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# Light charged Higgs boson with dominant decay to quarks and its search at LHC and future colliders [Phys.Rev.D98,115024(2018)]

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# Overview

# 1.Motivation

# Motivation of charged Higgs and MHDM(Multi-Higgs-Doublets-Model)

- A neutral-charged Spin 0 Higgs Boson has been detected at LHC
- Existence of Charged Higgs boson?

| | SPIN 0 | SPIN 1/2 | SPIN 1 |
|---|---|---|---|
| Charge 0 | $H$ | $\nu_e, \nu_\mu, \nu_\tau$ | $\gamma, Z, g$ |
| Charge $\pm 1$ | $H^\pm$ ? | $e^\pm, \mu^\pm, \tau^\pm, u, d, c, s, t, b$ | $W^\pm$ |

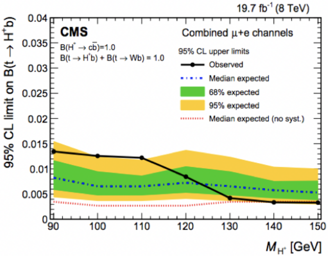
Reason for MHDM:

- Supersymmetry.
- Three generations of fermions. More generations (doublets) of scalars?
- Extra sources of CP-violation.

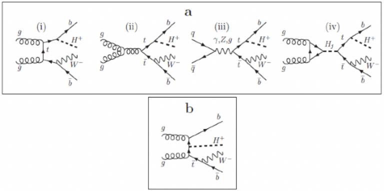
# 2.Charged Higgs Production

# Charged Higgs production mechanisms

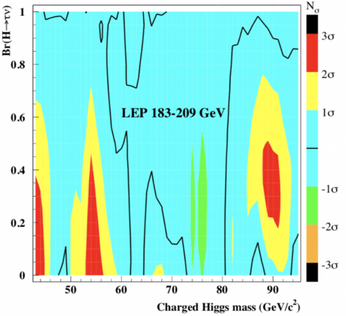
LHC [arXiv:1808.06575]



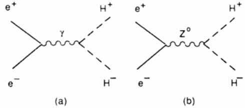

$$gg, q\bar{q}, b\bar{b}(\to t\bar{t} \to b\bar{t}H^+) \to b\bar{b}W^-H^+,$$
$$gg\ (\to b\bar{t}H^+) \to b\bar{b}W^-H^+$$




LEP [arXiv:1301.6065]




$$e^+e^- \to H^+H^-$$



# 3.2HDM (Two-Higgs-Doublet-Model)

# Charged Higgs in 2HDM

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (v_1 + \phi_1^{0,r} + i\phi_1^{0,i})/\sqrt{2} \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ (v_2 + \phi_2^{0,r} + i\phi_2^{0,i})/\sqrt{2} \end{pmatrix}.$$

$[v_1^2 + v_2^2 = v^2 = 2m_W^2 g]$

- To prevent tree-level Flavour-Changing-Neutral-Current(FCNC), Glashow and Weinberg introduced Natural Flavour Conservation (NFC). [Glashow and Weinberg, Phys. Rev. D 15 (1977) 1958]
- Each Higgs field couples to one fermion type only with NFC.

$$\mathcal{L}_{H^\pm} = -H^+\{\frac{\sqrt{2}V_{ud}}{v}\bar{u}(m_d X P_R + m_u Y P_L)d + \frac{\sqrt{2}m_l}{v} Z\bar{\nu}_L l_R\} + H.c.$$

- Four types of 2HDM (without tree-level FCNC) $[tan\beta = \frac{v_2}{v_1}]$

| | $X$ | $Y$ | $Z$ |
|---|---|---|---|
| Type I | $-\cot\beta$ | $\cot\beta$ | $-\cot\beta$ |
| Type II | $\tan\beta$ | $\cot\beta$ | $\tan\beta$ |
| Lepton-specific | $-\cot\beta$ | $\cot\beta$ | $\tan\beta$ |
| Flipped | $\tan\beta$ | $\cot\beta$ | $-\cot\beta$ |

# 4.3HDM (Three-Higgs-Doublet-Model)

# Charged Higgs in 3HDM

- Three isospin fields $\Phi_i (i = 1, 2, 3)$ are introduced.
- Two physical charged Higgses $(H_i^{\pm}, i = 2, 3)$.
- The mass matrix of the charged scalars is diagonalized by the $3 \times 3$ matrix $U$ :
  [Akeroyd, AG, Moretti, S and Hernandez-Sanchez,arXiv:1203.5769]

$$\begin{pmatrix} G^+ \\ H_2^+ \\ H_3^+ \end{pmatrix} = U \begin{pmatrix} \phi_d^+ \\ \phi_u^+ \\ \phi_\ell^+ \end{pmatrix}.$$

- The Yukawa couplings X,Y,Z will depend on this $3 \times 3$ matrix $U$ rather than a single parameter $\beta$ as in 2HDM.

# 5.Mixing matrix and Yukawa couplings

# Mixing matrix $U$ in 3HDM

- The matrix $U$ can be written explicitly as a function of four parameters $\tan\beta$, $\tan\gamma$, $\theta$, and $\delta$, where

$$\tan\beta = v_2/v_1, \qquad \tan\gamma = \sqrt{v_1^2 + v_2^2}/v_3 \,.$$

- $v_1$, $v_2$, and $v_3$ are the vacuum expectation values of the three Higgs doublets.
- $\theta$ is the mixing angle between light and heavy charged Higgses
- $\delta$ is the CP-violating phase.
- The explicit form of $U$ given as :
  [Akeroyd, AG, Moretti, S and Hernandez-Sanchez,arXiv:1203.5769]

$$= \begin{pmatrix} s_\gamma c_\beta & s_\gamma s_\beta & c_\gamma \\ -c_\theta s_\beta e^{-i\delta} - s_\theta c_\gamma c_\beta & c_\theta c_\beta e^{-i\delta} - s_\theta c_\gamma s_\beta & s_\theta s_\gamma \\ s_\theta s_\beta e^{-i\delta} - c_\theta c_\gamma c_\beta & -s_\theta c_\beta e^{-i\delta} - c_\theta c_\gamma s_\beta & c_\theta s_\gamma \end{pmatrix}$$

Here $s$, $c$ denote the sine or cosine of the respective parameter.

# Yukawa Couplings of light charged Higgs in 3HDM

$$U = \begin{pmatrix} s_\gamma c_\beta & s_\gamma s_\beta & c_\gamma \\ -c_\theta s_\beta e^{-i\delta} - s_\theta c_\gamma c_\beta & c_\theta c_\beta e^{-i\delta} - s_\theta c_\gamma s_\beta & s_\theta s_\gamma \\ s_\theta s_\beta e^{-i\delta} - c_\theta c_\gamma c_\beta & -s_\theta c_\beta e^{-i\delta} - c_\theta c_\gamma s_\beta & c_\theta s_\gamma \end{pmatrix}$$

- Yukawa couplings are:

$$X = \frac{U^\dagger_{d2}}{U^\dagger_{d1}}, \qquad Y = -\frac{U^\dagger_{u2}}{U^\dagger_{u1}}, \qquad Z = \frac{U^\dagger_{\ell 2}}{U^\dagger_{\ell 1}}.$$

- Five versions of 3HDM with NFC.

| | $u$ | $d$ | $\ell$ |
|---|---|---|---|
| 3HDM(Type I) | 2 | 2 | 2 |
| 3HDM(Type II) | 2 | 1 | 1 |
| 3HDM(Lepton-specific) | 2 | 2 | 1 |
| 3HDM(Flipped) | 2 | 1 | 2 |
| 3HDM(Democratic) | 2 | 1 | 3 |

# Constraints on X,Y,Z

$$U = \begin{pmatrix} s_\gamma c_\beta & s_\gamma s_\beta & c_\gamma \\ -c_\theta s_\beta e^{-i\delta} - s_\theta c_\gamma c_\beta & c_\theta c_\beta e^{-i\delta} - s_\theta c_\gamma s_\beta & s_\theta s_\gamma \\ s_\theta s_\beta e^{-i\delta} - c_\theta c_\gamma c_\beta & -s_\theta c_\beta e^{-i\delta} - c_\theta c_\gamma s_\beta & c_\theta s_\gamma \end{pmatrix}$$

- The constraints on X and Y couplings come from $Z \to b\bar{b}$ (LEP)
- $b \to s\gamma$ constrains the real part of $(XY^*)$. For $m_{H^\pm} = 100$ GeV case: [Michael Trott, Mark B. Wise,arXiv:1009.2813v3]

$$-1.1 \leq \mathrm{Re}(XY^*) \leq 0.7.$$

- The Electric Dipole Moment (EDM) of the neutron gives the following constraint for $m_{H^\pm} = 100$ GeV :

$$\mathrm{Im}(XY^*) \leq 0.1.$$

# 6.Numerical results

# Production of $H^{\pm}$ for $m_{H^{\pm}} < m_t$

- Tevatron searched for $H^{\pm}$ using $p\overline{p} \to t\overline{t}$ with one top quark decaying $t \to W^{\pm}b$ and the other via $t \to H^{\pm}b$
- $$\Gamma(t \to W^{\pm}b) = \frac{G_F m_t}{8\sqrt{2}\pi}[m_t^2 + 2M_W^2][1 - M_W^2/m_t^2]^2$$
- $$\Gamma(t \to H^{\pm}b) = \frac{G_F m_t}{8\sqrt{2}\pi}[m_t^2|Y|^2 + m_b^2|X|^2][1 - m_{H^{\pm}}^2/m_t^2]^2 .$$
- $BR(t \to H^{\pm}b)$ depends on magnitudes of $|X|, |Y|$

# Dominant decay products of $H^{\pm}$ for $m_{H^{\pm}} < m_t$

- For $m_{H^{\pm}} > m_t, H^{\pm} \to tb$ dominates for all 2HDMs and 3HDMs.
- Only focus on fermions by considering addtional neutral Higgs bosons to be much heavier than $H^{\pm}$.
- $$\Gamma(H^{\pm} \to \ell^{\pm}\nu) = \frac{G_F m_{H^{\pm}} m_{\ell}^2 |Z|^2}{4\pi\sqrt{2}} \ ,$$
- $$\Gamma(H^{\pm} \to ud) = \frac{3 G_F V_{ud} m_{H^{\pm}} (m_d^2 |X|^2 + m_u^2 |Y|^2)}{4\pi\sqrt{2}} \ .$$
- The mass of quarks are calculated at the scale of $m_{H^{\pm}}$
- $|X| \gg |Y|, |Z|, BR(H^{\pm} \to cb)$ could be dominant ($\sim$ 80%).

# Dominant $cb$ decay from light $H^{\pm}$ in 3HDM

Benefit of $cb$:

- Main background is WW, and $W^{\pm} \to cb$ is small due to small CKM matrix element ($V_{cb} \approx 0.04$).
- Using b-tagging to select signal events and to suppress the background.

Results of study:

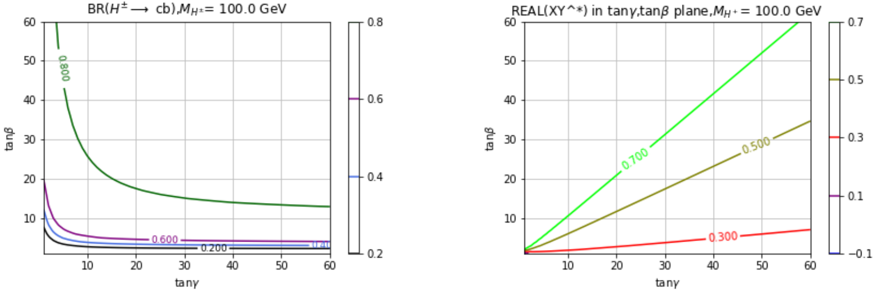
- Input fundamental parameters for $X, Y, Z$ are varied as follows :

$$\begin{array}{c} -\frac{\pi}{2} \leq \theta \leq 0 \\ 0 \leq \delta \leq 2\pi \end{array} ; \begin{array}{c} 1 \leq tan\beta \leq 60 \\ 1 \leq tan\gamma \leq 60 \end{array}$$

- 2 models (Flipped and Democratic) can have large $BR(cb)$.

| | $u$ | $d$ | $\ell$ |
|---|---|---|---|
| 3HDM(Type I) | 2 | 2 | 2 |
| 3HDM(Type II) | 2 | 1 | 1 |
| 3HDM(Lepton-specific) | 2 | 2 | 1 |
| 3HDM(Flipped) | 2 | 1 | 2 |
| 3HDM(Democratic) | 2 | 1 | 3 |

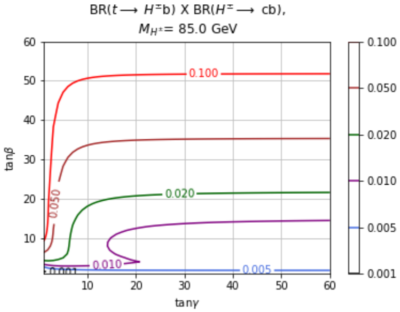
# Results for $BR(H^{\pm} \to cb)$ in Flipped 3HDM in $[tan\beta, tan\gamma]$ plane



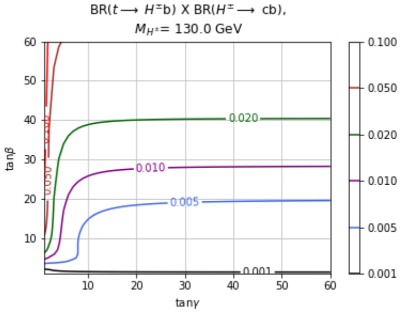

(a) (b)

Figure: Branching ratio of $H^{\pm}$ decay through $cb$ channel with $\theta = -\pi/3, \delta = 0, M_{H^{\pm}} = 100\ GeV$ in $[tan\beta, tan\gamma]$ plane. *Left Panel*: Contours of $BR(H^{\pm} \to cb)$. *Right Panel* :Contours of $Re(XY^{*})$ ($b \to s\gamma$ constraint).

# Results for $BR(t \to H^{\pm}b) \times BR(H^{\pm} \to cb)$ in Flipped 3HDM in $[tan\beta, tan\gamma]$ plane at LHC




(a)




(b)

Figure: $BR(t \to H^{\pm}b) \times BR(H^{\pm} \to cb)$ in $[tan\beta, tan\gamma]$ plane with $\theta = -\pi/3, \delta = 0, M_{H^{\pm}} = 85, 130\ GeV$. *Left Panel*: $M_{H^{\pm}} = 85\ GeV$ in $[tan\beta, tan\gamma]$ plane. *Right Panel* :$M_{H^{\pm}} = 130\ GeV$ in $[tan\beta, tan\gamma]$ plane.

# Results for $BR(H^{\pm} \to cb)$ in Democratic 3HDM in $[\delta, \theta]$ plane

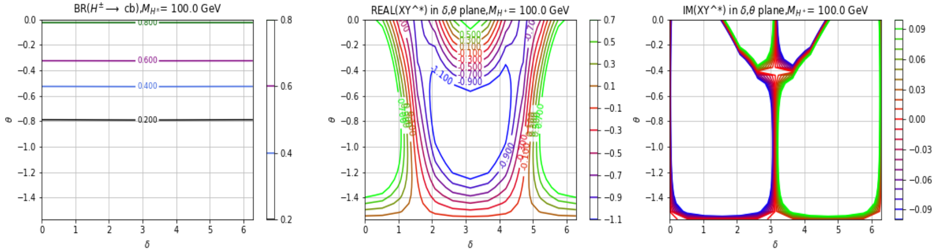



Figure: Branching ratio of $H^{\pm}$ decay through $cb$ channel with $tan\beta = 40, tan\gamma = 10, M_{H^{\pm}} = 100\ GeV$ in $[\delta, \theta]$ plane. *Left Panel*: Contours of $BR(H^{\pm} \to cb)$. *Central Panel* : Contours of $Re(XY^*)$ in $[\delta, \theta]$ plane($b \to s\gamma$ constraint). *Right Panel* : Contours of $Im(XY^*)$ in $[\delta, \theta]$ plane (EDM constraint).

# 7.Collider Searches and Detection Prospects

# Collider Searches and Detection Prospects on charged Higgs

- Tevatron set the limit on $80 \text{ GeV} \leq m_{H^\pm} \leq 90 \text{ GeV}$ : [DØ , Physics Letters B 682 (2009) 278286] $BR(t \to H^\pm b) < 0.21$ for $50\% \leq BR(H^\pm \to cs) \leq 100\%$
- At LHC, no current sensitivity for $80 \text{ GeV} \leq m_{H^\pm} \leq 90 \text{ GeV}$.
- LEP2 searches found a $2\sigma$ excess of events around $m_{H^\pm} = 89$ GeV.
- Production of $H^\pm$ at LHC depends on magnitude of $|X|, |Y|$.
- Production of $H^\pm$ at $e^+e^-$ colliders does not depend on magnitude of $|X|, |Y|$.
- FCC-ee, CEPC, and $e^+e^-$ Linear Collider (ILC) could be used to discover $H^\pm$ with small $|X|, |Y|$ in region $80 \text{ GeV} \leq m_{H^\pm} \leq 90$ GeV (which would escape detection at LHC).

# Summary

- We have studied the lightest charged Higgs in 3HDM with $m_{H^\pm} < m_t$.
- Two types of 3HDM (Flipped and Democratic) can have large $BR(H^\pm \to cb)$.
- First search for $t$ to $H^\pm b$ followed by $H^\pm$ to $cb$ carried out at LHC recently (August,2018), with limits for 90 GeV $\leq m_{H^\pm} \leq$ 150 GeV.
- Currently no sensitivity to 80 GeV $\leq m_{H^\pm} \leq$ 90 GeV, but sensitivity expected in the future.
- If light $H^\pm$ with small $|X|, |Y|$ escapes detection at LHC, then it will be discovered at future $e^+e^-$ colliders.

# Thanks for Listening

# References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