Large BR($H^{\pm} \to cb$) in models with three Higgs doublets

Andrew Akeroyd

Department of Physics and Astronomy

University of Southampton, UK

- $H^{\pm}$ in the three-Higgs-doublet model (3HDM)
- $H^{\pm}$ can be lighter than the top quark and is compatible with $b \to s\gamma$
- $H^{\pm} \to cb$ can be the dominant decay channel in some 3HDMs
- $t \to H^{\pm}b$ with $H^{\pm} \to cb$ is being searched for at the LHC

In collaboration with: W.J. Stirling, S. Moretti, J. Hernandez-Sanchez, K. Yagyu, E. Yildirim, M. Song

Nucl. Phys. B447 (1995) 3; Nucl. Phys. B544 (1999) 557; Phys. Rev. D85, 115002 (2012);

Int. J. of Mod. Phys. A32, 1750145 (2016); Phys. Rev. D98, 115024 (2018); arXiv:1908.00826

Video seminar at CERN, 26 Sep, 2019

Possibility of electrically charged scalars ($H^{\pm}$)

- A neutral scalar (spin=0) has been found at the LHC
- Searches for additional neutral scalars of high priority now
- There might exist charged scalars, $H^{\pm}$
- 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, $H^{\pm}$?

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 $v_1^2 + v_2^2 = v^2 = 2m_W^2/g = 246^2\text{GeV}^2$
- If up-type quarks, down-type quarks and charged leptons obtain their mass from just one vev (v_1 or v_2)

$\rightarrow$ flavour changing neutral currents (e.g. $hs\bar{b}$) are avoided (Natural Flavour Conservation, "NFC")

The Two Higgs Doublet Model (2HDM)

- Scalar potential of (CP-conserving) 2HDM with NFC has six free parameters
- Five physical scalars: h^0, H^0, A^0, H^+, H^-
- It is usual to assume that (of the three neutral scalars) h^0 has been discovered ($m_{h^0} \sim 125$ GeV)
- Three of the six unknown parameters are the masses $m_{H^\pm}$, m_{H^0} and m_{A^0}

Reasons to consider a non-minimal Higgs sector

- Why not? Three generations (doublets) of quarks and leptons.

Why not two or more generations (doublets) of scalars?

- Neutrino mass
- (Scalar) Dark matter
- Additional sources of CP violation
- Supersymmetry (requires at least two scalar doublets)

$\rightarrow$ Searches for additional scalars of high priority now

Interactions of $H^{\pm}$ with the fermions

- Four types of 2HDM (without tree-level flavour changing currents mediated by scalars)

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

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

- Models I and II were in the Higgs Hunters' Guide (1989) and are well studied; Model II is the structure in SUSY models
- Prior to 2009 very few studies of $H^{\pm}$ in the Lepton-specific and Flipped models

Three Higgs Doublet Model (3HDM)

- A 3HDM has 2 physical charged scalars $H_1^{\pm}$ and $H_2^{\pm}$
- Relatively few phenomenological studies of $H_i^{\pm}$ $(i = 1, 2)$
- The mass matrix of the charged scalars (which depends

on the scalar potential) is diagonalised by a 3×3 matrix U:

$$\begin{pmatrix} G^+ \\ H_1^+ \\ H_2^+ \end{pmatrix} = U \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \\ \phi_3^+ \end{pmatrix}.$$

where $G^{\pm}$ is a charged Goldstone boson, $H_i^{\pm}$ are mass eigenstates $(m_{H_1^{\pm}} < m_{H_2^{\pm}})$ and ϕ_i^+ are weak eigenstates

The five types of 3HDM

- Φ_1, Φ_2, Φ_3 are the three scalar $SU(2)\times U(1)$ doublets
- u,d,ℓ refer to the up-type quark quarks, down-type quarks and charged leptons

	u	d	ℓ
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific (type X)	Φ_2	Φ_2	Φ_1
Flipped (type Y)	Φ_2	Φ_1	Φ_2
Democratic (type Z)	Φ_2	Φ_1	Φ_3

$$\mathcal{L}_{H^\pm} = -\Big\{\frac{\sqrt{2}V_{ud}}{v}\overline{u}\,(m_d X_1 P_R + m_u Y_1 P_L)\, d\, H_1^+ + \frac{\sqrt{2}m_e}{v} Z_1 \overline{\nu_L}\ell_R H_1^+ + H.c$$

$$-\Big\{\frac{\sqrt{2}V_{ud}}{v}\overline{u}\,(m_d X_2 P_R + m_u Y_2 P_L)\, d\, H_2^+ + \frac{\sqrt{2}m_e}{v} Z_2 \overline{\nu_L}\ell_R H_2^+ + H.c.\Big\}$$

Yukawa couplings of $H^{\pm}$ in a 3HDM

Phenomenology of $H^{\pm}$ in a 3HDM has received much less attention than $H^{\pm}$ in 2HDMs Albright et 80, Grossman 94, AGA/Stirling 94

- In a 3HDM,couplings X_1, Y_1 and Z_1 for $H_1^{\pm}$ and X_2, Y_2 and Z_2 for $H_2^{\pm}$ are not simply given by $\tan\beta$ or $\cot\beta$
- They are defined in terms of the 3X3 matrix U:

$$X_1 = \frac{U^{\dagger}_{d2}}{U^{\dagger}_{d1}},\ Y_1 = -\frac{U^{\dagger}_{u2}}{U^{\dagger}_{u1}},\ Z_1 = \frac{U^{\dagger}_{\ell 2}}{U^{\dagger}_{\ell 1}},\ X_2 = \frac{U^{\dagger}_{d3}}{U^{\dagger}_{d1}},\ Y_2 = -\frac{U^{\dagger}_{u3}}{U^{\dagger}_{u1}},\ Z_2 = \frac{U^{\dagger}_{\ell 3}}{U^{\dagger}_{\ell 1}}$$

- d, u, ℓ take values $1, 2, 3$ (e.g. $d = 1, u = 2, \ell = 3$ for democratic 3HDM)

The couplings $|X_i|$, $|Y_i|$, and $|Z_i|$ in a 3HDM

- In a 2HDM, U is a 2X2 matrix with one parameter ($\tan\beta$)
- In a 3HDM U can be parametrised by four parameters

from the scalar potential

i) $\tan\beta = v_u/v_d$; ii) $\tan\gamma = \sqrt{v_d^2 + v_u^2}/v_\ell$ ($0 < v_d, v_u, v_\ell <$ 246GeV)

iii) A mixing angle $0 \geq \theta \geq -\pi/2$; iv) a phase $0 \leq \delta \leq 2\pi$

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

Varying these four parameters gives the allowed values of $|X_i|, |Y_i|, |Z_i|$ in each of the five models.

Phenomenological constraints on $|X_i|$, $|Y_i|$, $|Z_i|$

I am mainly concerned with X_1,Y_1,Z_1 (i.e. couplings for the lightest $H^\pm$ in a 3HDM), hereafter to be called X,Y,Z

Constraints from low-energy processes for $m_{H^\pm} = 100$ GeV:

- Derived assuming that only one $H^\pm$ contributes
- From $Z \to b\bar{b}$: $|Y| < 0.8$ and $|X| < 50$
- From Lepton flavour universality: $|Z| < 40$
- From $b \to s\gamma$: $-1.1 < \mathrm{Re}(XY^*) < 0.7$

Lower (upper) limit $\rightarrow$ destructive (constructive) interference of W and $H^\pm$ loops that contribute to decay

$b \to s\gamma$ constraint on $m_{H^\pm}$

- In a 2HDM in which u and d quarks receive mass from different doublets (i.e. Type II and Flipped) one has $XY^* = 1$
- Strong constraint $m_{H^\pm} > 450$ GeV in 2HDM (II and flipped) independent of values of X, Y
- In 2HDM (Type I and lepton specific) $XY^* = -\cot^2\beta$, and $H^\pm$ can be much lighter for small $\cot\beta$
- In a 3HDM $m_{H^\pm} > 450$ GeV can be weakened for Type II and flipped structures since $X_i Y_i^*$ is arbitrary ($\neq 1$ in general) and there are two charged scalars AGA/Moretti/Yagyu/Yildirim 2016

Partial decay widths of $H^{\pm}$

Tree-level expressions for partial decay widths:

$$\Gamma(H^{\pm} \to \ell^{\pm}\nu) = \frac{G_F m_{H^{\pm}} m_{\ell}^2 |Z|^2}{4\pi\sqrt{2}}$$

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

- Running quark masses are evaluated at the scale of $m_{H^{\pm}}$
- In 2HDMs one parameter ($\tan\beta$) determines the partial widths
- BRs are well known in the four types of 2HDM
- For $m_{H^{\pm}} > m_t$, $H^{\pm} \to tb$ usually dominates (m_t, m_b, V_{tb})

Scenario of large BR($H^{\pm} \to cb$) in 2HDMs/3HDMs

For $m_{H^{\pm}} < m_t$ (on which I will focus in this talk)

- BR($H^{\pm} \to \tau\nu$) and BR($H^{\pm} \to cs$) dominate in three versions of the 2HDM and 3HDM (Model I, Model II, Lepton specific)
- BR($H^{\pm} \to cb$) is always $<$ 1% in these models due to small V_{cb}
- Scenario of Large BR($H^{\pm} \to cb$) is of interest
- The necessary condition is: $|X| >> |Y|, |Z|$ Grossman 94, AGA/Stirling 94
- In which 2HDMs/3HDMs is this condition possible?

Scenario of $|X| >> |Y|, |Z|$ in Flipped 2HDM and 3HDM

Flipped 2HDM

- $|X| >> |Y|, |Z|$ for $\tan\beta >> 1$ ($|X| = \tan\beta = 1/|Y| = 1/|Z|$)
- However, constraint from $b \to s\gamma$ leads to $m_{H^\pm} > 450$ GeV
- One has BR($H^\pm \to tb$) ~ 1 for $m_{H^\pm} > m_t$
- $\to$ Large BR($H^\pm \to cb$) is only possible in Flipped 2HDM

IF additional New Physics is present to relax $b \to s\gamma$ constraint so that $m_{H^\pm} < m_t$ is possible (I will not consider this)

3HDM with flipped or democratic structure

- $m_{H^\pm} < m_t$ respects limits from $b \to s\gamma$ ($X_i Y_i^* \neq 1$ in general)
- Candidate models for $m_{H^\pm} < m_t$ and large BR($H^\pm \to cb$)

Magnitude of BR($H^\pm \to cb$) in 3HDMs (flipped/democratic)

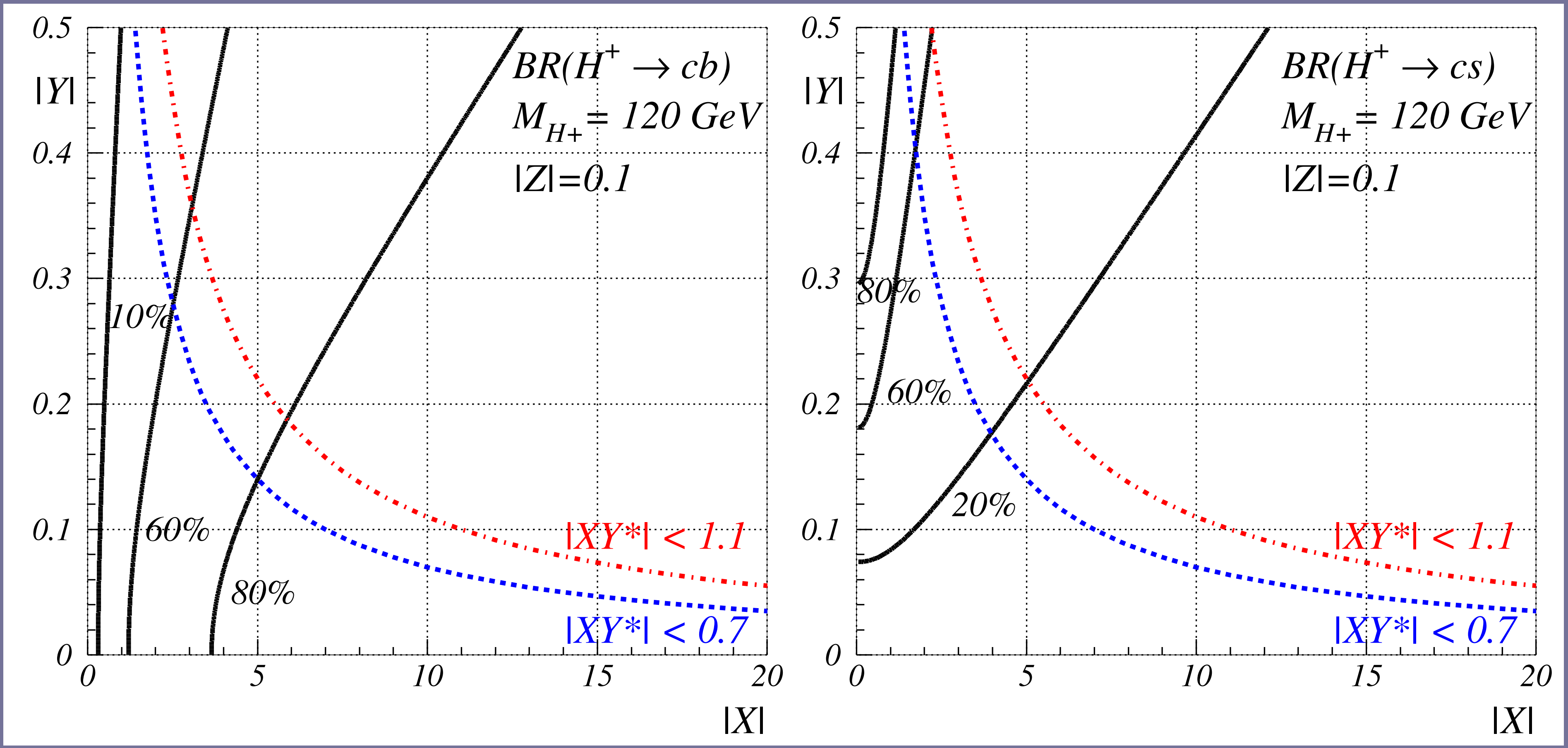
For $|X| >> |Y|, |Z|$ the ratio of the two dominant decays, BR($H^\pm \to cb$) and BR($H^\pm \to cs$), approaches a constant value:

$$\frac{\text{BR}(H^\pm \to cb)}{\text{BR}(H^\pm \to cs)} = R_{bs} \sim \frac{|V_{cb}|^2 m_b^2}{|V_{cs}|^2 m_s^2}$$

- $|V_{cs}| \sim 0.97$; $|V_{cb}| \sim 0.04$; $m_b \sim 2.95$ GeV (all well known)
- Main uncertainty in R_{bs} is from strange quark mass, m_s
- Unique feature that m_s plays an important role for BRs of $H^\pm$
- Lattice QCD gives $m_s = 94 \pm 3$ MeV at scale $Q = 2$ GeV
- We obtain BR($H^\pm \to cb$)$_{\text{max}} \sim 80\%$

BR($H^\pm \to cb$) and BR($H^\pm \to cs$) in a 3HDM

AGA/Moretti/Hernandez, 2012



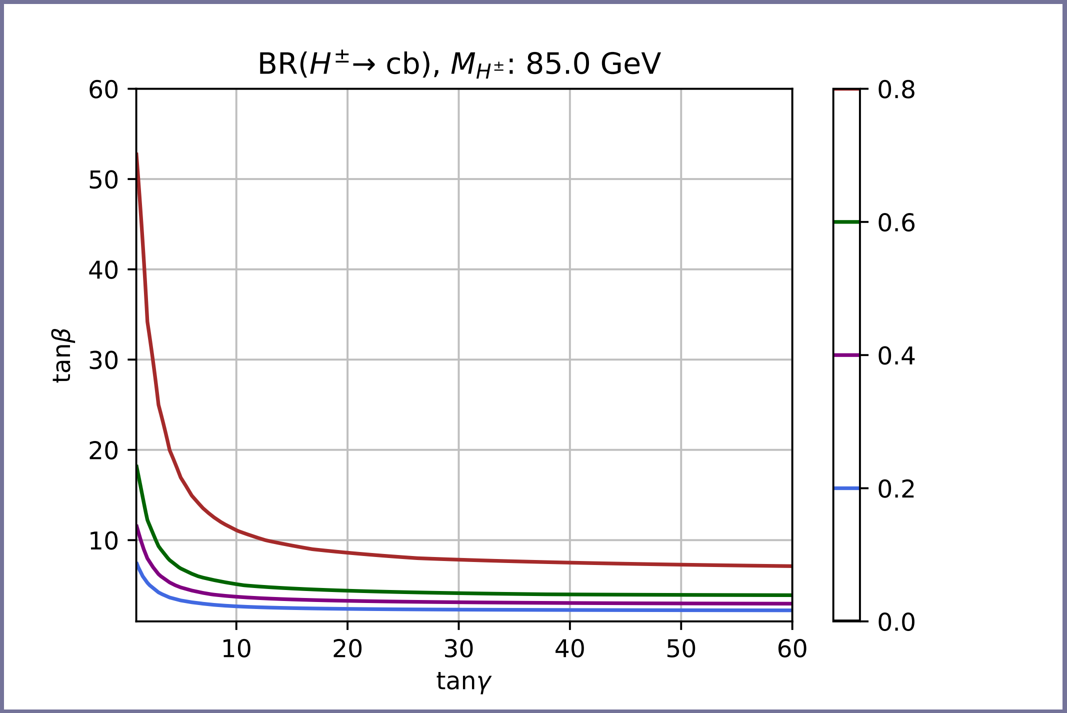
Left panel: BR($H^\pm \to cb$) in plane $[|X|, |Y|]$ with $b \to s\gamma$ Right panel: BR($H^\pm \to cs$)

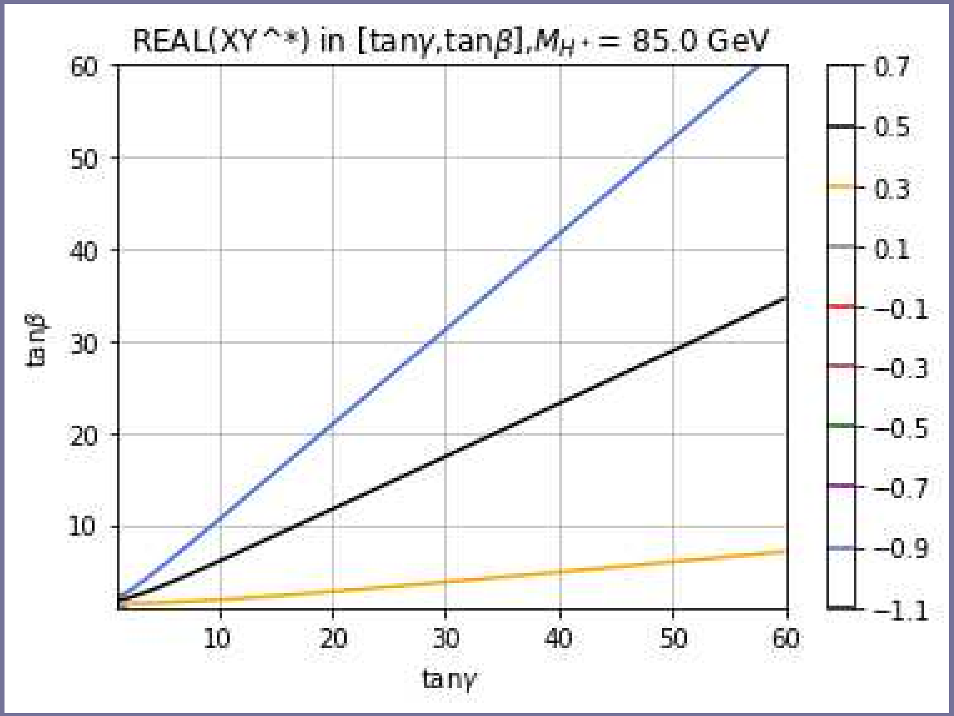
Summary of Models with/without large BR($H^{\pm} \to cb$)

	$m_{H^{\pm}} < m_t$	Large BR($H^{\pm} \to cb$)	Parameters for X, Y, Z
2HDM with NFC: Types I, LS	Yes	No	1
2HDM with NFC: Type II	No	No	1
2HDM with NFC: Flipped	No	No (Yes)	1
2HDM without NFC: Aligned	Yes	Yes	5
3HDM with NFC: Types I, II, LS	Yes	No	4
3HDM with NFC: Flipped, Democratic	Yes	Yes	4

- $m_{H^{\pm}} < m_t$ (or not) depends on $b \to s\gamma$ and Yukawa coupling structure
- $m_{H^{\pm}} < m_t$ is a necessary (but not sufficient) condition for a possibly large BR($H^{\pm} \to cb$)
- Large BR($H^{\pm} \to cb$) requires $|X| >> |Y|, |Z|$ (and $m_{H^{\pm}} < m_t$)
- I will discuss the lightest $H^{\pm}$ from the flipped 3HDM

BR($H^{\pm} \to cb$) and $b \to s\gamma$ constraint in the plane [$\tan\gamma, \tan\beta$] AGA/Moretti/Song 2018



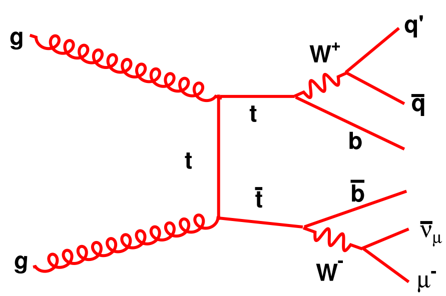


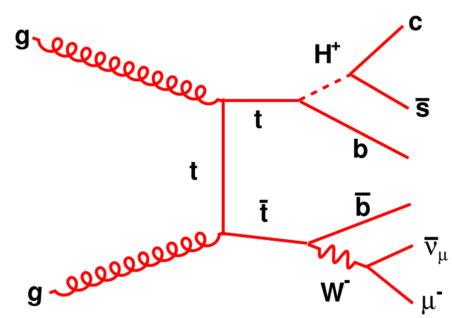
Allowed region lies below Re(XY^*) < 0.7. Sizeable parameter space for large BR($H^{\pm} \to cb$)

Direct searches for $t \longrightarrow H^{\pm}b$, $H^{\pm} \longrightarrow \tau\nu/cs/cb$ at the LHC

Direct searches for $t \to H^{\pm}b$, $H^{\pm} \to \tau\nu/cs/cb$ at the LHC

- Top quarks are produced in pairs e.g. $gg \to t\bar{t}$
- One top/anti-top decays via $\boxed{t/\bar{t} \to Wb}$, with $W \to e\nu$ or $\mu\nu$
- The other top/anti-top decays via $\boxed{t/\bar{t} \to H^{\pm}b}$





Direct searches for $t \to H^{\pm}b$ and $H^{\pm} \to \tau\nu/cs/cb$ at the LHC

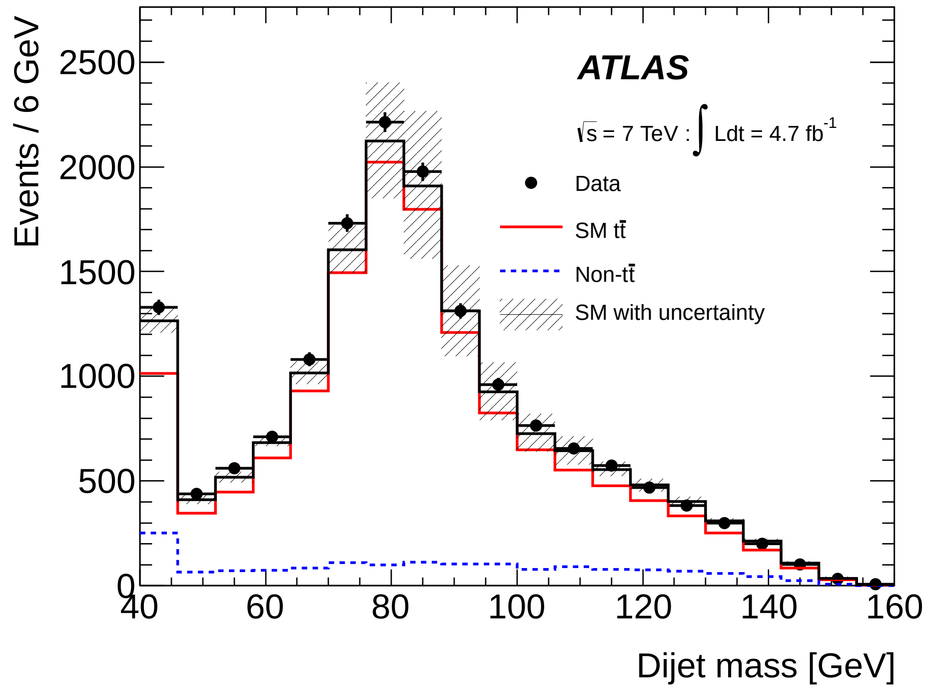
	ATLAS	CMS
7 TeV (5 fb^{-1})	cs, $\tau\nu$	$\tau\nu$
8 TeV (20 fb^{-1})	$\tau\nu$	cs, cb, $\tau\nu$
13 TeV (36 fb^{-1})	$\tau\nu$	$\tau\nu$

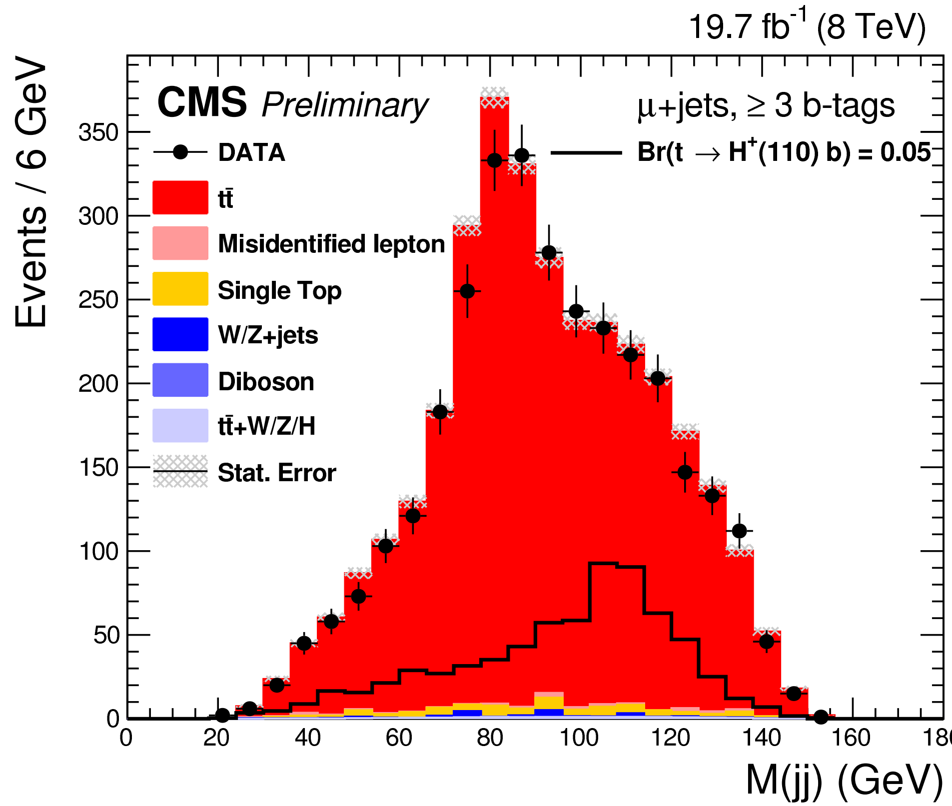
- For a given value of $m_{H^{\pm}}$ the limits on $\text{BR}(H^{\pm} \to \tau\nu)$ are stronger than those for $\text{BR}(H^{\pm} \to cs/cb)$
- For a given value of $m_{H^{\pm}}$ the limits on $\text{BR}(H^{\pm} \to cb)$ are stronger than those for $\text{BR}(H^{\pm} \to cs)$ $\to$ see later

Direct searches for $t \to H^{\pm}b$ and $H^{\pm} \to cs/cb$ at the LHC

- Decay $H^{\pm} \to cs$ gives two (non-b quark) jets
- Candidate signal events are e.g. $b\bar{b}e\nu$ plus two non-b jets.
- A peak at $m_{H^{\pm}}$ in invariant mass distribution of non-b jets
- Main background from $t/\bar{t} \to Wb$ and $W \to ud/cs$ would give a peak at m_W
- Decay $H^{\pm} \to cb$ provides a third b quark in the signal events
- Requiring a third (tagged) b quark reduces backgrounds, because $W \to ud/cs$ low b-fake rate and BR($W \to cb$) very small

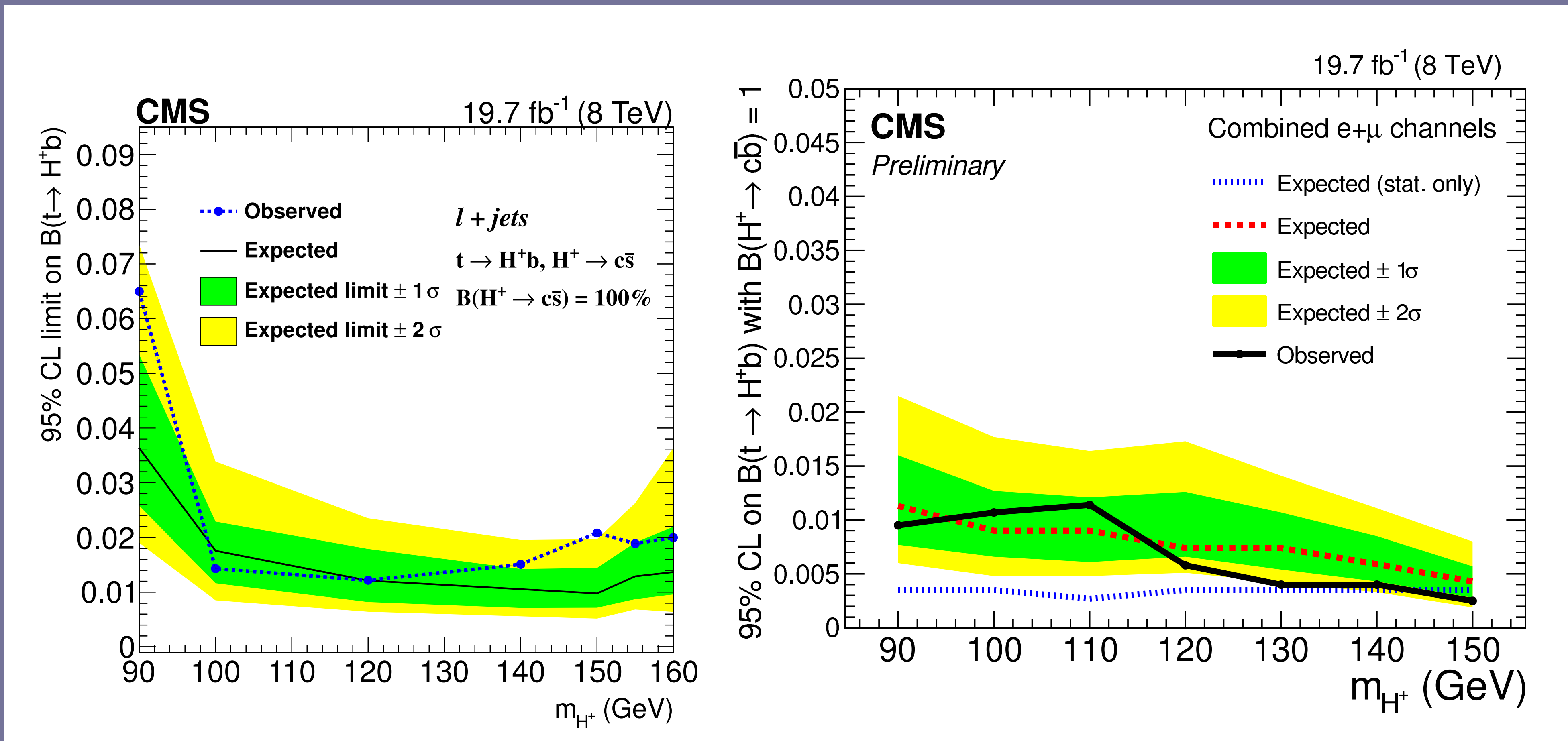
ATLAS 7 TeV data for $H^{\pm} \to cs$ 2013; CMS 8 TeV data for $H^{\pm} \to cb$ 2018





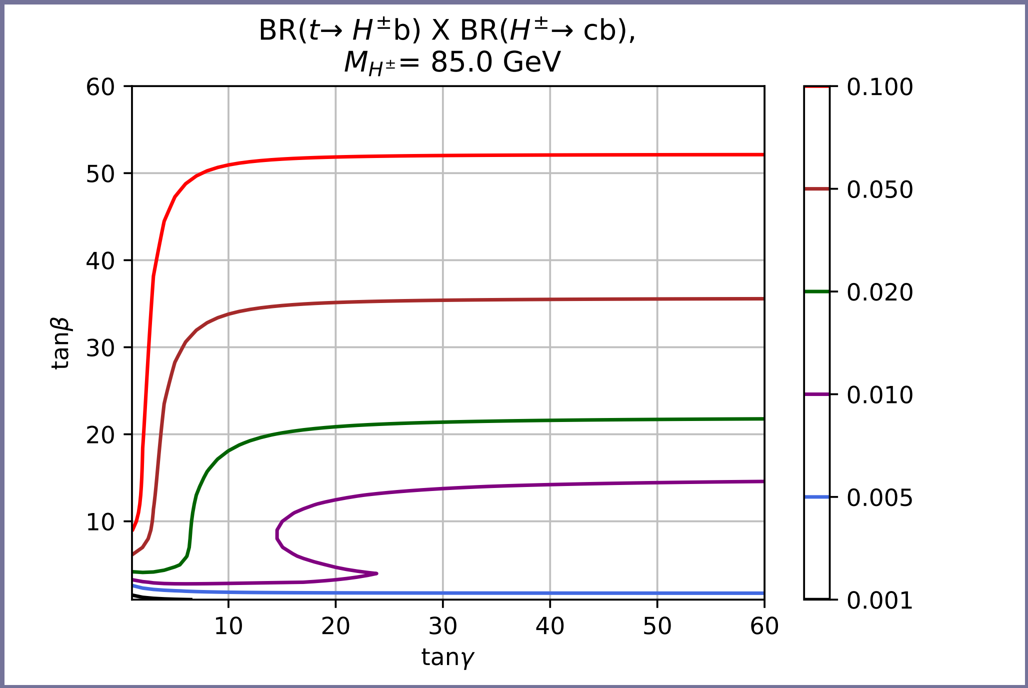
Invariant mass of jets. Left panel: ATLAS with $H^{\pm} \to cs$ Right panel: CMS with $H^{\pm} \to cb$

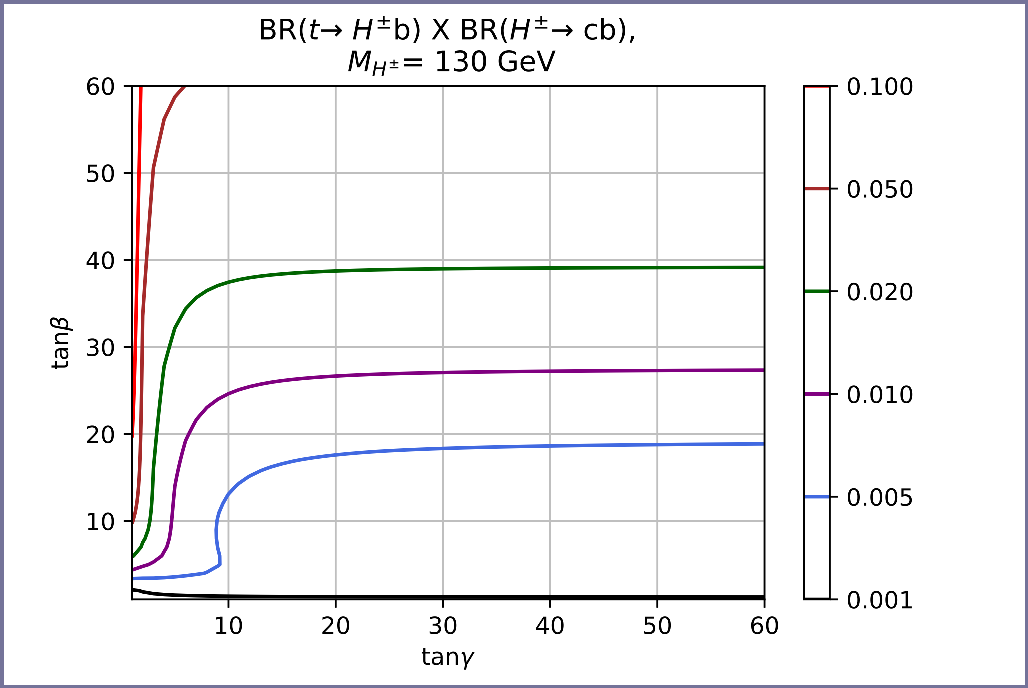
CMS limits on $t \to H^{\pm}b$ with BR$(H^{\pm} \to cs$ or $cb) = 100\%$ 2015, 2018



Excluded region in the plane $[m_{H^{\pm}}$,BR$(t \to H^{\pm}b)]$. No limits for $m_{H^{\pm}} < 90$ GeV due to large backgrounds.

BR($t \to H^\pm b$) $\times$ BR($H^\pm \to cb$) in plane [$\tan\gamma, \tan\beta$] for $\theta = -\pi/3$ and $\delta = 0$





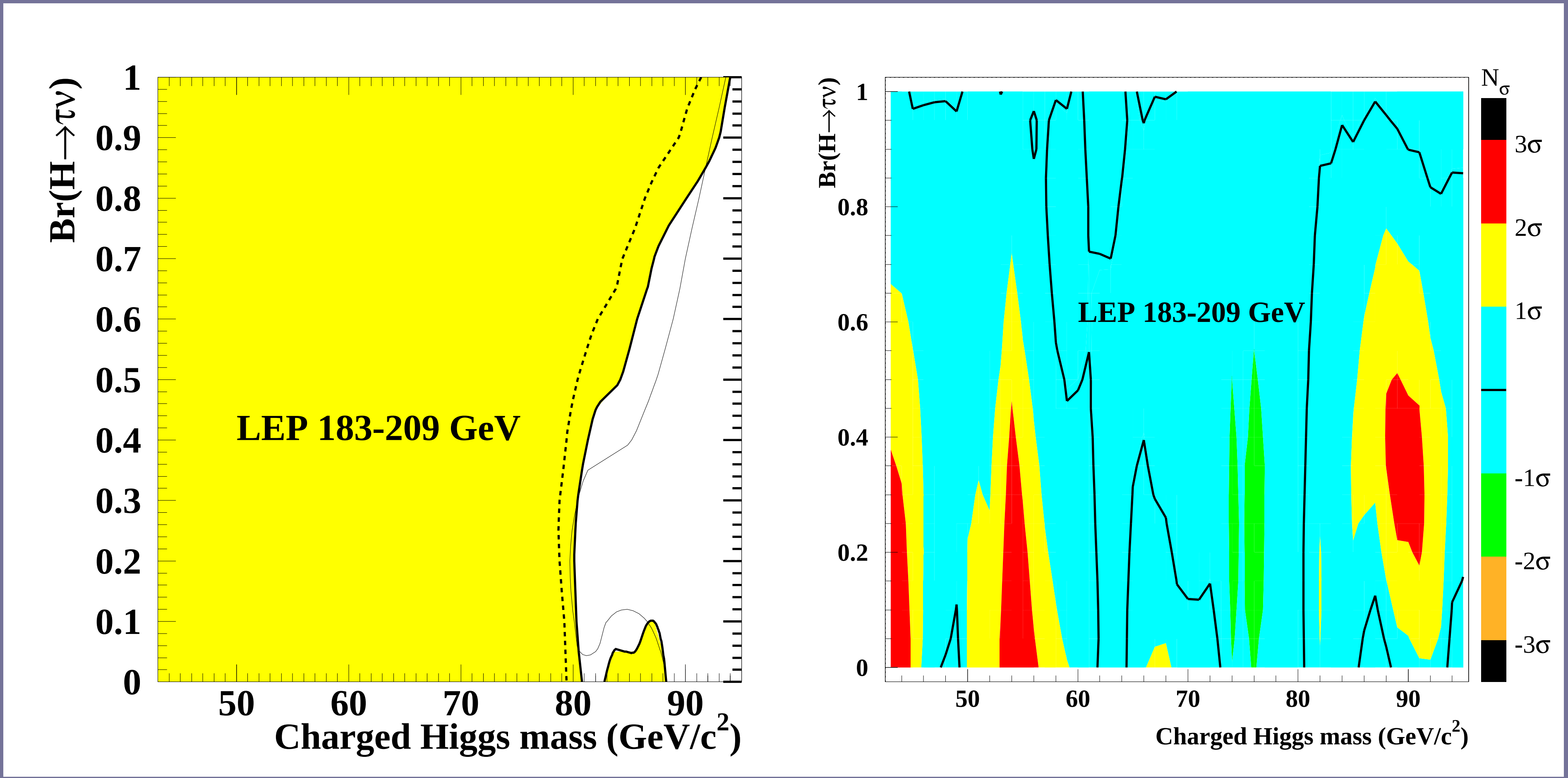
Excluded region above 0.01 for $m_{H^\pm} = 130$ GeV AGA/Moretti/Song PRD98,115024 (2018)

Region 80 GeV $< m_{H^\pm} <$ 89 GeV

- Searches for $t \to H^\pm b$, $H^\pm \to cb$ (or cs) have not set limits on the region 80 GeV $< m_{H^\pm} <$ 89 GeV
- Will sensitivity be reached with 140 fb^{-1} at $\sqrt{s} = 13$ TeV?
- LEP2 probed part of 80 GeV $< m_{H^\pm} <$ 89 GeV using $e^+e^- \to \gamma^*, Z^* \to H^+H^- \to cscs, cs\tau\nu, \tau\nu\tau\nu$, where cs is seen as 2 jets (no search done for $H^\pm \to cb$ with b–tagging)
- At LEP2, Yukawa couplings (X, Y) do not enter cross-section $\to$ event numbers for H^+H^- at LEP2 unaffected by small X, Y
- In contrast, production at LHC ($t \to H^\pm b$) depends on X, Y

Search for $e^+e^- \to H^+H^- \to cscs, cs\tau\nu, \tau\nu\tau\nu$ at LEP2

Combined LEP2 limits on $e^+e^- \to H^+H^-$ EPJC73 (2013) 2463 (arXiv:1301.6065)



Left panel: Excluded regions for a doublet $H^\pm$ at 95% c.l Right panel: LEP2 Data

Proposed search for $H^{\pm} \to cb$ at LEP2 (4-jet) AGA/Moretti/Song 1908.00826

$m_{H^{\pm}}$	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

- Number of signal events (S), number of background events (B), and corresponding significances ($\frac{S}{\sqrt{B}}$) in 4-jet channels ($H^+H^- \to jjjj$) at a single experiment at LEP2
- Numbers are for BR($H^{\pm} \to cb$) = 0.8 and BR($H^{\pm} \to cs$) = 0.2
- $4j0b$ is the LEP2 search (no b-tagging), and cannot probe $80\,GeV < m_{H^{\pm}} < 89\,GeV$ ($S/\sqrt{B}$ is low)
- $4j1b$ (exactly one tagged b) and $4j2b$ (exactly two tagged b) give sensitivity to $80\,GeV < m_{H^{\pm}} < 89\,GeV$ for large BR($H^{\pm} \to cb$)

Proposed search for $H^{\pm} \to cb$ at LEP2 (2-jet) AGA/Moretti/Song 1908.00826

$m_{H^{\pm}}$	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

- Number of signal events (S), number of background events (B), and corresponding significances ($\frac{S}{\sqrt{B}}$) in 2-jet channels ($H^+H^- \to jj\tau\nu$) at a single experiment at LEP2
- Numbers are for BR($H^{\pm} \to cb$) = 0.4, BR($H^{\pm} \to cs$) = 0.1 and BR($H^{\pm} \to \tau\nu$) = 0.5 (different BRs from 4-jet case)
- $4j1b$ gives improved sensitivity to $80\,GeV < m_{H^{\pm}} < 89\,GeV$

Slight excess at LEP2 around $m_{H^\pm} = 89$ GeV

AGA/Moretti/Song 1908.00826

- Slight excess (between 2σ and 3σ) for BR($H^\pm \to jj$) = 65% and BR($H^\pm \to \tau\nu$) = 35%, for $m_{H^\pm}$ around 89 GeV
- Assume this to be a genuine signal with BR($H^\pm \to cb$) = 0.5 (i.e. large), BR($H^\pm \to cs$) = 0.15, and BR($H^\pm \to \tau\nu$) = 0.35

$m_{H^\pm}$	88 GeV	89 GeV	90 GeV	88 GeV	89 GeV	90 GeV	
	S	S	S	$\frac{S}{\sqrt{B}}$	$\frac{S}{\sqrt{B}}$	$\frac{S}{\sqrt{B}}$	B
$4j0b$	13.98	12.28	10.64	0.42	0.37	0.32	1117.8
$4j1b$	6.47	5.68	4.93	0.68	0.59	0.52	91.44
$4j2b$	4.21	3.7	3.21	1.34	1.17	1.02	9.94
$2j0b$	11.65	10.23	8.87	0.65	0.57	0.5	316.9
$2j1b$	6.43	5.65	4.89	1.72	1.51	1.31	14.04

- Numbers are for a single LEP2 experiment
- Searches in the three channels $4j1b$, $4j2b$ and $2j1b$ would increase the significance (and combine all four experiments)

$H^{\pm}$ with 89 GeV at LHC

- If excess around $m_{H^{\pm}} = 89$ GeV is genuine then such an $H^{\pm}$ could be discovered at LHC
- Previous LHC searches for $t \to H^{\pm} b$, $H^{\pm} \to \tau\nu$ probed $80\,GeV < m_{H^{\pm}} < 89\,GeV$, but X, Y might be sufficiently small such that detection in past searches was not possible
- Future LHC searches for $H^{\pm} \to \tau\nu$ will probe smaller values of X, Y for $80\,GeV < m_{H^{\pm}} < 89\,GeV$
- Future LHC searches for $H^{\pm} \to cb/cs$ will (hopefully) probe the region $80\,GeV < m_{H^{\pm}} < 89\,GeV$

Conclusions

- A large BR($H^{\pm} \rightarrow cb$) is not expected in 2HDMs with NFC
- BR($H^{\pm} \rightarrow cb$) up to 80% is possible in:

i) 3HDM (flipped and democratic) and ii) Aligned 2HDM

- At present, one search (CMS, 8 TeV, 20 fb^{-1}) for $t \rightarrow H^{\pm}b$,

with $H^{\pm} \rightarrow cb$

- BR($t \rightarrow H^{\pm}b$) $\times$ BR($H^{\pm} \rightarrow cb$) $<$ 1% for

90 GeV $< m_{H^{\pm}} <$ 150 GeV

- No limits in the region 80 GeV $< m_{H^{\pm}} <$ 89 GeV
- LEP2 only partially covered 80 GeV $< m_{H^{\pm}} <$ 89 GeV

Magnitude of BR($t \to H^{\pm} b$)

We use the leading-order expressions for the decay width (with $|V_{tb}| = 1$) as follows:

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

- The QCD corrections essentially cancel out in the ratio of partial widths $\Gamma(t \to H_i^{\pm} b)/\Gamma(t \to Wb)$
- The corrections do not affect BR($t \to H_i^{\pm} b$) significantly
- We use $m_t = 175$ GeV and m_b evaluated at the scale of $m_{H^{\pm}}$ (i.e. $m_b \sim 2.95$ GeV)