Light charged Higgs boson with dominant decay to quarks and its search at LHC and future colliders

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1. Motivation

- A neutral Higgs boson (spin=0) has been found at the LHC.
- Classify elementary particles by their electric charge and spin:

	Spin 0	Spin 1/2	Spin 1
Neutral	h^0	ν_e, ν_μ, ν_τ	γ, Z, g
Charged	$(H^\pm)$?	$e^\pm, \mu^\pm, \tau^\pm, u, d, s, c, b, t$	$W^\pm$

- Why not a charged, spin 0 particle, $H^\pm$?

Reason for MHDM:

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

2. The Two Higgs Doublet Model (2HDM)

- Introduce a second $I = 1/2, Y = 1$ doublet to the SM Lagrangian:

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

$\tan\beta = v_2/v_1$, where $v_1^2 + v_2^2 = v^2 = 2m_W^2/g$.

- Four types of 2HDM (without tree-level flavour changing scalar currents) :Type I, II, Lepton-specific, and Flipped.
- The Yukawa couplings in 2HDM depend on $\tan\beta = v_2/v_1$.

$$\mathcal{L}_{H^\pm} = -\left\{ \frac{\sqrt{2}V_{ud}}{v} \overline{u}\,(m_d X P_R + m_u Y P_L)\, d\, H^+ + \frac{\sqrt{2}m_e}{v} Z \overline{\nu_L} \ell_R H^+ + H.c. \right\}$$

- 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	$\tan\beta$	$\cot\beta$	$-\cot\beta$

3. The Three Higgs Doublet Model (3HDM)

- A multi-Higgs doublet model (MHDM) has n scalar doublets.
- A MHDM has $n-1$ physical charged scalars $H^\pm$.
- The mass matrix of the charged scalars is diagonalised by the $n \times n$ matrix U:

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

- Yukawa couplings are defined in terms of the 3×3 mixing matrix U:

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

	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

- U can be parametrised by four parameters
  i) $\tan\beta = v_u/v_d$ ii) $\tan\gamma = \sqrt{v_d^2 + v_u^2}/v_\ell$ iii) Mixing angle θ iv) CP-phase δ.
- The explicit form of U given as:

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

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

4. LHC and LEP searches for $H^\pm$

LHC:

- Top quarks are produced in pairs e.g. $gg \to t\bar{t}$; then $t/\bar{t} \to Wb$ (with $W \to e\nu$ or $\mu\nu$) and $t/\bar{t} \to H^\pm b$.
- $H^\pm$ decay to fermions with hadronic and leptonic channels captured by the detector.

LEP:

- Production of charged Higgs pair from electron-positron collision by exchange of Z or photon.
- The cross-section only involves one unknown parameter, which is the mass of charged Higgs.

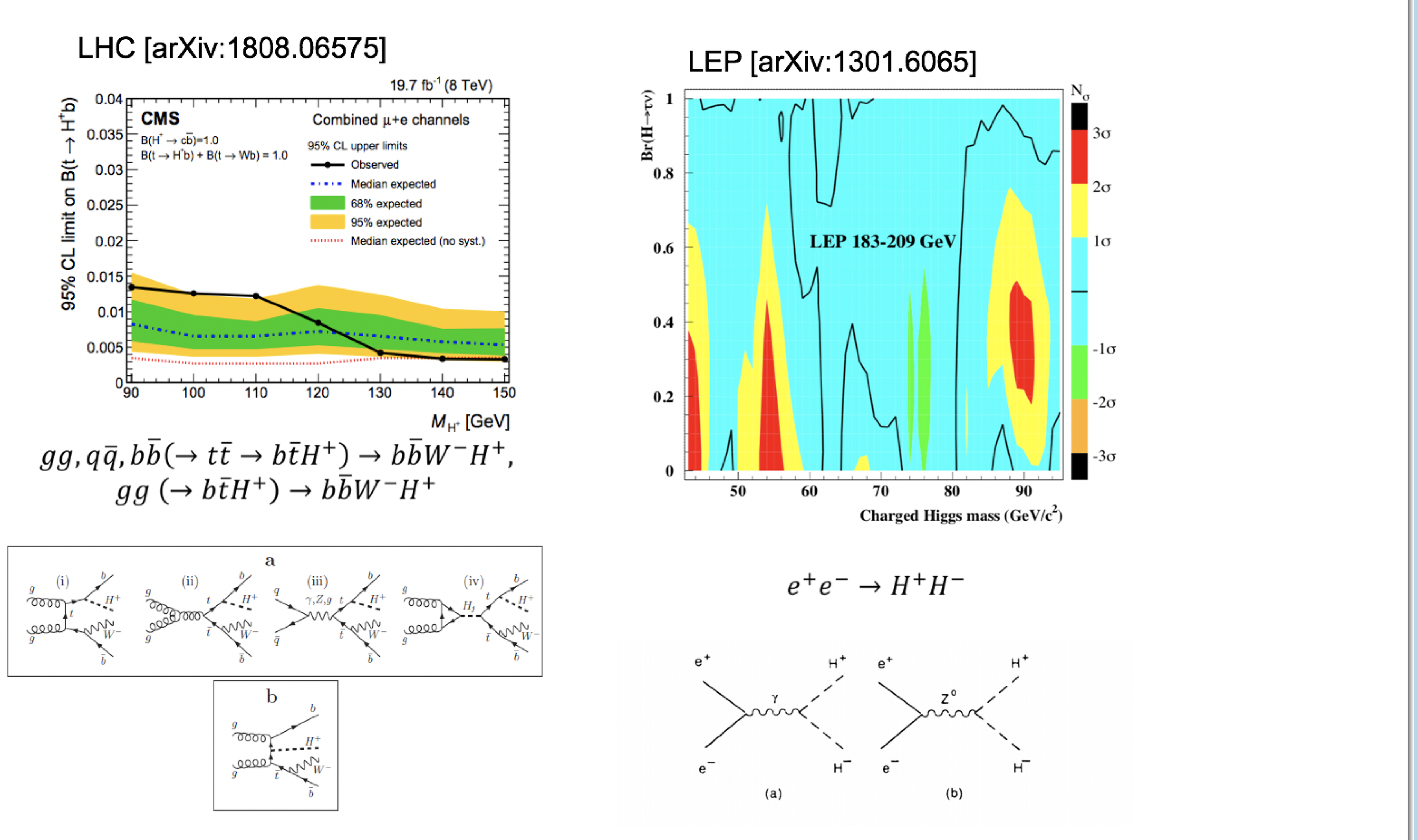

Figure 1:Left panel: CMS search for charged Higgs decay to charm and bottom with mass range 90 $\leq m_{H^\pm} \leq$ 150 GeV. Right panel: LEP combined results for charged Higgs through $\tau\nu_\tau$ with mass region 80 $\leq m_{H^\pm} \leq$ 90 GeV.

- First CMS search performance on charm and bottom from charged Higgs without any evidence within mass region from 90 to 150 GeV ;
- LEP had an excess of events around 2σ for charged Higgs mass range 80 to 90 GeV.

5. Large BR($H^\pm \to cb$) from Flipped and Democratic 3HDM

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

- For $m_{H^\pm} > m_t$ the channel $H^\pm \to tb$ dominates in all 2HDMs and in 3HDM.
- For $m_{H^\pm} < m_t$, a distinctive signal of $H^\pm$ from a 3HDM would contain: Large BR($H^\pm \to cb$)
- Only focus on fermions by considering addtional neutral Higgs bosons to be much heavier than $H^\pm$.

Advantage of cb:

- 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.

Constraints of |X|, |Y| :

- $b \to s\gamma$: $-1.1 \leq \mathrm{Re}XY^* \leq 0.7$ for $m_{H^\pm} = 100$ GeV .
- Electric dipole moment of neutron: $\mathrm{Im}XY^* \leq 0.1$ for $m_{H^\pm} = 100$ GeV

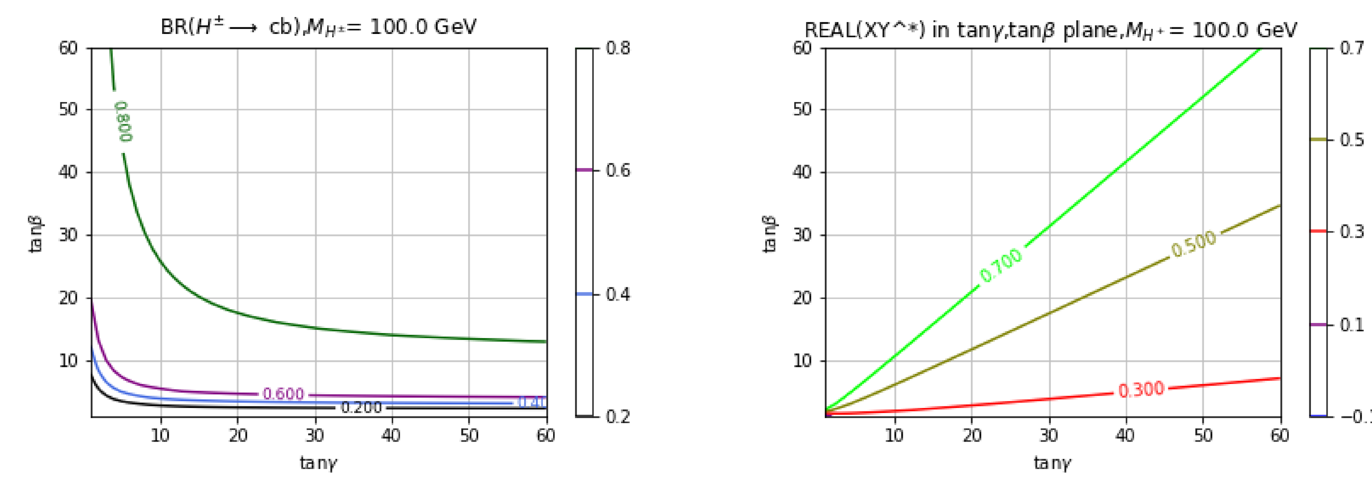

Figure 2:Flipped Model : BR($H^\pm \to cb$) channel with $\theta = -\pi/3, \delta = 0, M_{H^\pm} = 100\ GeV$ in [$tan\beta, tan\gamma$] plane. Left panel:$BR(H^\pm \to cb)$. Right panel :$Re(XY^*)$ ($b \to s\gamma$ constraint).

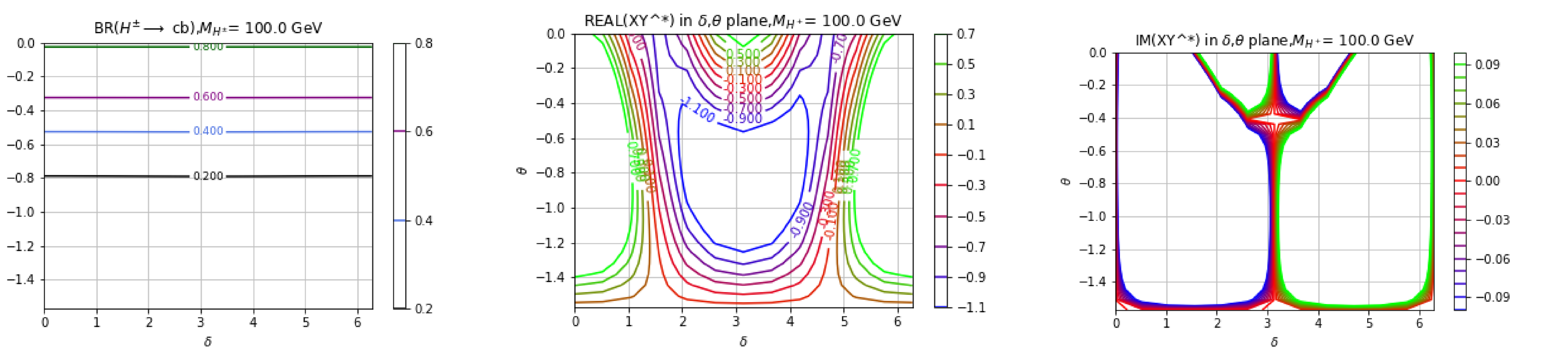

Figure 3:Democratic Model : BR($H^\pm \to cb$) channel with $tan\beta = 40, tan\gamma = 10, M_{H^\pm} = 100\ GeV$ in [δ, θ] plane. Left panel: $BR(H^\pm \to cb)$. Centre panel: $Re(XY^*)$ ($b \to s\gamma$ constraint). Right panel: $Im(XY^*)$ (EDM constraint)

6. BR($t \to H^\pm b$) multiplied by BR($H^\pm \to cb$) in Flipped 3HDM

$$\Gamma(t \to H^\pm b) = \frac{G_F m_t}{8\sqrt{2}\pi}[m_t^2|Y|^2 + m_b^2|X|^2][1 - m_{H^\pm}^2/m_t^2]^2$$

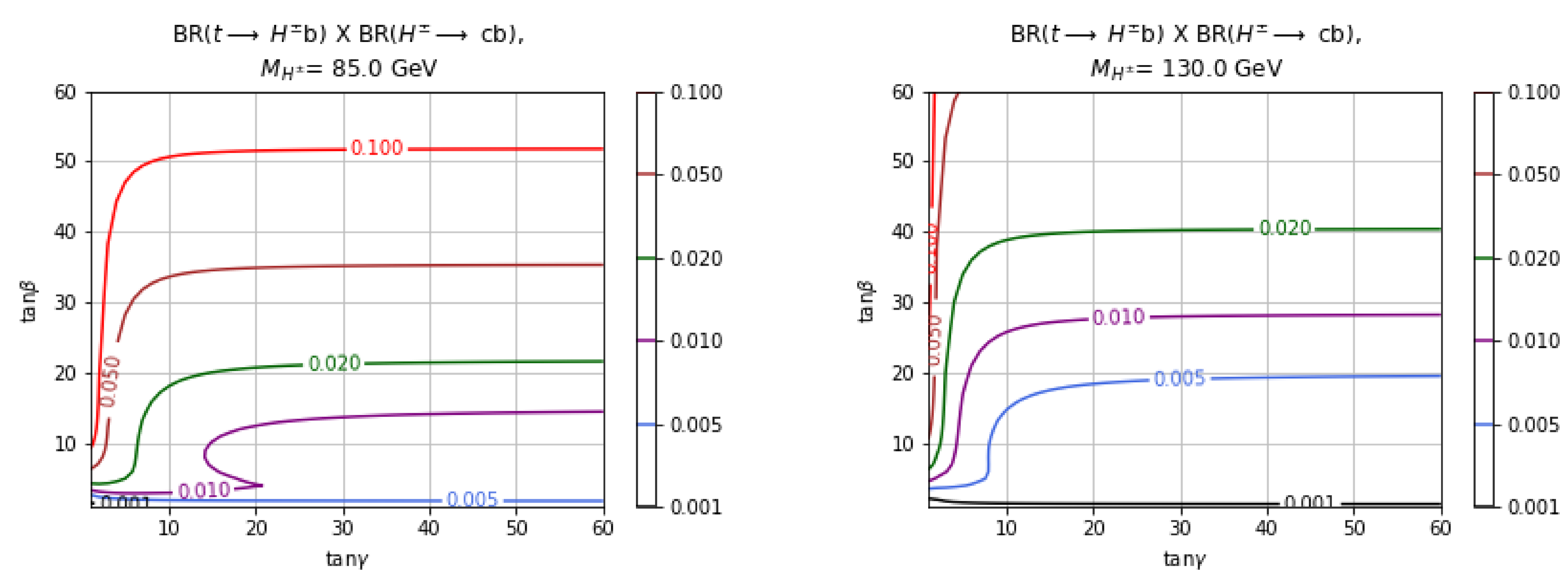

Figure 4:$BR(t \to H^\pm b) \times BR(H^\pm \to cb)$ in [$tan\beta, tan\gamma$] plane with $\theta = -\pi/3, \delta = 0, M_{H^\pm} = 85, 130\ GeV$.
Left panel: $M_{H^\pm} = 85\ GeV$. Right panel: $M_{H^\pm} = 130\ GeV$.

- Current limit $t \to H^\pm b$ for charged Higgs mass 130 GeV are excluded with BR($H^\pm \to cb$) > 0.01 at LHC.
- LHC has no sensitivity in the range between 80 GeV $\leq m_{H^\pm} \leq$ 90 GeV. Whole plane for 85 GeV can be potential signals.
- Tagging the b quark from $H^\pm \to cb$ would possibly allow sensitivity to BR ($t \to H^\pm b$)<0.5% .
- $t \to H^\pm b$ and $H^\pm \to cb$ are obtained by constraints $|X|, |Y|$. Small quantities of Yukawa couplings cause low production rates of Higgs.
- Dedicated search for $t \to H^\pm b$ and $H^\pm \to cb$ is motivated for region 80 GeV $\leq m_{H^\pm} \leq$ 90 GeV.

7. Conclusion

- 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 is expected in the future.
- Production of charged Higgs at e^+e^- colliders do not depend Yukawa couplings parameters.
- No detection of light charged Higgs due to small magnitude of $[|X|, |Y|]$ at LHC.
- It still can be discovered at future e^+e^- colliders use different production method.

8. References

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