

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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- Introduction
- Bosonic decays of charged Higgs: $H^\pm \rightarrow W^\pm A/W^\pm h$,
(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: $pp \rightarrow H^\pm bj$
(based on hep-ph/1509.00978 , JHEP'16, A.A, K.M Cheung, J.S.Lee and C.T-Lu)
- subprocess $W^\pm b \rightarrow bH^\pm$ 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

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.

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

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

leads to FCNCs at tree level.

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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)	$Y_{u,\ell}^1 = Y_d^2 = 0$

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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 $H^\pm = -s_\beta \phi_1^\pm + c_\beta \phi_2^\pm$.

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

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

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

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

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

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Sum rules: (Gunion, Haber, Wudka PRD'91):

- $\sum_i (H_i VV)^2 = 1$
- $(H_i VV)^2 + |H^\pm W^\mp H_i|^2 = 1$ for $i = 1, 2, 3$
- $\sin^2 \beta [(Y_{i,t}^S)^2 + (Y_{i,t}^P)^2] + \cos^2 \beta [(Y_{i,b}^S)^2 + (Y_{i,b}^P)^2] = 1$

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 $pp \rightarrow t\bar{t} \rightarrow t\bar{b}H^- + \text{c.c.}$

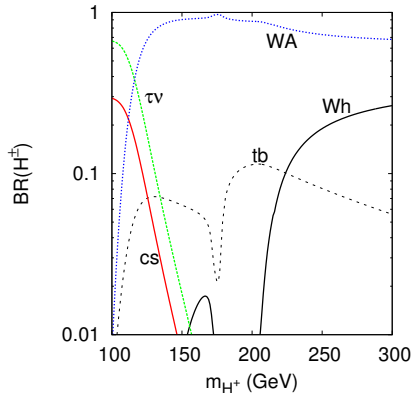
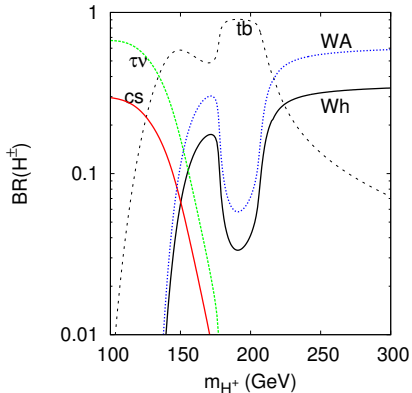
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- various direct production modes:
 - QCD: $gb \rightarrow tH^-$ and $gg \rightarrow t\bar{b}H^-$,
 - $gg \rightarrow W^\pm H^\mp$ (loop),
 - $b\bar{b} \rightarrow W^\pm H^\mp$
 - $q\bar{q} \rightarrow \gamma, Z \rightarrow H^+H^-$,
 - $gg \rightarrow H^+H^-$ (loop)
 - $q\bar{q}' \rightarrow W^* \rightarrow \phi H^\pm$ where $\phi = h^0, H^0, A^0$,

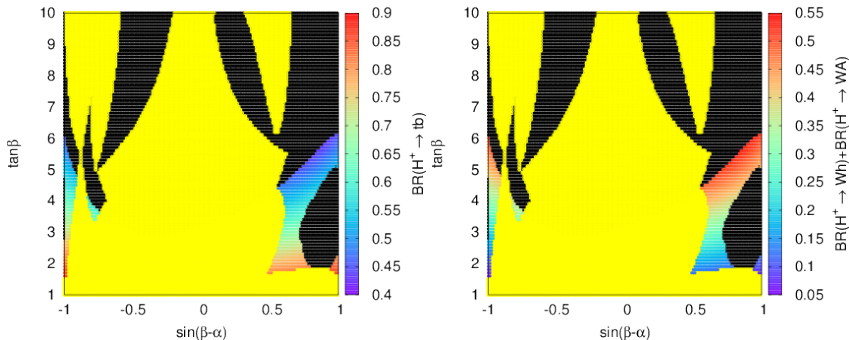
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 - $gg \rightarrow H^+H^-$ (loop)
 - $q\bar{q}' \rightarrow W^* \rightarrow \phi H^\pm$ where $\phi = h^0, H^0, A^0$,
- Resonant production: $c\bar{s}, c\bar{b} \rightarrow H^+$
- $W - Higgs$ fusion : $qb \rightarrow q'H^+b$
(See "Prospects for charged 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

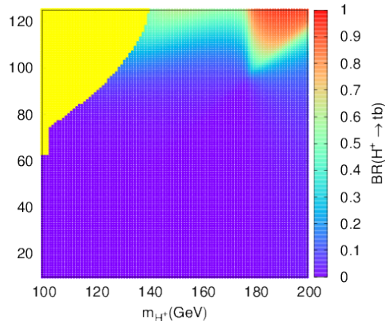
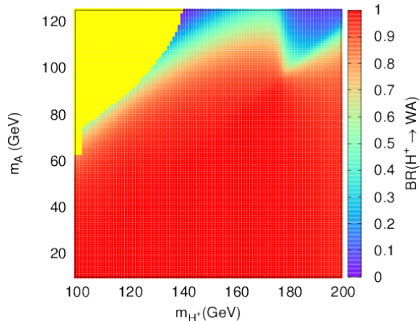


Yellow excluded by data, black by theoretical constraints

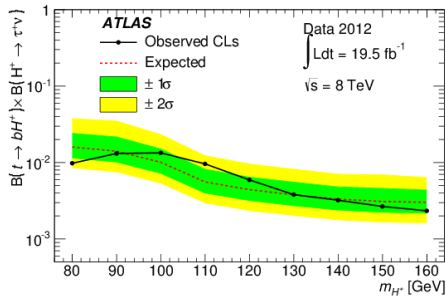
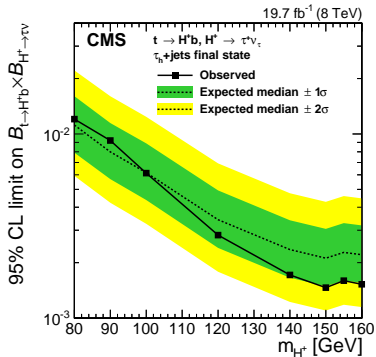


$$W^\pm H^\mp A \propto \frac{g}{2}, \quad W^\pm H^\mp h \propto \frac{g}{2} \cos(\beta - \alpha), \quad W^\pm H^\mp H \propto \frac{g}{2} \sin(\beta - \alpha)$$

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

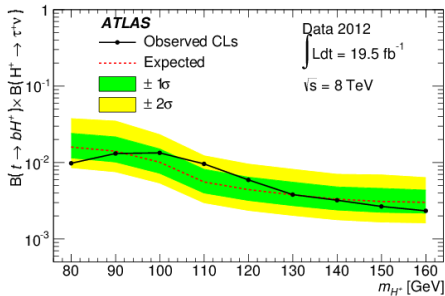
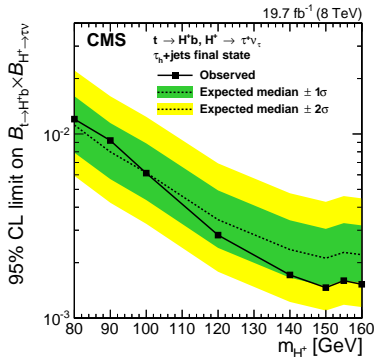


ATLAS and CMS Limit on H^\pm : low mass



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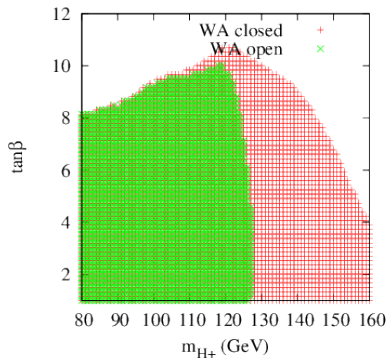
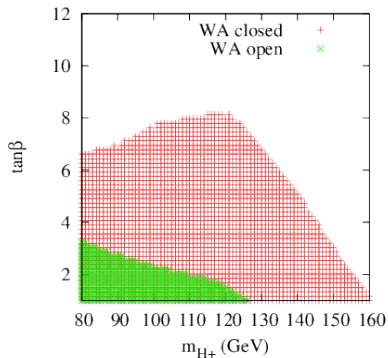
$$Br(t \rightarrow b H^+) = \frac{\Gamma(t \rightarrow b H^+)}{\Gamma(t \rightarrow b H^+) + \Gamma(t \rightarrow b W)} : \text{ depends only on } (\tan \beta, m_{H^\pm})$$

Implication for 2HDM

- In 2HDM-II and IV: $m_{H^\pm} > 580$ GeV for any $\tan \beta$
(Misiak, Steinhauser '2017)
- in 2HDM-I for $\tan \beta \geq 2-3$, no limit
- in 2HDM-III, light charged Higgs ≤ 200 GeV with large $\tan \beta > 30$ is excluded from $\tau \rightarrow \mu\nu\nu$

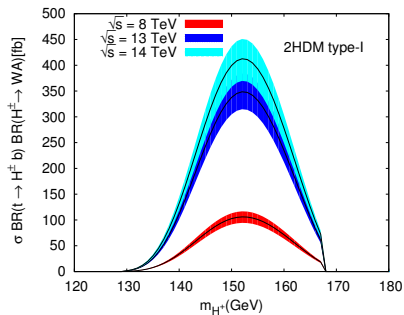
(T. Enomoto and R. Watanabe JHEP'16)

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



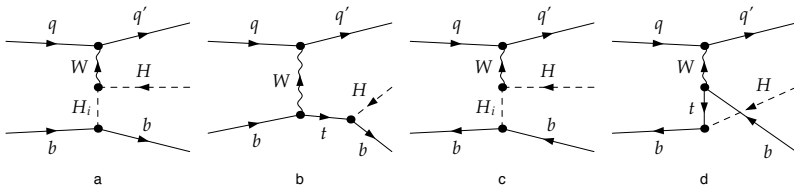
$$\sigma(pp \rightarrow t\bar{t}) \times \text{BR}(t \rightarrow H^\pm b) \times \text{BR}(H^\pm \rightarrow W^{\pm*} \phi),$$

$$\phi = A, h = 125 \text{ GeV}$$



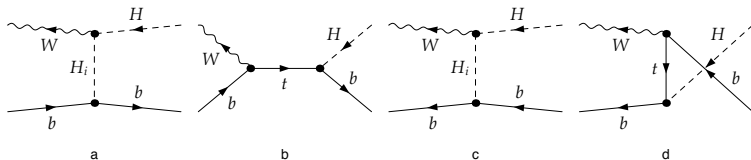
$W - H_i$ fusion: $qb \rightarrow q'H^+b$

- 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 LHCHSWG-2015-001)
- $W - H_i$ fusion process (MSSM case: S. Moretti, K. Odagiri, PRD'1997)



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

- In $q b/\bar{b} \rightarrow q' H^\pm b/\bar{b}$ 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
- $W^+(q_1) b(p_1) \rightarrow H^+(q_2) b(p_2)$
 $W^+(q_1) \bar{b}(p_1) \rightarrow H^+(q_2) \bar{b}(p_2)$
- use the effective W approximation



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

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

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

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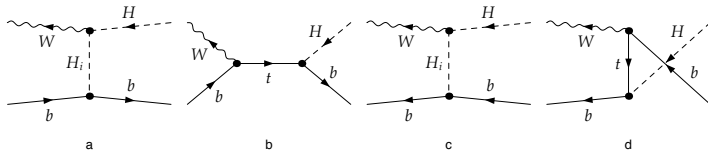
$$S_i = c_\beta O_{\phi_{2i}} - s_\beta O_{\phi_{1i}}, \quad P_i = O_{ai}$$

In type II and IV:

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

in types I and III

$$c_L = -\frac{1}{\tan \beta}, \quad c_R = \frac{m_t}{m_b} \frac{1}{\tan \beta}; \quad Y_i^S = \frac{O_{\phi_{2i}}}{s_\beta}, \quad Y_i^P = \frac{O_{ai}}{\tan \beta}$$



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

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

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

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

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

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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.

$$\text{ii } \sum_i S_i Y_i^S = \sum_i ((c_\beta O_{\phi_{2i}} - s_\beta O_{\phi_{1i}}) \frac{O_{\phi_{1i}}}{c_\beta}) = -\tan \beta$$

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

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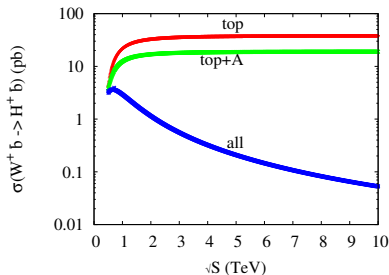
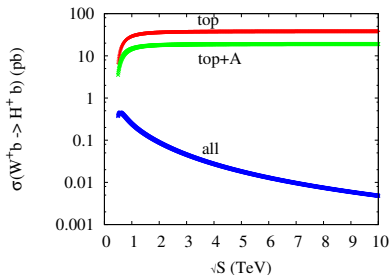
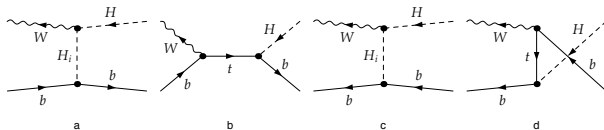
$$\text{i } 2c_L + \sum_i (S_i Y_i^S + P_i Y_i^P) = 2 \tan \beta + \sum_i S_i Y_i^S + \sum_i P_i Y_i^P = 0$$

$$\text{iii } \sum_i S_i Y_i^P = \sum_i ((c_\beta O_{\phi_{2i}} - s_\beta O_{\phi_{1i}}) (-\tan \beta O_{ai})) = 0$$

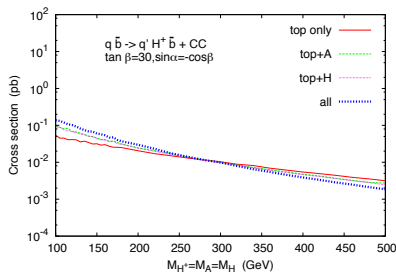
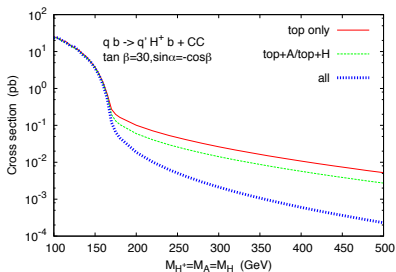
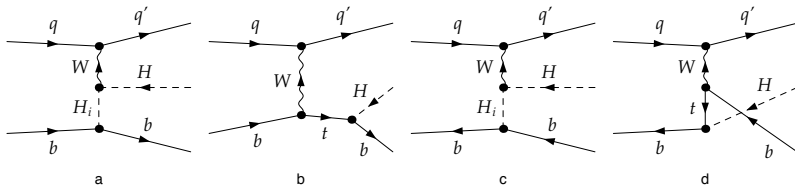
$$\sum_i P_i Y_i^S = 0$$

Subprocess cross section: strong cancellation

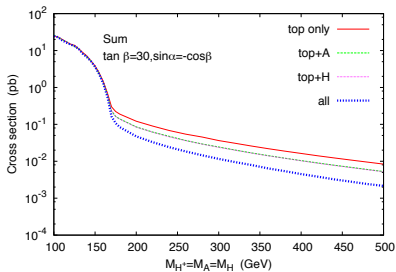
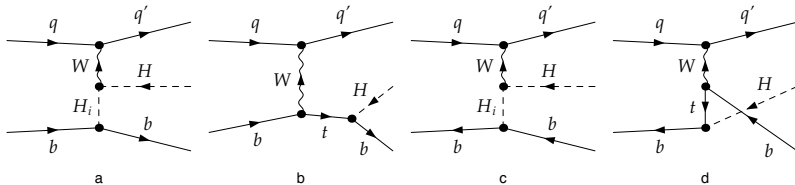
MSSM: $M_A \approx M_H \approx 400$ GeV, $\tan \beta = 30$



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



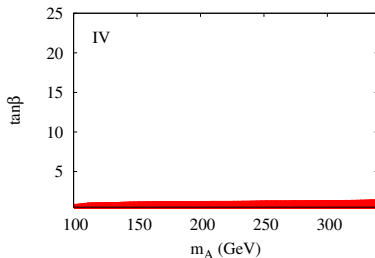
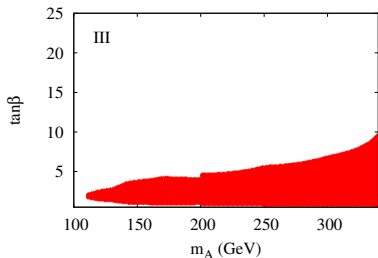
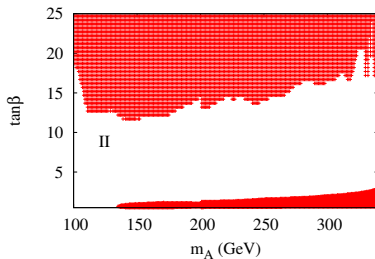
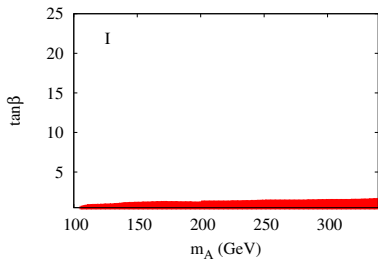
$pp \rightarrow jH^+b$ at LHC 14 TeV



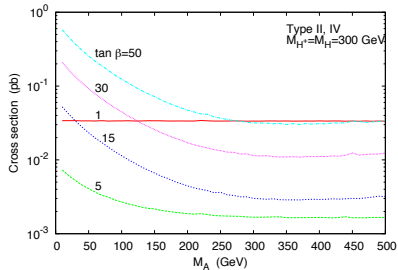
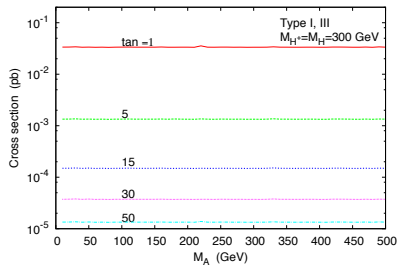
Large $\tan\beta$ and τ data at the LHC 7 \oplus 8 TeV

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

2HDM-II , III: $A^0_{\tau\tau} \propto \tan\beta$



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



- In 2HDM-I there is regions of the parameter space compliant with theoretical and experimental constraints yielding substantial BRs for $H^\pm \rightarrow W^{\pm*} h / W^{\pm*} A$ in which the $m_{H^\pm} < m_t - m_b$, wherein $W^{\pm*} \rightarrow l\nu$ ($l = e, \mu$).
- $\sigma(pp \rightarrow t\bar{t} \rightarrow tbH^+ \rightarrow tbWA)$ could be sizeable

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- $\sigma(pp \rightarrow t\bar{t} \rightarrow tbH^+ \rightarrow tbWA)$ could be sizeable
- We studied b - and \bar{b} -initiated processes of $pp \rightarrow jH^\pm b/\bar{b}$ 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 $pp \rightarrow jH^\pm b/\bar{b}$