Search for light Charged Higgs at the LHC

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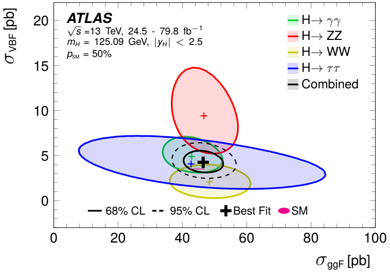
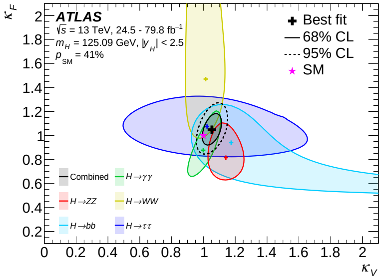
Outlines

- Introduction
- Two Higgs doublet model (2HDM)
- Charged Higgs production at the LHC and decays
- Bosonic decays of charged Higgs: $H^\pm \to W^\pm A^0/W^\pm h^0$
- $W4\gamma$, $W4b$, $W2b2\tau$ signatures for a light $H^\pm$ at the LHC.
- CP violation in charged Higgs production and decays.
- Conclusions

Introduction:





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After the Higgs-like discovery at $7 \oplus 8 \oplus 13$ TeV LHC, the mission of the LHC run at 13.6 TeV is:

- The improvement of the Higgs-like mass and Higgs-like coupling measurements.
- Find a clear hint of new physics beyond SM

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After the Higgs-like discovery at $7 \oplus 8 \oplus 13$ TeV LHC, the mission of the LHC run at 13.6 TeV is:

- The improvement of the Higgs-like mass and Higgs-like coupling measurements.
- Find a clear hint of new physics beyond SM
- Accurate measurements of the Higgs-like 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 terms:

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

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

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$$\delta\rho = \frac{\Sigma_{WW}(0)}{m_W^2} - \frac{\Sigma_{ZZ}(0)}{m_Z^2} \approx \frac{3 G_F m_t^2}{8\pi^2\sqrt{2}} + \ldots$$

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1. Doublets (I_i=1/2, Y_i=±1): it works at tree level;
   but "radiative corrections can modify "

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2. choose : $I = 3$ and $Y = 4$ such that $4I_i(I_i+1) = 3Y_i^2$, but it is rather complicated

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3. Triplet representation: like in type-II seesaw model (one-doublet and one-triplet)

$$m_W^2 = \frac{g^2}{4}(v_d^2 + 2v_t^2) \ , \ m_Z^2 = \frac{g^2}{4\cos_W^2}(v_d^2 + 4v_t^2) \ , \ \rho = \frac{v_d^2 + 2v_t^2}{v_d^2 + 4v_t^2} \neq 1$$

tune the triplet vev. In type-II see-saw: $v_t < 5 - 8$ GeV

$$\Phi_1 = \left(\begin{array}{c} \phi_1^+ \\ \frac{1}{\sqrt{2}}\left(v_1 + \phi_1^0 + i a_1\right) \end{array} \right) ; \quad \Phi_2 = \left(\begin{array}{c} \phi_2^+ \\ \frac{1}{\sqrt{2}}\left(v_2 + \phi_2^0 + i a_2\right) \end{array} \right) .$$

The most general potential for 2HDM:

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

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}\left(v_1 + \phi_1^0 + i a_1\right) \end{pmatrix} ; \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}\left(v_2 + \phi_2^0 + i a_2\right) \end{pmatrix} .$$

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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: G. Branco et al Phys rep'2012

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \phi_1^0 + ia_1) \end{pmatrix} ; \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \phi_2^0 + ia_2) \end{pmatrix} .$$

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

leads to FCNCs at tree level.

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

Type-I	$Y^1_{u,d} = 0,\ Y^1_\ell = 0$
Type-II	$Y^1_u = Y^2_{d,\ell} = 0$
Type-III (X)	$Y^1_{u,d} = Y^2_\ell = 0$
Type-IV (Y)	$Y^1_{u,\ell} = Y^2_d = 0$

2HDM:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}\left(v_1 + \phi_1^0 + ia_1\right) \end{pmatrix} \; ; \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}\left(v_2 + \phi_2^0 + ia_2\right) \end{pmatrix} .$$

- first rotate a_i and ϕ_i^+ in order to obtain the goldstones $G^0, G^\pm$
- CP-odd $A^0 = -s_\beta a_1 + c_\beta a_2$ and a pair of $H^\pm = -s_\beta \phi_1^\pm + c_\beta \phi_2^\pm$.

2HDM:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \phi_1^0 + ia_1) \end{pmatrix} ; \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \phi_2^0 + ia_2) \end{pmatrix} .$$

• first rotate a_i and ϕ_i^+ in order to obtain the goldstones $G^0, G^\pm$
• CP-odd $A^0 = -s_\beta a_1 + c_\beta a_2$ and a pair of $H^\pm = -s_\beta \phi_1^\pm + c_\beta \phi_2^\pm$.
• In the general case with CP violation, the neutral mass matrix $\mathcal{M}_0^2$ is diagonalized by an orthogonal 3×3 matrix O:

$$(\phi_1^0, \phi_2^0, a)_\alpha^T = O_{\alpha i}(H_1, H_2, H_3)_i^T$$

such that $O^T \mathcal{M}_0^2 O = \mathrm{diag}(M_{H_1}^2, M_{H_2}^2, M_{H_3}^2)$ with $M_{H_1} \leq M_{H_2} \leq M_{H_3}$.

$$
\begin{aligned}
\mathcal{L}_{H_i \bar{f} f} &= -\frac{g m_f}{2 m_W} \, \bar{f} \left(Y^S_{i,f} + i \, Y^P_{i,f} \, \gamma_5 \right) f \, H_i \,, \\
\mathcal{L}_{H^\pm t b} &= + \frac{g m_b}{\sqrt{2} m_W} \, \bar{b} \, (c_L \, P_L + c_R \, P_R) \, t \, H^- \; + \; \text{h.c.} \,, \\
\mathcal{L}_{H_i V V} &= -\frac{g m_V}{2 c_W} \underbrace{(\cos \beta \, O_{\phi_2 i} + \sin \beta \, O_{\phi_1 i})}_{H_i V V} g_{\mu\nu} V^\mu V^\nu \\
\mathcal{L}_{H_i H^\pm W^\pm} &= -\frac{g}{2} \, (S_i + i P_i) \left[H^- \left(i \overleftrightarrow{\partial}_\mu \right) H_i \right] \, W^{+\mu} \; + \; \text{h.c.} \,, \\
S_i &= c_\beta O_{\phi_2 i} - s_\beta O_{\phi_1 i} \,, \quad P_i = O_{ai}
\end{aligned}
$$

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

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

$$\mathcal{L}_{H_iVV} = -\frac{gm_V}{2c_W}\,\underbrace{(\cos\beta\,O_{\phi_2 i} + \sin\beta\,O_{\phi_1 i})}_{H_iVV}\,g_{\mu\nu}V^\mu V^\nu$$

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

$$S_i = c_\beta\,O_{\phi_2 i} - s_\beta\,O_{\phi_1 i}\,,\quad P_i = O_{ai}$$

Sum rules:

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

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: $h < H$, CP-odd A and $H^{\pm}$

- Couplings:

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

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

- Stability of the 2HDM potential requires that it should be bounded from below, i.e. that there is no direction in field space along which the potential becomes negatif.

Deshpande and E. Ma, PRD18'1978

$$\lambda_1 > 0 \quad , \quad \lambda_2 > 0$$
$$\lambda_3 > -\sqrt{\lambda_1 \lambda_2}$$
$$\lambda_3 + min(0, \lambda_4 - \mid \lambda_5 \mid) > -\sqrt{\lambda_1 \lambda_2}$$

- The vacuum of the model is global one if and only if: $m_{12}^2(m_{11}^2 - k^2 m_{22}^2)(\tan\beta - k) > 0 \qquad ; \quad k = \sqrt[4]{\frac{\lambda_1}{\lambda_2}}$

A. Barroso et al JHEP**06** (2013)

- Perturbative unitarity: $V_L^+ V_L^- \to V_L^+ V_L^-$, $h_i \; h_j \to h_i \; h_j$ ...

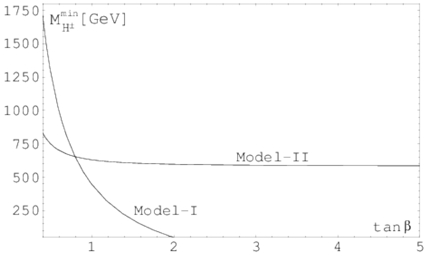
$$
\begin{aligned}
a_{\pm} &= \frac{1}{16\pi}\left\{\frac{3}{2}(\lambda_1+\lambda_2)\pm\sqrt{\frac{9}{4}(\lambda_1-\lambda_2)^2+(2\lambda_3+\lambda_4)^2}\right\},\\
b_{\pm} &= \frac{1}{16\pi}\left\{\frac{1}{2}(\lambda_1+\lambda_2)\pm\sqrt{\frac{1}{4}(\lambda_1-\lambda_2)^2+\lambda_4^2}\right\},\\
c_{\pm} &= d_{\pm}=\frac{1}{16\pi}\left\{\frac{1}{2}(\lambda_1+\lambda_2)\pm\sqrt{\frac{1}{4}(\lambda_1-\lambda_2)^2+\lambda_5^2}\right\},\\
e_1 &= \frac{1}{16\pi}\left(\lambda_3+2\lambda_4-3\lambda_5\right),\ ,\ e_2=\frac{1}{16\pi}\left(\lambda_3-\lambda_5\right),\\
f_+ &= \frac{1}{16\pi}\left(\lambda_3+2\lambda_4+3\lambda_5\right),\ ,\ f_-=\frac{1}{16\pi}\left(\lambda_3+\lambda_5\right),\\
f_1 &= f_2=\frac{1}{16\pi}\left(\lambda_3+\lambda_4\right).
\end{aligned}
$$

$b \to s\gamma$ constraints

- In 2HDM-II and IV: $m_{H\pm} > 800$ GeV for any $\tan\beta > 1$

  [Misiak et al EPJC'2017, JHEP'20]

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



- in 2HDM-III, light charged Higgs ≤ 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 $pp \to t\bar{t}^* \to t\bar{b}H^- + \text{c.c.}$

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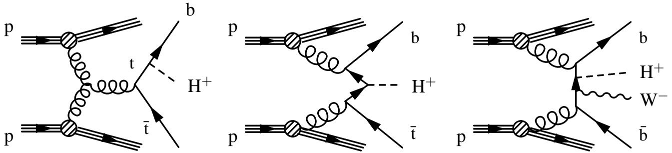
- various direct production modes:
  QCD: $gb \to tH^-$ and $gg \to t\bar{b}H^-$,



- $gg \to W^{\pm}H^{\mp}$ (loop) , $b\bar{b} \to h^*, H^*, A^* \to W^{\pm}H^{\mp}$
  $q\bar{q} \to \gamma^*, Z^* \to H^+H^-$, $gg \to H^+H^-$(loop)
  $q\bar{q}' \to W^* \to \phi H^{\pm}$ where $\phi = h, H, A$,

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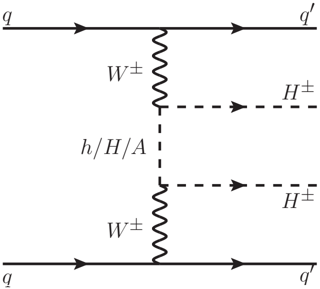
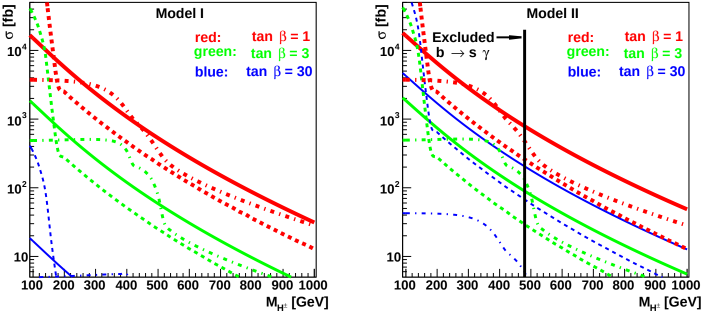
  $q\bar{q}' \to W^* \to \phi H^\pm$ where $\phi = h, H, A$,
- Resonant production: $c\bar{s}, c\bar{b} \to H^+$
- W-Z , W-γ fusion:
  $q\bar{q} \to W^\pm Z \to jjH^\pm$ or $W^\pm \gamma \to jjH^\pm$
  (loop mediated in 2HDM)
- W-Z fusion: possible with triplet representation

$$pp \to j_F j_F W^{\pm *} W^{\pm *} \to H^\pm H^\pm j_F j_F$$



$$\propto \frac{m_H^2 - m_A^2}{(t - m_H^2)(t - m_A^2)}$$

Cross sections pp $\to H^{\pm} X$

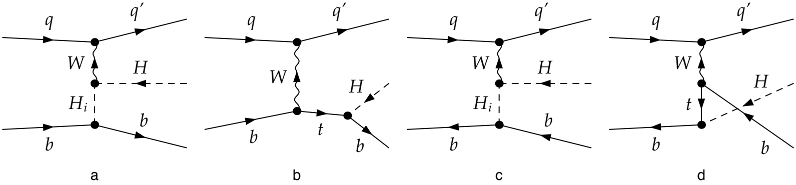


- "fermionic": $g\bar{b} \to H^+\bar{t}$, (solid), $gg \to H^+ b\bar{t}$, (dotted),
- "bosonic": $gg \to H_j \to H^+ W^-$, (dash-dotted).

W-Higgs fusion

- W-Higgs fusion : $qb \to q' H^+ b$

A.A, K.M. Cheung, J.S.Lee and C. T. Lu' JHEP'2016 (2HDM) , Moretti, Odagiri PRD'1997 (MSSM)



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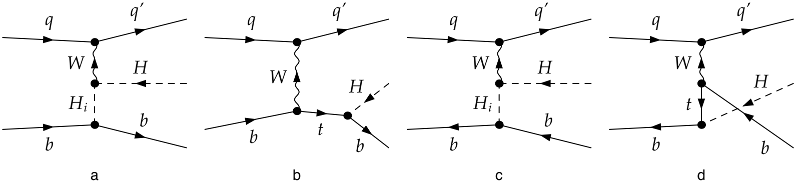


Taking the type II model as an example, we find

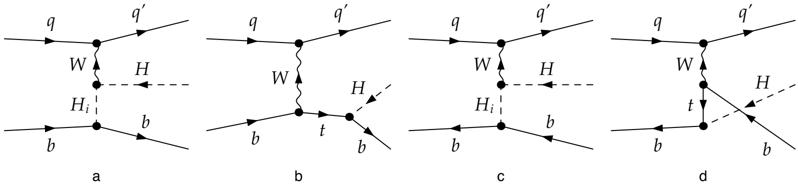
$$\sigma(W^+ b \to H^+ b)\big|_{t\ \mathrm{only}} \propto 4\tan^2\beta\,,$$

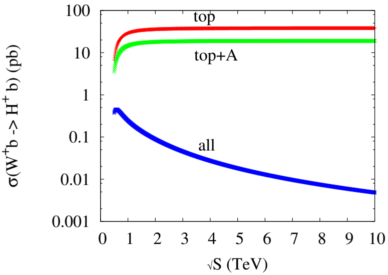
$$\sigma(t + H\ \mathrm{only}) = \sigma(t + A\ \mathrm{only}) \propto 2\tan^2\beta\,,$$

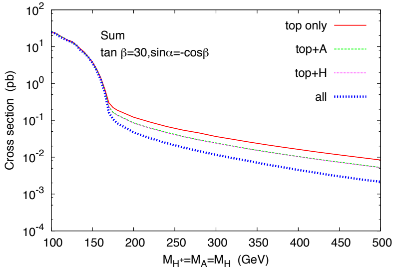
$$\sigma(W^+ b \to H^+ b)\big|_{t+H+A} \propto \mathcal{O}\left(\frac{m_t^2}{s} + \frac{M_{H_i}^2}{t}\right)$$

$pp \to jH^+ b$ at LHC 14 TeV

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







$H^{\pm}$ at linear collider: Battaglia: hep-ex/1102.1892

- $e^+e^- \to \gamma^*, Z^* \to H^+H^-$ S. Komamiya, PRD'38 (1988)
  LO: cross section is a function of $m_{H^{\pm}}$ only.
  NLO: is model dependent w/o SUSY :

  A.A, G. Moultaka NPB'98, Guasch, Hollik and Kraft NPB'01

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- $e^+e^- \to \gamma^*, Z^* \to \nu\tau^+H^-$
- $e^+e^- \to \gamma^*, Z^* \to t\bar{b}H^-$

  Gutierrez-Rodriguez and Sampayo, hep-ph/1999, Kanemura, Moretti and Odagiri JHEP 02 (2001)

$H^{\pm}$ at linear collider

- $e^+e^- \to W^{\pm}H^{\mp}$ (loops mediated: triangles and boxes)

  A.A , W. Hollik and G. Moultaka NPB 581 (2000), S. Kanemura EPJC 17 (2000)

- $e^+e^- \to Z^* \to W^{\pm}H^{\mp}$ (models with Higgs triplet)
- $e^+e^- \to \gamma^*, Z^* \to ZW^+H^-$, SW^+H^- , $S = h, H, A$

Charged Higgs decays

Fermionic decays

- $H^\pm \to \tau\nu$, cs , cb
- $H^\pm \to tb$

ATLAS report 3σ excess around $m_{H^\pm} = 130$ GeV: $H^+ \to cb$ [ATLAS-CONF-2021-037]

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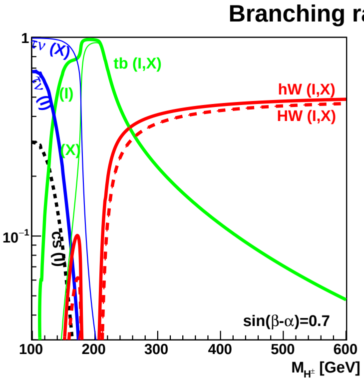
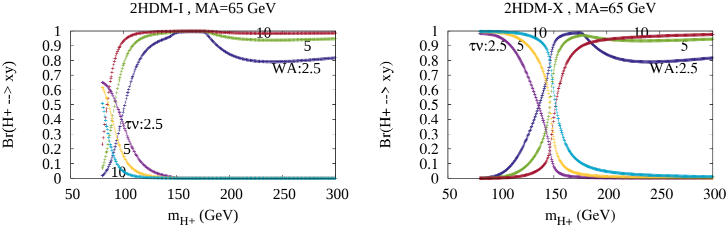
Bosonic decays

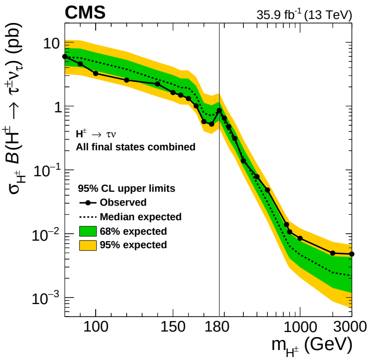
- $H^{\pm} \to W^{\pm}\phi^{0}$, $\phi^{0} = h^{0}, A^{0}, H^{0}$
- $H^{\pm} \to W^{\pm}\gamma, W^{\pm}Z$: small because loop mediated

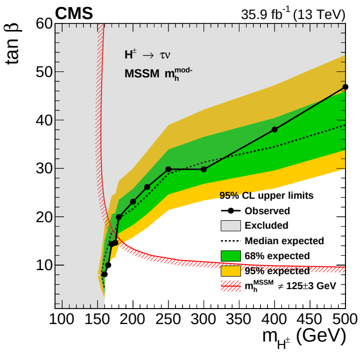
  A.A, R. Benbrik, and TC.Yuan, IJMP2007
- $H^{\pm} \to W^{\pm}Z$ exists at tree level in triplet models. (production through WZ fusion)

Branching ratio



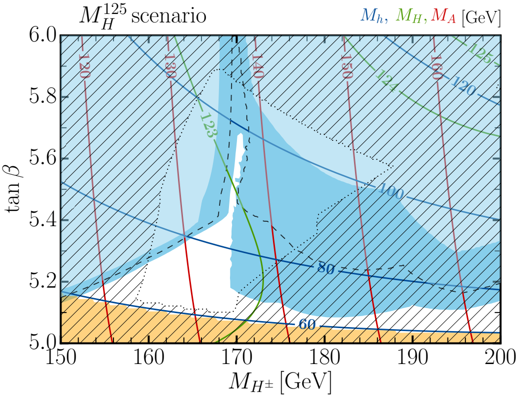

2HDM-I , MA=65 GeV
Br(H+ --> xy)
m_H+ (GeV)
τν:2.5
5
10
WA:2.5
5
10
2HDM-X , MA=65 GeV
Br(H+ --> xy)
m_H+ (GeV)
τν:2.5
5
10
WA:2.5
5
10


CMS
35.9 fb-1 (13 TeV)
H± → τν
All final states combined
95% CL upper limits
Observed
Median expected
68% expected
95% expected
m_H± (GeV)

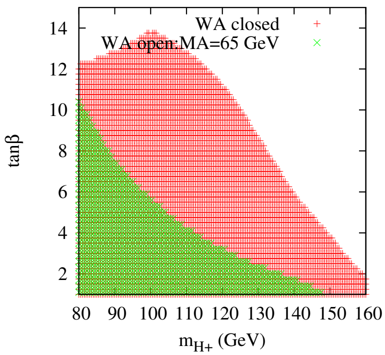

CMS
35.9 fb-1 (13 TeV)
tan β
H± → τν
MSSM m_h^mod-
95% CL upper limits
Observed
Excluded
Median expected
68% expected
95% expected
m_h^MSSM ≠ 125±3 GeV
m_H± (GeV)

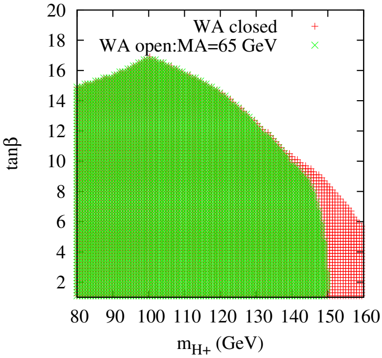
MSSM with $m_h < m_H = 125$ GeV:

E. Bagnaschi et al EPJC'18 hep-ph/ arXiv:1808.07542

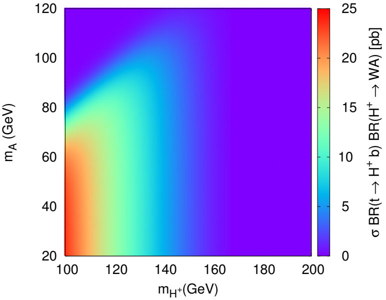


left: 2HDM-I, right: 2HDM-III, (WA open: $m_A = 65$ GeV)

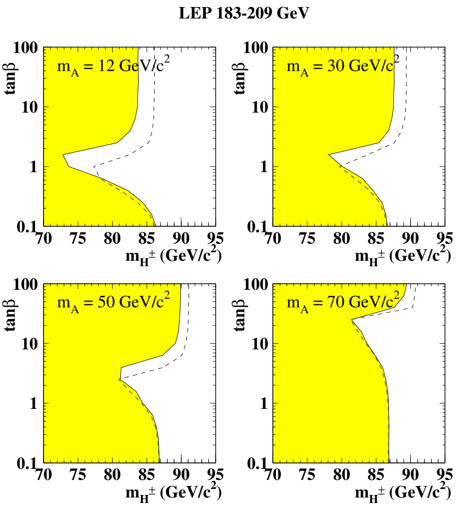




$\sigma(t\bar{t})xBr(t \to bH^-)xBr(H^- \to W^-A)$



Search for $H^{\pm} \to W^{\pm}A^{0}$ at LEP-II



CMS searches: $H^{\pm} \to HW^{\pm}$ hep-ex/2207.01046

$H^{\pm} \to AW \to \mu^{+}\mu^{-}W$ with $B(A \to \mu^{+}\mu^{-}) = 1$ hep-ex/1905.07453

very light a_1 in the NMSSM: [A.Akeroyd, A.A and Q.S. Yan EPJC'07]

$H^{\pm}W^{\mp}a_1 \propto \cos\theta_A$: θ_A is the doublet-singlet mixing.

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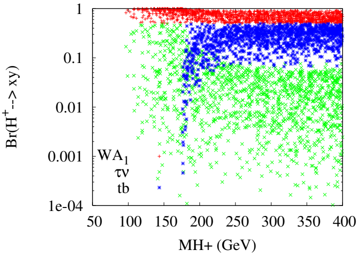

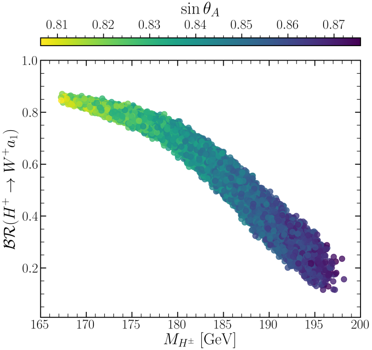

H^0-SM like ; $m_h < m_H = 125$ GeV

In the alignment limit $\cos(\beta-\alpha) \approx 1$, the heavy CP-even Higgs H^0 completely mimics the SM Higgs:

$$
\begin{aligned}
H^0 f\bar{f} &= \frac{\sin\alpha}{\sin\beta} \approx 1 \\
H^0 VV &= \cos(\beta-\alpha) \approx 1 \\
H^0 H^0 H^0 &= \frac{3g}{2m_W}(M_H^2(c_{\beta-\alpha}\frac{\sin 2\alpha}{\sin 2\beta} - 2s_{\beta-\alpha}) + \lambda_5 v^2 s_{\beta-\alpha}^2) \\
&\approx \frac{3g}{2m_W} m_H^2
\end{aligned}
$$

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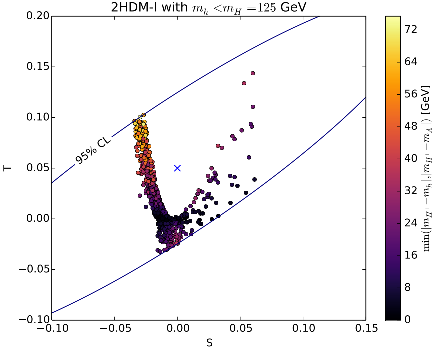
- $m_h \leq m_H = 125$ GeV: $H^0 \to h^0 h^0$ and/or $H^0 \to A^0 A^0$ might be open: $Br(H^0 \to h^0 h^0) + Br(H^0 \to A^0 A^0) \leq 10\%$
- if h^0 and A^0 too light: $Z \to h^0 A^0 \propto \cos^2(\beta-\alpha)$
- For $m_h \leq 125$ GeV and $m_H = 125$ GeV: EWPT imply that $H^\pm$ and A^0 would be also light.

EWPT: S and T



A.A, R. Benbrik, R. Enberg, W. Klemm, S. Moretti and S. Munir, PLB'17

$$M_W^{\text{CDF}} = 80.4435 \pm 0.0094 \ \text{GeV}.$$ [CDF collaboration ' Science 2022]

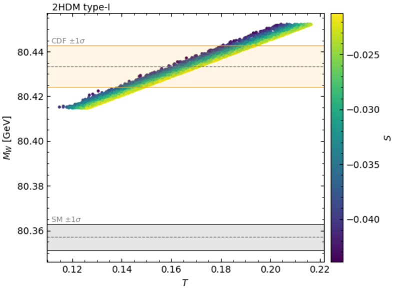
$$M_W^{\text{SM}} = 80.357 \pm 0.006 \ \ \text{GeV}.$$ [Review of Particle Physics ' 2020]

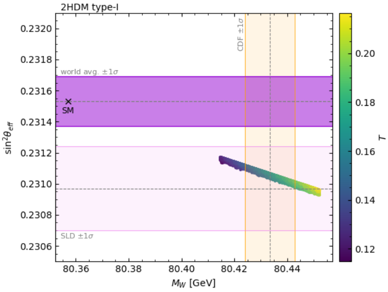
M_W^{CDF} presents a deviation from M_W^{SM} with a significance of 7.0 σ.

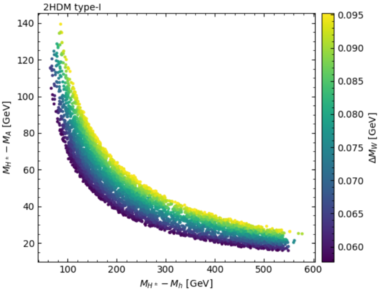
$$(M_W^{2HDM})^2 - (M_W^{SM})^2 = \frac{\alpha_0 c_W^2 M_Z^2}{c_W^2 - s_W^2}\left[-\frac{1}{2}S + c_W^2 T + \frac{c_W^2 - s_W^2}{4 s_W^2} U\right],$$

$$\Delta \sin^2 \theta_{\text{eff}} = \frac{\alpha_0}{c_W^2 - s_W^2}\left[\frac{1}{4}S - s_W^2 c_W^2 T\right].$$

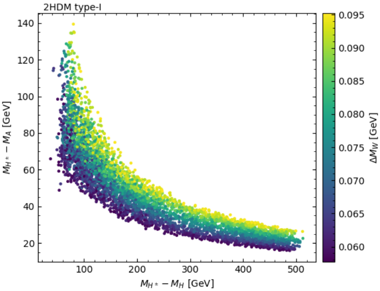
[S. Hessenberger and W. Hollik : hep-ph/ 2207.03845: 2 loops improvement]


2HDM type-I
CDF ±1σ
SM ±1σ
80.44
80.42
80.40
80.38
80.36
M_W [GeV]
0.12
0.14
0.16
0.18
0.20
0.22
T
−0.025
−0.030
−0.035
−0.040
S


2HDM type-I
CDF ±1σ
world avg. ±1σ
SM
SLD ±1σ
0.2320
0.2318
0.2316
0.2314
0.2312
0.2310
0.2308
0.2306
$\sin^2\theta_{eff}$
80.36
80.38
80.40
80.42
80.44
M_W [GeV]
0.20
0.18
0.16
0.14
0.12
T



2HDM type-I
$M_{H^\pm} - M_A$ [GeV]
$M_{H^\pm} - M_h$ [GeV]
ΔM_W [GeV]



2HDM type-I
$M_{H^\pm} - M_A$ [GeV]
$M_{H^\pm} - M_H$ [GeV]
ΔM_W [GeV]

Can h^0 be Fermiophobic ?

- In 2HDM-I, $h^0 f\bar{f} \propto \frac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$
  For negative $\sin(\beta-\alpha)$ and positive $\cos(\beta-\alpha)$,
  it is clear that $\cos\alpha \to 0$. h^0 becomes fermiophobic.
- $h^0 VV \propto \sin_{\beta-\alpha} \approx 0$; $h^0 \to \{VV^*, V^*V^*\}$ very suppressed;
  $h^0 \to \gamma\gamma$ could reach 100%

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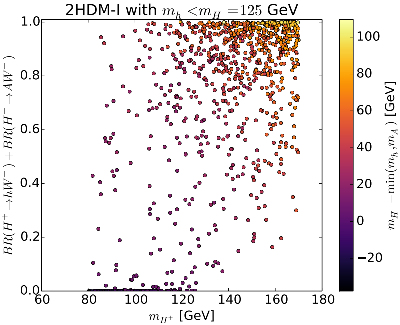
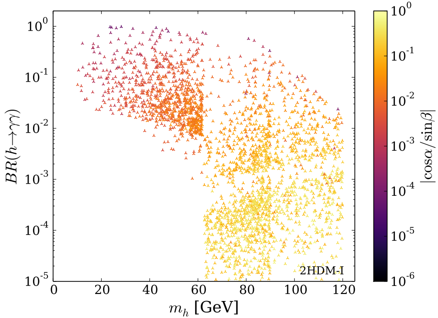
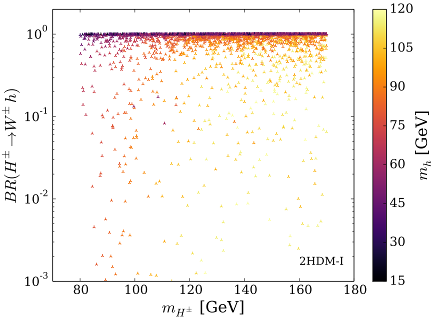
  $h^0 \to \gamma\gamma$ could reach 100%
- $H^\pm W^\mp h^0 \propto \cos(\beta-\alpha) \approx 1$
- light $H^\pm$ can be produced from $t \to bH^+$ and also
  $pp \to W^* \to \{H^\pm h^0, H^\pm A^0\}$; $pp \to \gamma^*, Z^* \to H^\pm H^\mp$
- with h^0 close to fermiophobic,
  $pp \to t\bar{t} \to bWbH^+ \to 2b2Wh^0 \to 2b + 2W + 2\gamma$;
  $pp \to H^\pm h^0 \to Wh^0h^0 \to 4\gamma + W$

Br($H^{\pm} \to W^{\pm} S$)

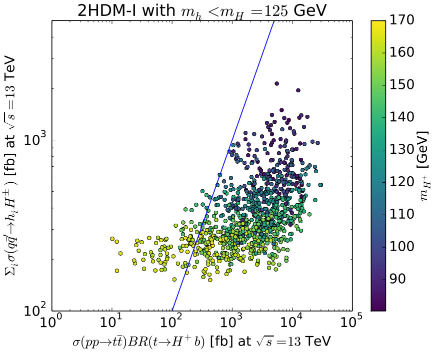


Br($h^0 \to \gamma\gamma$) and Br($H^\pm \to W^\pm h^0$)



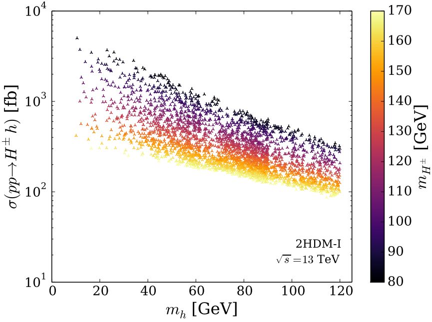


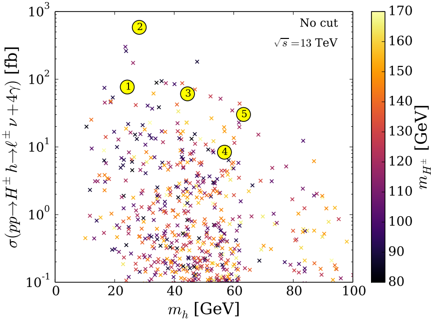
Comparison: $\sigma(pp \to t\bar{t}) \times BR(t \to H^+ b)$ vs. $\Sigma_i \sigma(q\bar{q}' \to H^\pm h_i)$



$\sigma(q\bar{q}' \to H^{\pm}h^0)$; $\sigma(q\bar{q}' \to l\nu 4\gamma)$

BP	m_h	$m_{H^\pm}$	m_A	$\sin_{\beta-\alpha}$	$\tan\beta$	$\sigma_{W^\pm 4\gamma}$[fb]	$Br(h^0 \to \gamma\gamma)$
1	24.2	152.2	111.1	-0.048	20.9	359	0.94
2	28.3	83.7	109.1	-0.050	20.2	2740	0.97
3	44.5	123.1	119.9	-0.090	10.9	285	0.70
4	56.9	97.0	120.3	-0.174	5.9	39	0.22
5	63.3	148.0	129.2	-0.049	20.7	141	0.71





Cuts and selection efficiencies

We require pseudorapidity $|\eta| < 2.5$ for the lepton and photons, and an isolation $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.4$ for all objects.

(i) all photons: $p_T^\gamma > 10$ GeV; charged lepton: $p_T^\ell > 20$ GeV,

(ii) imposes that $p_T^\gamma > 20$ GeV and $p_T^\ell > 10$ GeV.

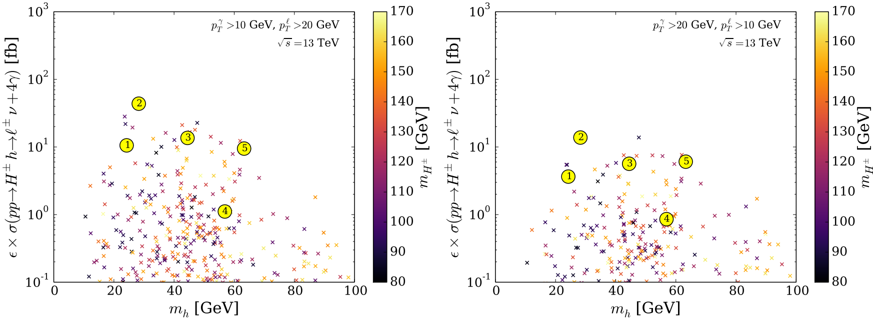
- The irreducible SM W+4γ Background $< 10^{-6}$ pb.

- The selection efficiencies: $\epsilon = \sigma(\text{cuts})/\sigma(\text{no cuts})$.

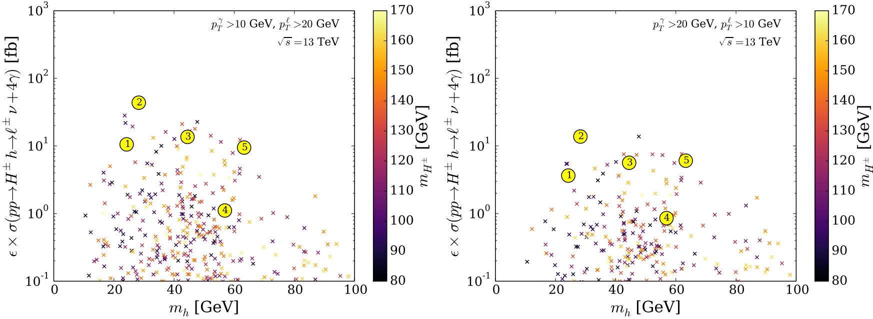
$p_T^\gamma >$10 GeV, $p_T^\ell >$20 GeV

$m_{H^+} \backslash m_h$	20	30	40	50	60	70	80	90	100
80	0.04	0.08	0.10	0.08	0.05	<0.01			
90	0.05	0.10	0.13	0.13	0.10	0.06	<0.01		
100	0.05	0.14	0.16	0.16	0.13	0.11	0.06	<0.01	
110	0.06	0.13	0.18	0.19	0.17	0.16	0.13	0.07	<0.01
120	0.07	0.14	0.20	0.22	0.24	0.22	0.17	0.13	0.06
130	0.10	0.16	0.23	0.25	0.28	0.25	0.24	0.20	0.15
140	0.10	0.18	0.23	0.27	0.28	0.31	0.28	0.27	0.21
150	0.11	0.19	0.26	0.31	0.31	0.33	0.32	0.29	0.27
160	0.12	0.21	0.26	0.29	0.34	0.34	0.34	0.30	0.32

$\sigma(q\bar{q}' \to H^{\pm}h \to l\nu + 4\gamma)$ with cuts



$\sigma(q\bar{q}' \to H^\pm h \to l\nu + 4\gamma)$ with cuts



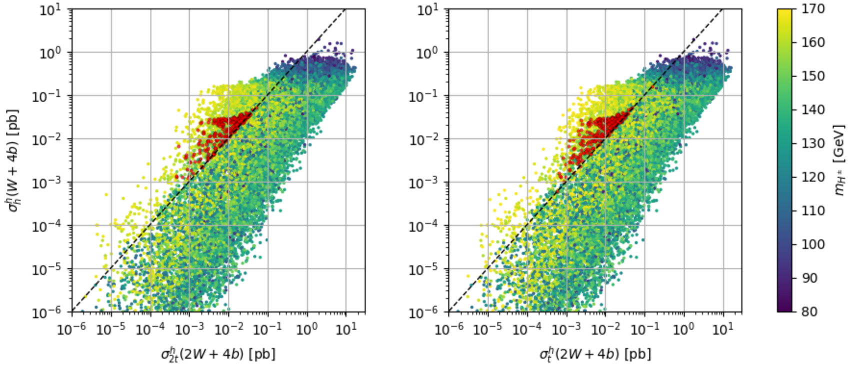
A full Monte Carlo (MC) analysis at the detector level shows that $W4\gamma$ signal is very promising, at the LHC with 300 fb^{-1} luminosity.

fermionic decays of h^0 and A^0

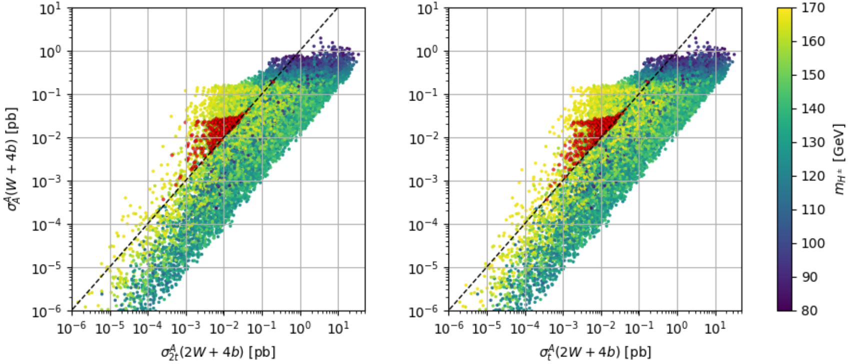
	production and decay chain
$\sigma_{2t}^{h_i}(2W2b2f)$	$2\ \sigma_{t\bar{t}} \times \mathrm{BR}(t \to bH^+) \times \mathrm{BR}(\bar{t} \to \bar{b}W) \times$ $\mathrm{BR}(H^\pm \to Wh_i) \times \mathrm{BR}(h_i \to f\bar{f})$
$\sigma_{t}^{h_i}(2W2b2f)$	$\sigma(pp \to t\bar{b}H^-) \times \mathrm{BR}(t \to bW) \times \mathrm{BR}(H^\pm \to Wh_i) \times$ $\mathrm{BR}(h_i \to f\bar{f})$

	Di-Higgs production and decay chain
$\sigma_{h_j}^{h_i}(2W2f2f')$	$\sigma(H^+H^-) \times \mathrm{BR}(H^\pm \to W^\pm h_i) \times \mathrm{BR}(H^\pm \to W^\pm h_j) \times$ $(\mathrm{BR}(h_i \to f\bar{f}) \times \mathrm{BR}(h_j \to f'\bar{f}') + h_i \longleftrightarrow h_j)\ \frac{1}{1+\delta_{ff'}}$
$\sigma_{h_j}^{h_i}(W2f2f')$	$\frac{1}{1+\delta_{ff'}}\ \sigma(H^\pm h_i) \times \mathrm{BR}(H^\pm \to W^\pm h_j) \times$ $(\mathrm{BR}(h_i \to f\bar{f}) \times \mathrm{BR}(h_j \to f'\bar{f}') + h_i \longleftrightarrow h_j)$

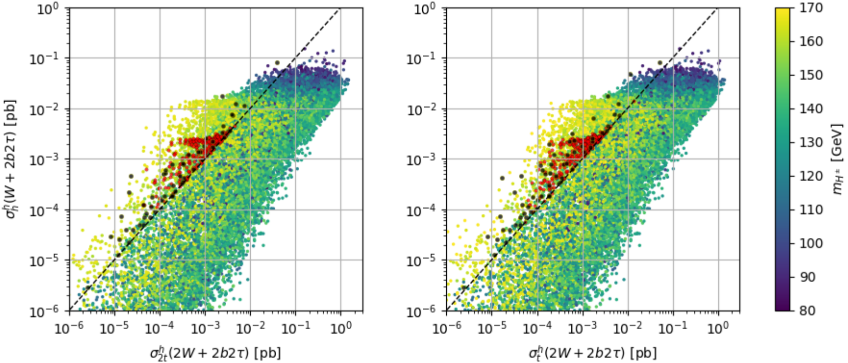
Table: $i, j = 1, 2$ and have $h_1 = h$ and $h_2 = A$; $f(f') = b$ or τ.



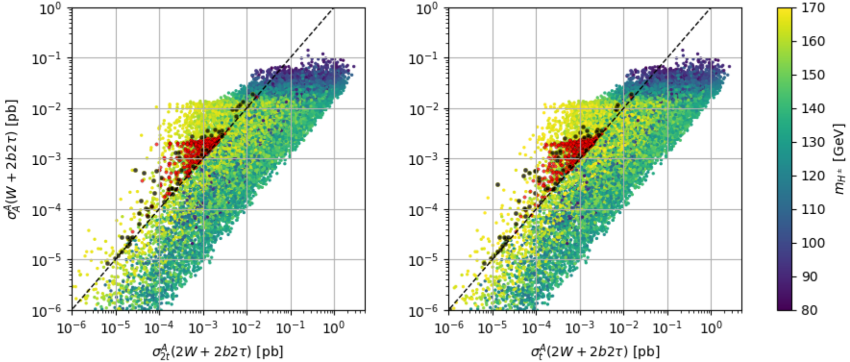
$\sigma(pp \to H^\pm h) \times \mathrm{BR}(H^\pm \to W^\pm h) \times \mathrm{BR}(h \to b\bar{b})^2$ compared to 2 σ_{2t} (left) and σ_t^h (right). Red points identify: $\sigma(H^+H^-) \times \mathrm{BR}(H^\pm \to W^\pm h)^2 \times \mathrm{BR}(h \to b\bar{b})^2$ in 2HDM-I.



$\sigma(pp \to H^\pm A) \times \mathrm{BR}(H^\pm \to W^\pm A) \times \mathrm{BR}(A \to b\bar{b})^2$ compared to σ^A_{2t} (left) and σ^A_t (right). Red points identify: $\sigma(H^+H^-) \times \mathrm{BR}(H^\pm \to W^\pm A)^2 \times \mathrm{BR}(A \to b\bar{b})^2$ in 2HDM-I.



$2\sigma(pp \to H^\pm h) \times \mathrm{BR}(H^\pm \to Wh) \times \mathrm{BR}(h \to b\bar{b}) \times \mathrm{BR}(h \to \tau^+\tau^-)$ compared to σ^h_{2t} (left) and σ^h_t (right). The red points identify $\sigma(H^+H^-)\mathrm{xBR}(H^\pm \to Wh)^2\mathrm{xBR}(h \to b\bar{b})\mathrm{xBR}(h \to \tau^+\tau^-)$ for 2HDM-I while the black points are for 2HDM-X rates: $\sigma(pp \to H^\pm h) \times \mathrm{BR}(H^\pm \to W^\pm h) \times \mathrm{BR}(h \to \tau^+\tau^-)^2$.



$2\sigma(pp \to H^\pm A)x\mathrm{BR}(H^\pm \to WA)x\mathrm{BR}(A \to b\bar{b})x\mathrm{BR}(A \to \tau^+\tau^-)$ compared to σ_{2t}^A (left) and σ_t^A (right). The red points identify $\sigma(H^+H^-)x\mathrm{BR}(H^\pm \to WA)^2x\mathrm{BR}(A \to b\bar{b})x\mathrm{BR}(A \to \tau^+\tau^-)$ for 2HDM-I while the black points are for 2HDM-X rates: $\sigma(pp \to H^\pm A) \times \mathrm{BR}(H^\pm \to W^\pm A) \times \mathrm{BR}(A \to \tau^+\tau^-)^2$.

CP violation in $H^{\pm}$ production and decays

We investigate the following CP violating $H^{\pm}$ rate asymmetries:

- **Decay rate asymmetries** $A^{CP}_{D,f}$, defined by:

$$A^{CP}_{D,f}\;(H^{\pm}\to f)=\frac{\Gamma(H^{+}\to f)-\Gamma(H^{-}\to \bar{f})}{2\Gamma^{\rm tree}(H^{+}\to f)}\,, \qquad (1)$$

where $f=t\bar{b}$; $W^{\pm}H^{0}_{i}$ with $i=1,2$.

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• **Production rate asymmetry** A^{CP}_P:

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• **Combined Asymmetries** A^{CP}_f for $H^\pm$ production and subsequent decays (using NWA):

$$A^{CP}_f = \frac{\sigma(pp \to \bar{t}H^+ \to \bar{t}f) - \sigma(pp \to tH^- \to t\bar{f})}{2\sigma^{\rm tree}(pp \to \bar{t}H^+ \to \bar{t}f)} = A^{CP}_P + A^{CP}_{D,f}$$

- In order to get CPV, we need both non-zero CPV phases in the Lagrangian and CP conserving phases (strong phases) in the absorptive parts of the one-loop amplitudes.
- In the C2HDM, the CP violating phases arise from: $h_i^0 ff$ couplings or $H^\pm W^\mp h_i^0$ couplings or $H^\pm G^\mp h_i^0$ couplings
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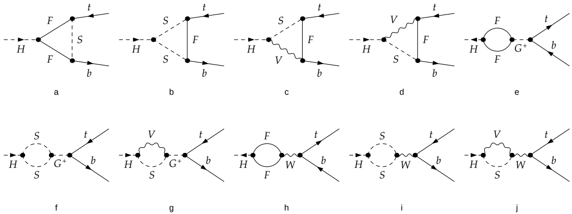

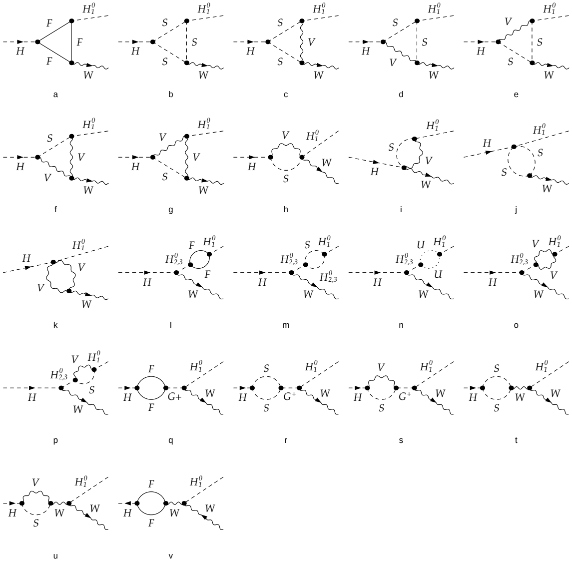
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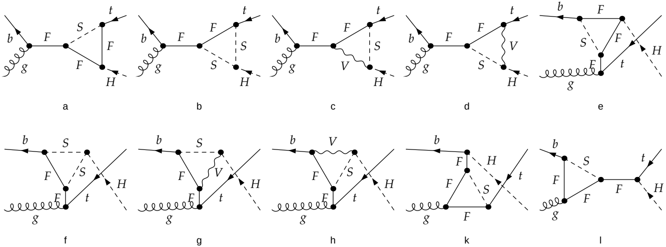
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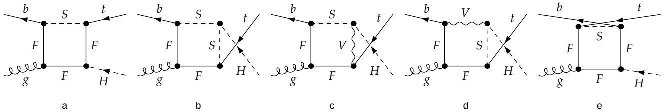
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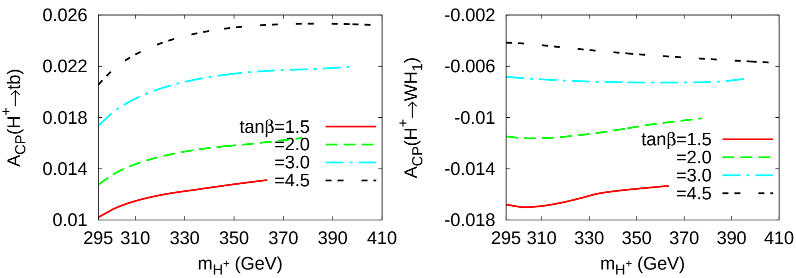
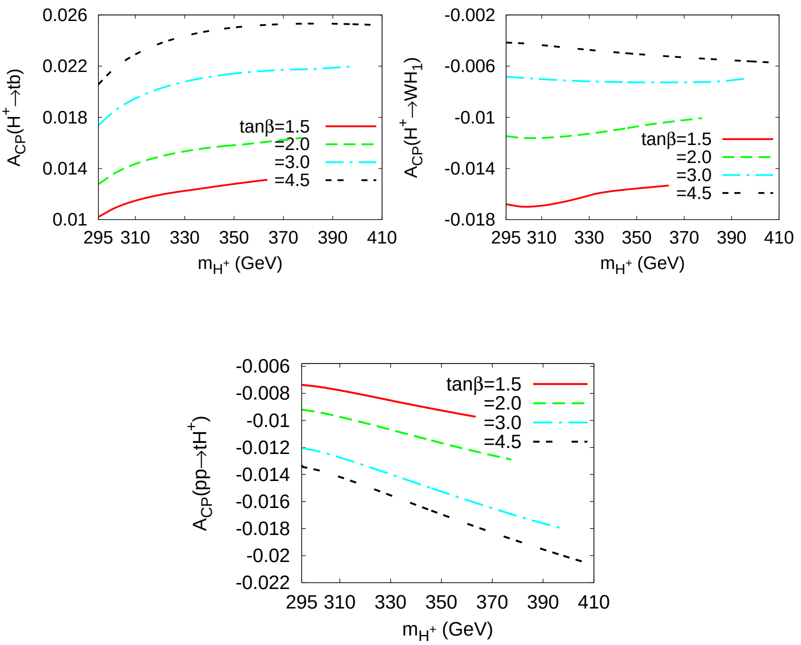
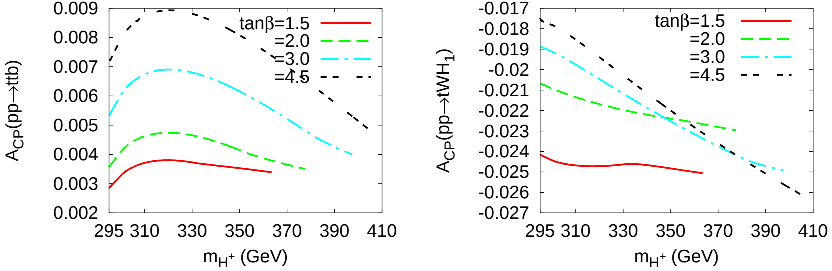

0.026
0.022
0.018
0.014
0.01
295 310 330 350 370 390 410
m_{H^+} (GeV)
$A_{CP}(H^+ \to tb)$
tanβ=1.5
=2.0
=3.0
=4.5
-0.002
-0.006
-0.01
-0.014
-0.018
295 310 330 350 370 390 410
m_{H^+} (GeV)
$A_{CP}(H^+ \to WH_1)$
tanβ=1.5
=2.0
=3.0
=4.5



0.026
0.022
0.018
0.014
0.01
$A_{CP}(H^+ \to tb)$
tanβ=1.5
=2.0
=3.0
=4.5
295 310 330 350 370 390 410
m_{H^+} (GeV)
-0.002
-0.006
-0.01
-0.014
-0.018
$A_{CP}(H^+ \to WH_1)$
tanβ=1.5
=2.0
=3.0
=4.5
295 310 330 350 370 390 410
m_{H^+} (GeV)
-0.006
-0.008
-0.01
-0.012
-0.014
-0.016
-0.018
-0.02
-0.022
$A_{CP}(pp \to tH^+)$
tanβ=1.5
=2.0
=3.0
=4.5
295 310 330 350 370 390 410
m_{H^+} (GeV)



$A_{CP}(pp \to ttb)$
m_{H^+} (GeV)
tanβ=1.5
=2.0
=3.0
=4.5
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
295 310 330 350 370 390 410
$A_{CP}(pp \to tWH_1)$
m_{H^+} (GeV)
tanβ=1.5
=2.0
=3.0
=4.5
-0.017
-0.018
-0.019
-0.02
-0.021
-0.022
-0.023
-0.024
-0.025
-0.026
-0.027
295 310 330 350 370 390 410

Conclusions

- In 2HDM-I there is regions of the parameter space compliant with all constraints yielding substantial BRs for $H^{\pm} \to W^{\pm *} h / W^{\pm *} A$ in which the $m_{H^{\pm}} < m_t - m_b$.
- $\sigma(pp \to t\bar{t} \to tbH^{+} \to tbWA^{0})$ and/or $pp \to H^{\pm} h / H^{\pm} A / H^{\pm} H^{\mp}$ 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.

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- light $H^\pm$ in the 80–160 GeV mass range, still being consistent with all LHC, LEP Tevatron and B-physics data.
- $pp \to H^\pm h^0 \to W^\pm + 4\gamma$ with significant events.
- After reasonable cuts on the p_T of the photons and the lepton, $\sigma_{W^\pm 4\gamma}$ can still enjoy a cross section of the order 10 fb and more in an essentially background-free environment.