

$4b + X/4b + W$ via electroweak multi-Higgs production as smoking gun signals for the Type I 2HDM

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- Brief overview of Type I two Higgs doublet model (2HDM).
- Electroweak (EW) production of multiple (pseudo) scalars.
- $4b + X$ mediated dominantly via EW processes.
- Reconstructing the masses of all the BSM Higgs bosons.
- $4b + W$ and $W \rightarrow \ell\nu$ only via EW processes.
- χ^2 variable as a selection cut.

Overview of Type I 2HDM

- 2HDM is the minimal but phenomenologically rich extension of SM under the same gauge symmetry.
- After EWSB the scalar sector of the 2HDM consists of two $SU(2)$ Higgs doublets Φ_i , $i = 1, 2$.

$$\Phi_i = \left(\begin{array}{c} \phi_i^+ \\ \frac{v_i + \rho_i + i\eta_i}{\sqrt{2}} \end{array} \right), \quad v_i = \langle \rho_i \rangle \quad v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV}, \quad \tan \beta = v_2/v_1.$$

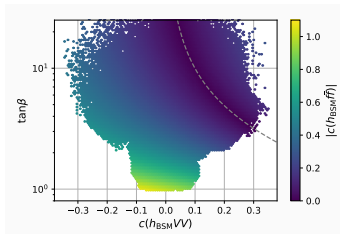
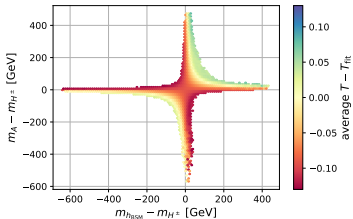
- Scalar spectrum: Two CP even Higgses (h and H), a pseudoscalar (A) and a pair of charged Higgs (H^\pm).
- Alignment limit: $\sin(\beta - \alpha) \rightarrow 1$ implies that the couplings of h is like SM Higgs boson.
- The Yukawa Lagrangian in terms of the mass eigenstates:

$$\begin{aligned} \mathcal{L}_{\text{Yuk}, I}^{2\text{HDM}} = & - \sum_{f=u,d,\ell} \frac{m_f}{v} \left(\xi_h^f \bar{f} h f + \xi_H^f \bar{f} H f - i \xi_A^f \bar{f} \gamma_5 A f \right) \\ & - \left\{ \frac{\sqrt{2} V_{ud}}{v} \bar{u} \left(\xi_A^u m_u P_L + \xi_A^d m_d P_R \right) H^+ d + \frac{\sqrt{2} m_l}{v} \xi_A^l \bar{\nu}_L H^+ l_R + \text{h.c.} \right\} \end{aligned}$$

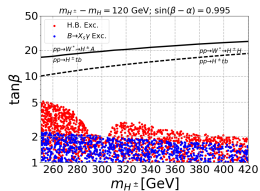
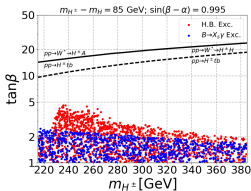
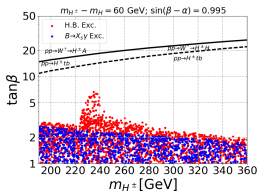
ξ_h^u	ξ_h^d	ξ_h^ℓ	ξ_H^u	ξ_H^d	ξ_H^ℓ	ξ_A^u	ξ_A^d	ξ_A^ℓ
c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β	$\cot \beta$	$-\cot \beta$	$-\cot \beta$

- $\xi_A^f \propto 1/\tan \beta \Rightarrow$ **fermiophobic A , H^\pm** for $\tan \beta \gg 1$.
 $\xi_H^f = s_\alpha/s_\beta = c_{\beta-\alpha} - s_{\beta-\alpha}/\tan \beta \Rightarrow$ **fermiophobic H** for $\tan \beta \gg 1$, $\sin(\beta - \alpha) \rightarrow 1$.

Limits: (1) Theoretical (2) EWPOs (3) $B \rightarrow X_s \gamma$ (4) Collider constraints



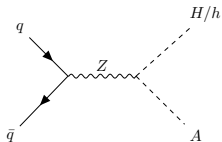
Henning Bahl, Tim Stefaniak, Jonas Wittbrodt, JHEP 06 (2021), 183.



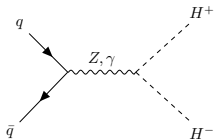
P. Sanyal, T. Mondal, JHEP 05 (2022) 040.

EW production of multi Higgs final states

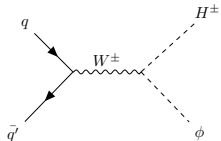
1. Pair of neutral scalars:



2. H^\pm pair creation:



3. Charged two body states:



The charged two body (2BFS) are not possible via QCD processes.

4b + X via EW process

EW processes contributing to the 4b + X mode:

$$\begin{aligned}
 q\bar{q}' & \left\{ \begin{array}{l} 1. AAW : pp \rightarrow H^\pm A \rightarrow [AW][A] \rightarrow 4b + X \\ 2. AAAW : pp \rightarrow H^\pm H \rightarrow [AW][AA] \rightarrow 4b + X \\ 3. AAZW : pp \rightarrow H^\pm H \rightarrow [AW][AZ] \rightarrow 4b + X \end{array} \right. \\
 q\bar{q} & \left\{ \begin{array}{l} 4. AAA : pp \rightarrow HA \rightarrow [AA][A] \rightarrow 4b + X \\ 5. AAZ : pp \rightarrow HA \rightarrow [AZ][A] \rightarrow 4b + X \\ 6. AAWW : pp \rightarrow H^+ H^- \rightarrow [AW][AW] \rightarrow 4b + X \end{array} \right.
 \end{aligned}$$

Benchmark Points:

BP	m_A [GeV]	m_{H^\pm} [GeV]	m_H [GeV]	$\tan \beta$	$\sin(\beta - \alpha)$	m_{12}^2 [GeV ²]	BR($H \rightarrow AA$)	BR($H \rightarrow AZ$)
1	70	169.7	144.7	7.47	0.988	2355.0	0.99	0.006
2	50	169.8	150.0	17.11	0.975	1275.0	0.48	0.505

Cross sections at 13 TeV:

BP	AAW [fb]	AAAW [fb]	AAZW [fb]	AAA [fb]	AAZ [fb]	AAWW [fb]
1	165.7	96.9	0.43	199.8	0.88	31.6
2	228.2	45.1	35.3	117.3	91.8	34.8

Background: QCD multi-jet = 8.98×10^6 pb and $t\bar{t}$ + jets = 834pb.

Stefano Moretti, Shoab Munir, Tanmoy Mondal and Prasenjit, arXiv:2304.07719

Pseudoscalar mass reconstruction

- b -jets ≥ 4 , $p_T > 20$ GeV, $|\eta| < 5$.
- Three possible combinations of two b -jet pairs out of four leading b -jets: (1,2; 3,4), (1,3; 2,4) and (1,4; 2,3).
- The combination which minimizes

$$\Delta R = |(\Delta R_1 - 0.8)| + |(\Delta R_2 - 0.8)|$$

is selected, where

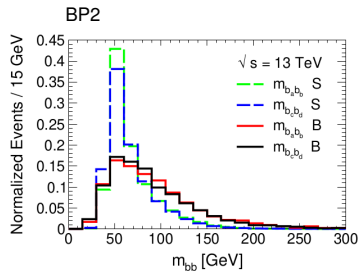
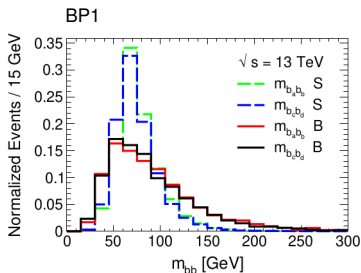
$$\Delta R_1 = \sqrt{(\eta_a - \eta_b)^2 + (\phi_a - \phi_b)^2}$$

$$\Delta R_2 = \sqrt{(\eta_c - \eta_d)^2 + (\phi_c - \phi_d)^2}$$

- After b -jet pairing, we impose asymmetry cut

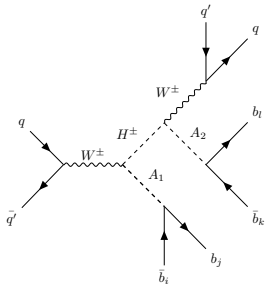
$$\alpha = \frac{|m_1 - m_2|}{m_1 + m_2} < 0.2$$

m_1 and m_2 are the invariant masses of two b -jet pairs.

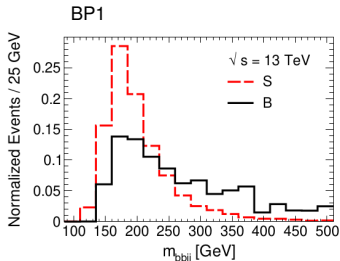


Charged Higgs mass reconstruction

H^\pm reconstruction based on the AAW topology



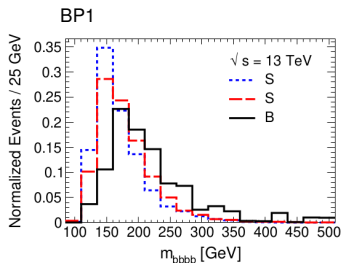
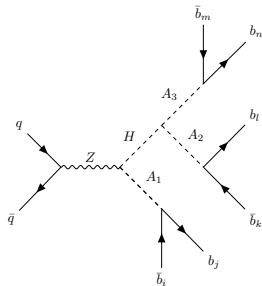
- b -jets ≥ 4 and jets ≥ 2 such that $jj \in X$ ($q\bar{q}' \rightarrow A_1 H^\pm \rightarrow A_1 A_2 W \rightarrow 4b + jj$).
- Leading two jets satisfy $m_{jj} = m_W \pm 25$ GeV.
- The combination of two b -jet pairs with invariant mass within 45 GeV window around m_A and satisfying the asymmetry cut is selected.
- Prompt pseudoscalar: A_1 , non-prompt pseudoscalar: A_2 . Then $p_T(A_1) > p_T(A_2)$.
- If $b_i b_j$ is from A_1 and $b_k b_l$ is from A_2 . Then $(p_i + p_j)_T > (p_k + p_l)_T$.
- $b_k b_l$ and the jet pair make the four jet system. The invariant mass of $b_k b_l jj$ reconstructs the mass of H^\pm .
- If more than one combination of four jet system is possible. The correct combination gives the maximum separation of the reconstructed H^\pm and A_1 in the $\eta - \phi$ space.



Heavy Higgs mass reconstruction

H reconstruction based on the AAA topology

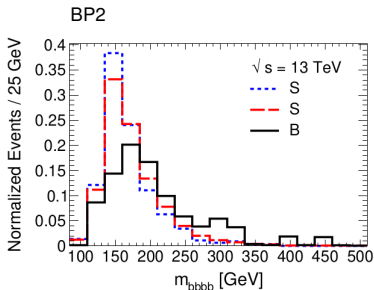
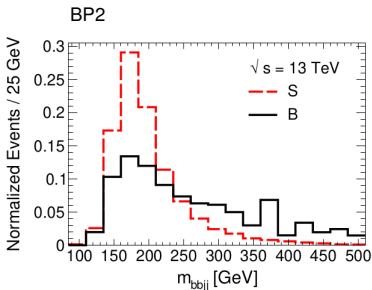
- b -jets ≥ 6 ($q\bar{q} \rightarrow A_1 H \rightarrow A_1 A_2 A_3 \rightarrow 6b$)
- The combination of three b -jet pairs with invariant mass within 45 GeV window around m_A and satisfying the asymmetry cut is selected.
- Prompt pseudoscalar: A_1 , non-prompt pseudoscalar: $A_{2,3}$
Then $p_T(A_1) > p_T(A_{2,3})$
- If $b_i b_j$ is from A_1 , then $(p_i + p_j)_T > (p_k + p_l)_T$ and $(p_i + p_j)_T > (p_m + p_n)_T$.
- $b_k b_l$ and $b_m b_n$ make the $4b$ -jet system. The invariant mass of the $4b$ -jet system reconstructs the mass of H .
- If more than one combination of $4b$ -jet system is possible. The correct combination gives the maximum separation of the reconstructed H and A_1 in the $\eta - \phi$ space.



Hurdles of H mass reconstruction:

1. $6b$ -jet events are very rare. Events with $5b$ jets are considered and the 6th b -jet is assumed to be one of the light jets.
2. The reconstruction starts to fail if $H \rightarrow AZ$ dominates over $H \rightarrow AA$ decay.

BP	A			H^\pm			H		
	σ_S [fb]	σ_B [fb]	$\frac{S}{\sqrt{B}}$	σ_S [fb]	σ_B [fb]	$\frac{S}{\sqrt{B}}$	σ_S [fb]	σ_B [fb]	$\frac{S}{\sqrt{B}}$
1	15.5	11151.7	8σ	2.22	592.3	5σ	1.8	256.4	6.15σ
2	9.26	10369.3	5σ	1.31	460.8	3.34σ	0.8	162.2	3.43σ



arXiv:2304.07719

$4b + \ell + \cancel{E}_T$ via EW process

Dominant Signal:

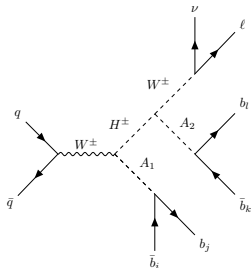
$$AAW : pp \rightarrow H^\pm A \rightarrow [AW][A] \rightarrow 4b + \ell + \cancel{E}_T$$

Subdominant Signal:

$$AAAW : pp \rightarrow H^\pm H \rightarrow [AW][AA] \rightarrow 4b + \ell + \cancel{E}_T$$

$$AAZW : pp \rightarrow H^\pm H \rightarrow [AW][AZ] \rightarrow 4b + \ell + \cancel{E}_T$$

$$AAWW : pp \rightarrow H^+ H^- \rightarrow [AW][AW] \rightarrow 4b + \ell + \cancel{E}_T$$



Dominant Background: $t\bar{t}$ + jets = 458 pb (fully leptonic + semileptonic modes).

χ^2 variable: Based on AAW signal topology and the signal hypothesis

$$\chi^2 = \left(\frac{m_{bb} - m_A}{\sigma_{m_A}} \right)^2 + \left(\frac{m_{bb\nu} - m_{H^\pm}}{\sigma_{m_{H^\pm}}} \right)^2$$

Benchmark points	m_A [GeV]	m_{H^\pm} [GeV]	m_H [GeV]	$s_{\beta - \alpha}$	m_{12}^2 [GeV ²]	$\tan\beta$
BP1	50	142.811	141.438	0.955275	1202.02	15.9863
BP2	50	184.916	161.629	0.95158	2336.07	10.0867
BP3	50	225.747	208.539	0.957129	4729.08	8.28101
BP4	70	152.41	159.024	0.983444	3123.09	6.05755
BP5	70	190.812	177.972	0.989558	3651.57	8.09766
BP6	70	236.081	219.12	0.960527	6073.61	7.04902

1. b -jet pairing algorithm is used to make the two b -jet pairs out of the four leading b -jets.
2. Assuming that the MET corresponds to only one neutrino from the leptonic decay of the W -boson in the AAW mode, the z -component of neutrino momentum can be estimated.

$$\vec{p}_{T\nu} = - \sum_{i \in obs} \vec{p}_{T_i}, \quad m_W^2 = (E_\ell + E_\nu)^2 - (\vec{p}_\ell + \vec{p}_\nu)^2$$

Rewriting this in terms of the x, y, z components of the neutrino momentum, we get a quadratic equation

$$A p_{z\nu}^2 + B p_{z\nu} + C = 0$$

where the coefficients are

$$A = 4(E_\ell^2 - p_{z\ell}^2),$$

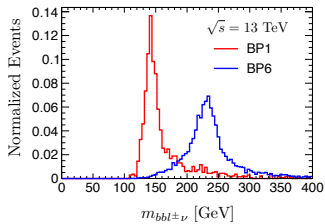
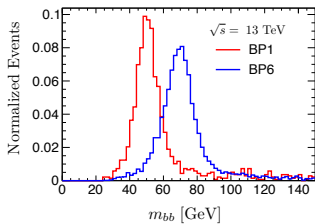
$$B = -4a p_{z\ell},$$

$$C = 4E_\ell^2(p_{x\nu}^2 + p_{y\nu}^2) - a^2$$

and $a = m_W^2 - m_\ell^2 + 2p_{x\ell} p_{x\nu} + 2p_{y\ell} p_{y\nu}$.

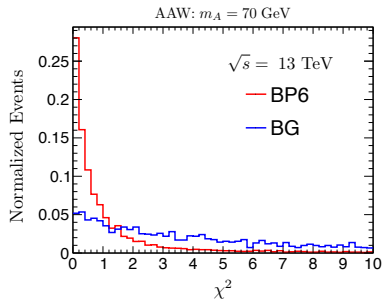
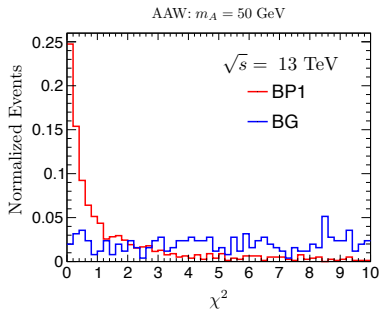
$$p_{z\nu} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}$$

3. σ_{m_A} and $\sigma_{m_{H^\pm}}$ are the expected uncertainties in the measurement of the masses of A and H^\pm .



1. σ_{m_A} is the width of the invariant mass of the b -jet pair with leading b -jet.
2. $\sigma_{m_{H^\pm}}$ is the width of the invariant mass of the b -jet pair together with the lepton and the neutrino at the generator level (truth information).

Benchmark points	m_A [GeV]	m_{H^\pm} [GeV]	σ_{m_A} [GeV]	$\sigma_{m_{H^\pm}}$ [GeV]
BP1	50	142.811	13.97	19.92
BP2	50	184.916	12.13	35.81
BP3	50	225.747	12.14	36.15
BP4	70	152.41	17.92	28.19
BP5	70	190.812	18.00	28.00
BP6	70	236.081	17.92	40.23



P. Sanyal and D. Wang

Signal Background Analysis

Selection cuts to study the discovery prospects of $4b + \ell + \cancel{E}_T$:

1. $p_T^b > 20 \text{ GeV}$, $p_T^\ell > 10 \text{ GeV}$, $|\eta^{b,\ell}| < 2.5$, $\cancel{E}_T > 10 \text{ GeV}$

2. $\chi^2 < 1$

3. $\alpha = \frac{|m_1 - m_2|}{m_1 + m_2} < 0.1$

4. $\Delta\eta = |\eta_1 - \eta_2| < 1.1$, $\eta_1 = \frac{\eta_a + \eta_b}{2}$, $\eta_2 = \frac{\eta_c + \eta_d}{2}$.

Cut Flow	Benchmark points	Modes	Parton Level	Basic Cut	$\chi^2 < 1$	$\alpha < 0.1$	$\Delta\eta < 1.1$	Significance
$m_A = 50 \text{ GeV}$	BP1	AAW	125.69	0.504	0.239	0.164	0.132	13.55
		AAAW	41.04	1.282	0.156	0.089	0.077	
		AAZW	2.68	0.026	0.003	0.002	0.001	
		AAWW	35.26	0.317	0.043	0.027	0.024	
		BG	458000	772.2	5.04	1.28	0.82	
	BP2	AAW	57.62	0.440	0.268	0.177	0.144	6.77
		AAAW	13.48	0.738	0.132	0.054	0.045	
		AAZW	5.70	0.119	0.020	0.010	0.008	
		AAWW	13.54	0.221	0.055	0.033	0.027	
		BG	458000	772.2	28.85	6.41	3.21	
	BP3	AAW	30.72	0.298	0.181	0.122	0.096	3.16
		AAAW	1.83	0.125	0.019	0.007	0.005	
		AAZW	4.91	0.140	0.026	0.013	0.010	
		AAWW	6.51	0.115	0.032	0.019	0.013	
		BG	458000	772.2	58.62	9.39	4.58	
$m_A = 70 \text{ GeV}$	BP4	AAW	72.73	0.665	0.372	0.230	0.194	11.20
		AAAW	33.18	1.306	0.282	0.137	0.117	
		AAZW	0.002	–	–	–	–	
		AAWW	25.00	0.379	0.078	0.042	0.035	
		BG	458000	772.2	18.23	4.40	2.75	
	BP5	AAW	38.84	0.592	0.321	0.213	0.169	4.93
		AAAW	5.20	0.363	0.077	0.039	0.032	
		AAZW	8.13	0.244	0.050	0.027	0.022	
		AAWW	10.79	0.284	0.070	0.042	0.033	
		BG	458000	772.2	43.05	13.97	8.02	
	BP6	AAW	20.20	0.394	0.244	0.161	0.127	2.92
		AAAW	1.32	0.139	0.032	0.014	0.011	
		AAZW	3.75	0.165	0.044	0.022	0.017	
		AAWW	4.79	0.164	0.056	0.033	0.026	
		BG	458000	772.2	98.93	21.76	11.45	

Conclusions

- In a fermiophobic BSM framework like Type I 2HDM, the EW induced multi-Higgs production dominates over the QCD induced processes.
- EW processes provides the charged 2BFSSs and 3BFSSs which complements the widely studied QCD processes.
- $4b + X$ final state obtained through EW processes is useful to reconstruct the masses of all the BSM Higgses.
- $4b + \ell + \cancel{E}_T$ is the signature state charecteristic of EW processes with no QCD counterpart.
- Strong signal-background discriminator is necessary to reduce the $t\bar{t} + \text{jets}$ background. χ^2 based on dominant signal topology and signal hypothesis serves the purpose.

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THANK YOU