The forgotten charged Higgs decay mode at the LHC

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Hierarchy / Naturalness Problem

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Introduction

Beyond the SM

- The improvement of the scalar boson mass and scalar boson coupling measurements.
- Find a clear hint of new physics beyond SM
- Accurate measurements of the scalar boson couplings to SM particles would help to determine if the Higgs-like particle is the SM Higgs or a Higgs that belongs to a higher representations:
  more doublets, doublet & triplets, doublet & singlets
- Most of the High representations predicts: singly and/or doubly charged Higgs

Extended Higgs sector: EWPT

Mass term:

$$\sum_i (D_\mu \Phi_i)^+ (D_\mu \Phi_i) \;\; , \;\; D_\mu = \partial_\mu + ig\vec{T}_a \vec{W}^a{}_\mu + ig' \frac{Y}{2} B_\mu$$

$$m_W^2 = \sum_i g^2 \frac{v_i^2}{2} (I_i(I_i+1) - \frac{Y_i^2}{4}) \;\; , \;\; m_Z^2 = \frac{g^2}{4c_W^2} \sum_i v_i^2 Y_i^2$$

$$\rho = \frac{m_W^2}{c_W^2 m_Z^2} = \frac{\sum_i v_i^2 (I_i(I_i+1) - \frac{Y_i^2}{4})}{\sum_i v_i^2 \frac{Y_i^2}{2}} \approx 1.00037 \pm 0.00023$$

1. Doublets (I_i=1/2, Y_i=$\pm$1): tree ok but "rad. corrections"
2. $4I_i(I_i+1) = 3Y_i^2$: $I = 3$ and $Y = 4$, rather complicated
3. Triplet representation: tune the triplet vev. In type-II see-saw: $v_\Delta < 5 - 8$ GeV

SM + 1 doublet

$$\Phi_1 = \begin{pmatrix} \varphi_1^+ \\ \frac{1}{\sqrt{2}}\left(v_1 + \varphi_1^0 + ia_1\right) \end{pmatrix} \; ; \quad \Phi_2 = \begin{pmatrix} \varphi_2^+ \\ \frac{1}{\sqrt{2}}\left(v_2 + \varphi_2^0 + ia_2\right) \end{pmatrix} .$$

The most general potential for 2HDM:

$$\begin{aligned} V(\Phi_1, \Phi_2) &= m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 + (m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c}) \\ &+ \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ &+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ &+ \frac{1}{2}[\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + (\lambda_6 \Phi_1^\dagger \Phi_1 + \lambda_7 \Phi_2^\dagger \Phi_2)\Phi_1^\dagger \Phi_2 + \mathrm{h.c.}], \end{aligned}$$

SM + 1 doublet

$$\Phi_1 = \begin{pmatrix} \varphi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \varphi_1^0 + ia_1) \end{pmatrix} ; \quad \Phi_2 = \begin{pmatrix} \varphi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \varphi_2^0 + ia_2) \end{pmatrix} .$$

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- $\mathbb{Z}_2$: $\Phi_i \to -\Phi_i \Leftrightarrow \lambda_{6,7} = 0$
- No explicit CP violation: $Im(m_{12}^2 \lambda_{5,6,7}) = 0$

2HDM: Haber's talk

$$\Phi_1 = \begin{pmatrix} \varphi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \varphi_1^0 + ia_1) \end{pmatrix} ; \quad \Phi_2 = \begin{pmatrix} \varphi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \varphi_2^0 + ia_2) \end{pmatrix} .$$

$$-\mathcal{L}_Y = \sum_{a=1,2} \left[\bar{Q}_L \, Y_d^a \, \Phi_a d_R + \bar{Q}_L \, Y_u^a \, \tilde{\Phi}_a u_R + \bar{L}_L \, Y_\ell^a \, \Phi_a \ell_R + \text{h.c.} \right] ,$$

• Classification of 2HDMs satisfying the Glashow-Weinberg condition which guarantees the absence of tree-level FCNC.

Type-I	$Y_{u,d}^1 = 0, \, Y_\ell^1 = 0$
Type-II	$Y_u^1 = Y_{d,\ell}^2 = 0$
Type-III (X)	$Y_{u,d}^1 = Y_\ell^2 = 0$
Type-IV (Y)	$Y_{u,\ell}^1 = Y_d^2 = 0$

$$\mathcal{L}_{H_i\bar{f}f} = -\frac{gm_f}{2m_W}\,\bar{f}\left(Y^S_{i,f} + i\,Y^P_{i,f}\gamma_5\right) f\,H_i\,,$$

$$\mathcal{L}_{H^\pm tb} = +\frac{gm_b}{\sqrt{2}m_W}\,\bar{b}\,(c_L\,P_L + c_R\,P_R)\,t\,H^- \;+\; \mathrm{h.c.}\,,$$

$$\mathcal{L}_{H_iVV} = -\frac{gm_V}{2c_W}\,\underbrace{(\cos\beta O_{\varphi_2 i} + \sin\beta O_{\varphi_1 i})}_{H_iVV}\,g_{\mu\nu}\,V^\mu V^\nu$$

$$\mathcal{L}_{H_iH^\pm W^\pm} = -\frac{g}{2}\,(S_i + iP_i)\left[H^-\left(i\,\overset{\leftrightarrow}{\partial}_\mu\right)H_i\right]\,W^{+\mu} \;+\; \mathrm{h.c.}\,,$$

$$S_i = c_\beta O_{\varphi_2 i} - s_\beta O_{\varphi_1 i}\,,\quad P_i = O_{ai}$$

Sum rules:

- $\Sigma_i(H_iVV)^2 = 1$
- $(H_iVV)^2 + |H^\pm W^\mp H_i|^2 = 1$ for $i = 1,2,3$
- $\sin^2\beta[(Y^S_{i,t})^2 + (Y^P_{i,t})^2] + \cos^2\beta[(Y^S_{i,b})^2 + (Y^P_{i,b})^2] = 1$

CP conserving 2HDM: CP-even h,H, CP-odd A and $H^{\pm}$

The Yukawa Lagrangian:

$$-\mathcal{L}_{Yuk} = \sum_{\psi=u,d,l} \left(\frac{m_\psi}{v} \kappa_\psi^h \bar{\psi}\psi h^0 + \frac{m_\psi}{v} \kappa_\psi^H \bar{\psi}\psi H^0 - i \frac{m_\psi}{v} \kappa_\psi^A \bar{\psi}\gamma_5 \psi A^0 \right) +$$

$$\left(\frac{V_{ud}}{\sqrt{2}v} \bar{u}(m_u \kappa_u^A P_L + m_d \kappa_d^A P_R) d H^+ + \frac{m_l \kappa_l^A}{\sqrt{2}v} \bar{\nu}_L l_R H^+ + H.c. \right)$$

	κ_u^h	κ_d^h	κ_l^h	κ_u^A	κ_d^A	κ_l^A
Type-I	c_α/s_β	c_α/s_β	c_α/s_β	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-III	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-IV	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β	$\cot\beta$	$\tan\beta$	$-\cot\beta$

CP conserving 2HDM: CP-even: CP-odd A and $H^\pm$

- Couplings:

$$hVV \propto \sin_{\beta-\alpha} \ , \ \ HVV \propto \cos_{\beta-\alpha} \ , \ \ AVV = 0$$
$$hH^\pm W^\mp \propto \cos_{\beta-\alpha} \ , \ \ HH^\pm W^\mp \propto \sin_{\beta-\alpha} \ , \ \ AH^\pm W^\mp \propto \frac{g}{2}$$
$$H^\pm W^\mp \gamma = 0 \ (e.m\ inv) \ , \ \ H^\pm W^\mp Z = 0 \ \ but \ \ loop\ mediated$$

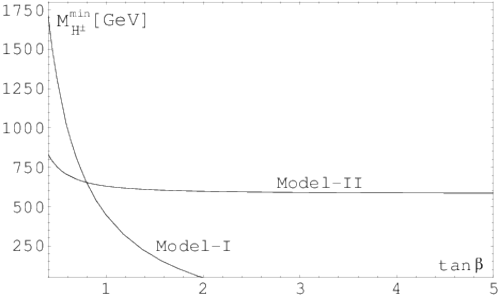
- 2 alignment limits:
  - h=125 GeV SM-like: $\sin_{\beta-\alpha} = 1$ (NH)
  - $h < H$=125 GeV SM-like: $\cos_{\beta-\alpha} = 1$: (IH)
    non-detected decays: $Br(H \to h^0 h^0, A^0 A^0) < (10 - 15)\%$

$b \to s\gamma$ constraints

- In 2HDM-II and IV: $m_{H\pm} > 600$ GeV for any $\tan\beta > 1$

  [Misiak arXiv:1702.04571 EPJC'2017]

- in 2HDM-I there is no limit on $H^{\pm}$ for $\tan\beta \geq 2$



- in 2HDM-III, light charged Higgs $\leq$ 200 GeV with large $\tan\beta > 30$ is excluded from $\tau \to \mu\nu\nu$

[T. Enomoto and R. Watanabe JHEP'2016]

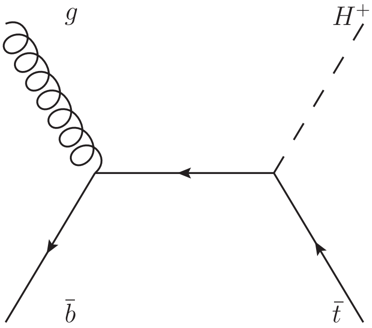
Charged Higgs production

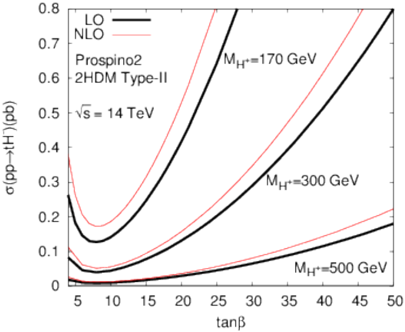
(See "Prospects for charged Higgs searches at the LHC," arXiv:1607.01320: A. Akeroyd et al)

- Light charged Higgs, i.e, with $m_{H^\pm} \leq m_t - m_b$: are copiously produced from $t\bar{t}$ production $pp \to t\bar{t} \to t\bar{b}H^-$ + c.c.
- various direct production modes:
  QCD: $gb \to tH^-$ and $gg \to t\bar{b}H^-$,
  $gg \to W^\pm H^\mp$ (loop),
  $b\bar{b} \to W^\pm H^\mp$
  $q\bar{q} \to \gamma, Z \to H^+H^-$,
  $gg \to H^+H^-$(loop)
  $q\bar{q}' \to W^* \to \varphi H^\pm$ where $\varphi = h^0, H^0, A^0$,
- Resonant production: $c\bar{s}, c\bar{b} \to H^+$
- $W - Higgs$ fusion : $qb \to q'H^+b$

A.A, K.M. Cheung, J.S.Lee and C. T. Lu'JHEP'2016

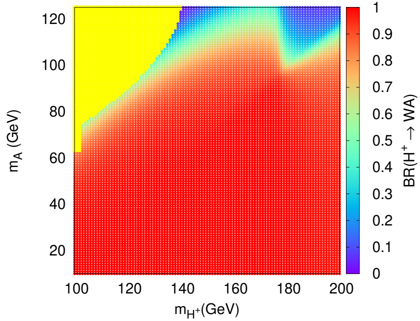
$bg \to tH^+$

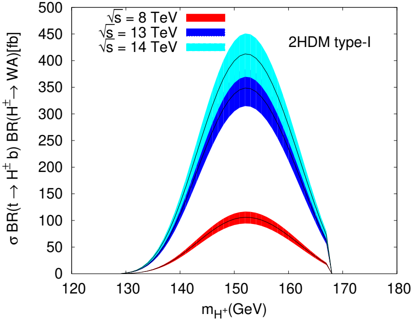

g
H+
b̄
t̄


LO
NLO
Prospino2
2HDM Type-II
√s = 14 TeV
MH+=170 GeV
MH+=300 GeV
MH+=500 GeV
σ(pp→tH⁻)(pb)
tanβ
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5
10
15
20
25
30
35
40
45
50

Bosonic decay: 2HDM-I:

Arhrib, Benbrik, Stefano, Eur.Phys.J.C 77 (2017) 9, 621

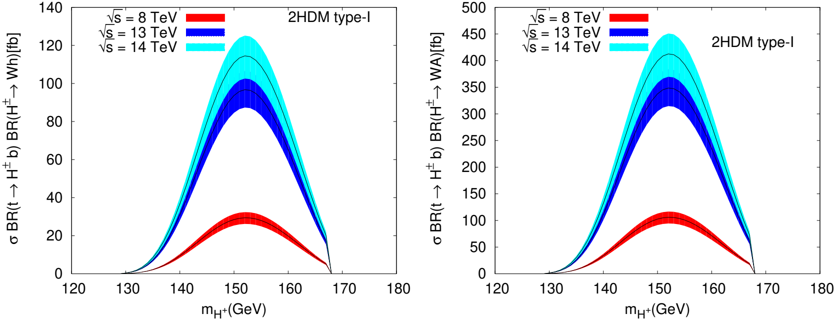




- $m_h = 125$ GeV, $\sin(\beta-\alpha) = 1.$, $\tan\beta = 5$, $m_H = 300$ GeV, $m_1^2 2 = 16 \times 10^3$ GeV^2

Bosonic decay: 2HDM-I:

Arhrib, Benbrik, Stefano, Eur.Phys.J.C 77 (2017) 9, 621



- $m_h = 125$ GeV, Alignment limit, $\tan\beta = 5$, $m_H = 300$ GeV, $m_1^2 2 = 16 \times 10^3$ GeV^2.
- $\sin(\beta - \alpha) = 0.95$ (left panel) ($H^\pm \to W^\pm h$ is open)
- $W^\pm H^\mp A \propto \frac{g}{2}$, $W^\pm H^\mp h \propto \frac{g}{2} \cos(\beta - \alpha)$, $W^\pm H^\mp H \propto \frac{g}{2} \sin(\beta - \alpha)$

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

Wang, Arhrib, Benbrik, Krab, Manaut, Stefano, Qi-Shu

- Yan Wang's Talk arxiv :2107.01451
- Krab's Talk arxiv : 2106.13656

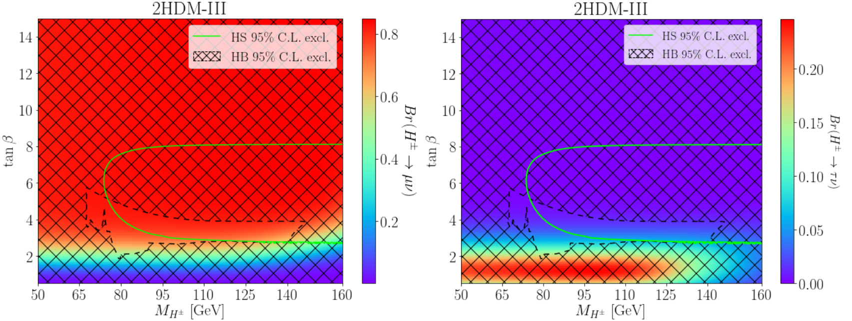
2HDM type III with FCNC at the tree-level

$$
\begin{aligned}
-\mathcal{L}_Y^{III} &= \sum_{f=u,d,\ell} \frac{m_j^f}{v}\left[(\xi_h^f)_{ij}\bar{f}_{Li}f_{Rj}h + (\xi_H^f)_{ij}\bar{f}_{Li}f_{Rj}H - i(\xi_A^f)_{ij}\bar{f}_{Li}f_{Rj}A\right] \\
&+ \frac{\sqrt{2}}{v}\sum_{k=1}^{3}\bar{u}_i\left[\left(m_i^u(\xi_A^{u*})_{ki}V_{kj}P_L + V_{ik}(\xi_A^d)_{kj}m_j^d P_R\right)\right]d_j H^+ \\
&+ \frac{\sqrt{2}}{v}\bar{\nu}_i(\xi_A^\ell)_{ij}m_j^\ell P_R \ell_j H^+ + H.c.,
\end{aligned}
$$

φ	$(\xi_\varphi^u)_{ij}$	$(\xi_\varphi^d)_{ij}$	$(\xi_\varphi^\ell)_{ij}$
h	$\frac{c_\alpha}{s_\beta}\delta_{ij} - \frac{c_{\beta-\alpha}}{\sqrt{2}s_\beta}\sqrt{\frac{m_i^u}{m_j^u}}\chi_{ij}^u$	$-\frac{s_\alpha}{c_\beta}\delta_{ij} + \frac{c_{\beta-\alpha}}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^d}{m_j^d}}\chi_{ij}^d$	$-\frac{s_\alpha}{c_\beta}\delta_{ij} + \frac{c_{\beta-\alpha}}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^\ell}{m_j^\ell}}\chi_{ij}^\ell$
H	$\frac{s_\alpha}{s_\beta}\delta_{ij} + \frac{s_{\beta-\alpha}}{\sqrt{2}s_\beta}\sqrt{\frac{m_i^u}{m_j^u}}\chi_{ij}^u$	$\frac{c_\alpha}{c_\beta}\delta_{ij} - \frac{s_{\beta-\alpha}}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^d}{m_j^d}}\chi_{ij}^d$	$\frac{c_\alpha}{c_\beta}\delta_{ij} - \frac{s_{\beta-\alpha}}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^\ell}{m_j^\ell}}\chi_{ij}^\ell$
A	$\frac{1}{t_\beta}\delta_{ij} - \frac{1}{\sqrt{2}s_\beta}\sqrt{\frac{m_i^u}{m_j^u}}\chi_{ij}^u$	$t_\beta\delta_{ij} - \frac{1}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^d}{m_j^d}}\chi_{ij}^d$	$t_\beta\delta_{ij} - \frac{1}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^\ell}{m_j^\ell}}\chi_{ij}^\ell$

2HDM-III:

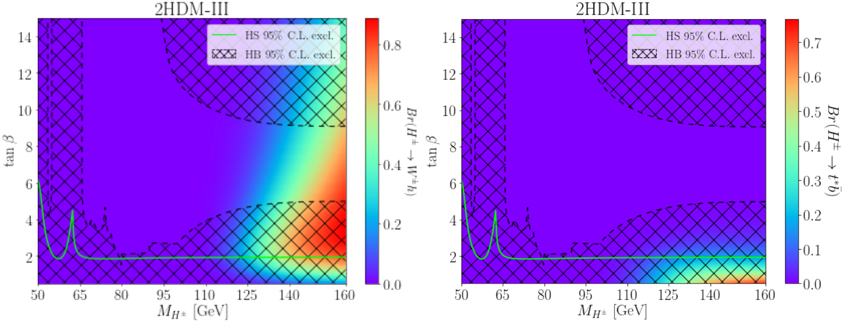
Arhrib, Benbrik, Boukidi, Rouchad, Semlali in progress



- $m_h = 125$ GeV, Alignment limit

2HDM-III:

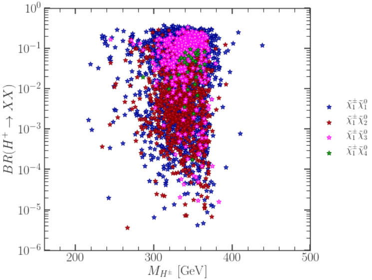
Arhrib, Benbrik, Boukidi, Semlali ....in progress

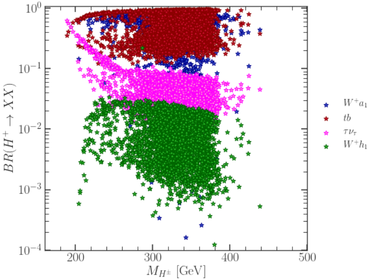


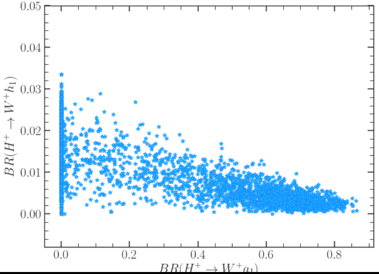
- $m_H = 125$ GeV.

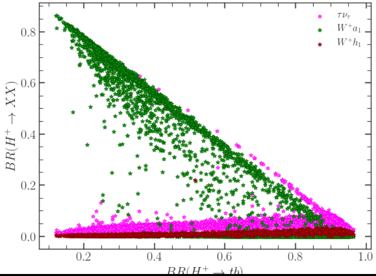
NMSSM :

Arhrib, Benbrik, Boukidi, ...in progress









Conclusions

- In 2HDM-I there is regions of the parameter space compliant with theoretical and experimental constraints yielding substantial BRs for $H^\pm \to W^{\pm *}h/W^{\pm *}A$ in which the $m_{H^\pm} < m_t - m_b$, wherein $W^{\pm *} \to l\nu$ ($l = e, \mu$).
- $\sigma(pp \to t\bar{t} \to tbH^+ \to tbWA^0)$ could be sizeable
- light $H^\pm$ in the 80–160 GeV mass range, still being consistent with all LHC, LEP Tevatron and B-physics data.
- In 2HDM-III, with $m_h < m_H = 125$ GeV, EWPT imply that $H^\pm$ is rather light and decay to $\mu^+\nu$ and in the same time $h^0 \to \mu^+\mu$ could be large.
- In the NMSSM, $H^\pm \to W^{\pm *}h/W^{\pm *}A$ as well.

- **Rachid BENBRIK**
- **The forgotten charged Higgs decay mode at the LHC**