New channels for light charged Higgs boson searches at the Large Hadron Collider

Mohamed Krab

Sultan Moulay Slimane U., Morocco

Based on arXiv:2106.13656 & arXiv:2107.01451

in collaboration with

A. Arhrib, R. Benbrik, B. Manaut, S. Moretti, Y. Wang and Q.-S. Yan

30th International Symposium on Lepton Photon Interactions at High Energies

10-14 January 2022

General Two-Higgs Doublet Model

[G. C. Branco *et al.*, 1106.0034]

The scalar sector of the 2HDM contains two complex $SU(2)$ doublets with hypercharge $Y = +1$,

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ \phi_a^0 \end{pmatrix} = \begin{pmatrix} \phi_a^+ \\ (v_a + \rho_a^0 + i\eta_a)/\sqrt{2} \end{pmatrix}, \qquad a = 1, 2. \tag{1}$$

The most general scalar potential for Φ_1 and Φ_2 is given by

$$\begin{aligned} V(\Phi_1, \Phi_2) &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] \\ &+ \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ &+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ &+ \left\{ \frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \left[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)\right] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\}. \end{aligned} \tag{2}$$

- Z_2 symmetry $\Longrightarrow$ $\lambda_6 = \lambda_7 = m_{12}^2 = 0$ (soft violation $\Longrightarrow$ m_{12}^2).
- After EWSB: m_h, m_H, m_A, $m_{H^\pm}$, α (mix. ang.), $\tan\beta (= v_2/v_1)$ and m_{12}^2.

Yukawa Couplings

[G. C. Branco *et al.*, 1106.0034]

▷ Absence of FCNCs (Z_2 symmetry) $\implies$ four Types of 2HDM.

Model	u_R^i	d_R^i	e_R^i
Type-I	Φ_2	Φ_2	Φ_2
Type-II	Φ_2	Φ_1	Φ_1
Type-X	Φ_2	Φ_2	Φ_1
Type-Y	Φ_2	Φ_1	Φ_2

▷ The Yukawa couplings can be written as

$$-\mathcal{L}_{\rm Yukawa} = \sum_{f=u,d,l} \left(\frac{m_f}{v} \kappa_f^h \bar{f} f h + \frac{m_f}{v} \kappa_f^H \bar{f} f H - i \frac{m_f}{v} \kappa_f^A \bar{f} \gamma_5 f A \right) + \left(\frac{V_{ud}}{\sqrt{2} v} \bar{u} (m_u \kappa_u^A P_L + m_d \kappa_d^A P_R) d H^+ + \frac{m_l \kappa_l^A}{\sqrt{2} v} \bar{\nu}_L l_R H^+ + H.c. \right). \quad (3)$$

	κ_u^h	κ_d^h	κ_l^h	κ_u^H	κ_d^H	κ_l^H	κ_u^A	κ_d^A	κ_l^A
Type-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	c_β/s_β	$-c_\beta/s_\beta$	$-c_\beta/s_\beta$
Type-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	c_β/s_β	$-c_\beta/s_\beta$	s_β/c_β

Theoretical and Experimental Constraints

Numerically scanning of the parameter space with the following constraints imposed:

- ▷ Unitarity, perturbativity and vacuum stability.
- ▷ Oblique parameters S, T and U.

  (2HDMC) [D. Eriksson, J. Rathsman and O. Stal, 0902.0851]

- ▷ LEP, TeVatron and LHC results for
  - ◦ Additional Higgs bosons (HiggsBounds-5).

    [P. Bechtle *et al.*, 2006.06007]

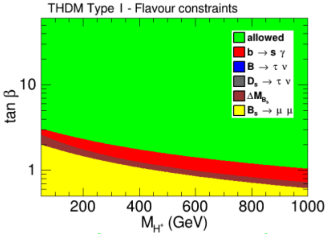
  - ◦ Measured Higgs signal strengths (HiggsSignals-2).

    [P. Bechtle *et al.*, 2012.09197]

- ▷ Flavour constraints (SuperIso).

  [F. Mahmoudi, 0808.3144]

Parameters	2HDM-I, -X
m_h	$[10,\ 120]$
m_H	125
m_A	$[10,\ 120]$
$m_{H^\pm}$	$[80,\ 170]$
$s_{\beta-\alpha}$	$[-0.3,\ -0.05]$
$\tan\beta$	$[2,\ 60]$
m_{12}^2	$[0,\ m_H^2 \sin\beta\cos\beta]$
$\lambda_6 = \lambda_7$	0



[A. Arbey *et al.*, 1706.07414]

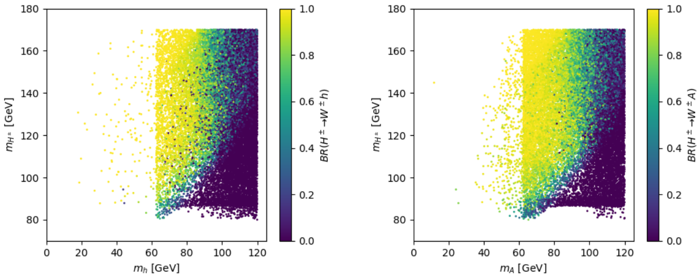
Bosonic Decays

- ▷ Most existing experimental searches target the fermionic decay channels of charged Higgs bosons.
- ▷ The bosonic decay, $H^\pm \to W^\pm h/A$, has a naturally large branching ratio close to the alignment limit. [A. Arhrib, R. Benbrik and S. Moretti, 1607.02402]

  [H. Bahl, T. Stefaniak and J. Wittbrodt, 2103.07484]

  [A. Arhrib, R. Benbrik, M. K., B. Manaut *et al.*, 2106.13656]

  [Y. Wang, A. Arhrib, R. Benbrik, M. K. *et al.*, 2107.01451]



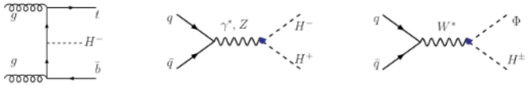
Charged Higgs Production

Production processes involving top (anti)quarks:

- Top pair production and decay chain (NWA):
  $\sigma^{\phi}_{2t}(2W+4\text{SM}) = \sigma(pp \to t\bar{t} \to bH^+\bar{b}W^- \to bW^+\phi\bar{b}W^- \to W^+W^-b\bar{b} + (\phi \to)2\text{SM})$
- Associated production with top plus bottom and decay chain ($m_{H^\pm} \sim m_t$):
  $\sigma^{\phi}_{t}(2W+4\text{SM}) = \sigma(pp \to t\bar{b}H^- \to bW^+\bar{b}W^-\phi \to W^+W^-b\bar{b} + (\phi \to)2\text{SM})$

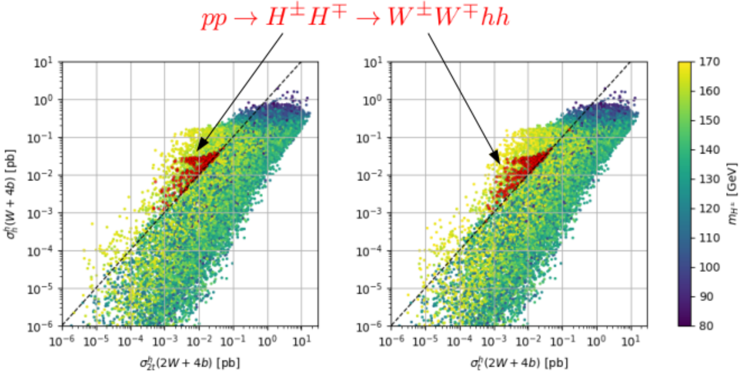
Di-Higgs processes:

- Pair production and decay chain:
  $\sigma^{\phi}_{\phi}(2W+4\text{SM}) = \sigma(pp \to H^\pm H^\mp \to W^\pm\phi W^\mp\phi \to W^\pm W^\mp + 4\text{SM})$
- Associated production with ϕ and decay chain:
  $\sigma^{\phi}_{\phi}(W+4\text{SM}) = \sigma(pp \to H^\pm\phi \to W^\pm\phi\phi \to W^\pm + 4\text{SM})$



Results

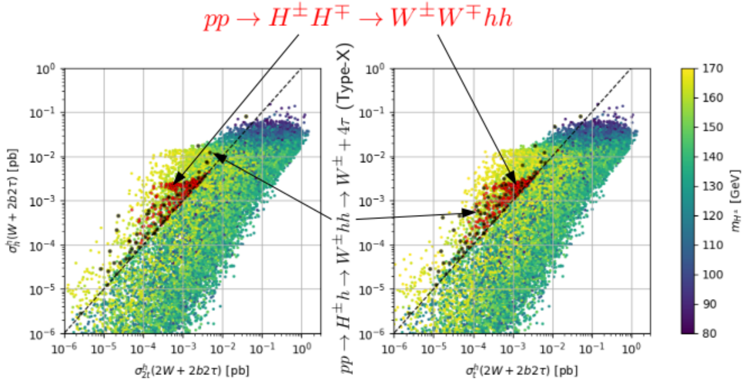
The relative magnitudes of the production and decay rates of $4b$ final states from $pp \to H^{\pm}h \to W^{\pm}hh$ and from the processes involving top (anti)quarks.



- $\mathrm{BR}(h \to b\bar{b})$ can reach values above 80%.

Results

The relative magnitudes of the production and decay rates of $2b2\tau$ final states from $pp \to H^{\pm}h \to W^{\pm}hh$ and from the processes involving top (anti)quarks.



▷ $\mathrm{BR}(h \to \tau^+\tau^-) \sim 7\%$ (Type-I), $\sim 100\%$ (Type-X).

Results

BPs for Type-I

Parameters	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8
m_h (GeV)	91.00	96.84	103.34	99.61	95.57	94.00	94.00	94.00
m_H (GeV)	125.00	125.00	125.00	125.00	125.00	125.00	125.00	125.00
m_A (GeV)	102.04	112.35	93.80	88.98	94.41	105.00	105.00	105.00
$m_{H^\pm}$ (GeV)	167.02	166.34	161.02	169.46	167.02	176.00	186.00	196.00
$s_{\beta-\alpha}$	-0.18	-0.11	-0.19	-0.06	-0.09	-0.09	-0.09	-0.09
$\tan\beta$	40.87	58.17	54.79	39.10	32.44	30.00	30.00	30.00
m_{12}^2 (GeV^2)	204.22	161.85	196.73	252.94	277.81	294.00	294.00	294.00
$\sigma_{2t}^h(2W+4b)$	2.30	1.65	2.06	–	2.42	–	–	–
$\sigma_t^h(2W+4b)$	3.85	2.35	2.26	0.85	3.84	5.03	4.68	3.52
$\sigma_{2t}^A(2W+4b)$	0.70	0.25	4.63	–	2.47	–	–	–
$\sigma_t^A(2W+4b)$	1.17	0.36	5.07	3.03	3.92	0.83	0.44	1.08
$\sigma_h^h(2W+4b)$	13.58	15.99	2.29	0.97	5.38	14.08	13.27	7.35
$\sigma_A^h(2W+4b)$	4.13	2.44	5.14	3.46	5.50	2.32	1.25	2.24
$\sigma_A^A(2W+4b)$	1.26	0.37	11.55	12.35	5.62	0.38	0.12	0.68
$\sigma_h^A(2W+4b)$	4.13	2.44	5.14	3.46	5.50	2.32	1.25	2.24
$\sigma_h^h(W+4b)$	75.88	77.61	26.47	17.68	46.00	73.25	68.00	48.81
$\sigma_A^h(W+4b)$	23.07	11.86	59.44	63.04	47.00	12.07	6.42	14.90
$\sigma_A^A(W+4b)$	17.48	6.12	64.39	69.22	43.51	9.16	4.91	11.45
$\sigma_h^A(W+4b)$	57.51	40.06	28.68	19.41	42.59	55.59	52.02	37.51

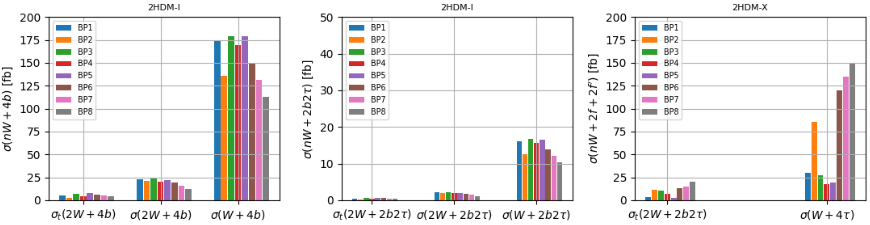
BPs for Type-X

Parameters	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8
m_h (GeV)	83.66	83.23	100.04	115.35	95.12	84.84	103.41	86.87
m_H (GeV)	125.00	125.00	125.00	125.00	125.00	125.00	125.00	125.00
m_A (GeV)	113.60	109.52	93.55	79.30	101.38	108.83	90.46	112.97
$m_{H^\pm}$ (GeV)	166.22	169.14	166.18	158.67	169.99	176.64	186.78	195.68
$s_{\beta-\alpha}$	-0.10	-0.13	-0.17	-0.10	-0.13	-0.12	-0.13	-0.12
$\tan\beta$	18.57	14.41	10.51	17.42	13.90	15.37	15.36	14.53
m_{12}^2 (GeV^2)	367.17	408.42	801.13	728.57	645.95	437.53	631.00	456.00
$\sigma_{2t}^h(2W+2b2\tau)$	2.42	–	2.54	0.18	–	–	–	–
$\sigma_t^h(2W+2b2\tau)$	3.61	11.33	3.68	0.19	1.77	13.23	1.84	19.07
$\sigma_{2t}^A(2W+2b2\tau)$	0.08	–	4.74	6.43	–	–	–	–
$\sigma_t^A(2W+2b2\tau)$	0.11	0.29	6.88	6.72	0.99	0.30	13.35	0.97
$\sigma_h^h(W+4\tau)$	17.29	48.02	4.48	0.19	6.29	66.34	7.55	80.44
$\sigma_A^h(W+4\tau)$	0.54	1.25	8.36	6.72	3.51	1.48	54.84	4.07
$\sigma_A^A(W+4\tau)$	0.38	0.93	9.33	10.68	3.31	1.14	64.36	3.14
$\sigma_h^A(W+4\tau)$	12.12	35.62	5.00	0.29	5.94	50.98	8.86	62.04

- BPs satisfying both conditions $m_{H^\pm} < m_t$ and $m_{H^\pm} > m_t$ are chosen.
- We also take into account the mixing cases, e.g. $pp \to H^\pm h \to W^\pm A h$.

Results

The total production rates of $(2)W + 4b$, $(2)W + 2b2\tau$ and $W + 4\tau$ from different production channels of $H^{\pm}$ in Type-I and -X.

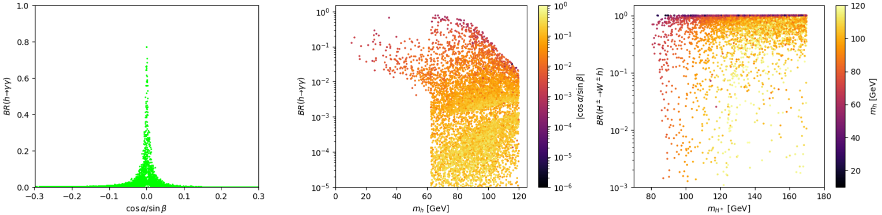


- ▷ Final states from di-Higgs processes are large compared to those from processes involving top (anti)quarks.
- ▷ Signatures from $pp \to H^{\pm}h/A$ are always dominant in both Type-I and -X scenarios.

Results

However, h can become fermiophobic,

- ▷ If $\cos\alpha$ vanishes, $h \to \gamma\gamma$ can be large, dominated by H^+ loop
- ▷ $h \to f\bar{f}/gg$ suppressed by $\cos\alpha$
- ▷ $h \to VV$ suppressed by $\sin(\beta-\alpha)$ and kinematics



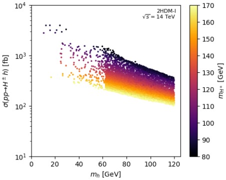
[A. Arhrib, R. Benbrik, R. Enberg *et al.*, 1706.01964]

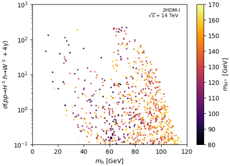
[Y. Wang, A. Arhrib, R. Benbrik, M. K. *et al.*, 2107.01451]

Results

Therefore, it would be promising to investigate $W^{\pm}+4\gamma$ final state via $H^{\pm}h$ production channel, i.e. $pp \to H^{\pm}h \to W^{\pm}hh \to W^{\pm}+4\gamma$.

	M_h	M_A	$M_{H^\pm}$	$\sin(\beta-\alpha)$	$\tan\beta$	m_{12}^2	$\sigma_{13}(W+4\gamma)$ (fb)	$\sigma_{14}(W+4\gamma)$ (fb)
BP1	25.57	72.39	111.08	−0.074	13.58	11.97	101.40	112.55
BP2	35.12	111.24	151.44	−0.076	13.32	16.66	167.75	186.20
BP3	45.34	162.07	128.00	−0.136	7.57	80.96	10.76	11.93
BP4	53.59	126.09	91.49	−0.127	8.00	51.16	27.05	29.88
BP5	63.13	85.59	104.99	−0.055	18.10	190.24	179.31	198.61
BP6	65.43	111.43	142.15	−0.087	11.52	325.36	174.49	194.30
BP7	67.82	79.83	114.09	−0.111	8.94	326.32	177.72	197.23
BP8	69.64	195.73	97.43	−0.111	8.86	357.10	196.04	217.18
BP9	73.18	108.69	97.34	−0.122	8.06	594.64	193.56	214.57
BP10	84.18	115.26	148.09	−0.067	14.82	473.88	61.92	68.98
BP11	68.96	200.84	155.40	−0.112	8.64	531.46	62.02	69.14
BP12	71.99	91.30	160.10	−0.104	9.74	472.22	58.99	65.80
BP13	74.08	102.49	163.95	−0.092	10.56	503.74	55.58	62.04
BP14	81.53	225.76	168.69	−0.101	9.75	501.29	51.85	57.91





- ▷ The irreducible SM $W^{\pm}+4\gamma$ background is less than 10^{-6} pb.
- ▷ In presence of background generated by both real and fake photons (from jets), the signal is essentially background free [arXiv:2107.01451].

Conclusions

- A charged Higgs boson is always predicted in the multi Higgs doublet model.
- When it is light, production channels like $pp \to H^\pm h/A$ and $pp \to H^\pm H^\mp$ followed by $H^\pm \to W^\pm h/A$ could well be the most promising discovery channels for $H^\pm$.
- We suggested the final states $2W + 4b$, $2W + 2b2\tau$, $W + 4b$, $W + 2b2\tau$ and $W^\pm + 4\tau$ as potential discovery channels.
- In the fermiophobic limit, $W + 4\gamma$ signature can give the best reach since it is essentially background free.
- Benchmark points are proposed, for both the 2HDM Type-I and -X, to motivate future searches for light charged Higgs boson.

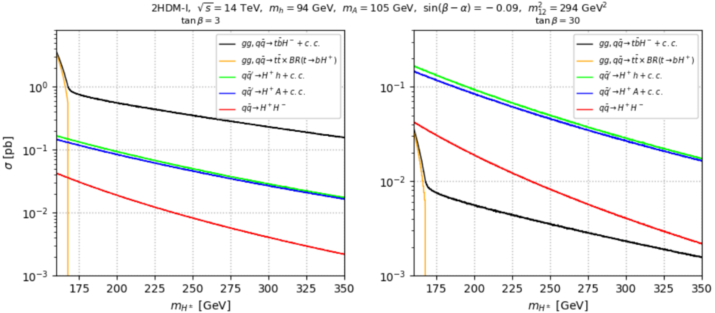
Thank you!

Conclusions

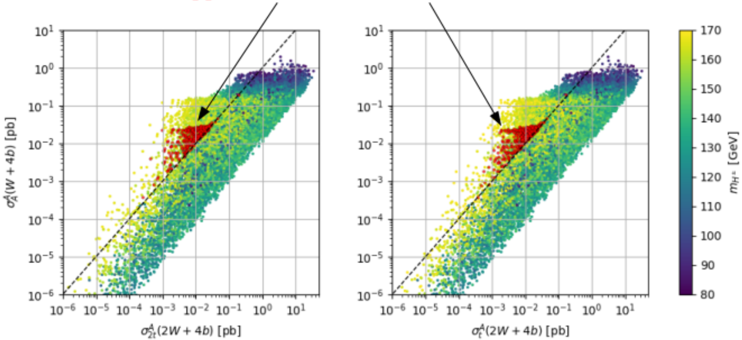
- A charged Higgs boson is always predicted in the multi Higgs doublet model.
- When it is light, production channels like $pp \to H^\pm h/A$ and $pp \to H^\pm H^\mp$ followed by $H^\pm \to W^\pm h/A$ could well be the most promising discovery channels for $H^\pm$.
- We suggested the final states $2W + 4b$, $2W + 2b2\tau$, $W + 4b$, $W + 2b2\tau$ and $W^\pm + 4\tau$ as potential discovery channels.
- In the fermiophobic limit, $W + 4\gamma$ signature can give the best reach since it is essentially background free.
- Benchmark points are proposed, for both the 2HDM Type-I and -X, to motivate future searches for light charged Higgs boson.

Thank you!

Charged Higgs production



$$pp \to H^{\pm}H^{\mp} \to W^{\pm}W^{\mp}AA$$



$pp \to H^{\pm}H^{\mp} \to W^{\pm}W^{\mp}AA$