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

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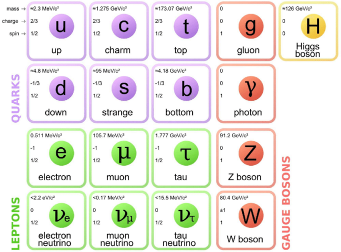
Outline

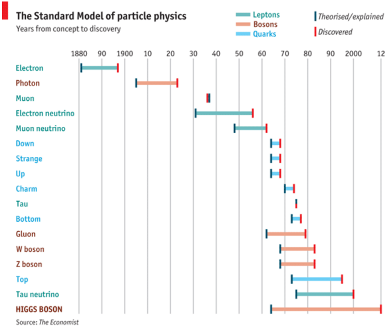
- Brief overview of Type I two Higgs doublet model (2HDM).
- Importance of the Electroweak (EW) production of multiple (pseudo) scalars.
- $4b + X$ mediated dominantly via EW processes.
- Reconstructing the masses of all the BSM Higgs bosons.
- $4b + W$ and $W \to \ell\nu$ only via EW processes.
- χ^2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

Overview of 2HDM

- The Standard Model (SM) is the most successful model in explaining the fundamental particles of the Universe and their interactions.



Particle Content of SM



Timeline of Discovery

- SM has theoretical and observational shortcomings.

- 2HDM is the minimal but phenomenologically rich extension of SM under the same gauge symmetry.

G. C. Branco, et al., 2011

- The scalar sector of the 2HDM consists of two $SU(2)$ Higgs doublets Φ_i, $i = 1,\ 2$.

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \frac{v_i+\rho_i+i\eta_i}{\sqrt{2}} \end{pmatrix}, \qquad v_i = \langle\rho_i\rangle \quad v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV}.$$

- Mostly studied: CP conserving 2HDM with softly broken $\mathbb{Z}_2$ (to avoid Higgs mediated FCNC) symmetry.

$$V_{\rm 2HDM} = -m_{11}^2\Phi_1^\dagger\Phi_1 - m_{22}^2\Phi_2^\dagger\Phi_2 - \left[\underline{m_{12}^2\Phi_1^\dagger\Phi_2} + \text{h.c.}\right] + \frac{1}{2}\lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{1}{2}\lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2$$
$$+\lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \left\{\frac{1}{2}\lambda_5\left(\Phi_1^\dagger\Phi_2\right)^2 + \text{h.c.}\right\}$$

- Type I 2HDM: $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$, $u_R^i \to -u_R^i$, $d_R^i \to -d_R^i$ and $e_R^i \to -e_R^i$.

- After EW symmetry breaking, the scalar sector consists of two CP even Higgses (h and H), one CP odd scalar (A) and a pair of charged Higgs ($H^\pm$).

- Parameters: $m_h = 125$ GeV, $m_H,\ m_A,\ m_{H^\pm},\ m_{12}^2,\ v,\ \tan\beta(= v_2/v_1),\ \sin(\beta-\alpha)$

- Alignment limit: $\sin(\beta-\alpha) \to 1$ implies that the couplings of h is like SM Higgs boson.

- After EW symmetry breaking the Yukawa Lagrangian in terms of the mass eigenstates is:

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

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 $\tan\beta >> 1$.
  $\xi_H^f = s_\alpha/s_\beta = c_{\beta-\alpha} - s_{\beta-\alpha}/\tan\beta \Rightarrow$ fermiophobic H for $\tan\beta >> 1$, $\sin(\beta-\alpha) \to 1$.

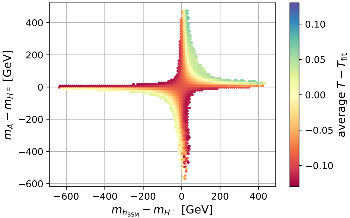
- Other couplings:

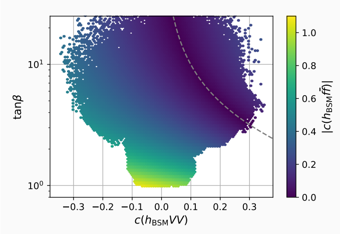
  (A) $hVV : \sin(\beta-\alpha) g_{hVV}^{\text{SM}}$, $HVV : \cos(\beta-\alpha) g_{hVV}^{\text{SM}}$, $AVV : 0$ where $V = Z, W^\pm$.

  (B) $hAZ_\mu : \frac{g}{2c_W}\cos(\beta-\alpha)(p+p')_\mu$, $HAZ_\mu : -\frac{g}{2c_W}\sin(\beta-\alpha)(p+p')_\mu$

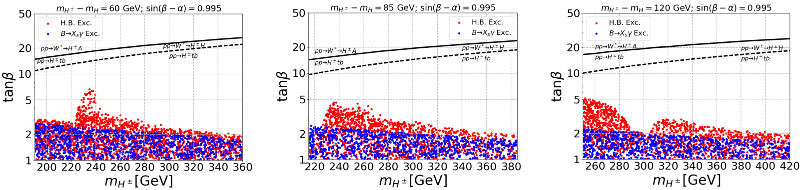
  (C) $H^\pm h W_\mu^\mp : \mp i\frac{g}{2}\cos(\beta-\alpha)(p+p')_\mu$, $H^\pm H W_\mu^\mp : \pm i\frac{g}{2}\sin(\beta-\alpha)(p+p')_\mu$,
  $H^\pm A W_\mu^\mp : \frac{g}{2}(p+p')_\mu$

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





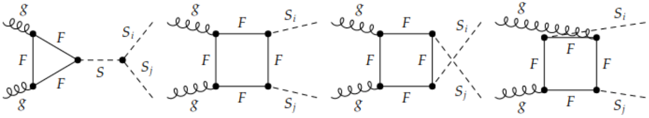
Henning Bahl, Tim Stefaniak, Jonas Wittbrodt, JHEP 06 (2021), 183.



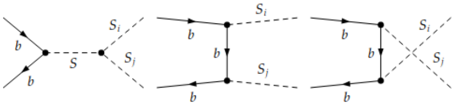
P. Sanyal, T. Mondal, JHEP 05 (2022) 040.

QCD induced multi Higgs final states.

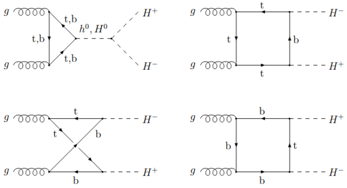
1. Pair of neutral scalars via gluon fusion:



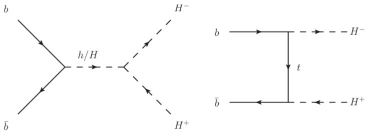
2. $b\bar{b}$ induced pair of neutral scalars:



3. $H^{\pm}$ pair creation via gluon fusion:

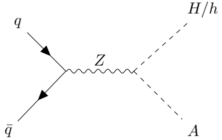


4. $b\bar{b}$ induced $H^{\pm}$ pair creation:

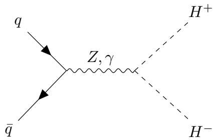


EW production of multi Higgs final states

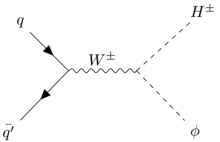
1. Pair of neutral scalars:



2. $H^{\pm}$ pair creation:



3. Charged two body states:



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

Charged 2BFS and 3BFS via EW processes

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Regular Article - Theoretical Physics

Electroweak production of multiple (pseudo)scalars in the 2HDM

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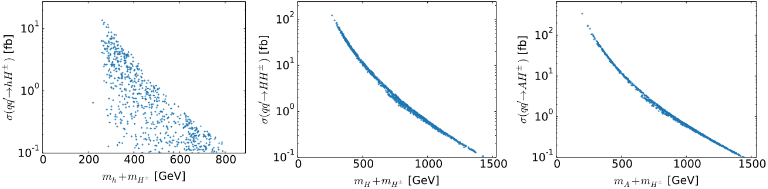
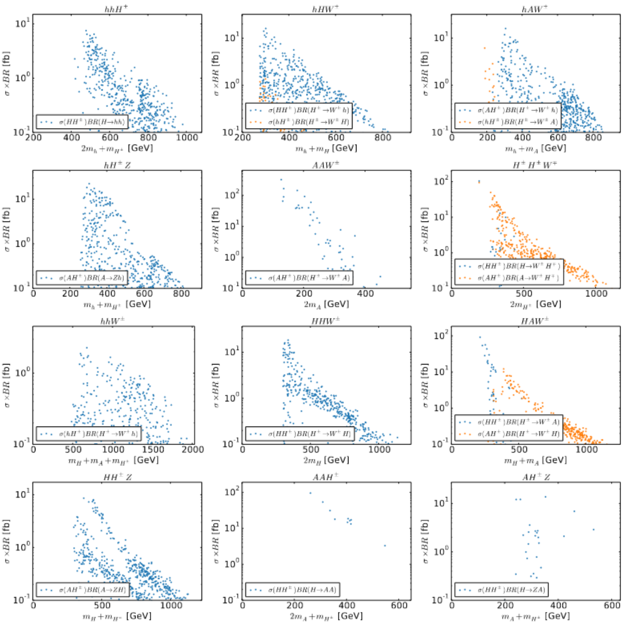
Parameter space scans:
m_H : 150 − 750 GeV; $m_{H\pm}$: 50 − 750 GeV; m_A : 50 − 750 GeV;
$\sin(\beta-\alpha)$: −1.0 − 1.0; m_{12}^2 : 0 − $m_A^2 \sin\beta\cos\beta$; $\tan\beta$: 2 − 25

Cross sections at 13 TeV for three possible charged 2BFSs



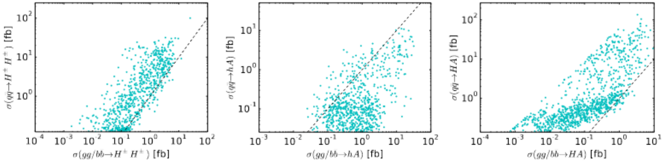
Cross sections at 13 TeV for the various charged 3BFSs



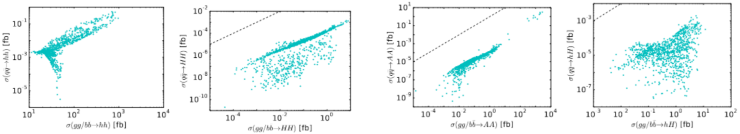
Neutral 2BFS and 3BFS

The neutral 2BFSs have contributions from QCD as well as EW processes.

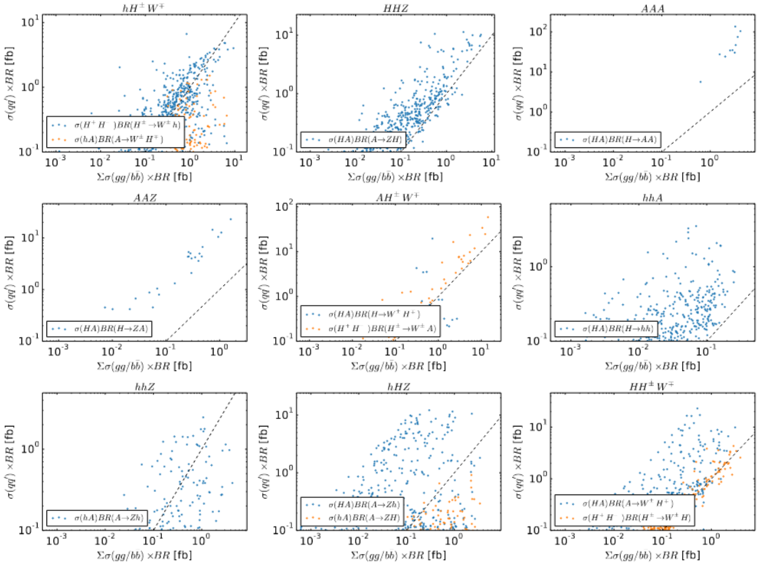
1. The two 2BFs where the EW processes dominate the combined gg and $b\bar{b}$ QCD process:



2. The two 2BFs where the combined gg and $b\bar{b}$ QCD processes dominate the EW processes:



Cross sections at 13 TeV for the various neutral 3BFSs



Triple Higgs couplings

1. $\lambda_{hAA} = \frac{1}{4vs_\beta c_\beta}\Big\{(4M^2 - 2m_A^2 - 3m_h^2)c_{\alpha+\beta} + (2m_A^2 - m_h^2)c_{\alpha-3\beta}\Big\}, \quad M^2 = m_{12}^2/s_\beta c_\beta.$

   $\lambda_{hAA} = \frac{1}{v}(2M^2 - 2m_A^2 - m_h^2), \qquad \text{for} \ \ \sin(\beta-\alpha)\to 1$

2. $\lambda_{Hhh} = \frac{1}{2vc_\beta s_\beta} c_{\beta-\alpha}\Big\{(3M^2 - 2m_h^2 - m_H^2)s_{2\alpha} - M^2 s_{2\beta}\Big\}$

   $\lambda_{Hhh} = 0, \qquad \text{for} \ \ \sin(\beta-\alpha)\to 1$

3. $\lambda_{HAA} = \frac{1}{4vs_\beta c_\beta}\Big\{(4M^2 - 2m_A^2 - 3m_H^2)s_{\alpha+\beta} - (m_H^2 - 2m_A^2)s_{\alpha-3\beta}\Big\}$

   $\lambda_{HAA} = \frac{2}{vt_{2\beta}}(m_H^2 - M^2), \qquad \text{for} \ \ \sin(\beta-\alpha)\to 1$

$4b + X$ via EW process

EW processes contributing to the $4b + X$ mode:

$$q\bar{q}' \begin{cases} 1.\ AAW: \ pp \to H^{\pm}A \to [AW][A] \to 4b + X \\ 2.\ AAAW: \ pp \to H^{\pm}H \to [AW][AA] \to 4b + X \\ 3.\ AAZW: \ pp \to H^{\pm}H \to [AW][AZ] \to 4b + X \end{cases}$$

$$q\bar{q} \begin{cases} 4.\ AAA: \ pp \to HA \to [AA][A] \to 4b + X \\ 5.\ AAZ: \ pp \to HA \to [AZ][A] \to 4b + X \\ 6.\ AAWW: \ pp \to H^{+}H^{-} \to [AW][AW] \to 4b + X \end{cases}$$

Benchmark Points:

BP	m_A [GeV]	$m_{H^{\pm}}$ [GeV]	m_H [GeV]	$\tan\beta$	$\sin(\beta - \alpha)$	m^2_{12} [GeV^2]	BR($H \to AA$)	BR($H \to AZ$)
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, Shoaib 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

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

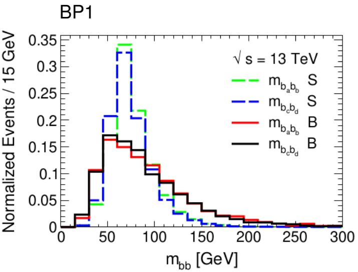
is selected, where

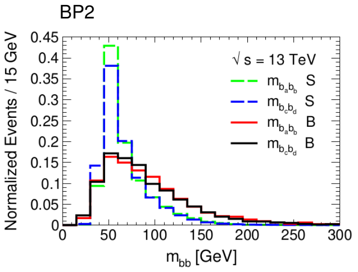
$$\Delta R_1 = \sqrt{(\eta_a - \eta_b)^2 + (\phi_a - \phi_b)^2}$$
$$\Delta R_2 = \sqrt{(\eta_c - \eta_d)^2 + (\phi_c - \phi_d)^2}$$

- After b-jet pairing, we impose assymmetry 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.

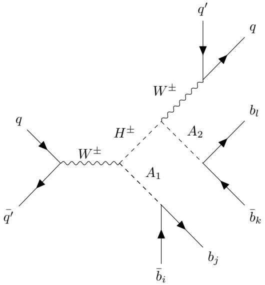




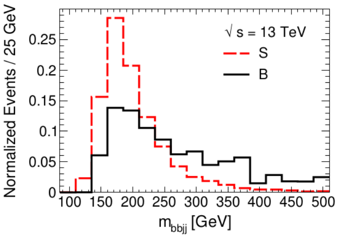
arXiv:2304.07719

Charged Higgs mass reconstruction

$H^{\pm}$ reconstruction based on the *AAW* topology



BP1



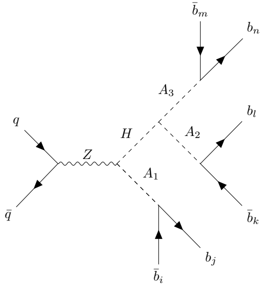
- b-jets ≥ 4 and jets ≥ 2 such that $jj \in X$ ($q\bar{q}' \to A_1 H^{\pm} \to A_1 A_2 W \to 4b + jj$).
- Leading two jets satisfy $m_{jj} = m_W \pm 25$ GeV.
- The combination of two b-jet pairs with invariant mass within 45 GeV window around m_A and satisfying the assymmetry cut is selected.
- Prompt 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.

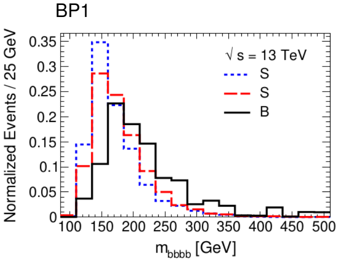
arXiv:2304.07719

Heavy Higgs mass reconstruction

H reconstruction based on the *AAA* topology

- b-jets ≥ 6 ($q\bar{q} \to A_1 H \to A_1 A_2 A_3 \to 6b$)
- The combination of three b-jet pairs with invariant mass within 45 GeV window around m_A and satisfying the assymmetry 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.





arXiv:2304.07719

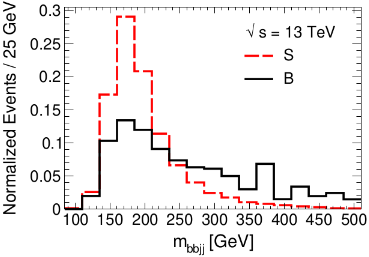
Hurdles of H mass reconstruction:

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.

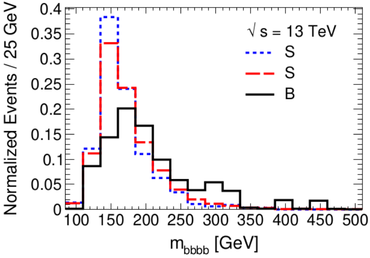
2. The reconstruction starts to fail if $H \to AZ$ dominates over $H \to AA$ decay.

	Reconstructed Higgs bosons								
	A			$H^{\pm}$			H		
BP	σ_S	σ_B	$\frac{S}{\sqrt{B}}$	σ_S	σ_B	$\frac{S}{\sqrt{B}}$	σ_S	σ_B	$\frac{S}{\sqrt{B}}$
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

BP2



BP2



arXiv:2304.07719

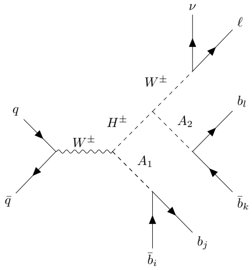
$4b + \ell + \not{E}_T$ via EW process

Dominant Signal:

$$AAW: \; pp \to H^{\pm} A \to [AW][A] \to 4b + \ell + \not{E}_T$$

Subdominant Signal:

$$AAAW: \; pp \to H^{\pm} H \to [AW][AA] \to 4b + \ell + \not{E}_T$$
$$AAZW: \; pp \to H^{\pm} H \to [AW][AZ] \to 4b + \ell + \not{E}_T$$
$$AAWW: \; pp \to H^{+} H^{-} \to [AW][AW] \to 4b + \ell + \not{E}_T$$



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

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

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

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

χ^2 Variable

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.

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

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

$$Ap_{z_\nu}^2 + Bp_{z_\nu} + C = 0$$

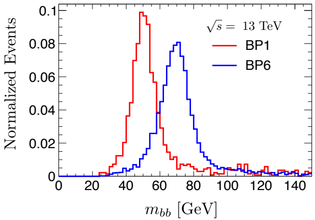
where the coefficients are

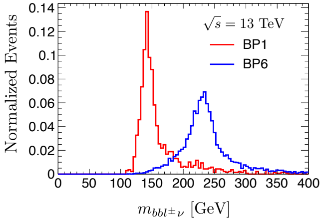
$$\begin{aligned} A &= 4(E_\ell^2 - p_{z_\ell^2}), \\ B &= -4ap_{z_\ell}, \\ C &= 4E_\ell^2(p_{x_\nu}^2 + p_{y_\nu}^2) - a^2 \end{aligned}$$

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

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

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]	σm_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

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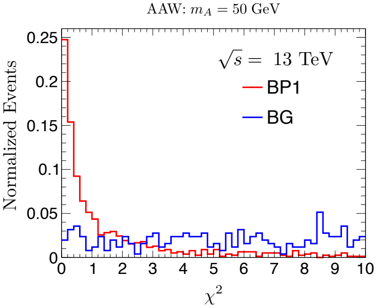

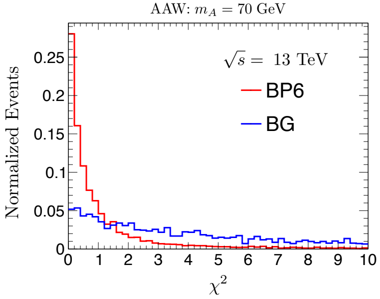

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Signal Background Analysis

Selection cuts to study the discovery prospects of $4b + \ell + \not{E}_T$:

1. $p_T^b > 20$ GeV, $p_T^\ell > 10$ GeV, $|\eta^{b,l}| < 2.5$, $\not{E}_T > 10$ 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 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 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

- EW processes provides the charged 2BFSs and 3BFSs which complements the widely studied QCD processes.

- The neutral 2BFSs and therefore the neutral 3BFSs via EW processes can dominate the QCD induced processes.

- $4b + X$ final state obtained through EW processes is useful to reconstruct the masses of all the BSM Higgses.

- $4b + \ell + \not{E}_T$ is the signature state charecteristc of EW processes with no QCD counterpart.

- Strong signal-background discriminator is necessary to reduce the $t\bar{t}$ + jets background. χ^2 based on dominant signal topology and signal hypothesis serves the purpose.

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THANK YOU