Electroweak Multi-Higgs production: A smoking gun for the Type I 2HDM

Prasenjit Sanyal

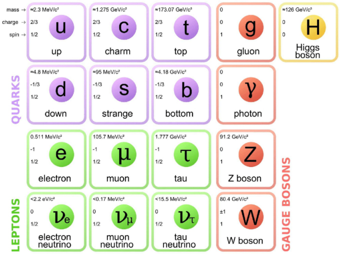
Asia Pacific Center for Theoretical Physics, Korea

Outline

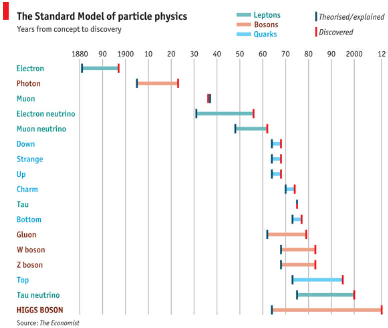
- Brief overview of Type I two Higgs doublet model (2HDM).
- Importance of the Electroweak (EW) production of multiple (pseudo) scalars.
- $4b + X$ mediated dominantly via EW processes.
- Reconstructing the masses of all the BSM Higgses.

Overview of two Higgs doublet model (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: $\mathcal{CP}$ conserving 2HDM with softly broken $\mathcal{Z}_2$ (to avoid Higgs mediated FCNC) symmetry.

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

- Based on the $\mathcal{Z}_2$ charge assignments to the fermions, there are four possible Yukawa structures $-$ Type I, II, X and Y.

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

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

- Alignment limit: $\sin(\beta - \alpha) \sim 1$ 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:

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

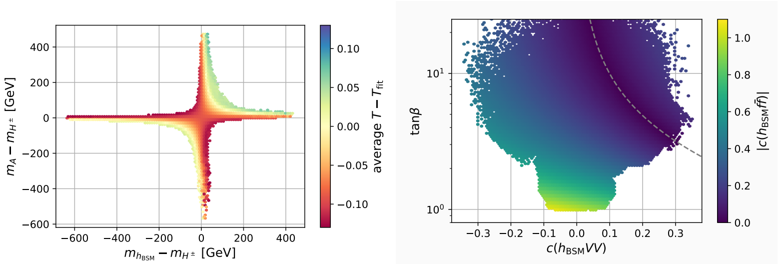
ξ_h^u	ξ_h^d	ξ_h^ℓ	ξ_H^u	ξ_H^d	ξ_H^ℓ	ξ_A^u	ξ_A^d	ξ_A^ℓ
c_α / s_β	c_α / s_β	c_α / s_β	s_α / s_β	s_α / s_β	s_α / s_β	$\cot\beta$	$-\cot\beta$	$-\cot\beta$

- $\xi_A^f \propto 1/\tan\beta \longrightarrow$ fermiophobic A, $H^\pm$
  $\sin\alpha = 0 \Rightarrow \tan\beta = \frac{\sin(\beta-\alpha)}{\cos(\beta-\alpha)} \longrightarrow$ fermiophobic H

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

- Unitarity and vacuum stability bounds can be satisfied by proper choice of $m_{12}^2 \in [0, m_H^2 \sin\beta\cos\beta]$.

- The EWPO, T - parameter depends strongly on the mass splitting of the charged Higgs and the neutral scalars.

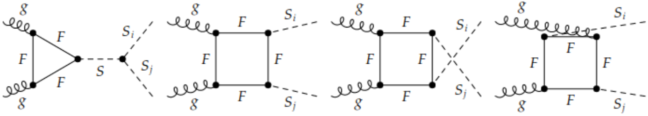


Henning Bahl, Tim Stefaniak, Jonas Wittbrodt, JHEP 06 (2021), 183.

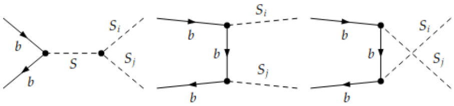
- Higgs signal strength measurements constrain $|\cos(\beta - \alpha)| \leqslant 0.3$.

QCD induced multi Higgs final states.

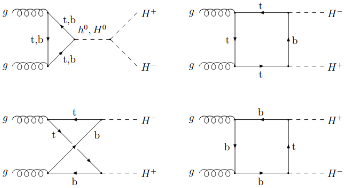
1. Pair of neutral scalars via gluon fusion:



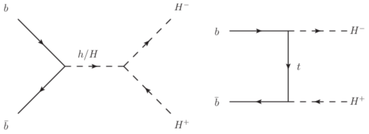
2. $b\bar{b}$ induced pair of neutral scalars:



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

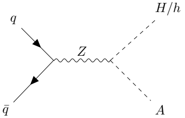


4. $b\bar{b}$ induced $H^\pm$ pair creation:

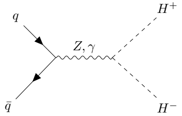


EW production of multi Higgs final states

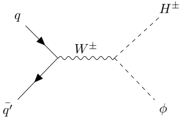
1. Pair of neutral scalars:



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

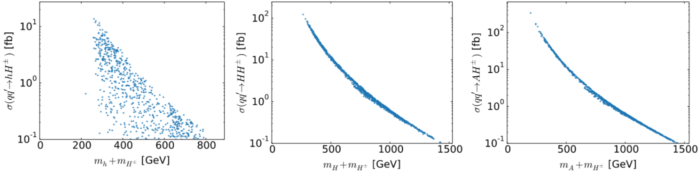
Electroweak production of multiple (pseudo)scalars in the 2HDM

Rikard Enberg[1,a], **William Klemm**[1,2,b], **Stefano Moretti**[3,c], **Shoaib Munir**[4,5,d]

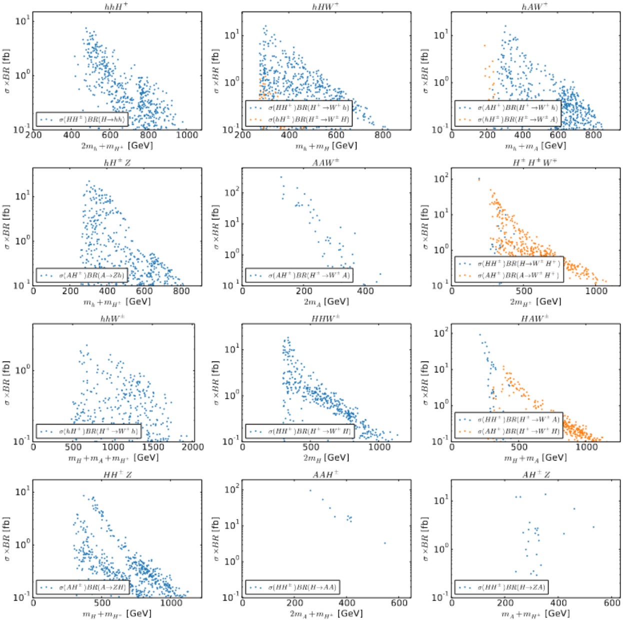
[1] Department of Physics and Astronomy, Uppsala University, Box 516, 751 20 Uppsala, Sweden
[2] School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK
[3] School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK
[4] School of Physics, Korea Institute for Advanced Study, Seoul 130-722, Republic of Korea
[5] East African Institute for Fundamental Research (ICTP-EAIFR), University of Rwanda, Kigali, Rwanda

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:



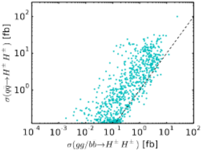
Cross sections at 13 TeV for the various charged 3BFSs:

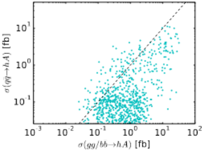


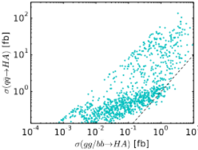
Neutral 2BFS and 3BFS

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

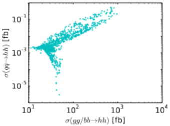
1. The two 2BFs where the EW processes dominate the combined gg and $b\bar{b}$ QCD process:

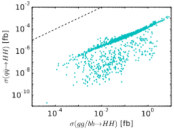


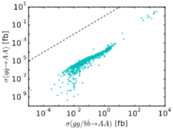


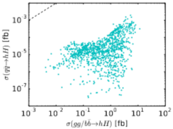


2. The two 2BFs where the combined gg and $b\bar{b}$ QCD processes dominate the EW processes:

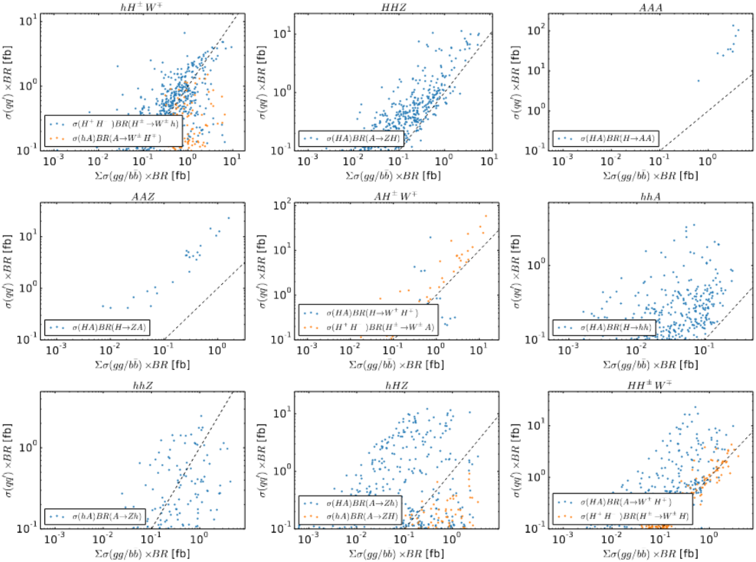




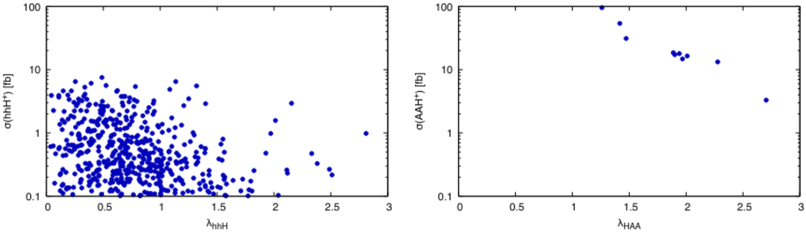




Cross sections at 13 TeV for the various neutral 3BFSs:



The triple Higgs coupling λ_{hhH} and λ_{HAA} can be sizable compared to the Higgs self coupling in SM.



A Left: $\sigma(HH^{\pm})BR(H \to hh)$. Right: $\sigma(HH^{\pm})BR(H \to AA)$

B The triple Higgs couplings are normalized with respect to the SM triple Higgs coupling.

$4b + X$ via EW process

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

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

$$q\bar{q} \begin{cases} 3.\ AAA: \ pp \to HA \to [AA][A] \to 4b + X, \\ 4.\ AAW^{+}W^{-}: \ pp \to H^{+}H^{-} \to [AW^{+}][AW^{-}] \to 4b + X \end{cases}$$

Benchmark Points:

BP	m_A [GeV]	$m_{H^\pm}$ [GeV]	m_H [GeV]	$\tan\beta$	$\sin(\beta-\alpha)$	m_{12}^2 [GeV^2]
1	50	169.8	150.0	17.11	0.975	1275.0
2	70	169.7	144.7	7.47	0.988	2355.0
3	110	234.7	250.1	26.0	0.969	2324.7

Cross sections [fb] at 13 TeV:

BP	$AAW^{\pm}$	$AAAW^{\pm}$	AAA	$AAW^{+}W^{-}$
1	228.21	33.829	87.93	34.77
2	165.70	68.61	141.45	31.60
3	35.21	3.16	5.0	6.85

Under preparation
Collaborators: Stefano Moretti, Shoaib Munir and Tanmoy Mondal

Pseudoscalar mass reconstruction

- Events with at least four resolved *b*-jets with $p_T > 20$ GeV, $|\eta| < 5$ and separation of $R = 0.4$ from the leptons and jets are selected.
- In each event there are 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

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

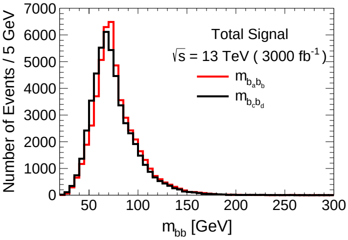
is selected, where

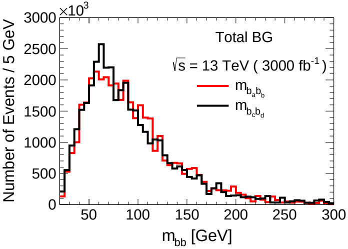
$$\Delta R_1 = \sqrt{(\eta_a - \eta_b)^2 + (\phi_a - \phi_b)^2}$$
$$\Delta R_2 = \sqrt{(\eta_c - \eta_d)^2 + (\phi_c - \phi_d)^2}$$

- 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.

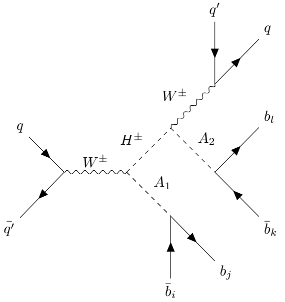


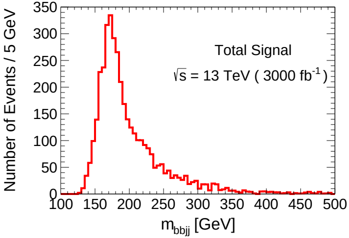


Under preparation

Charged Higgs mass reconstruction

$H^{\pm}$ mass reconstruction is done based on the dominant $AAW^{\pm}$ mode:





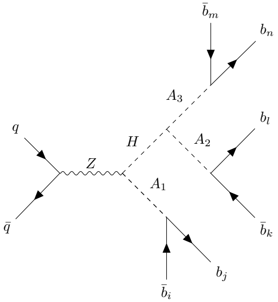
- Events with leading two jets satisfying the invariant mass condition $m_{jj} = m_W \pm 15$ GeV are selected.
- In each event all possible combinations of two b-jet pairs are considered. The combination for which each b-jet pair satisfying the invariant mass condition of $m_A \pm 15$ GeV along with the assymmetry cut is selected.
- Prompt pseudoscalar: A_1, non-prompt pseudoscalar: A_2. Then $p_T(A_1) > p_T(A_2)$.
- $b_i b_j$ and $b_k b_l$ satisfy the invariant mass conditions and assymmetry cut. 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 coming from W boson 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.

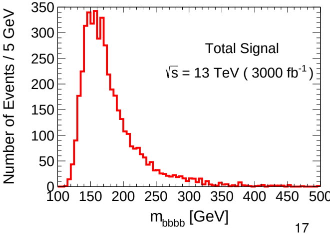
Under preparation

Heavy Higgs mass reconstruction

H mass reconstruction is done based on the mode which contain $H \to AA \to 4b$ decay. AAA mode serves the purpose.

- In each event all possible combinations of three b-jet pairs are considered. The combination for which each b-jet pair satisfying the invariant mass condition of $m_A \pm 15$ GeV and the assymmetry cut is selected.
- Prompt pseudoscalar: A_1, non-prompt pseudoscalar: $A_{2,3}$ Then $p_T(A_1) > p_T(A_{2,3})$
- $b_i b_j$, $b_k b_l$ and $b_m b_n$ satisfy the invariant mass conditions and assymmetry cut. 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.





Under preparation

Hurdles of H mass reconstruction:

1. $6b$-jet events are very rare because of finite miss-tagging probability. Therefore, events with $5b$ jets are to be considered and the 6^{th} b-jet is assumed to be one of the light jets. Light jet with leading transverse momentum is given the priority as the miss-tagged b-jet.

2. The reconstruction algorithm fails if $H \to AZ$ is allowed and dominates over $H \to AA$ decay.

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.

Conclusions

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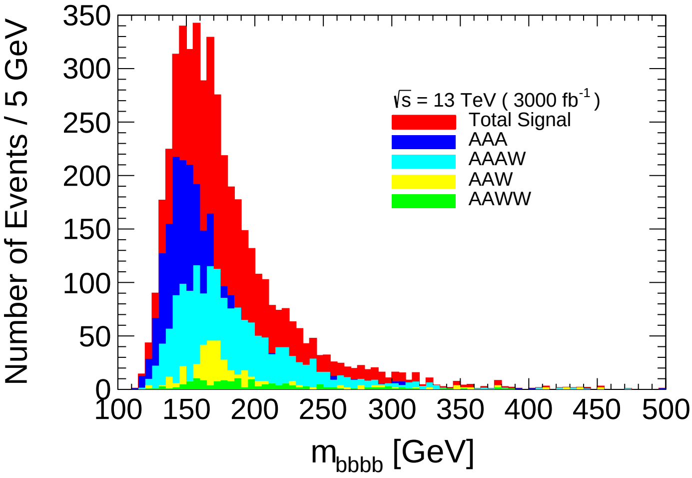
THANK YOU

Backup



Number of Events / 5 GeV
350
300
250
200
150
100
50
0
100
150
200
250
300
350
400
450
500
m_{bbbb} [GeV]
$\sqrt{s}$ = 13 TeV (3000 fb^{-1})
Total Signal
AAA
AAAW
AAW
AAWW