

# Decay of charged Higgs bosons into charm and bottom quarks in multi-Higgs doublet models

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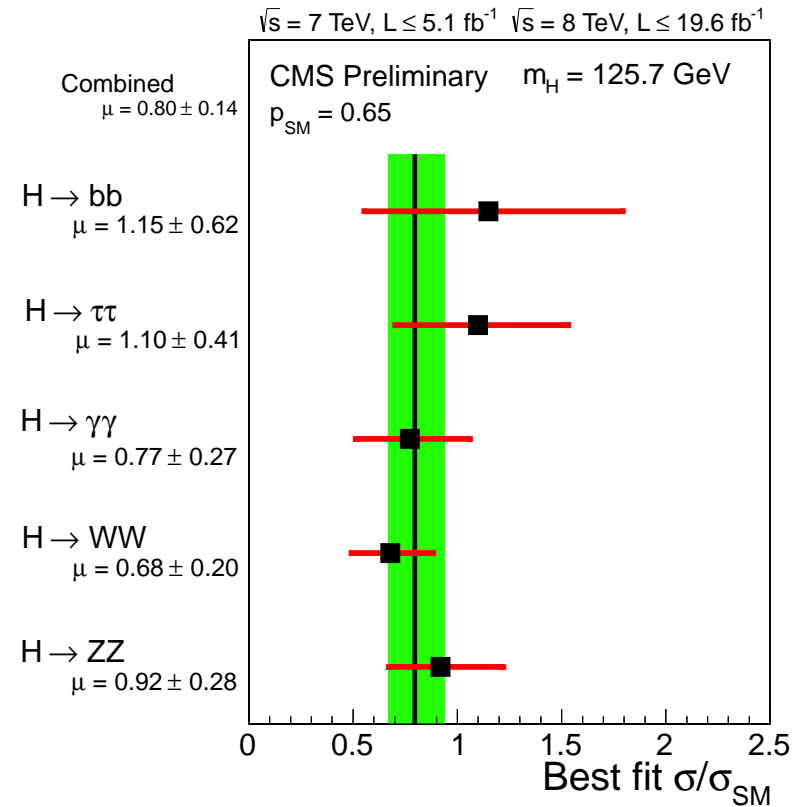
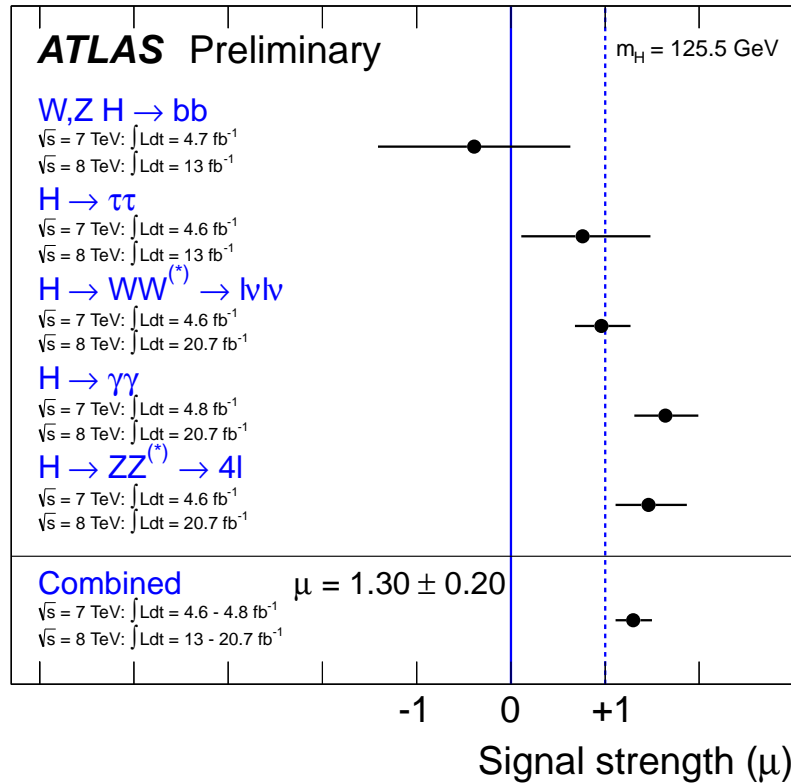
- Charged scalars ( $H^\pm$ ) predicted in many models beyond the SM
  - $H^\pm$  in the three-Higgs-doublet model (3HDM)
  - $H^\pm \rightarrow cb$  can be the dominant decay channel
  - Large  $\text{BR}(H^\pm \rightarrow cb)$  unlikely in most two-Higgs-doublet models
  - $t \rightarrow H^\pm b$  with  $H^\pm \rightarrow cb$  can be searched for at the LHC
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# Discovery of Higgs-like 125 GeV boson at the LHC



Observed in channels  $h^0 \rightarrow \gamma\gamma, ZZ, W^+W^-$ ; some evidence for  $h^0 \rightarrow \tau^+\tau^-$ ,  $h^0 \rightarrow b\bar{b}$

## 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	$h^0$	$\nu_e, \nu_\mu, \nu_\tau$	$\gamma, Z, g$
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 either  $v_1$  or  $v_2$  (but not both)  
→ flavour changing neutral currents (e.g.  $hs\bar{b}$ ) are avoided

- Scalar potential of 2HDM has **seven** 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)
- $\longrightarrow$  **six** unknown parameters in the 2HDM scalar potential
- **Three** of these are the masses  $m_{H^\pm}, m_{H^0}$  and  $m_{A^0}$
- SM had one unknown parameter (mass of  $h^0$ ), but now this is measured

## Reasons to consider a non-minimal Higgs sector

- Why not? Three generations of quarks and leptons.

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

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

→ Searches for additional scalars of high priority now

## Models with $n \geq 3$ scalar doublets

A multi-Higgs doublet model (MHDM) has  $n$  scalar doublets

- A MHDM has  $n - 1$  physical charged scalars  $H^\pm$
- I will consider the “democratic” 3HDM
- $u, d, \ell$  obtain mass from  $v_u, v_d, v_\ell$  respectively
- The mass matrix of the charged scalars (which depends on scalar potential) is diagonalised by the  $3 \times 3$  matrix  $U$ :

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

I will assume  $H_2^\pm$  to be the lightest and relabel it as  $H^\pm$ .

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

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

- Models I and II were in the Higgs Hunters' Guide and are well studied; Model II is the structure in SUSY models
- There were only a few studies on  $H^\pm$  in the Lepton-specific and Flipped models prior to 2009, but now the phenomenology is well-studied



## 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  $X$ ,  $Y$  and  $Z$  are not simply given by  $\tan \beta$  or  $\cot \beta$
- They are defined in terms of the 3X3 matrix  $U$ :

$$X = \frac{U_{12}}{U_{11}}, \quad Y = -\frac{U_{22}}{U_{21}}, \quad Z = \frac{U_{32}}{U_{31}}$$

- In a 2HDM,  $U$  is a 2X2 matrix with one parameter ( $\tan \beta$ )
- In a 3HDM  $X, Y, Z$  are not strongly correlated

The couplings  $|X|$ ,  $|Y|$ , and  $|Z|$  in a 3HDM

$U$  can be parametrised by four parameters from scalar potential

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

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  $|X|, |Y|, |Z|$ .

## The couplings $|X|$ , $|Y|$ , and $|Z|$ in a 3HDM

The unitarity of  $U$  leads to the constraint

$$|X|^2|U_{11}|^2 + |Y|^2|U_{12}|^2 + |Z|^2|U_{13}|^2 = 1$$

- The magnitudes of  $X$ ,  $Y$  and  $Z$  cannot all be simultaneously less than one, or all be simultaneously greater than one.
- This is due to the fact that all three vacuum expectation values cannot be simultaneously large or small,  $v_d^2 + v_u^2 + v_\ell^2 = v^2 = 246^2 \text{GeV}^2$

$$\sum_{i=2}^n |X_i|^2 = \frac{v^2}{v_d^2} - 1, \quad \sum_{i=2}^n |Y_i|^2 = \frac{v^2}{v_u^2} - 1, \quad \sum_{i=2}^n |Z_i|^2 = \frac{v^2}{v_\ell^2} - 1$$

## Phenomenological constraints on $|X|$ , $|Y|$ , (and $|Z|$ )

In this talk I am mainly concerned with constraints on  $|X|$ ,  $|Y|$

Main constraints are from low energy process:

- $Z \rightarrow b\bar{b}$ :  $|Y| < 0.72 + 0.24 \left( \frac{m_{H^\pm}}{100\text{GeV}} \right)$
- $b \rightarrow s\gamma$ :  $-1.1 < \text{Re}XY^* < 0.7$  for  $m_{H^\pm} = 100 \text{ GeV}$

Lower (upper) limit  $\rightarrow$  destructive (constructive) interference of  $W$  and  $H^\pm$

- In 2HDM in which  $u$  and  $d$  quarks receive mass from different doublets (e.g Type II) one has  $XY^* = 1$

$\rightarrow m_{H^\pm} > 300 \text{ GeV}$  and so  $t \rightarrow H^\pm b$  not possible

- In democratic 3HDM  $H^\pm$  can be light since  $XY^*$  is arbitrary

Scenario of large  $\text{BR}(H^\pm \rightarrow cb)$  in a 3HDM

## Partial decay widths of $H^\pm$

Tree-level expressions:

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

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

- 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  $m_{H^\pm} > m_t$  the channel  $H^\pm \rightarrow tb$  dominates in all 2HDMs

## Scenario of large $\text{BR}(H^\pm \rightarrow cb)$

For  $m_{H^\pm} < m_t$

- $\text{BR}(H^\pm \rightarrow \tau\nu)$  and  $\text{BR}(H^\pm \rightarrow cs)$  dominate in three versions of the 2HDM (Model I, Model II, Leptophilic)
- $\text{BR}(H^\pm \rightarrow cb)$  is always  $< 1\%$  due to small  $V_{cb}$

A distinctive signal of  $H^\pm$  from a 3HDM would be:

Large  $\text{BR}(H^\pm \rightarrow cb)$

Grossman 94, AGA/Stirling 94

The necessary condition is:  $|X| \gg |Y|, |Z|$

- This condition is possible in the Flipped 2HDM and 3HDM

## Scenario of $|X| \gg |Y|, |Z|$ in Flipped 2HDM and 3HDM

### Flipped 2HDM

- $|X| \gg |Y|, |Z|$  for  $\tan \beta \gg 1$  ( $|X| = \tan \beta = 1/|Y| = 1/|Z|$ )
- However, constraint from  $b \rightarrow s\gamma$  leads to  $m_{H^\pm} > 300 \text{ GeV}$
- One has  $\text{BR}(H^\pm \rightarrow tb) \sim 1$  for  $m_{H^\pm} > m_t$
- $\rightarrow$  Large  $\text{BR}(H^\pm \rightarrow cb)$  is only possible in Flipped 2HDM

IF additional New Physics is present to relax  $b \rightarrow s\gamma$  constraint so that  $m_{H^\pm} < m_t$  is possible

### 3HDM

- $m_{H^\pm} < m_t$  respects limits from  $b \rightarrow s\gamma$  ( $XY^* \neq 1$  in general)



## Magnitude of $\text{BR}(H^\pm \rightarrow cb)$ in 3HDM

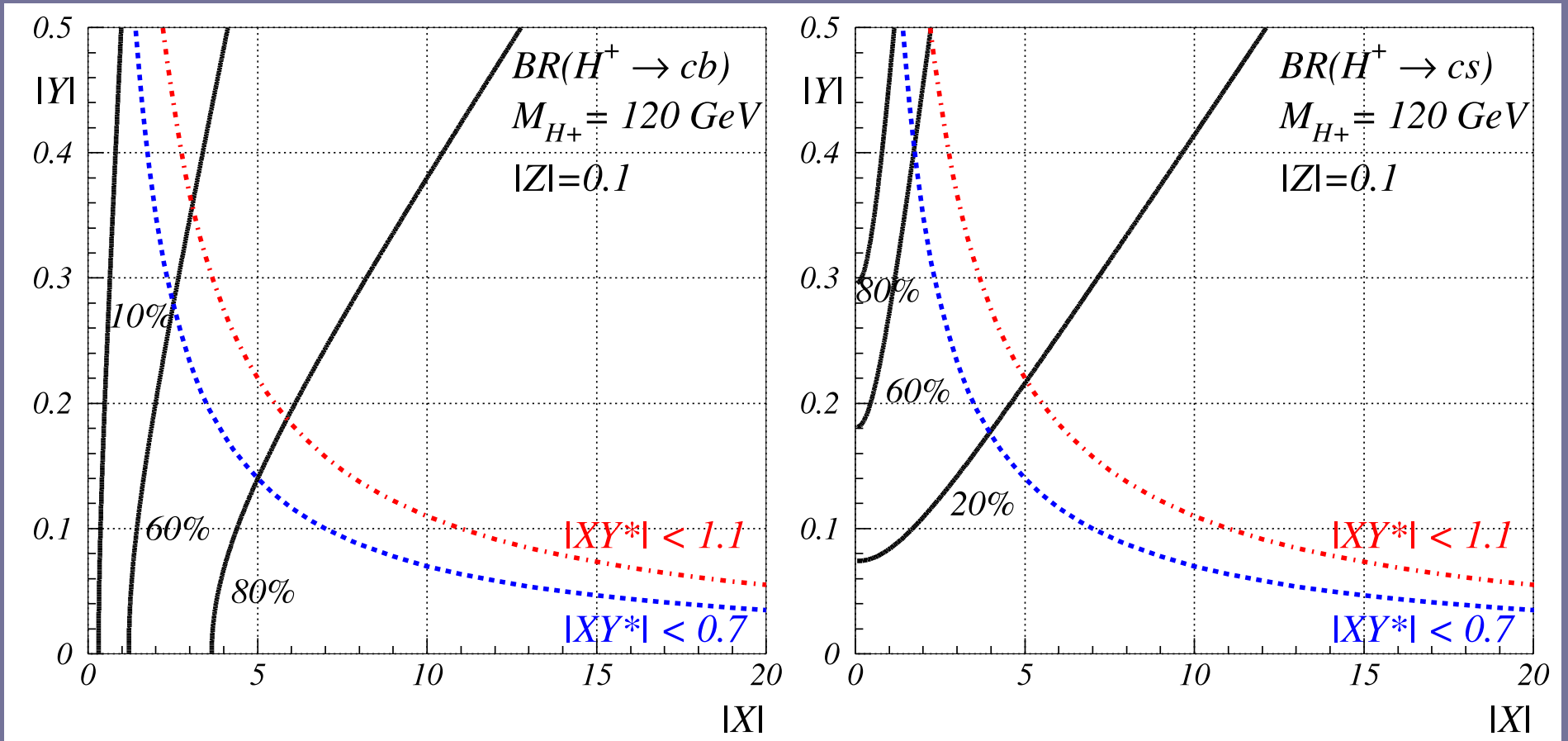
For  $|X| \gg |Y|, |Z|$  the ratio of the two dominant decays,  $\text{BR}(H^\pm \rightarrow cb)$  and  $\text{BR}(H^\pm \rightarrow cs)$ , approaches a constant value:

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

- $|V_{cs}| \sim 0.97$ ;  $|V_{cb}| \sim 0.04$ ;  $m_b \sim 2.95$  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 in  $H^\pm$  phenomenology
- Lattice QCD gives  $m_s = 94 \pm 3$  MeV at scale  $Q = 2$  GeV

## Magnitude of $\text{BR}(H^\pm \rightarrow cb)$ in 3HDM

- First numerical study of  $\text{BR}(H^\pm \rightarrow cb)$  used  $m_s = 180$  MeV and  $m_b = 5$  GeV AGA/Stirling 94
- With these unrealistic values  $\text{BR}(H^\pm \rightarrow cb)_{\text{max}} = 55\%$
- Logan et al 09, Aoki et al 09 used  $m_s = 80$  MeV at the scale of  $m_{H^\pm}$  and obtained  $\text{BR}(H^\pm \rightarrow cb)_{\text{max}} = 70\%$
- We use the lattice result for  $m_s$  at  $Q = 2$  GeV and run it to  $Q = m_{H^\pm}$ , which gives  $m_s = 55$  MeV
- We obtain  $\text{BR}(H^\pm \rightarrow cb)_{\text{max}} \sim 80\%$  AGA/Moretti/Hernandez 12



Left panel: BR( $H^\pm \rightarrow cb$ ) in plane  $[|X|, |Y|]$

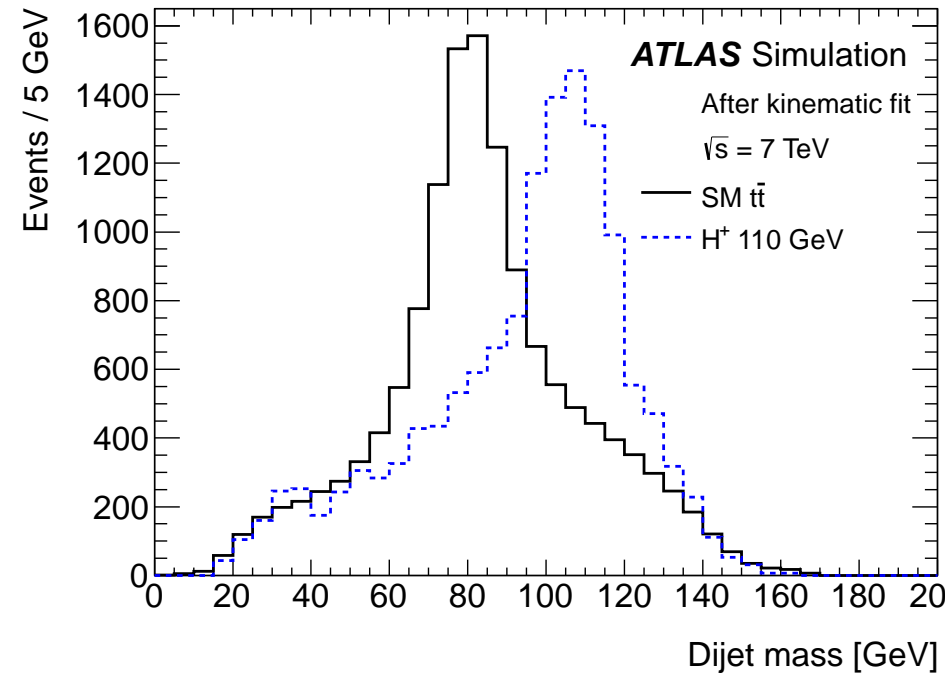
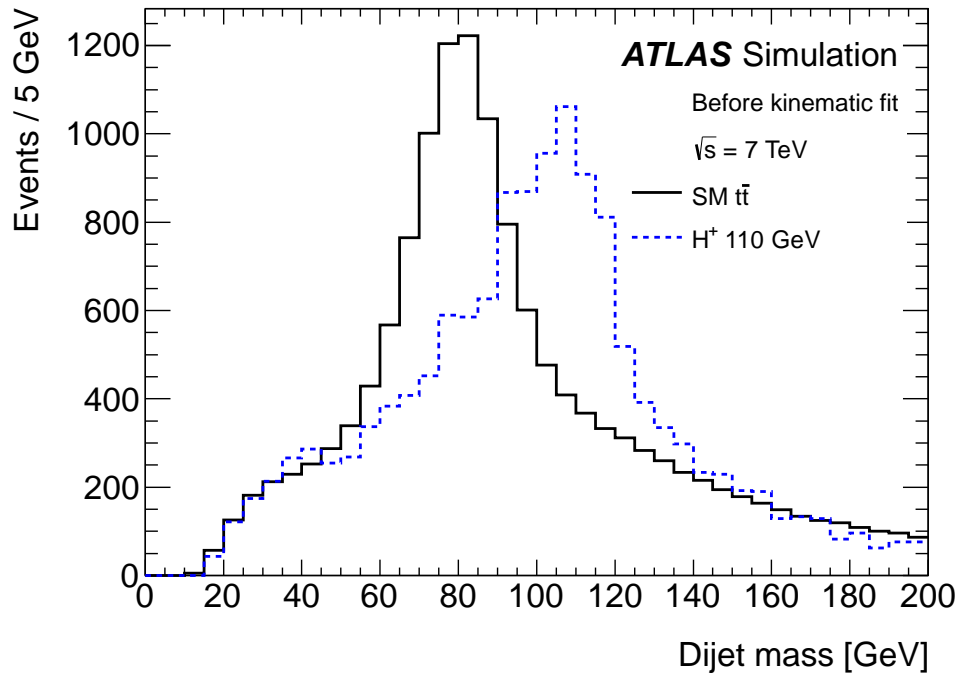
Right panel: BR( $H^\pm \rightarrow cs$ )

Direct searches for  $t \rightarrow H^\pm b$  and  $H^\pm \rightarrow cs$  at the LHC  
and application to case of  $H^\pm \rightarrow cb$

## Direct searches for $t \rightarrow H^\pm b$ and $H^\pm \rightarrow cs$ at the LHC

- Only ATLAS has performed a search for  $t \rightarrow H^\pm b$  and  $H^\pm \rightarrow cs$
- Top quarks are produced in pairs e.g.  $gg \rightarrow t\bar{t}$
- One top/anti-top decays via  $t/\bar{t} \rightarrow Wb$ , with  $W \rightarrow e\nu$  or  $\mu\nu$
- The other top/anti-top decays via  $t/\bar{t} \rightarrow H^\pm b$
- $H^\pm \rightarrow cs$  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  $t/\bar{t} \rightarrow Wb$  and  $W \rightarrow ud/cs$  would give a peak at  $m_W$

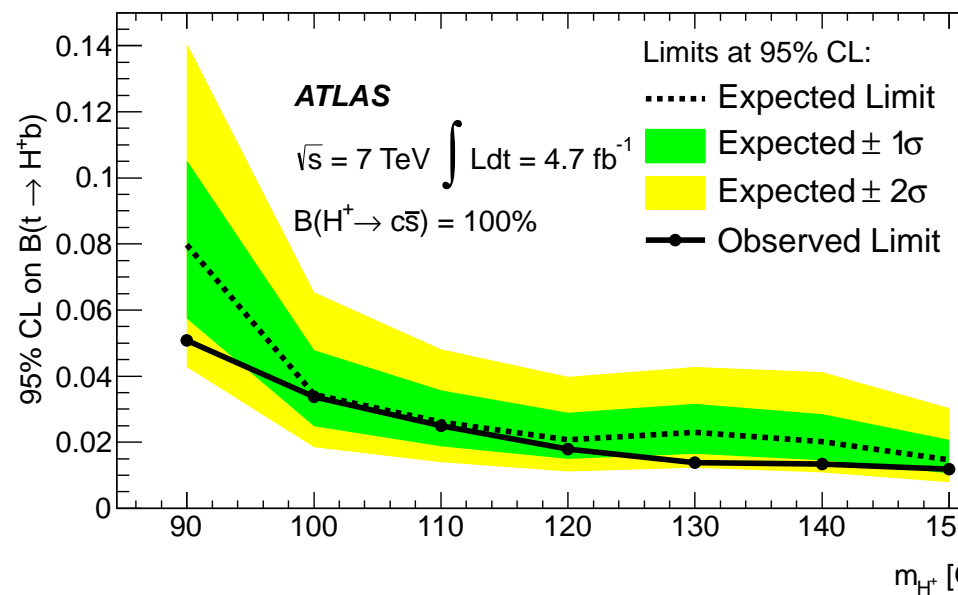
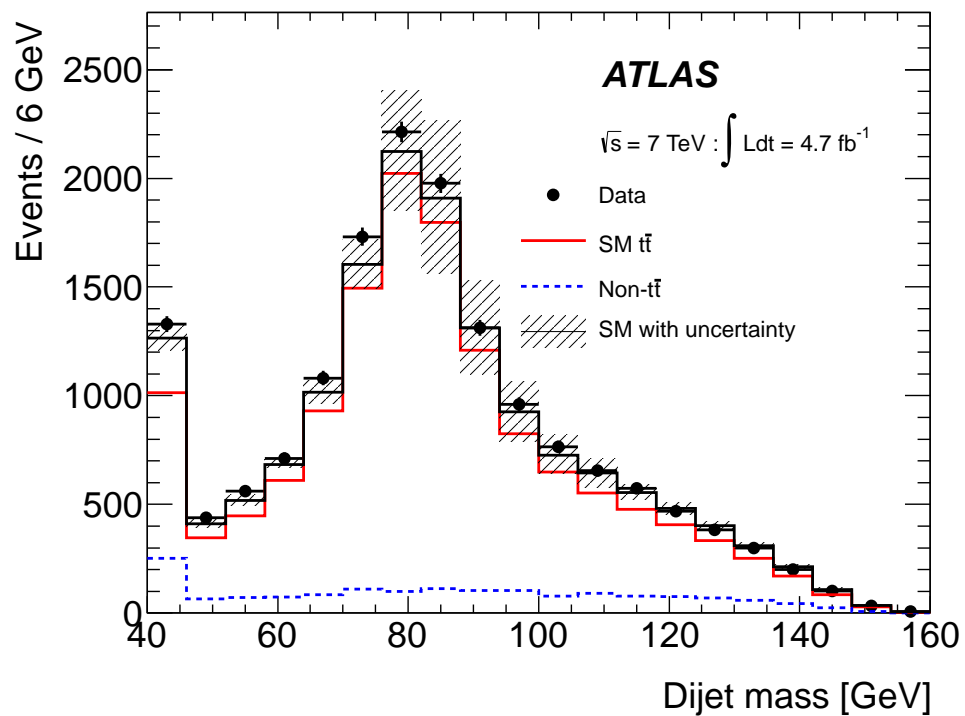
ATLAS simulation of invariant mass distribution of  $H^\pm \rightarrow cs$  originating from  $t \rightarrow H^\pm b$



Left panel: Before kinematic fit

Right panel: After kinematic fit [arXiv:1302.369](https://arxiv.org/abs/1302.369)

ATLAS limits on  $t \rightarrow H^\pm b$  with  $\text{BR}(H^\pm \rightarrow cs) = 100\%$  [arXiv:1302.3694](https://arxiv.org/abs/1302.3694)



Left panel: Comparison of simulation and data; Right panel: Excluded region in the plane  $[m_{H^\pm}, \text{BR}(t \rightarrow H^\pm b)]$

Applying a third  $b$ -tag to improve sensitivity to  $H^\pm \rightarrow cb$

- ATLAS search also applies to case of dominant  $H^\pm \rightarrow cb$
- Main background from  $W \rightarrow ud/cs$ ;  $W \rightarrow cb$  has very small rate
- $b$ -tagging efficiency  $\epsilon_b = 0.5$
- $c$ -quark mistagged as a  $b$ -quark  $\epsilon_c = 0.1$
- light quark ( $u, d, s$ ) mistagged as a  $b$ -quark  $\epsilon_j = 0.01$
- Estimate gain in sensitivity as:

$$\frac{[S/\sqrt{B}]_{\text{btag}}}{[S/\sqrt{B}]_{\text{no btag}}} \sim \frac{\epsilon_b \sqrt{2}}{\sqrt{(\epsilon_j + \epsilon_c)}} \sim \boxed{2.13}$$



## Which $b$ -quark came from where?

Of the three tagged  $b$  quarks, need to identify:

- Which originates from  $H^\pm \rightarrow cb$

(for the invariant mass distribution of  $m_{H^\pm}$ )

- Which originates from  $t \rightarrow Wb$  and  $\bar{t} \rightarrow H^\pm b$

(don't want these  $b$  in invariant mass distribution of  $m_{H^\pm}$ )

- Can (possibly) be done with a kinematical fit to  $m_t$
- $b$  quarks from  $t \rightarrow Wb$  and  $t \rightarrow H^\pm b$  should reconstruct to  $m_t$
- Then use third  $b$  quark and non- $b$  quark to plot invariant mass distribution, which should peak at  $m_{H^\pm}$

## Magnitude of $\text{BR}(t \rightarrow H^\pm b) \times \text{BR}(H^\pm \rightarrow cb)$

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

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

- The QCD corrections essentially cancel out in the ratio of partial widths  $\Gamma(t \rightarrow H^\pm b)/\Gamma(t \rightarrow Wb)$
- The corrections do not affect  $\text{BR}(t \rightarrow H^\pm b)$  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)

Current and future sensitivity to  $\text{BR}(t \rightarrow H^\pm b) \times \text{BR}(H^\pm \rightarrow cb)$

In numerical analysis we fix  $m_{H^\pm} = 120$  GeV and  $|Z| = 0.1$

- Current ATLAS limit for  $m_{H^\pm} = 120$  GeV is

$$\text{BR}(t \rightarrow H^\pm b) < 0.02 \quad (\text{assuming } \text{BR}(H^\pm \rightarrow cs) = 100\%)$$

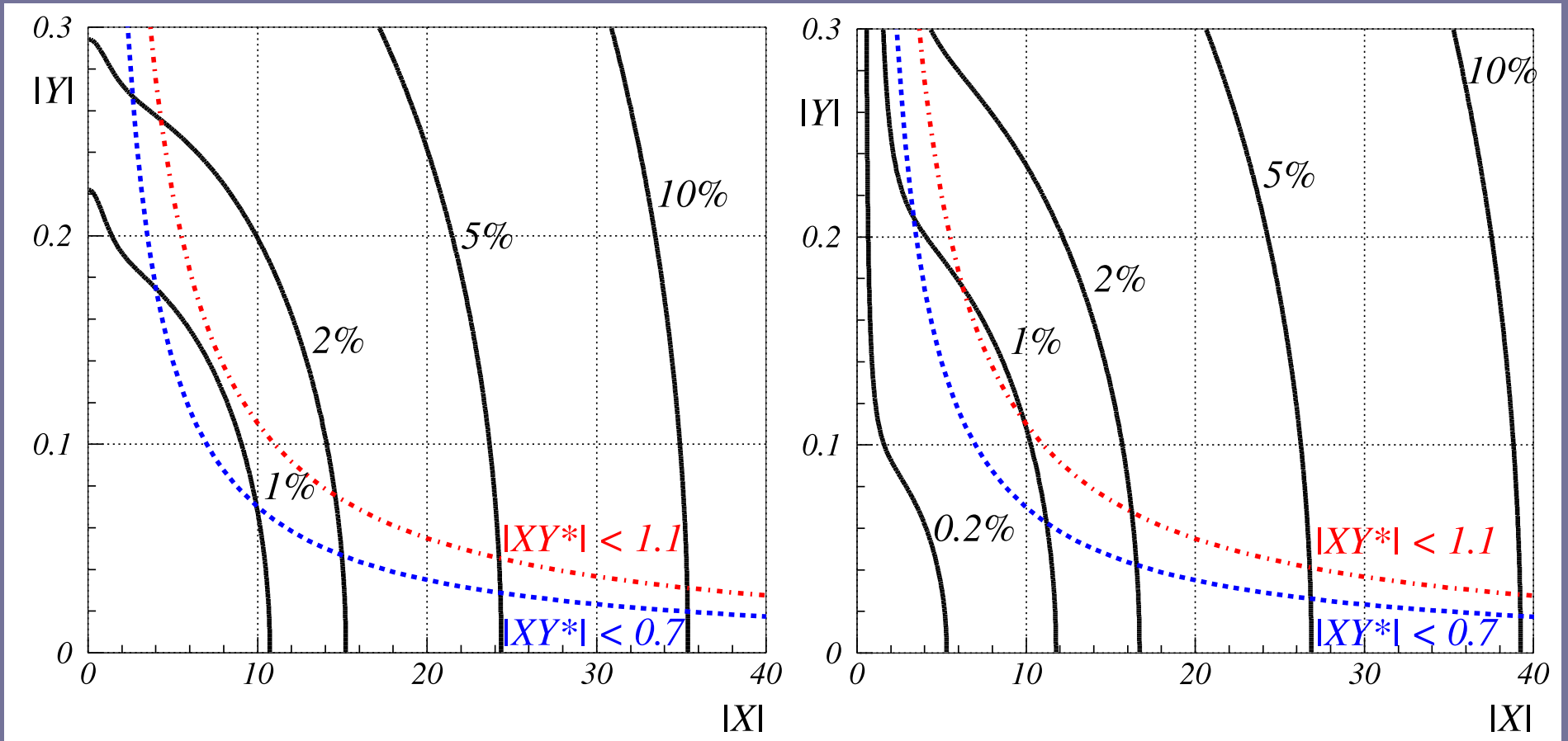
- In plane of  $[|X|, |Y|]$  show contours of:

i)  $\text{BR}(t \rightarrow H^\pm b) \times [\text{BR}(H^\pm \rightarrow cb) + \text{BR}(H^\pm \rightarrow cs)]$

ii)  $\text{BR}(t \rightarrow H^\pm b) \times \text{BR}(H^\pm \rightarrow cb)$

- Compare the regions of plane  $[|X|, |Y|]$  which are excluded

from  $b \rightarrow s\gamma$  and  $t \rightarrow H^\pm b$



Left panel:  $\text{BR}(t \rightarrow H^\pm b) \times [\text{BR}(H^\pm \rightarrow cb) + \text{BR}(H^\pm \rightarrow cs)]$ ; Right panel:  $\text{BR}(t \rightarrow H^\pm b) \times \text{BR}(H^\pm \rightarrow cb)$

## Summary of Figures

- Constraints from  $t \rightarrow H^\pm b$  on plane  $[|X|, |Y|]$  are competitive with those from  $b \rightarrow s\gamma$
- $\text{BR}(t \rightarrow H^\pm b) < 2\%$  rules out two regions which cannot be excluded from  $b \rightarrow s\gamma$ : i)  $15 < |X| < 40$  and  $0 < |Y| < 0.04$ , and ii)  $0 < |X| < 4$  and  $0.3 > |Y| > 0.8$
- Tagging the  $b$  quark from  $H^\pm \rightarrow cb$  would possibly allow sensitivity to  $\text{BR}(t \rightarrow H^\pm b) < 0.5\%$  or less
- $t \rightarrow H^\pm b$  and  $H^\pm \rightarrow cb$  could provide stronger constraints on the  $[|X|, |Y|]$  plane than  $b \rightarrow s\gamma$  (or perhaps discover  $H^\pm \rightarrow cb\dots$ )

## Conclusions

- A scalar particle has been found. Maybe more scalars (including charged scalars) are waiting to be discovered?
- $H^\pm \rightarrow cb$  can be the dominant decay in the 3HDM
- $H^\pm \rightarrow cb$  has a small branching ratio in most 2HDMs
- ATLAS search ( $4.7 \text{ fb}^{-1}$  and  $\sqrt{s} = 7 \text{ TeV}$ ) for  $t \rightarrow H^\pm b$ ,  $H^\pm \rightarrow cs$  is sensitive to  $H^\pm \rightarrow cb$
- Tagging the  $b$  quark from  $H^\pm \rightarrow cb$  could further improve sensitivity to the fermionic couplings of  $H^\pm$  ( $|X|$  and  $|Y|$ )
- A (possibly) straightforward extension of ongoing searches for  $t \rightarrow H^\pm b$ ,  $H^\pm \rightarrow cs$