Light charged Higgs boson with dominant decay to cb quarks and b-tagging search at e^+e^- colliders [arXiv:1810.05403],[arXiv:1908.00826]

Muyuan Song

University of Southampton

September 14, 2019

Supervisors: Prof. Stefano Moretti
Dr.Andrew Akeroyd

Overview

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

- 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, Dark Matter...
- Extra sources of CP-violation (Matter-antimatter asymmetry)...

Light charged Higgs in 3HDM (Weinberg)

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

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i^{0,real} + i\phi_i^{0,imag})/\sqrt{2} \end{pmatrix}, \sum_i v_i^2 = v_{sm}^2 = (246\,GeV)^2$$

- A unitary 3×3 matrix U is introduced in order to specify charged Higgs mass eigenstates from charged fields rotation: [C. Albright,J. Smith and S.-H.H.Tye] [Y. Grossman]

$$\begin{pmatrix} G^+ \\ H_2^+ \\ H_3^+ \end{pmatrix} = U \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \\ \phi_3^+ \end{pmatrix}.$$

Yukawa Couplings of lighter charged Higgs in 3HDM

- We take H_3^+ to be much heavier than H_2^+, the Yukawa interactions of H_2^+ is:

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

- Yukawa couplings for H_2^+ can be written as:

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

- Five independent versions of Yukawa interactions of 3HDM with NFC based on charged assignment of two softly-broken discrete Z_2 symmetries.

	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

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 H_2^+ and H_3^+
- δ is the CP-violating 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.

Experiment constraints on X,Y

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

- $b \to s\gamma$ constrains the real part of (XY^*). For $m_{H^\pm} = 100$ GeV case within 2σ interval: [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 (CP-violation can manifest from Yukawa couplings) gives the following constraint for $m_{H^\pm} = 100$ GeV :

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

Study dominant tree-level fermionic decay modes of light $H^{\pm}$

- Take $M_{H^{\pm}} < M_t$ limit and study leading decays.
- Only focus on fermions by considering additional neutral scalars to be much heavier than $H^{\pm}$.
- $|X| \gg |Y|, |Z|, BR(H^{\pm} \to cb)$ could be dominant ($\sim$ 80%).
- Study BR($H^{\pm} \to cb$) for different types of 3HDM as function of mixing matrix parameters ($\tan\beta$, $\tan\gamma$, θ, δ).
- 2 types (Flipped and Democratic) can have large $BR(H^{\pm} \to cb)$.

	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

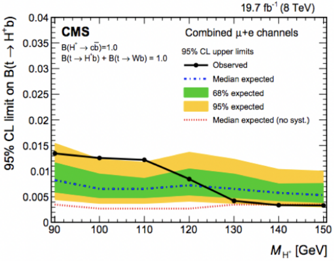
Dominant cb decay from light $H^{\pm}$ in 3HDM

Benefit of cb:

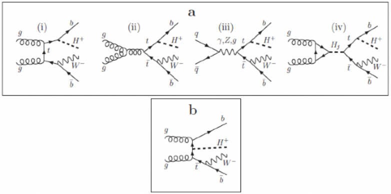
- $H^{\pm} \to cb$ can be large in Flipped 2HDM for $M_{H^{\pm}} \leq M_t$, but $M_{H^{\pm}} \leq M_t$ scenario is ruled out by $b \to s\gamma$ constraint.
- In 3HDM, large $H^{\pm} \to cb$ and $M_{H^{\pm}} \leq M_t$ is allowed by $b \to s\gamma$.
- Search gap at LHC within region 80 GeV $\to$ 90 GeV ($M_{H^{\pm}} \sim M_w$).
- Background to $H^{\pm} \to cb$ from $W^{\pm} \to cb$ 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.

Search for light charged Higgs from LHC and LEP2

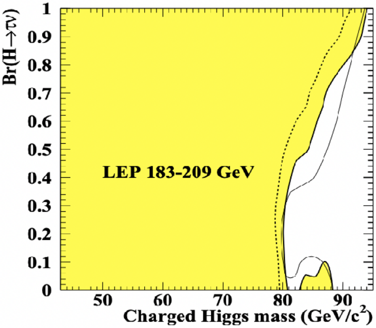
LHC [arXiv:1808.06575]



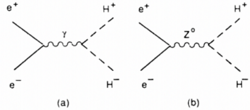
$$gg, q\bar{q}, b\bar{b}(\to t\bar{t} \to b\bar{t}H^+) \to b\bar{b}W^-H^+,$$
$$gg\ (\to b\bar{t}H^+) \to b\bar{b}W^-H^+$$



LEP [arXiv:1301.6065]



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



Prospects for searches for $H^{\pm}$ at LEP2 within mass region 80 GeV $\rightarrow$ 90 GeV

- LHC search covered (cb/cs and $\tau\nu$), while LEP search only covered (cs and $\tau\nu$). But LHC did not cover mass between 80 and 90 GeV.
- LEP search did not cover b-tagging strategy.
- We took 4-jet decay searches ($cs/cb + cb/cs$) and 2-jet decay searches ($cs/cb + \tau\nu$) from $\sigma(e^+e^- \rightarrow H^+H^-)$
- Requiring exactly two and exactly one b-jet in 4-jet search / exactly one b-jet in 2-jet search to evaluate event signals.
- Take b-tagging efficiency (e_b) and fake-b tagging efficiencies (e_c, e_s) to calculate significances ($\frac{S}{\sqrt{B}}$) based on the background event numbers from OPAL result. [Eur. Phys. J.C (2012) 72:2076]

Statistical Significances of $H^{\pm}$ tests through mass variety

$M_{H^\pm}$	80 GeV	85 GeV	89 GeV	80 GeV	85 GeV	89 GeV	
	S	S	S	$\frac{S}{\sqrt{B}}$	$\frac{S}{\sqrt{B}}$	$\frac{S}{\sqrt{B}}$	B
4j0b	69.50	46.01	29.07	2.08	1.38	0.87	1117.8
4j1b	31.74	21.01	13.27	3.32	2.20	1.39	91.44
4j2b	22.43	14.85	9.38	7.12	4.71	3.00	9.94
2j0b	26.89	17.80	11.24	1.51	1.00	0.63	316.9
2j1b	15.28	10.11	6.39	4.08	2.70	1.71	14.04

Table: Number of signal events (S), number of background events (B), and corresponding significances ($\frac{S}{\sqrt{B}}$) in single experiment at LEP2.

4-jet channels with $\text{BR}(H^\pm \to cb) = 0.8$ and $\text{BR}(H^\pm \to cs) = 0.2$.

2-jet channels with $\text{BR}(H^\pm \to \tau\nu) = 0.5$, $\text{BR}(H^\pm \to cb) = 0.4$ and $\text{BR}(H^\pm \to cs) = 0.1$.

Summary

- We have studied the scenario of the lighter charged Higgs in 3HDM with $m_{H^\pm} < m_t$.
- Two types of 3HDM (Flipped and Democratic) can have large $BR(H^\pm \to cb)$. b-tagging could be a good strategy to search for charged Higgs signals.
- LHC searched for $H^\pm \to cb, cs, \tau\nu$ but did not cover mass region between 80 to 90 GeV for hadronic decays. LEP only searched for $H^\pm \to cs$ and $\tau\nu$ in that mass region.
- Our analysis showed the significances of $H^\pm$ with large BR($H^\pm \to cb$) can be increased after b-tagging in both 4-jets and 2-jets channels .
- We suggest an updated LEP2 search that includes b-tagging in the mass region 80 $\to$ 90 GeV.

Thanks for Listening

Backup slides

3HDM Scalar potential under $Z_2 \times Z_2$ symmetry

$$
\begin{aligned}
V = \sum_{i=1}^{3} m_{ii}^2(\Phi_i^\dagger \Phi_i) - \Big(\sum^{ij=12,13,23} m_{ij}^2(\Phi_i^\dagger \Phi_j) + H.c\Big) \\
+\frac{1}{2}\sum_{i=1}^{3} \lambda_i(\Phi_i^\dagger \Phi_i)^2 + \sum^{ij=12,13,23} \lambda_{ij}(\Phi_i^\dagger \Phi_i)(\Phi_j^\dagger \Phi_j) \\
+ \sum^{ij=12,13,23} \lambda'_{ij}(\Phi_i^\dagger \Phi_j)(\Phi_j^\dagger \Phi_i) + \frac{1}{2}\Big[\sum^{ij=12,13,23} \lambda''_{ij}(\Phi_i^\dagger \Phi_j)^2 + H.c\Big]
\end{aligned}
$$

- 18 free parameters which two are fixed by W boson mass and SM neutral Higgs mass.

Fermionic decay modes of lighter $H^{\pm}$ from LEP collider

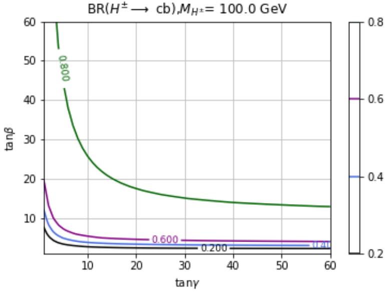
Production cross-section of $H^{\pm}$ pair:

- $$\sigma_{H^+H^-} = \frac{\pi\alpha^2}{3s}\left(\sqrt{1 - \frac{4M^2_{H^\pm}}{s}}\right)^3 F(s, M_z, \Gamma_z, \theta_w)$$

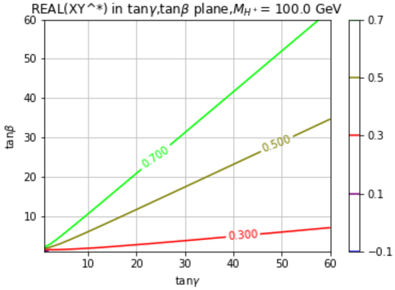
Decay channel of $H^{\pm}$:

- $$\Gamma(H^\pm \to \ell^\pm \nu) = \frac{G_F m_{H^\pm} m_\ell^2 |Z|^2}{4\pi\sqrt{2}} \ ,$$
- $$\Gamma(H^\pm \to ud) = \frac{3 G_F V_{ud} m_{H^\pm}(m_d^2|X|^2 + m_u^2|Y|^2)}{4\pi\sqrt{2}} \ .$$

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



(a)



(b)

Figure: Branching ratio of $H^{\pm} \to cb$ with $\theta = -\pi/3, \delta = 0, M_{H^{\pm}} = 100\ GeV$ in $[tan\gamma, tan\beta]$ 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

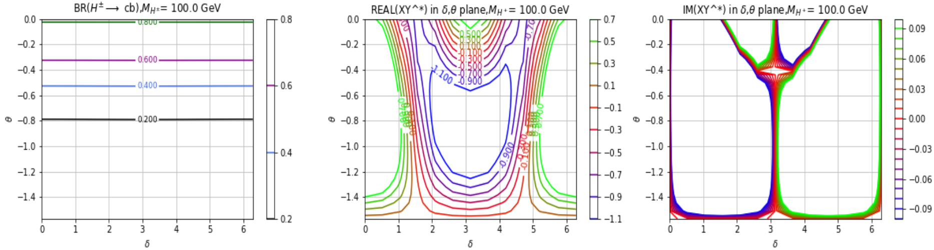


Figure: Branching ratio of $H^{\pm}$ decay through cb channel with $tan\beta = 40, tan\gamma = 10, M_{H^{\pm}} = 100\ GeV$ in $[\delta, \theta]$ plane. *Left Panel*: Contours of $BR(H^{\pm} \to cb)$. *Central Panel* : Contours of $Re(XY^*)$ in $[\delta, \theta]$ plane($b \to s\gamma$ constraint). *Right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

Results of Democratic 3HDM approach with $BR(t \to H^{\pm} b) \times BR(H^{\pm} \to cb)$ in $[\delta, \theta]$ plane for LHC

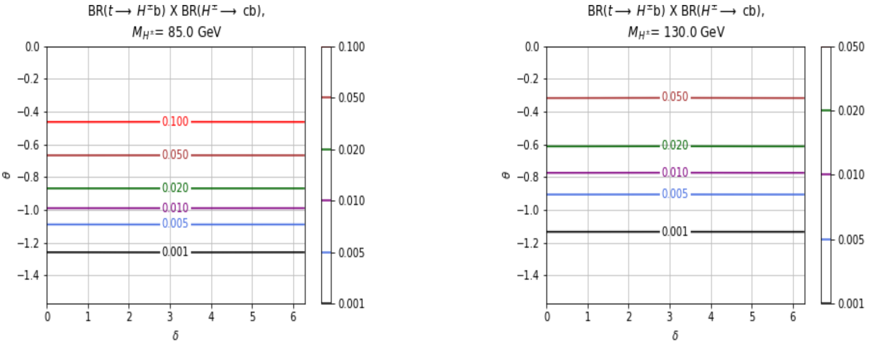
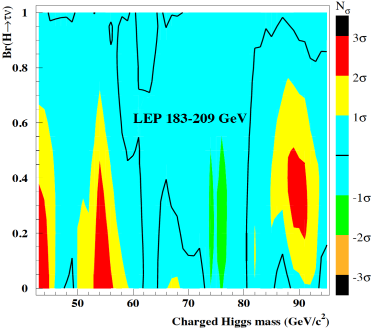
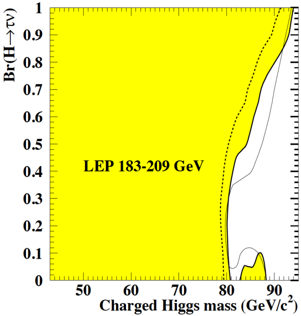


Figure: $BR(t \to H^{\pm} b) \times BR(H^{\pm} \to cb)$ in $[\delta, \theta]$ plane with $tan\beta = 40, tan\gamma = 10, M_{H^{\pm}} = 85, 130\ GeV$. *Left Panel*: $M_{H^{\pm}} = 85 GeV$ plane. *Right Panel* : $M_{H^{\pm}} = 130\ GeV$ plane.

LEP search results on $Br(H^{\pm} \to \tau\nu)$ [arXiv: 1301.6065]





Left Panel : Statistical Significance from background expectation. *Right Panel* : excluded regions in the $Br(H^{\pm} \to \tau\nu)$ vs $M_{H^{\pm}}$ plane. The shaded area is excluded at 95 % C.L or higher. Solid line is expected exclusion limit at 95 %. The dotted line is observed limit at 99.7 % C.L.

LHC collider search approach

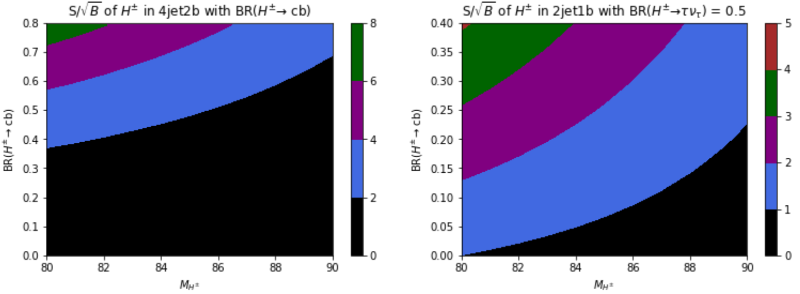
- $$\Gamma(t \to W^{\pm} b) = \frac{G_F m_t}{8\sqrt{2}\pi}[m_t^2 + 2M_W^2][1 - M_W^2/m_t^2]^2$$
- $$\Gamma(t \to H^{\pm} b) = \frac{G_F m_t}{8\sqrt{2}\pi}[m_t^2|Y|^2 + m_b^2|X|^2][1 - m_{H^{\pm}}^2/m_t^2]^2 .$$
- $BR(t \to H^{\pm} b)$ depends on magnitudes of $|X|, |Y|$. It affects production rate of charged Higgs even LHC has sensitivity for mass region 80 to 90 GeV.
- LEP search involves only gauge couplings and unknown charged Higgs mass parameter.

LEP2 and CEPC/FCC-ee Input parameters

	$\sqrt{s}$	$\mathcal{L}(\text{fb}^{-1})$	ϵ_b	ϵ_c	ϵ_j	$M_{H^\pm}$
LEP2	189 GeV $\to$ 209 GeV	0.6	0.7	0.06	0.01	80 GeV $\to$ 90 GeV
CEPC/FCC-ee	240 GeV	1000	0.7	$0.01 < \epsilon_c < 0.06$	0.01	80 GeV $\to$ 120 GeV

Table: Input parameters used in the numerical analysis at LEP2 and at CEPC/FCC-ee.

Numerical analysis in statistical Significances of $H^{\pm}$ against BR($H^{\pm} \to cb$)



(a) (b)

Figure: Values of $S\sqrt{B}$ in the plane $[M_{H^{\pm}}, BR(H^{\pm} \to cb)]$ at a single LEP2 experiment. *Left Panel*: In 4-jet channel with two b-tags, with BR($H^{\pm} \to cb$) $+ BR(H^{\pm} \to cs)$= 1. *Right Panel*: In 2-jet channel with one b-tag, with BR($H^{\pm} \to \tau\nu$) $= 0.5$, and BR($H^{\pm} \to cb$) $+ BR(H^{\pm} \to cs) = 0.5$.

References

ATLAS Collaboration and others (2018)
Evidence for the associated production of the Higgs boson and a top quark pair with the ATLAS detector
Journal Name Phys. Rev. D21 (1980) 711.

C. Albright, J. Smith and S.-H.H. Tye(1980)
Signatures for charged Higgs boson production in $e + e$ collisions
Journal Name Physical Review D,85(11),115002.

Thomas G. Rizzo (1988)
$b \to s\gamma$ in the two-Higgs-doublet model
Journal Name Physical Review D,38, 820.

DØ Collaboration (2009)

S. L. Glashow and S. Weinberg, Phys. Rev. D 15 (1977) 1958

On theories of enhanced CP violation in $B_{s,d}$ meson mixing,Michael Trott, Mark B. Wise