New Discovery Modes for a Light Charged Higgs Boson at the LHC

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in collaboration with

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Charged Higgs Online workshop

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General 2-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 $\implies \lambda_6 = \lambda_7 = m_{12}^2 = 0$ (soft violation $\implies m_{12}^2$).
- 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) $\Longrightarrow$ 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

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

	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.

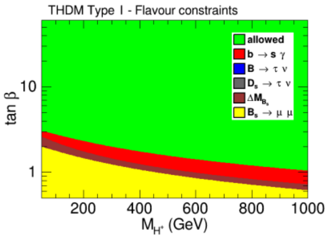
  (2HDMC) [D. Eriksson, J. Rathsman and O. Stal, 0902.0851]
- ▷ LEP, TeVatron and LHC results for
  - ◦ Additional Higgs bosons (HiggsBounds-5).

    [P. Bechtle *et al.*, 2006.06007]
  - ◦ Measured Higgs signal strengths (HiggsSignals-2).

    [P. Bechtle *et al.*, 2012.09197]
- ▷ Flavor 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



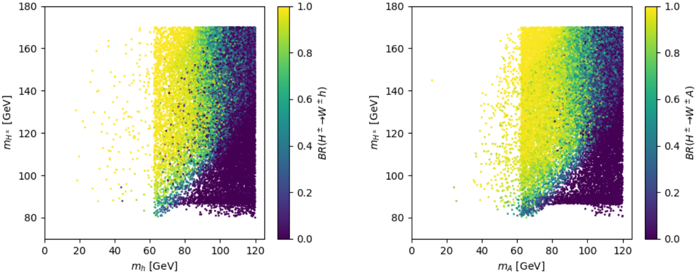
[A. Arbey, F. Mahmoudi, O. Stal and T. Stefaniak, 1706.07414]

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]

  [Y. Wang *et al.*, 2107.01451 (talk by Yan Wang)]



Charged Higgs Production

Production processes involving top (anti)quarks:

- Top pair production and decay chain (NWA):

$$\sigma^{\phi}_{2t}(2W+2b+2f) = 2\sigma_{t\bar{t}} \times \mathrm{BR}(t \to bH^{+}) \times \mathrm{BR}(\bar{t} \to \bar{b}W^{-}) \times \mathrm{BR}(H^{\pm} \to W^{\pm}\phi) \times \mathrm{BR}(\phi \to f\bar{f})$$

- Associated production with top plus bottom and decay chain ($m_{H^{\pm}} \sim m_t$):

$$\sigma^{\phi}_{t}(2W+2b+2f) = \sigma(pp \to t\bar{b}H^{-}) \times \mathrm{BR}(t \to bW^{+}) \times \mathrm{BR}(H^{\pm} \to W^{\pm}\phi) \times \mathrm{BR}(\phi \to f\bar{f})$$

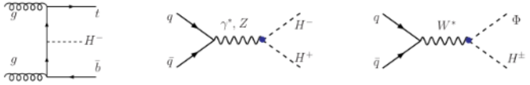
Di-Higgs processes:

- Pair production and decay chain:

$$\sigma^{\phi}_{\phi}(2W+2f+2f') = \sigma(H^{+}H^{-}) \times \mathrm{BR}(H^{\pm} \to W^{\pm}\phi)^{2} \times \mathrm{BR}(\phi \to f\bar{f}) \times \mathrm{BR}(\phi \to f'\bar{f}')$$

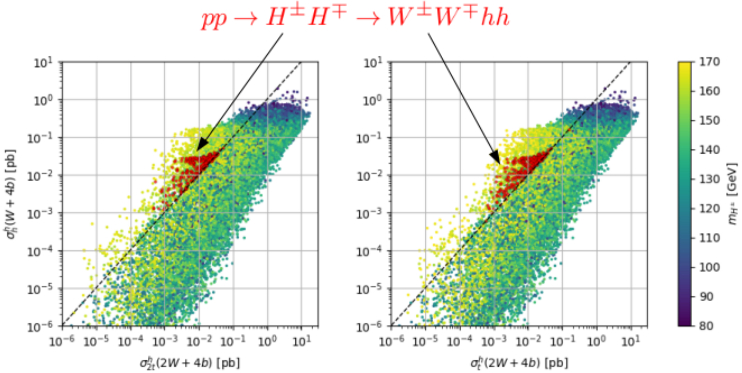
- Associated production with h/A and decay chain:

$$\sigma^{\phi}_{\phi}(W+2f+2f') = \sigma(H^{\pm}\phi) \times \mathrm{BR}(H^{\pm} \to W^{\pm}\phi) \times \mathrm{BR}(\phi \to f\bar{f}) \times \mathrm{BR}(\phi \to f'\bar{f}')$$



Results

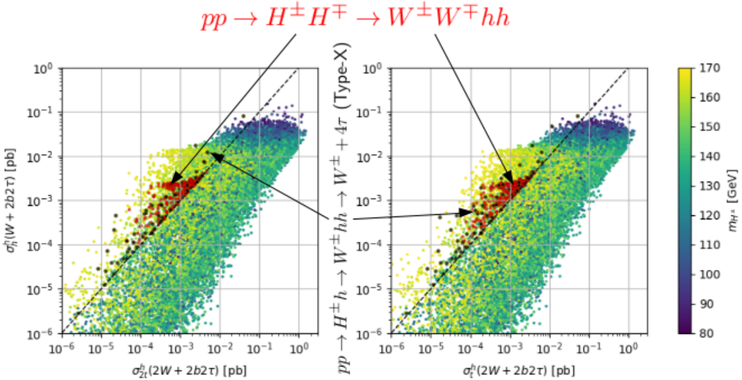
The relative magnitudes of the production and decay rates of $4b$ final states from $pp \to H^{\pm}h \to W^{\pm}hh$ and from the processes involving top (anti)quarks.



▷ $\mathrm{BR}(h \to b\bar{b})$ 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).

BPs for Type-I and -X

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

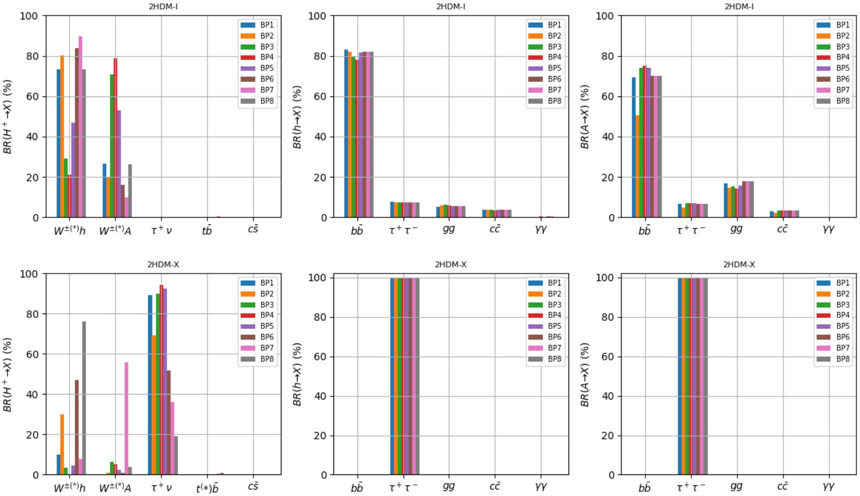
BPs for Type-X

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. $pp \to H^\pm h \to W^\pm A h$.

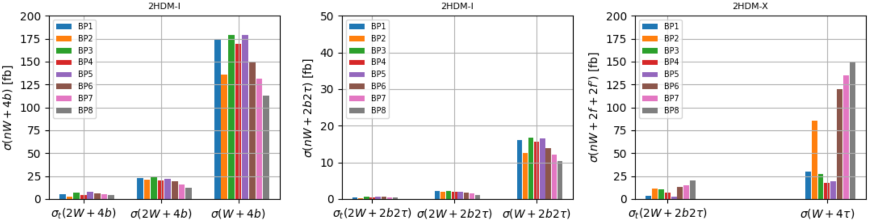
BPs for Type-I and -X

The branching ratios of $H^{\pm}$, h and A for the selected BPs.



BPs for Type-I and -X

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.

Conclusions

- Charged Higgs boson is predicted - in multi Higgs doublet model - to be lighter or heavier than m_t.
- 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 $H^{\pm}$ and even h/A.
- We have examined the final states $2W + 4b$, $2W + 2b2\tau$, $W + 4b$, $W + 2b2\tau$ and $W + 4\tau$ as potential discovery channels.
- We proposed eight BPs, for both the 2HDM Type-I and -X, to motivate future searches for light charged Higgs boson.
- In the 2HDM Type-I, the total production rates of $(2)W + 4b$, or even $(2)W + 2b2\tau$, from di-Higgs processes are quite interesting.
- The production and decay rate of $W + 4\tau$ final state is the one of interest and is more sizeable in the case of the 2HDM Type-X.

Thank you for your attention!

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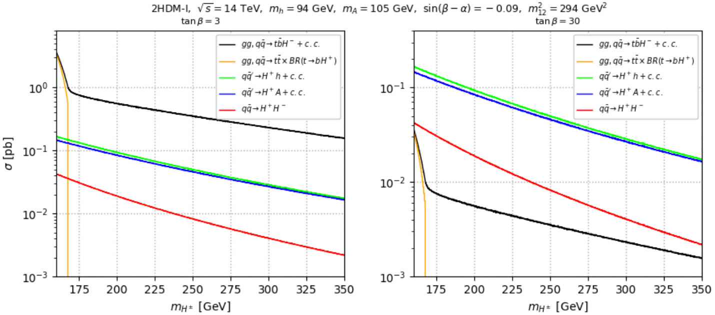
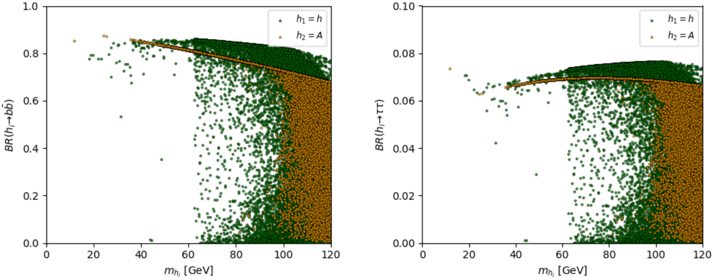
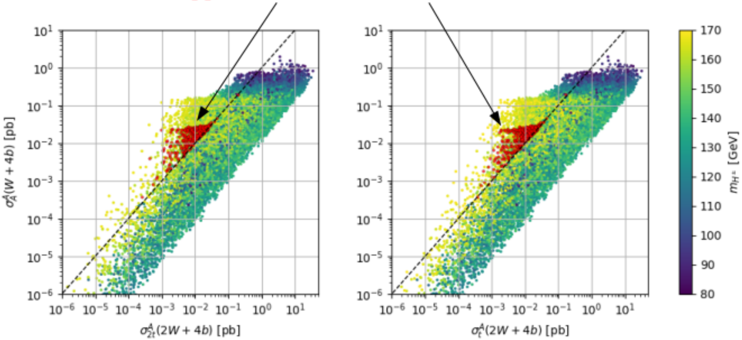
Charged Higgs production

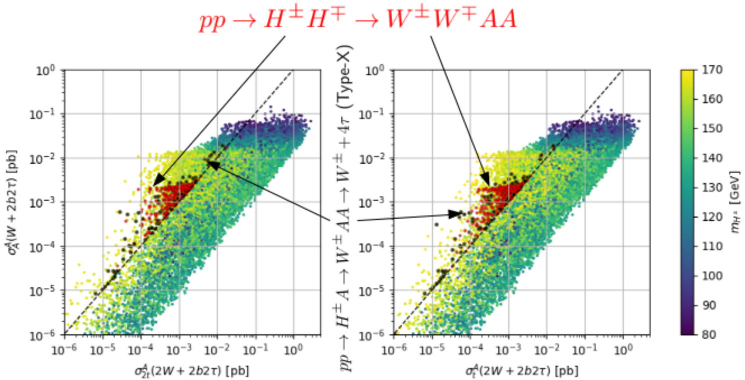


BRs of $h/A \to b\bar{b}$ and $h/A \to \tau^+\tau^-$



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





$pp \to H^\pm H^\mp \to W^\pm W^\mp AA$
$pp \to H^\pm A \to W^\pm AA \to W^\pm + 4\tau$ (Type-X)
$\sigma_A^A(W + 2b2\tau)$ [pb]
$\sigma_{2t}^A(2W + 2b2\tau)$ [pb]
$\sigma_t^A(2W + 2b2\tau)$ [pb]
$m_{H^\pm}$ [GeV]
170
160
150
140
130
120
110
100
90
80