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

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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

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

- 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 1980] [Y. Grossman 1994]

$$\left(\begin{array}{c} G^+ \\ H_2^+ \\ H_3^+ \end{array} \right) = U \left(\begin{array}{c} \phi_1^+ \\ \phi_2^+ \\ \phi_3^+ \end{array} \right).$$

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:

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

- Five 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 1980]

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

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]

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

- 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 :

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

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 $H^{\pm}$.

Tree-level partial width of $H^{\pm}$:

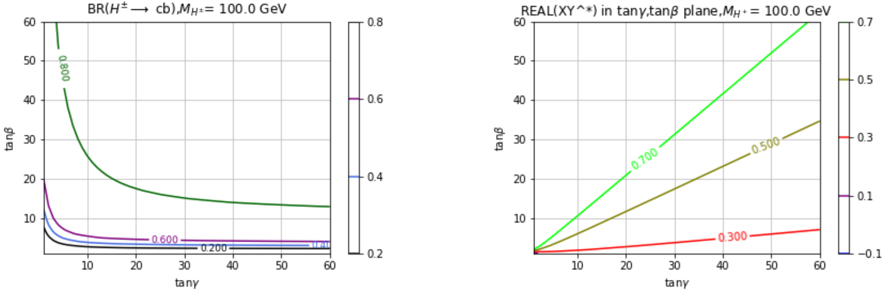
- $$\Gamma(H^{\pm} \to \ell^{\pm}\nu) = \frac{G_F m_{H^{\pm}} m_{\ell}^2 |Z|^2}{4\pi\sqrt{2}} \ ,$$
- $$\Gamma(H^{\pm} \to ud) = \frac{3 G_F V_{ud} m_{H^{\pm}} (m_d^2 |X|^2 + m_u^2 |Y|^2)}{4\pi\sqrt{2}} \ .$$

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

- $|X| \gg |Y|, |Z|$, $BR(H^{\pm} \to cb)$ could be dominant ($\sim$ 80%). [Grossman 1994, AGA/Sterling 1994]
- $BR(H^{\pm} \to cs)$ and $BR(H^{\pm} \to \tau\nu)$ are usually dominant at 2HDM / 3HDM (Type I, Type II, Lepton-specific).
- 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

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

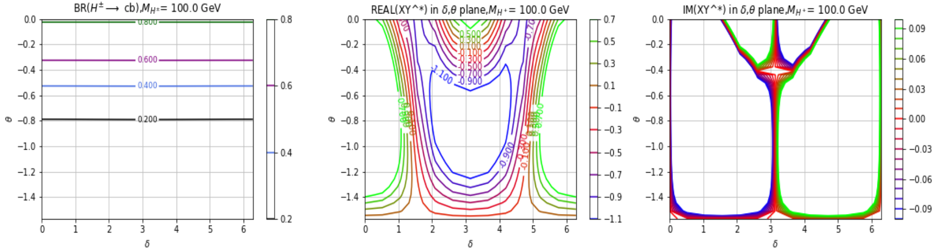


Figure: Branching ratio of $H^{\pm}$ decay through cb channel with $tan\beta = 40, tan\gamma = 10, M_{H^{\pm}} = 100\ GeV$ in $[\delta, \theta]$ plane. *Left Panel*: Contours of $BR(H^{\pm} \to cb)$. *Central Panel* : Contours of $Re(XY^*)$ in $[\delta, \theta]$ plane($b \to s\gamma$ constraint). *Right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

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

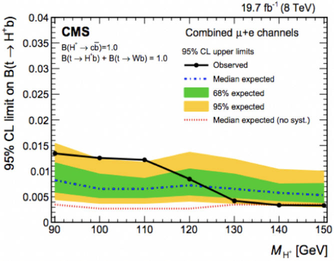
Benefit of cb:

- Distinctive decay channel to separate NFC 2HDM and NFC 3HDM.
- $H^\pm \to cb$ 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 $b \to s\gamma$.

- Beneficial for $M_{H^\pm} \sim M_w$ search.
- Search gap at LHC within region 80 GeV $\to$ 90 GeV.
- 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.

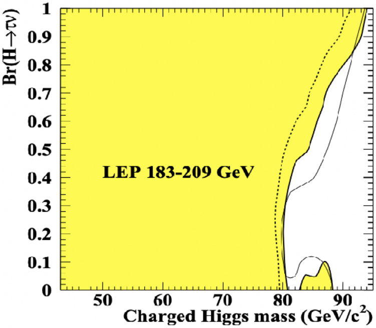
Search for light charged Higgs from LHC and LEP2

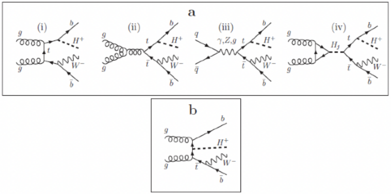
LHC [arXiv:1808.06575]



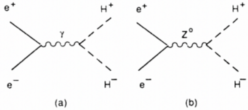
$$gg, q\bar{q}, b\bar{b}(\to t\bar{t} \to b\bar{t}H^+) \to b\bar{b}W^-H^+,$$
$$gg\ (\to b\bar{t}H^+) \to b\bar{b}W^-H^+$$

LEP [arXiv:1301.6065]





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



Prospect 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 $\tau\nu$).
- LHC did not cover mass between 80 and 90 GeV while 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]

Proposed search in significances of $H^\pm$ at LEP2 under 4 jets

$M_{H^\pm}$	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

Table: Number of signal events (S), number of background events (B), and corresponding significances ($\frac{S}{\sqrt{B}}$) in single experiment at LEP2 under 4-jets ($H^+H^- \to jjjj$).

- 4-jet channels with $\mathrm{BR}(H^\pm \to cb) = 0.8$ and $\mathrm{BR}(H^\pm \to cs) = 0.2$.
- 4j0b is the LEP2 search without b-tagging. $\frac{S}{\sqrt{B}}$ is small.
- 4j1b and 4j2b have sensitivity between $80 < M_{H^\pm} < 90$ GeV. (Especially 4j2b is about 3 times larger than the no b-tagging search.)

Proposed search in significances of $H^{\pm}$ at LEP2 under 2 jets

$M_{H^{\pm}}$	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
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 under 2-jets ($H^+H^- \to jjl\nu$).

- 2-jet channels with BR($H^{\pm} \to \tau\nu$) $= 0.5$, BR($H^{\pm} \to cb$) $= 0.4$ and BR($H^{\pm} \to cs$) $= 0.1$.
- 2j0b is the LEP2 search without b-tagging. $\frac{S}{\sqrt{B}}$ is small.
- 2j1b improved the sensitivity between $80 < M_{H^{\pm}} < 90$ GeV.

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

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

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

Production mechanism of $H^{\pm}$ pair from LEP collider

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

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

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

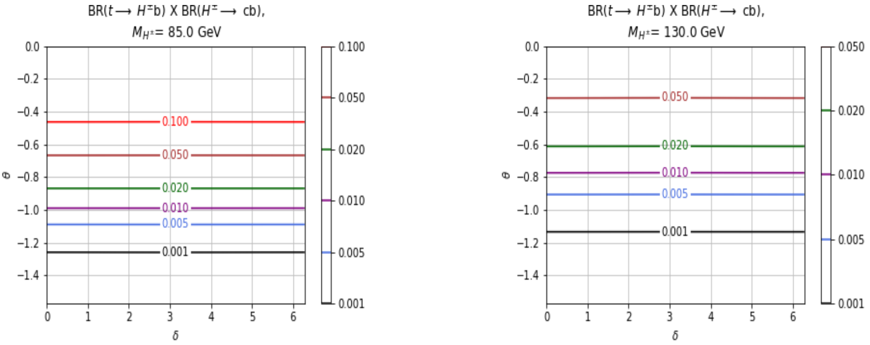
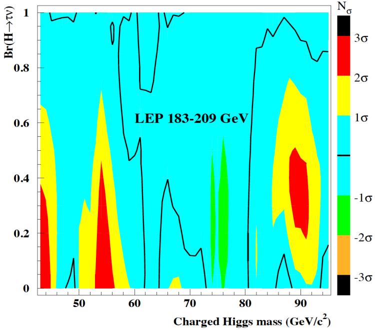
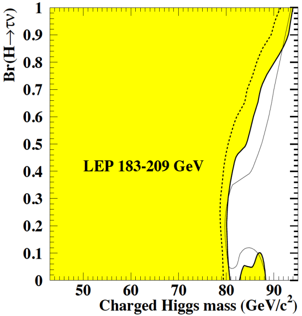


Figure: $BR(t \to H^{\pm}b) \times BR(H^{\pm} \to cb)$ in $[\delta, \theta]$ plane with $tan\beta = 40, tan\gamma = 10, M_{H^{\pm}} = 85, 130\ GeV$. *Left Panel*: $M_{H^{\pm}} = 85 GeV$ plane. *Right Panel* : $M_{H^{\pm}} = 130\ GeV$ plane.

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

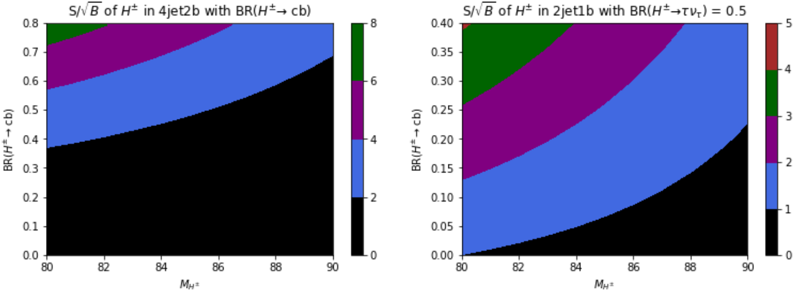
- $$\Gamma(t \to W^{\pm} b) = \frac{G_F m_t}{8\sqrt{2}\pi}[m_t^2 + 2M_W^2][1 - M_W^2/m_t^2]^2$$
- $$\Gamma(t \to H^{\pm} b) = \frac{G_F m_t}{8\sqrt{2}\pi}[m_t^2|Y|^2 + m_b^2|X|^2][1 - m_{H^{\pm}}^2/m_t^2]^2 \, .$$
- $BR(t \to H^{\pm} b)$ depends on magnitudes of $|X|, |Y|$. It affects production rate 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 $\rightarrow$ 209 GeV	0.6	0.7	0.06	0.01	80 GeV $\rightarrow$ 90 GeV
CEPC/FCC-ee	240 GeV	1000	0.7	$0.01 < \epsilon_c < 0.06$	0.01	80 GeV $\rightarrow$ 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($H^{\pm} \to cb$) $+ BR(H^{\pm} \to cs) = 0.5$.

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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