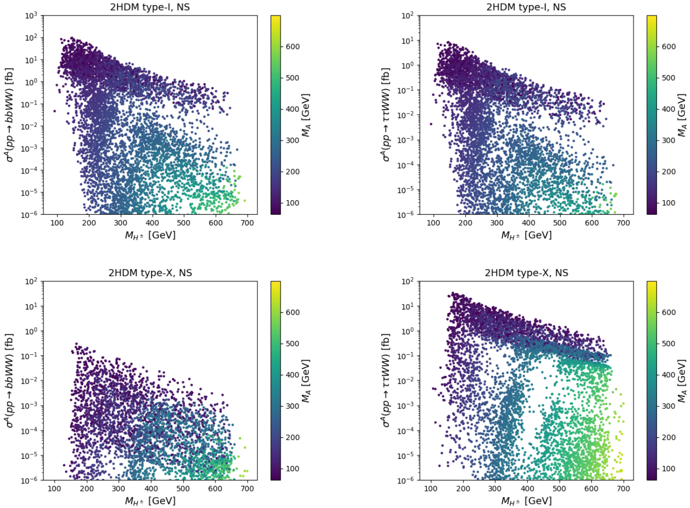
$$\sigma^S(pp \to xWW) = \sigma(pp \to H^\pm W^\mp \to W^\pm S W^\mp \to xW^\pm W^\mp), \quad (4)$$
$$\sigma^S(pp \to xWbj) = \sigma(pp \to H^\pm bj \to W^\pm Sbj \to xW^\pm bj), \quad (5)$$

where S can be either h or A, and x stands for bb, $\tau\tau$ or $\gamma\gamma$.

- In both Scenario, we could expect the following signatures: $bbWW, \tau\tau WW, \gamma\gamma WW$, $bbWbj, \tau\tau Wbj$ and $\gamma\gamma Wbj$

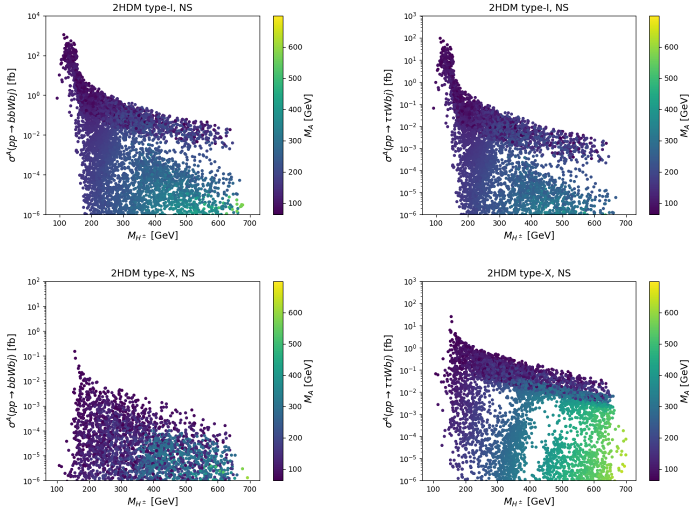
Normal scenario

- $pp \to H^{\pm}W^{\mp} \to \; W^{\pm}W^{\mp}A \to b\bar{b}WW, \tau\tau WW$



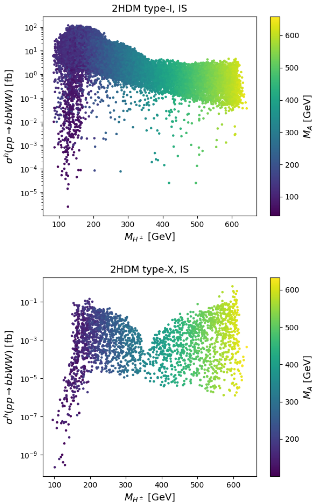
Normal scenario

- $pp \to H^{\pm}bj \to \ W^{\pm}Abj \to bbWbj, \tau\tau Wbj$



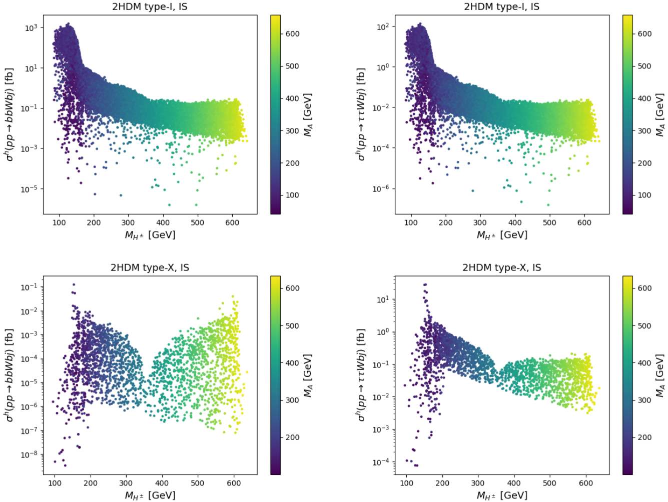
Inverted scenario

- $pp \to H^{\pm}W^{\mp} \to \ W^{\pm}W^{\mp}h \to WWb\bar{b}, WW\tau\tau$



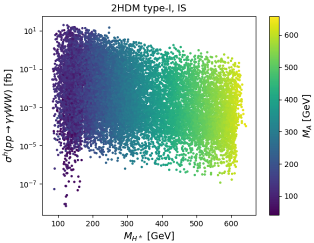
Inverted scenario

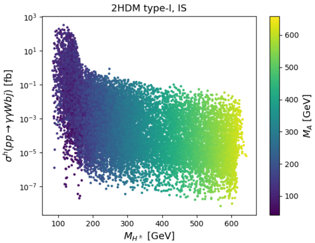
- $pp \to H^{\pm}bj \to \; W^{\pm}hbj \to bbWbj, \tau\tau Wbj$



Inverted Scenario

- $pp \to H^{\pm}W^{\mp} \to \; W^{\pm}W^{\mp}h \to \gamma\gamma WW$
- $pp \to H^{\pm}bj \to \; W^{\pm}hbj \to \gamma\gamma Wbj$





Benchmarks Points type-I

Parameters	BP1	BP2	BP3	BP4	BP5	BP6
M_h (GeV)	125.09	125.09	125.09	125.09	125.09	125.09
M_H (GeV)	135.07	144.62	132.07	130.26	135.12	134.75
M_A (GeV)	200.95	219.65	67.01	74.07	62.97	66.54
$M_{H^\pm}$ (GeV)	226.20	259.66	146.88	144.66	113.18	123.09
$\sin(\beta-\alpha)$	0.994	0.985	0.989	0.985	0.991	0.968
$\tan\beta$	3.97	2.77	3.53	3.55	4.26	4.37
m_{12}^2 (GeV^2)	4322.16	6675.8	4565.08	4417.98	4055.61	3949.10
BR($H^\pm \to XY$) in %						
BR($H^\pm \to W^\pm H$)	35.41	46.78	–	–	–	–
BR($H^\pm \to W^\pm A$)	–	–	98.12	95.37	92.47	95.19
BR($h \to XY$) in %						
BR($H \to bb$)	53.68	29.76	11.01	11.20	1.68	0.16
BR($H \to \tau\tau$)	5.26	2.95	1.07	1.09	0.16	0.01
BR($H \to \gamma\gamma$)	0.34	0.33	0.11	0.24	0.03	0.07
BR($A \to XY$) in %						
BR($A \to bb$)	22.54	17.96	79.98	78.51	80.80	80.08
BR($A \to \tau\tau$)	2.43	1.97	6.96	6.97	6.94	6.95
BR($A \to \gamma\gamma$)	0.05	0.05	0.01	0.01	0.01	0.01
σ in fb						
$\sigma^H(pp \to bbWW)$	9.23	8.95	–	–	–	–
$\sigma^H(pp \to \tau\tau WW)$	0.90	0.88	–	–	–	–
$\sigma^H(pp \to \gamma\gamma WW)$	0.05	0.09	–	–	–	–
$\sigma^A(pp \to bbWW)$	–	–	93.43	88.32	81.14	72.36
$\sigma^A(pp \to \tau\tau WW)$	–	–	8.13	7.84	6.97	6.28
$\sigma^A(pp \to \gamma\gamma WW)$	–	–	0.02	0.02	0.01	0.01
$\sigma^H(pp \to bbWbj)$	0.55	0.53	–	–	–	–
$\sigma^H(pp \to \tau\tau Wbj)$	0.05	0.05	–	–	–	–
$\sigma^H(pp \to \gamma\gamma Wbj)$	< 0.01	0.01	–	–	–	–
$\sigma^A(pp \to bbWbj)$	–	–	349.75	410.27	1088.35	815.06
$\sigma^A(pp \to \tau\tau Wbj)$	–	–	30.43	36.43	93.51	70.82
$\sigma^A(pp \to \gamma\gamma Wbj)$	–	–	0.056	0.08	0.15	0.12

Table: 2HDM type-I selected BPs in the NS.

Parameters	BP1	BP2	BP3	BP4	BP5	BP6
M_h (GeV)	64.68	68.22	69.29	112.45	115.42	71.68
M_H (GeV)	125.09	125.09	125.09	125.09	125.09	125.09
M_A (GeV)	130.84	147.98	132.88	53.72	51.90	135.54
$M_{H^\pm}$ (GeV)	126.68	139.15	163.20	101.36	119.45	115.38
$\sin(\beta-\alpha)$	0.127	0.140	-0.062	0.175	0.134	-0.144
$\tan\beta$	3.46	3.35	3.13	4.02	3.80	6.94
m_{12}^2 (GeV^2)	1053.71	511.93	850.14	2757.59	2782.55	177.81
BR($H^\pm \to XY$) in %						
BR($H^\pm \to W^\pm h$)	94.72	95.95	99.54	–	–	94.11
BR($H^\pm \to W^\pm A$)	–	–	0.03	90.00	97.52	–
BR($h \to XY$) in %						
BR($h \to bb$)	85.76	85.49	85.39	5.38	1.08	9.71
BR($h \to \tau\tau$)	7.37	7.41	7.43	0.51	0.10	0.85
BR($h \to \gamma\gamma$)	< 0.01	< 0.01	0.02	< 0.01	< 0.01	51.14
BR($A \to XY$) in %						
BR($A \to bb$)	30.88	16.29	36.79	82.60	82.94	13.45
BR($A \to \tau\tau$)	3.07	1.66	3.67	6.87	6.85	1.35
BR($A \to \gamma\gamma$)	0.02	0.02	0.03	0.01	0.01	0.01
σ in fb						
$\sigma^h(pp \to bbWW)$	118.15	115.14	115.07	–	–	3.65
$\sigma^h(pp \to \tau\tau WW)$	10.16	9.99	10.01	–	–	0.32
$\sigma^h(pp \to \gamma\gamma WW)$	< 0.01	< 0.01	0.03	–	–	19.24
$\sigma^A(pp \to bbWW)$	–	–	0.02	100.57	103.02	–
$\sigma^A(pp \to \tau\tau WW)$	–	–	< 0.01	8.37	8.51	–
$\sigma^A(pp \to \gamma\gamma WW)$	–	–	< 0.01	0.01	0.01	–
$\sigma^h(pp \to bbWbj)$	1524.43	838.06	22.80	–	–	63.37
$\sigma^h(pp \to \tau\tau Wbj)$	131.05	72.70	1.98	–	–	5.55
$\sigma^h(pp \to \gamma\gamma Wbj)$	0.01	0.01	0.01	–	–	333.74
$\sigma^A(pp \to bbWbj)$	–	–	< 0.01	2179.63	1618.58	–
$\sigma^A(pp \to \tau\tau Wbj)$	–	–	< 0.01	181.28	133.67	–
$\sigma^A(pp \to \gamma\gamma Wbj)$	–	–	< 0.01	0.22	0.15	–

Table: 2HDM type-I selected BPs in the IS.

- 2HDM type-I paramters, branching ratios and signal cross sections corresponding to the selected BPs

CONCLUSION

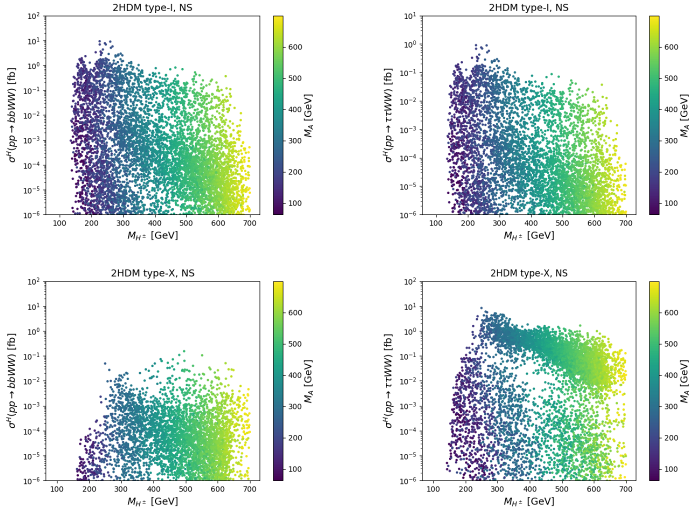
- We point out that the $bbWW$ and $bbWbj$ signals are plagued by the huge QCD background, especially the $t\bar{t}$ one, yielding poor significance.
- The signatures $\tau\tau WW$ and $\tau\tau Wbj$ can give the best reach since they would suppress the tt background, especially if we require at least one leptonic decay of tau leptons.
- We also suggest $\gamma\gamma WW$ and $\gamma\gamma Wbj$ as clean signatures in the inverted scenario.
- Such signals could provide a complementary search for a charged Higgs boson at the LHC.

Thank you for listening!

Backup

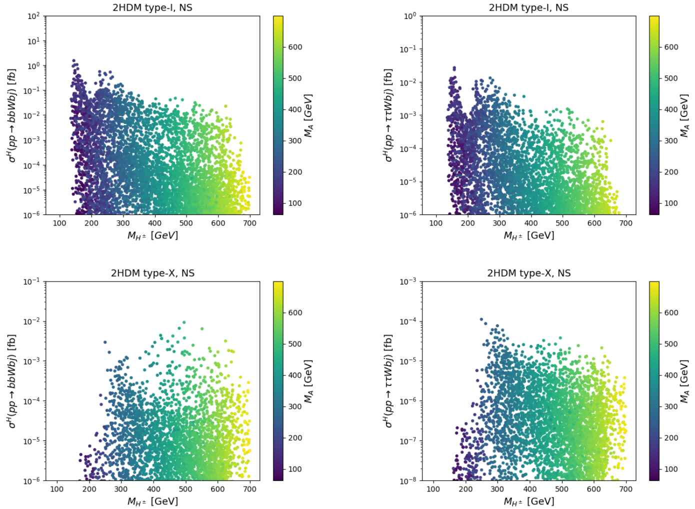
Normal scenario

- $pp \to H^{\pm}W^{\mp} \to \ W^{\pm}W^{\mp}H \to WWb\bar{b}, WW\tau\tau$



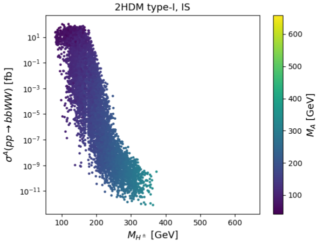
Normal scenario

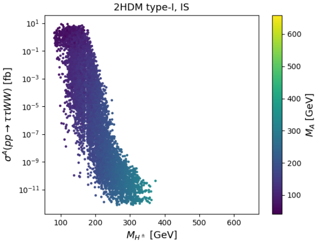
- $pp \to H^{\pm}bj \to \; W^{\pm}Hbj \to bbWbj, \tau\tau Wbj$

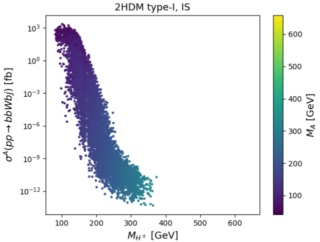


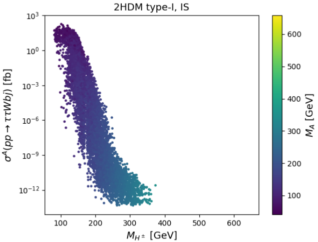
Inverted Scenario

- $pp \to H^{\pm}W^{\mp} \to \; W^{\pm}W^{\mp}A \to WWb\bar{b}, WW\tau\tau$
- $pp \to H^{\pm}bj \to \; W^{\pm}Abj \to bbWbj, \tau\tau Wbj$









Benchmarks Points type-X

Parameters	BP1	BP2	BP3	BP4	BP5	BP6
M_h (GeV)	125.09	125.09	125.09	125.09	125.09	125.09
M_H (GeV)	146.55	155.71	171.94	194.37	165.65	163.04
M_A (GeV)	251.36	263.79	69.87	73.03	65.94	66.4
$M_{H^\pm}$ (GeV)	249.84	262.81	168.56	182.11	155.45	157.54
$\sin(\beta-\alpha)$	0.952	0.957	0.952	0.951	0.960	0.961
$\tan\beta$	5.97	6.43	5.95	6.25	6.60	6.77
m_{12}^2 (GeV^2)	3496.62	3676.93	4831.6	5891.78	4064.40	3838.03
BR($H^\pm \to XY$) in %						
BR($H^\pm \to W^\pm H$)	57.20	60.26	–	–	–	–
BR($H^\pm \to W^\pm A$)	–	–	92.04	94.30	78.23	80.13
BR($h \to XY$) in %						
BR($H \to bb$)	0.54	0.38	0.05	0.01	0.06	0.09
BR($H \to \tau\tau$)	92.06	84.60	9.48	3.18	16.25	24.36
BR($H \to \gamma\gamma$)	0.02	0.02	< 0.01	< 0.01	< 0.01	< 0.01
BR($A \to XY$) in %						
BR($A \to bb$)	0.05	0.03	0.89	0.72	0.6	0.54
BR($A \to \tau\tau$)	8.0	6.76	98.60	98.78	98.95	99.02
BR($A \to \gamma\gamma$)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
σ in fb						
$\sigma^H(pp \to bbWW)$	0.04	0.02	–	–	–	–
$\sigma^H(pp \to \tau\tau WW)$	8.31	5.95	–	–	–	–
$\sigma^H(pp \to \gamma\gamma WW)$	< 0.01	< 0.01	–	–	–	–
$\sigma^A(pp \to bbWW)$	–	–	0.29	0.21	0.14	0.12
$\sigma^A(pp \to \tau\tau WW)$	–	–	32.65	28.84	24.47	23.68
$\sigma^A(pp \to \gamma\gamma WW)$	–	–	< 0.01	< 0.01	< 0.01	< 0.01
$\sigma^H(pp \to bbWbj)$	0.02	< 0.01	–	–	–	–
$\sigma^H(pp \to \tau\tau Wbj)$	0.49	0.35	–	–	–	–
$\sigma^H(pp \to \gamma\gamma Wbj)$	< 0.01	< 0.01	–	–	–	–
$\sigma^A(pp \to bbWbj)$	–	–	0.03	0.01	0.15	0.08
$\sigma^A(pp \to \tau\tau Wbj)$	–	–	4.30	2.53	24.94	14.74
$\sigma^A(pp \to \gamma\gamma Wbj)$	–	–	< 0.01	< 0.01	< 0.01	< 0.01

Table: 2HDM type-X selected BPs in the NS.

Parameters	BP1	BP2	BP3	BP4	BP5	BP6
M_h (GeV)	62.84	64.20	64.66	63.37	66.57	64.32
M_H (GeV)	125.09	125.09	125.09	125.09	125.09	125.09
M_A (GeV)	136.51	163.01	158.98	151.78	163.69	148.30
$M_{H^\pm}$ (GeV)	156.59	169.29	196.97	150.48	154.02	151.52
$\sin(\beta-\alpha)$	-0.011	-0.021	-0.023	0.003	-0.008	-0.017
$\tan\beta$	7.35	7.22	6.69	8.76	6.95	9.69
m_{12}^2 (GeV^2)	346.61	388.33	107.71	388.48	609.71	282.56
BR($H^\pm \to XY$) in %						
BR($H^\pm \to W^\pm h$)	82.26	92.29	95.47	57.99	70.22	53.51
BR($H^\pm \to W^\pm A$)	< 0.01	–	0.01	–	–	–
BR($h \to XY$) in %						
BR($h \to bb$)	0.33	0.30	0.41	0.21	0.44	0.09
BR($h \to \tau\tau$)	99.26	99.32	99.20	99.42	99.17	99.55
BR($h \to \gamma\gamma$)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
BR($A \to XY$) in %						
BR($A \to b\bar{b}$)	0.32	0.11	0.29	0.15	0.16	0.11
BR($A \to \tau\tau$)	94.78	31.66	59.44	89.46	37.97	93.91
BR($A \to \gamma\gamma$)	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
σ in fb						
$\sigma^h(pp \to bbWW)$	0.07	0.07	0.10	0.02	0.09	0.01
$\sigma^h(pp \to \tau\tau WW)$	20.70	21.98	24.14	10.86	19.85	8.13
$\sigma^h(pp \to \gamma\gamma WW)$	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
$\sigma^A(pp \to bbWW)$	< 0.01	–	< 0.01	–	–	–
$\sigma^A(pp \to \tau\tau WW)$	< 0.01	–	< 0.01	–	–	–
$\sigma^A(pp \to \gamma\gamma WW)$	< 0.01	–	< 0.01	–	–	–
$\sigma^h(pp \to bbWbj)$	0.05	0.01	0.01	0.06	0.12	0.02
$\sigma^h(pp \to \tau\tau Wbj)$	15.90	2.77	1.54	27.21	27.76	17.40
$\sigma^h(pp \to \gamma\gamma Wbj)$	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
$\sigma^A(pp \to bbWbj)$	< 0.01	–	< 0.01	–	–	–
$\sigma^A(pp \to \tau\tau Wbj)$	< 0.01	–	< 0.01	–	–	–
$\sigma^A(pp \to \gamma\gamma Wbj)$	< 0.01	–	< 0.01	–	–	–

Table: 2HDM type-X selected BPs in the IS.

- 2HDM type-X paramters, branching ratios and signal cross sections corresponding to the selected BPs