Light charged Higgs boson with dominant decay to quarks and its search at LHC and future colliders [Phys. Rev. D 98, 115024]

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Overview

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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	ν_e, ν_μ, ν_τ	γ, Z, g
Charge ± 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.

Light charged Higgs in 3HDM

- Three isospin fields $\Phi_i(i = 1, 2, 3)$ are introduced, and each contain a vacuum expectation value with sum rule

$$\sum_i v_i^2 = v_{sm}^2 = (246 GeV)^2$$

- The mass matrix of the charged scalars is diagonalized by the 3×3 matrix U :[C. Albright,J. Smith and S.-H.H.Tye]

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

- By considering heavy H_3^+ decouples, the light charged Higgs H_2^+ can have:

$$\mathcal{L}_{H_2^\pm} = -H_2^+\{\frac{\sqrt{2}V_{ud}}{v_{sm}}\bar{u}(m_d X P_R + m_u Y P_L)d + \frac{\sqrt{2}m_l}{v_{sm}} Z \bar{\nu}_L l_R\} + H.c.$$

- The lightest charged Higgs Yukawa couplings X,Y,Z will depend on this matrix U.

Mixing matrix U in 3HDM

- The matrix U can be written explicitly as a function of four parameters $\tan\beta$, $\tan\gamma$, θ, and δ, 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.
- θ is the mixing angle between light and heavy charged Higgses
- δ is the CP phase.
- The explicit form of U given as :
  [C. Albright,J. Smith and S.-H.H.Tye]

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

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

Yukawa Couplings of light charged Higgs in 3HDM

- As heavy H_3^+ decouples, Yukawa couplings for H_2^+ can be isolated:

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

- Five versions of 3HDM with NFC.

	u	d	ℓ
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

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

- The constraints on X and Y couplings come from $Z \to b\bar{b}$
- Coupling Z is constrained from $Z \to \tau\bar{\tau}$
- $b \to s\gamma$ 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 (or CP-violation arised from charged Higgs couplings) gives the following constraint for $m_{H^\pm} = 100$ GeV :

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

Study $H^{\pm}$ decay through Yukawa couplings

- For $m_{H^{\pm}} > m_t, H^{\pm} \to tb$ could dominate 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:

- Strategy to distinguish between 2HDM and 3HDM.
- Main background is WW, and $W^{\pm} \to cb$ is small due to small CKM matrix element ($V_{cb} \approx 0.04$).
- Use b-tagging to select signal events and to suppress the background.

Results of study:

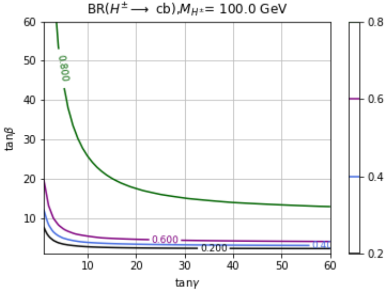
- Input fundamental parameters for X, Y, Z are varied as follows :

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

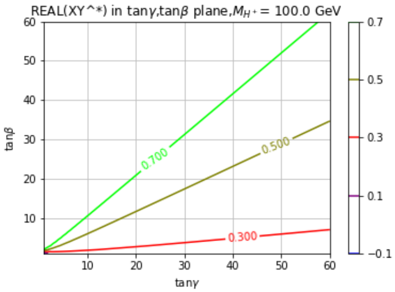
- 2 types (Flipped and Democratic) can have large $BR(cb)$.

	u	d	ℓ
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 $BR(H^{\pm} \to cb)$ in Democratic 3HDM in $[\delta, \theta]$ plane

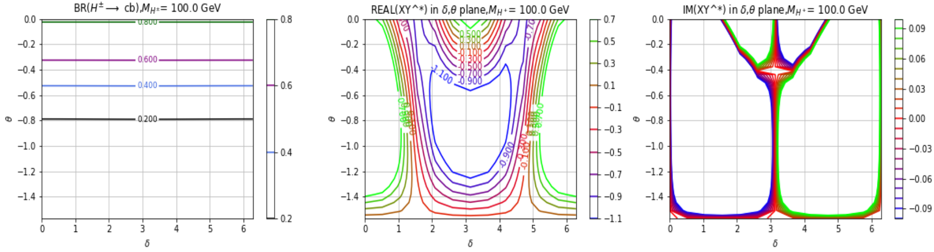


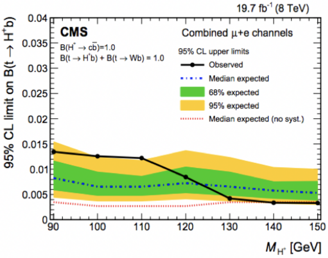
Figure: Branching ratio of $H^{\pm}$ decay through cb channel with $tan\beta = 40, tan\gamma = 10, M_{H^{\pm}} = 100\ GeV$ in $[\delta, \theta]$ plane. *Left Panel*: Contours of $BR(H^{\pm} \to cb)$. *Central Panel* : Contours of $Re(XY^*)$ in $[\delta, \theta]$ plane($b \to s\gamma$ constraint). *Right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

LHC collider search approach

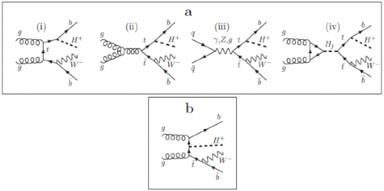
- Tevatron searched for $H^{\pm}$ using $p\bar{p} \to t\bar{t}$ with one top quark decaying $t \to W^{\pm}b$ and the other via $t \to H^{\pm}b$
- Production of $H^{\pm}$ for $m_{H^{\pm}} < m_t$ at LHC is similar.
- $$\Gamma(t \to W^{\pm}b) = \frac{G_F m_t}{8\sqrt{2}\pi}[m_t^2 + 2M_W^2][1 - M_W^2/m_t^2]^2$$
- $$\Gamma(t \to H^{\pm}b) = \frac{G_F m_t}{8\sqrt{2}\pi}[m_t^2|Y|^2 + m_b^2|X|^2][1 - m_{H^{\pm}}^2/m_t^2]^2 \,.$$
- $BR(t \to H^{\pm}b)$ depends on magnitudes of $|X|, |Y|$. It affects production rate of charged Higgs.
- LEP search involves only gauge couplings and unknown charged Higgs mass parameter.

Recent charged Higgs research from colliders

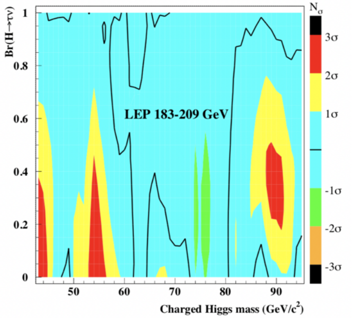
LHC [arXiv:1808.06575]



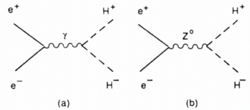
$$gg, q\bar{q}, b\bar{b}(\to t\bar{t} \to b\bar{t}H^+) \to b\bar{b}W^-H^+,$$
$$gg\ (\to b\bar{t}H^+) \to b\bar{b}W^-H^+$$



LEP [arXiv:1301.6065]



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



Collider searches with mass limits

- Tevatron set the limit on 80 GeV $\leq m_{H^{\pm}} \leq$ 90 GeV [DØ , Physics Letters B 682 (2009) 278–286] : $BR(t \to H^{\pm} b) < 0.21$ for 50% $\leq BR(H^{\pm} \to cs) \leq$ 100%
- At LHC, no current sensitivity for 80 GeV $\leq m_{H^{\pm}} \leq$ 90 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 $|X|, |Y|$.
- LEP2 searches found a 2 and more σ excess of events around $m_{H^{\pm}} = 89$ GeV.
- ILC, CEPC, and FCC-ee could be used to discover $H^{\pm}$ with small $|X|, |Y|$ in region 80 GeV $\leq m_{H^{\pm}} \leq$ 90 GeV (which would escape detection at LHC).

Summary

- We have studied the lightest charged Higgs case in 3HDM with $m_{H^\pm} < m_t$.
- Two types of 3HDM (Flipped and Democratic) can have large $BR(H^\pm \to cb)$. b-tagging could be a good strategy to search for charged Higgs signals.
- 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 (Blind Spot), then it still could be searched at future e^+e^- colliders.
- Promotion of higher energy e^+e^- colliders is necessary.

Thanks for Listening

References

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