Enhanced charged Higgs production through W-Higgs fusion

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Based on hep-ph/1607.02402 and work in progress A.A, R. Benbrik, R. Enberg, W. Klemm, S. Moretti and S. Munir,
hep-ph/1509.00978 , JHEP'16 A.A, K.M Cheung, J.S.Lee and C.T-Lu

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Outlines

- Introduction
- Bosonic decays of charged Higgs: $H^{\pm} \to W^{\pm}A/W^{\pm}h$,
  (h-SM like and H-SM like)
  (based on hep-ph/1607.02402 and work in progress, A.A, R. Benbrik, R. Enberg, W. Klemm, S. Moretti and S. Munir)
- Charged Higgs production: W-Higgs fusion: $pp \to H^{+}bj$
  (based on hep-ph/1509.00978 , JHEP'16, A.A, K.M Cheung, J.S.Lee and C.T-Lu)
- subprocess $W^{\pm}b \to bH^{\pm}$ and unitarity
- Numerical results (constraints from τ data in the $(m_A, \tan\beta)$ plan).
- Conclusions

Introduction:

After the Scalar boson discovery at $7 \oplus 8$ TeV LHC, the mission of the LHC run at 13 TeV is:

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

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After the Scalar boson discovery at 7 $\oplus$ 8 TeV LHC, the mission of the LHC run at 13 TeV is:

- 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

2HDM: G. Branco et al Phys rep'2012

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

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

leads to FCNCs at tree level.

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leads to FCNCs at tree level.

• 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)	$Y_{u,\ell}^1 = Y_d^2 = 0$

2HDM:

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- 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:

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• 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 $M_{H_1} \leq M_{H_2} \leq M_{H_3}$.

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

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

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

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

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

Sum rules: (B.Grzadkowski et al PRD'1999):

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

Charged Higgs production

- 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),
  $b\bar{b} \to W^\pm H^\mp$
  $q\bar{q} \to \gamma, Z \to H^+H^-$,
  $gg \to H^+H^-$(loop)
  $q\bar{q}' \to W^* \to \phi H^\pm$ where $\phi = h^0, H^0, A^0$,

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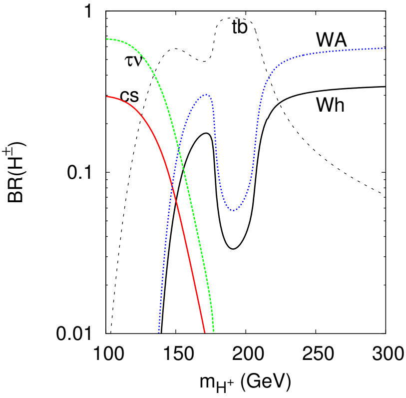
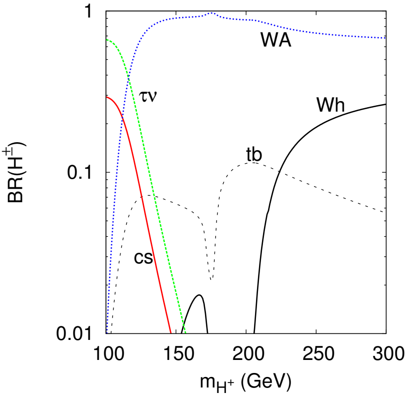
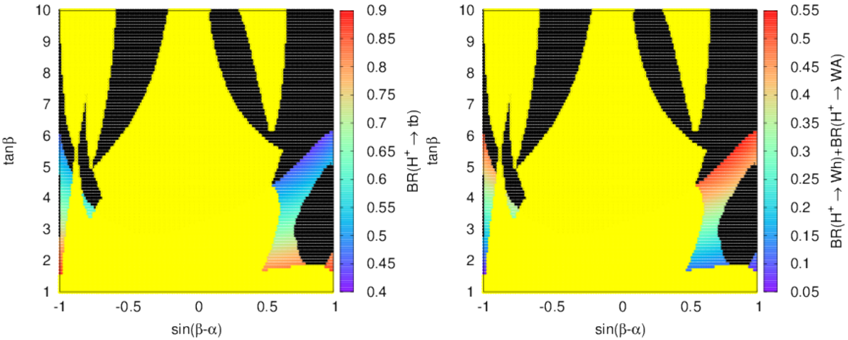
  $gg \to H^+H^-$(loop)
  $q\bar{q}' \to W^* \to \phi H^\pm$ where $\phi = h^0, H^0, A^0$,
- Resonant production: $c\bar{s}, c\bar{b} \to H^+$
- $W - Higgs$ fusion : $qb \to q'H^+b$
  (See "Prospects for charged Higgs searches at the LHC," arXiv:1607.01320: A. Akeroyd et al)

$H^{\pm}$ decays: $\tan\beta = 4.5$, $m_H = 300$ GeV, (left) $m_A = 125$ GeV (right) $m_A = 90$ GeV: 2HDM-I



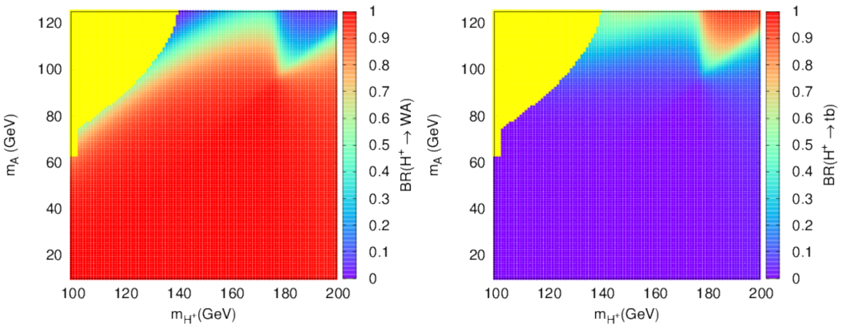


Yellow excluded by data, black by theoretical constraints

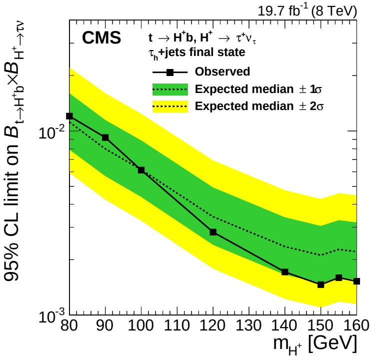


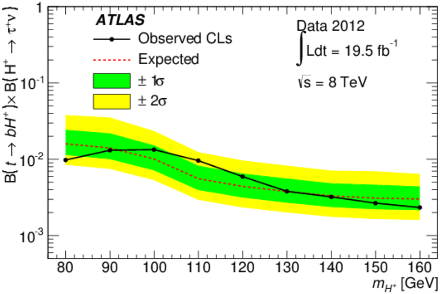
$$W^{\pm}H^{\mp}A \propto \frac{g}{2}\ ,\ W^{\pm}H^{\mp}h \propto \frac{g}{2}\cos(\beta-\alpha),\ W^{\pm}H^{\mp}H \propto \frac{g}{2}\sin(\beta-\alpha)$$

very light A^0: $\tan\beta = 5$, $m_H = 300$ GeV, $\sin(\beta - \alpha) = 1$



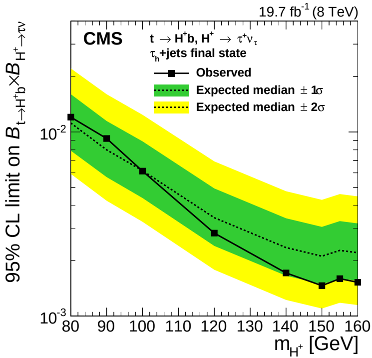
ATLAS and CMS Limit on $H^\pm$: low mass

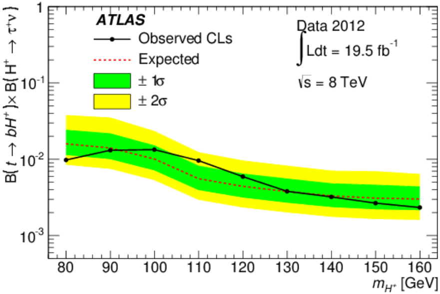




ATLAS and CMS Limits from $H^\pm \to c\bar{s}$ are weaker.

ATLAS and CMS Limit on $H^{\pm}$: low mass





ATLAS and CMS Limits from $H^{\pm} \to c\bar{s}$ are weaker.

$Br(t \to bH^{+}) = \frac{\Gamma(t\to bH^{+})}{\Gamma(t\to bH^{+})+\Gamma(t\to bW)}$: depends only on $(\tan\beta, m_{H^{\pm}})$

Implication for 2HDM

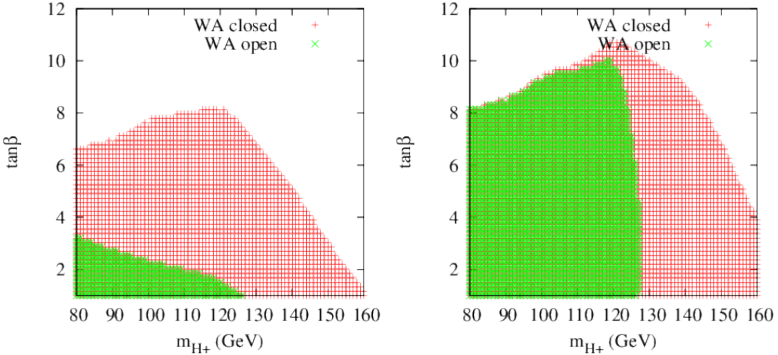
- In 2HDM-II and IV: $m_{H^\pm} > 480$ GeV for any $\tan\beta$ (Misiak PRL'2015)

- in 2HDM-I $m_{H^\pm} > 100$ GeV: for $\tan\beta \geq 1.5$

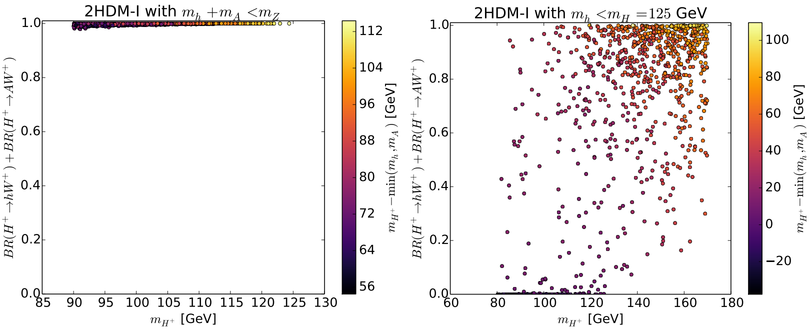
- in 2HDM-III, light charged Higgs ≤ 200 GeV with large $\tan\beta > 30$ is excluded from $\tau \to \mu\nu\nu$

  (T. Enomoto and R. Watanabe JHEP'16)

Implication for 2HDM: (left) 2HDM-I, (right) 2HDM-III, *WA* open for $m_A = 40$ GeV

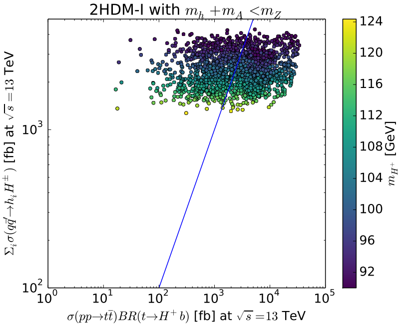


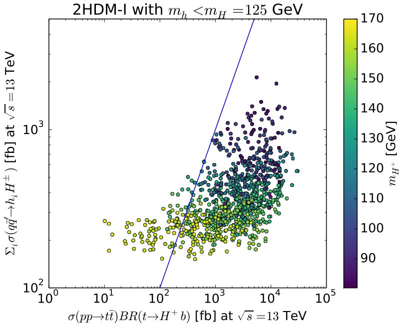
H^0-SM like



2HDM-I with $m_h + m_A < m_Z$
$BR(H^+ \to hW^+) + BR(H^+ \to AW^+)$
m_{H^+} [GeV]
$m_{H^+} - \min(m_h, m_A)$ [GeV]
2HDM-I with $m_h < m_H = 125$ GeV
$BR(H^+ \to hW^+) + BR(H^+ \to AW^+)$
m_{H^+} [GeV]
$m_{H^+} - \min(m_h, m_A)$ [GeV]

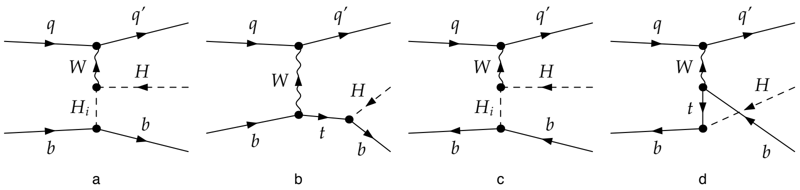
Comparison: $\sigma(pp \to t\bar{t}) \times BR(t \to H^+ b)$ vs. $\Sigma_i \sigma(q\bar{q}' \to H^\pm h_i)$





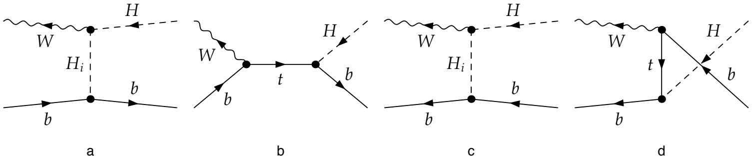
$W - H_i$ fusion: $qb \to q' H^+ b$

- In 2HDM:$Z^0 W^\pm H^\mp$ mediated at 1-loop ;
- W-Z fusion process to produce $H^\pm$ is very suppressed (E. Asakawa and S. Kanemura PLB'05)
- W-Z fusion possible only in Model with triplet representation such as Georgi-Machacek model (see note by M. Zaro and H.Logan LHCHXSWG-2015-001)
- $W - H_i$ fusion process (MSSM case: S. Moretti, K.Odagiri, PRD'1997)



Subprocess $W^+ b \to H^+ b$ and unitarity

- In $q\,b/\bar{b} \to q' H^{\pm}\, b/\bar{b}$ the dominant contribution comes from the region where the W emitted from the incoming quark q is close to on shell and one can approximately represent the process by $W - b$ or $W - \bar{b}$ scattering
- $W^+(q_1)\ b(p_1) \ \to\ H^+(q_2)\ b(p_2)$
  $W^+(q_1)\ \bar{b}(p_1) \ \to\ H^+(q_2)\ \bar{b}(p_2)$
- use the effective W approximation



The interactions needed for these subprocesses can be obtained from the Yukawa interactions and from the covariant derivatives:

$$\mathcal{L}_{H_i\bar{b}b} = -\frac{gm_b}{2m_W}\,\bar{b}\left(Y_i^S + i\,Y_i^P\,\gamma_5\right) b\,H_i\,,$$

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

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

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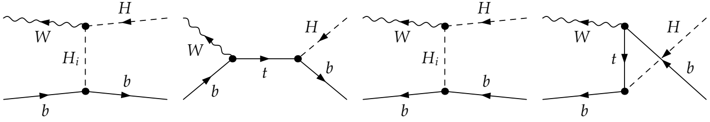
In type II and IV:

$$c_L = \tan\beta\,, \quad c_R = \frac{m_t}{m_b}\,\frac{1}{\tan\beta}\,; \quad Y_i^S = \frac{O_{\phi_1 i}}{c_\beta}\,, \quad Y_i^P = -\tan\beta\,O_{ai}$$

in types I and III

$$c_L = -\frac{1}{\tan\beta}\,, \quad c_R = \frac{m_t}{m_b}\,\frac{1}{\tan\beta}\,; \quad Y_i^S = \frac{O_{\phi_2 i}}{s_\beta}\,, \quad Y_i^P = \frac{O_{ai}}{\tan\beta}$$



a b c d

The amplitude of each diagram for $W^+(q_1)b(p_1) \to H^+(q_2)b(p_2)$ reads

$$\mathcal{M}_{(b)} = \frac{-g^2 m_b C_v}{2m_W(s - m_t^2)} \{\bar{u}(p_2)\,(c_L\ \not{p}_t \not{\epsilon}(q_1)P_L\ +\ c_R\, m_t \not{\epsilon}(q_1)P_L)u(p_1)$$

$$\mathcal{M}_{(a)}^{H_i} = \frac{-g^2 m_b(S_i + iP_i)}{4m_W(t - M_{H_i}^2)}(q_2 + p_{H_i})^\mu \epsilon_\mu(q_1)\{\bar{u}(p_2)(Y_i^S + iY_i^P\gamma_5)u(p_1)$$

$s = (p_1 + q_1)^2 = (p_2 + q_2)^2,\ t = (p_1 - p_2)^2 = (q_2 - q_1)^2,$
$u = (p_1 - q_2)^2 = (p_2 - q_1)^2$ and $\epsilon^\mu(q_1)$ polarization vector of W^+.

In the high-energy limit, $s, |t|, |u| \gg m_W^2, m_t^2, M_{H_i}^2, M_{H^\pm}^2$, we find that

$$\mathcal{M} = \mathcal{M}_{(b)} + \sum_i \mathcal{M}_{(a)}^{H_i} \approx \frac{g^2 m_b}{4m_W^2} \times$$

$$\left\{ \left[\sum_i (S_i Y_i^S - P_i Y_i^P) + i \sum_i (S_i Y_i^P + P_i Y_i^S) \right] \bar{u}(p_2) P_R u(p_1) + \right.$$

$$\left. \left[\left(2c_L + \sum_i (S_i Y_i^S + P_i Y_i^P) \right) - i \sum_i (S_i Y_i^P - P_i Y_i^S) \right] \bar{u}(p_2) P_L u(p_1) \right\}$$

we have taken:

- longitudinally polarized W: $\epsilon^\mu(q_1) \approx q_1^\mu / m_W = (p_t^\mu - p_1^\mu)/m_W$
- p_t: top quark momenta $p_t^2 = s$.
- the square of the momenta of H_i is $p_{H_i}^2 = (p_1 - p_2)^2 = t$.

We note that, in the high-energy limit,

$$\overline{|\mathcal{M}|^2} \propto \left\{ \left| 2\, c_L + \sum_i (S_i g_i^S + P_i g_i^P) \right|^2 + \left| \sum_i (S_i g_i^S - P_i g_i^P) \right|^2 + \left| \sum_i (-S_i g_i^P + P_i g_i^S) \right|^2 + \left| \sum_i (S_i g_i^P + P_i g_i^S) \right|^2 \right\} (-t)$$

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$$\left. + \left| \sum_i (-S_i g_i^P + P_i g_i^S) \right|^2 + \left| \sum_i (S_i g_i^P + P_i g_i^S) \right|^2 \right\} (-t)$$

therefore the absence of this unitarity-breaking term requires the following three types of sum rules:

$$i)\ 2\, c_L + \sum_i (S_i Y_i^S + P_i Y_i^P) = 0\,,$$

$$ii)\ \sum_i S_i Y_i^S = \sum_i P_i Y_i^P\,, \quad and \quad iii)\ \sum_i S_i Y_i^P = \sum_i P_i Y_i^S = 0\,.$$

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$$\left. + \left| \sum_i (-S_i g_i^P + P_i g_i^S) \right|^2 + \left| \sum_i (S_i g_i^P + P_i g_i^S) \right|^2 \right\} (-t)$$

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• The first one gives the relation between tbH^+ coupling and $W^\pm H^\mp H_i$ and $H_i b\bar{b}$: $(Y_i^S S_i + Y_i^P P_i)$

• The second relation shows the sum over the Higgs states of the scalar products should be the same as that of the pseudoscalar.

Proof in 2HDM-II

ii $\sum_i S_i Y_i^S = \sum_i ((c_\beta O_{\phi_2 i} - s_\beta O_{\phi_1 i}) \frac{O_{\phi_1 i}}{c_\beta} = -\tan\beta$

$\sum_i P_i Y_i^P = \sum_i O_{ai}(-\tan\beta O_{ai}) = -\tan\beta$

then: $\sum_i S_i Y_i^S = \sum_i P_i Y_i^P$

Proof in 2HDM-II

ii $\sum_i S_i Y_i^S = \sum_i ((c_\beta O_{\phi_2 i} - s_\beta O_{\phi_1 i}) \frac{O_{\phi_1 i}}{c_\beta} = -\tan\beta$

$\sum_i P_i Y_i^P = \sum_i O_{ai}(-\tan\beta O_{ai}) = -\tan\beta$

then: $\sum_i S_i Y_i^S = \sum_i P_i Y_i^P$

i $2\,c_L + \sum_i (S_i Y_i^S + P_i Y_i^P) = 2\tan\beta + \sum_i S_i Y_i^S + \sum_i P_i Y_i^P = 0$

Proof in 2HDM-II

ii $\sum_i S_i Y_i^S = \sum_i ((c_\beta O_{\phi_2 i} - s_\beta O_{\phi_1 i}) \frac{O_{\phi_1 i}}{c_\beta} = -\tan\beta$

$\sum_i P_i Y_i^P = \sum_i O_{ai}(-\tan\beta O_{ai}) = -\tan\beta$

then: $\sum_i S_i Y_i^S = \sum_i P_i Y_i^P$

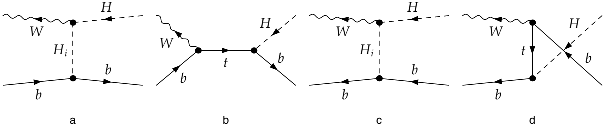
i $2\, c_L + \sum_i (S_i Y_i^S + P_i Y_i^P) = 2\tan\beta + \sum_i S_i Y_i^S + \sum_i P_i Y_i^P = 0$

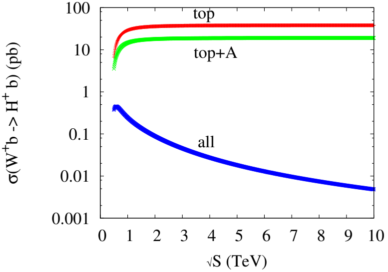
iii $\sum_i S_i Y_i^P = \sum_i ((c_\beta O_{\phi_2 i} - s_\beta O_{\phi_1 i})(-\tan\beta O_{ai}) = 0$

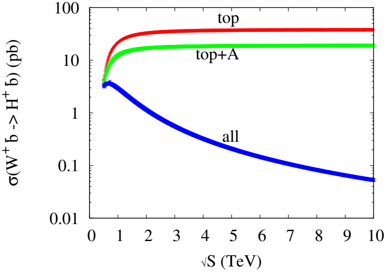
$\sum_i P_i Y_i^S = 0$

Subprocess cross section: strong cancellation

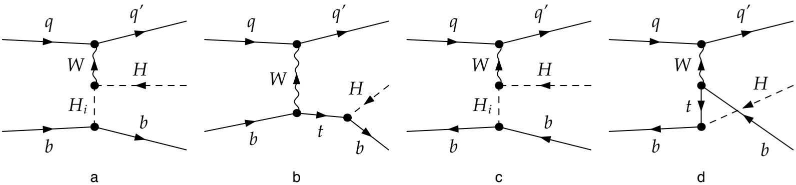
MSSM: $M_A \approx M_H \approx 400$ GeV, $\tan\beta = 30$

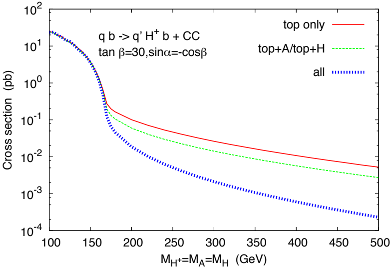


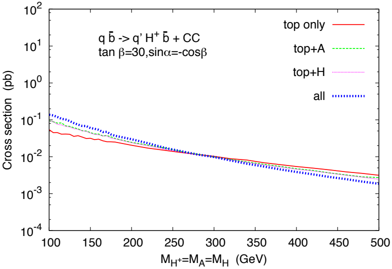




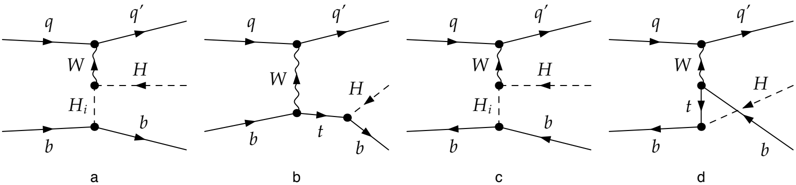
$\{qb, q\bar{b}\} \to q'H^+b$ at LHC-14 TeV

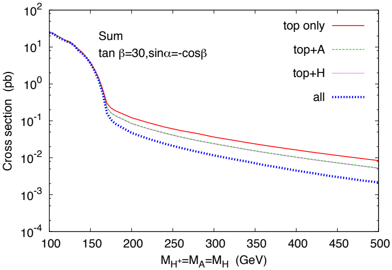






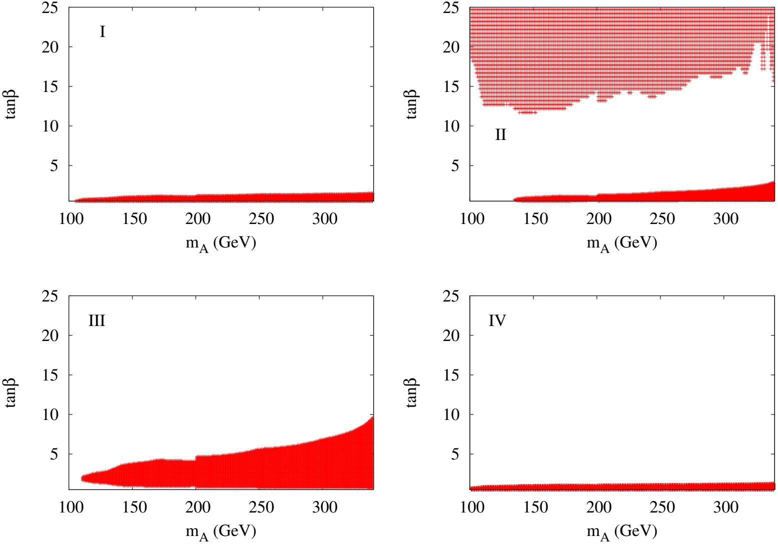
$pp \to jH^+ b$ at LHC 14 TeV



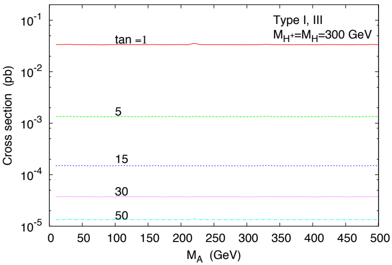


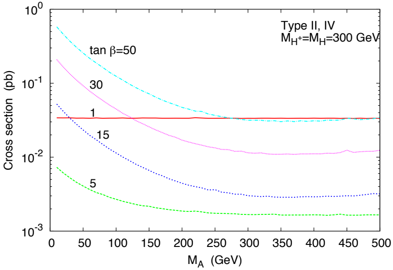
Large tan β and τ data at the LHC $7 \oplus 8$ TeV

2HDM-I , IV: $A^0\tau\tau \propto \frac{1}{\tan\beta}$ 2HDM-II , III: $A^0\tau\tau \propto \tan\beta$



$pp \to jH^+b$ and light A^0





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 $W^{\pm *} \to l\nu$ $(l = e, \mu)$.
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- $\sigma(pp \to t\bar{t} \to tbH^{+} \to tbWA)$ could be sizeable
- We studied b- and $\bar{b}$-initiated processes of $pp \to jH^{\pm}b/\bar{b}$ in the 2HDM at the LHC-14 in the decoupling limit
- Due to unitarity, we have shown strong cancellations between the top diagram and the W-$H_i(H_i = h, H, A)$ diagrams which rendered the process very suppressed.
- Light CP-odd can enhance $pp \to jH^{\pm}b/\bar{b}$