Light charged Higgs boson in $H^{\pm}h$ associated production at the LHC

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in collaboration with

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Two-Higgs Doublet Model (2HDM)

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

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

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

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

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

- 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) $\Longrightarrow$ 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

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

	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	$-c_\beta/s_\beta$	$-c_\beta/s_\beta$

Parameter scans

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]

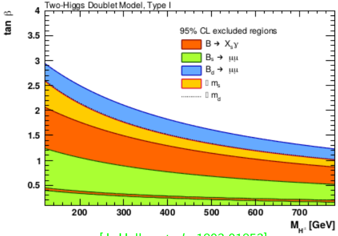
- ▷ LEP, TeVatron and LHC results for
  - ◦ Additional Higgs bosons (HiggsBounds-5).

    [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]

Parameter	Scanned range
m_h (GeV)	$(10, 120)$
m_H (GeV)	125.09
m_A (GeV)	$(10, 120)$
$m_{H^\pm}$ (GeV)	$(80, 170)$
$\sin(\beta - \alpha)$	$(-0.3, -0.05)$
$\tan\beta$	$(2, 60)$
m_{12}^2 (GeV^2)	$(0, m_H^2 \sin\beta\cos\beta)$



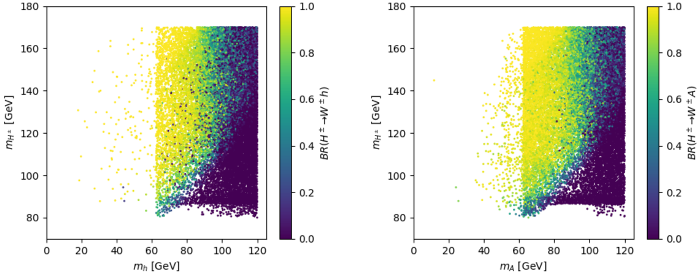
[J. Haller *et al.*, 1803.01853]

Bosonic Decays

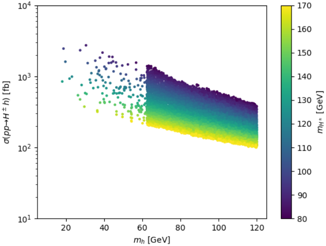
- ▷ Most existing experimental searches target the fermionic decay channels of charged Higgs bosons.
- ▷ The bosonic decays, $H^{\pm} \to W^{\pm}h/A$, have a naturally large branching ratio close to the alignment limit. [A. Arhrib, R. Benbrik and S. Moretti, 1607.02402]

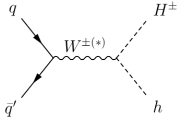
  [H. Bahl, T. Stefaniak and J. Wittbrodt, 2103.07484]

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

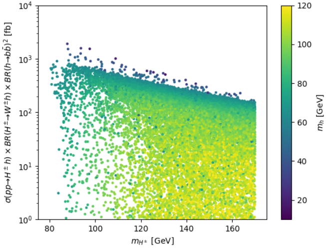


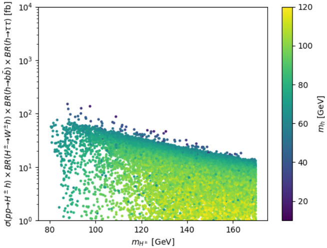
$pp \to H^{\pm}h$ and its $W^{\pm} + 4f$ final states





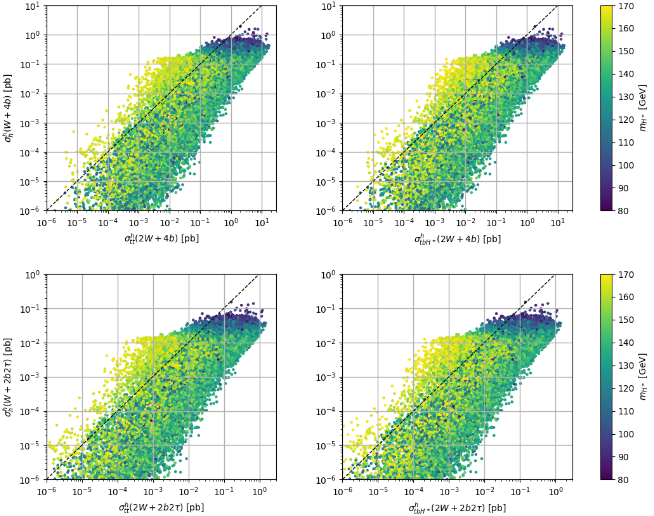
- $H^{\pm}W^{\mp}h \propto \cos(\beta - \alpha) \approx 1$
- $pp \to H^{\pm}h$ maximized, can exceed $tbH^{\pm}$ at large $\tan\beta$
- $W^{\pm} + 4b/2b2\tau$ signatures





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

$pp \to H^{\pm}h \to W^{\pm} + 4f$ & $pp \to tbH^{\pm} \to 2W^{\pm} + 4f$



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

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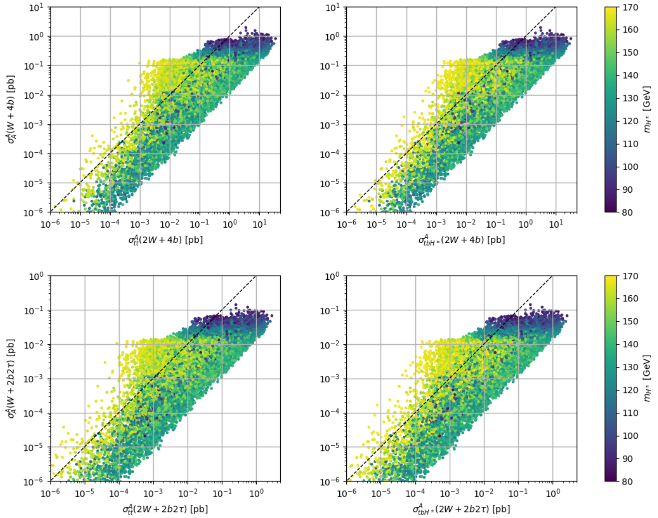


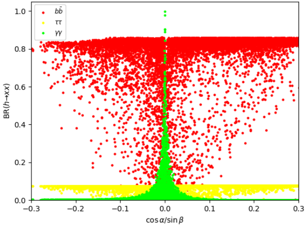
[A. Arhrib, R. Benbrik, M. K., B. Manaut *et al.*, 2106.13656]

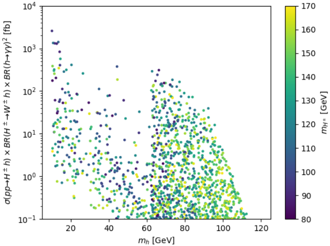
Benchmark Points

Parameters	BP1	BP2	BP3	BP4	BP5	BP6
m_h	64.39	65.20	68.65	106.15	117.58	117.76
m_H	125.00	125.00	125.00	125.00	125.00	125.00
m_A	107.74	104.30	114.53	63.11	64.49	63.86
$m_{H^\pm}$	107.61	106.02	115.66	103.66	109.35	116.65
$\sin(\beta-\alpha)$	-0.06	-0.06	-0.09	-0.10	-0.08	-0.07
$\tan\beta$	45.03	57.64	48.67	58.11	47.86	48.98
m_{12}^2	90.47	73.50	96.16	194.09	286.82	281.68
BR($H^\pm \to W^\pm h_i$) in %						
BR($H^\pm \to W^\pm h$)	99.86	99.89	99.91	–	–	–
BR($H^\pm \to W^\pm A$)	–	–	–	99.89	99.89	99.95
$\sigma \times$ BR in fb						
$\sigma_{tt}^h(2W+4b)$	250.27	158.55	172.07	–	–	–
$\sigma_{tt}^A(2W+4b)$	–	–	–	155.70	199.79	155.51
$\sigma_h^h(W+4b)$	521.93	525.88	397.13	–	–	–
$\sigma_A^A(W+4b)$	–	–	–	525.52	437.92	380.03
$\sigma_{tt}^h(2W+2b2\tau)$	21.50	13.65	14.94	–	–	–
$\sigma_{tt}^A(2W+2b2\tau)$	–	–	–	13.38	17.25	13.40
$\sigma_h^h(W+2b2\tau)$	44.83	45.27	34.49	–	–	–
$\sigma_A^A(W+2b2\tau)$	–	–	–	45.17	37.81	32.74

[A. Arhrib, R. Benbrik, M. K., B. Manaut *et al.*, 2204.xxxx]

$pp \to H^{\pm}h \to W^{\pm} + 4\gamma$





Light fermiophobic Higgs boson

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

Nearly background free

- $\sigma_{SM}(\ell^{\pm} + 4\gamma) < 10^{-6}$ pb for $P_T^{\ell,\gamma} > 10$ GeV
- A large significance is expected

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

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

Benchmark Points

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

$\rightarrow$ In presence of background generated by both real and fake photons (from jets), the signal is essentially background free.

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

Conclusions

- A charged Higgs boson is always predicted in the multi Higgs doublet model.
- When it is light, production channels $pp \to H^\pm h/A$ followed by $H^\pm \to W^\pm h/A$ could well be the most promising discovery channels for $H^\pm$.
- We have suggested the final states $W + 4b$ and $W + 2b2\tau$ 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 to motivate future searches for light charged Higgs bosons.

Thank you!

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Thank you!