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

Stefano Moretti

NExT Institute, SHEP, University of Southampton, UK

- Charged scalars ($H^{\pm}$) predicted in many models beyond the SM
- $H^{\pm}$ in the three-Higgs-doublet model (3HDM)
- $H^{\pm} \to cb$ can be the dominant decay channel
- Large BR($H^{\pm} \to cb$) with $t \to H^{\pm}b$ unlikely in 2HDMs
- $t \to H^{\pm}b$ with $H^{\pm} \to cb$ can be searched for at the LHC

Collaborators: A. Akeroyd (Soton, UK) and J. Hernandez-Sanchez (Puebla, Mexico)

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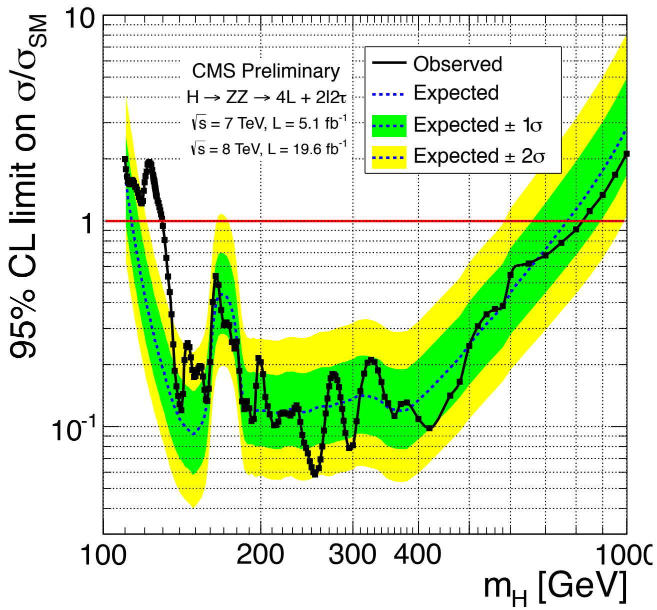
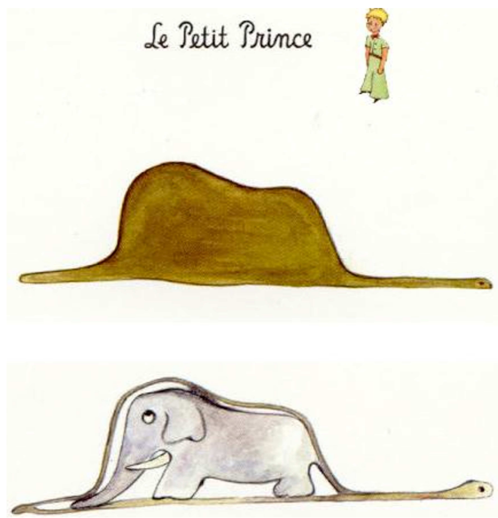
A Higgs boson discovery: possible New Physics?





'On ne voit bien qu'avec le coeur. L'essentiel est invisible pour les yeux.'

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, $H^{\pm}$?

Reasons to consider a non-minimal Higgs sector

- Why not? Three generations of quarks and leptons.

Why not two or more generations (doublets, which we have discovered) of scalars? Exactly three (3HDM)?

- (Scalar) Dark Matter(DM) with Inert Doublets
- CP violation, FCNCs, Hierarchy of Yukawa couplings
- Axion models with Peccei-Quinn symmetry
- Supersymmetry (requires at least two scalar doublets and in even numbers: 2HDM, 4HDM & 6HDM)

$\rightarrow$ 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, ℓ obtain mass from v_u, v_d, v_ℓ respectively
- The mass matrix of the charged scalars (which depends on scalar potential) is diagonalised by the 3×3 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 $H^{\pm}$.

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, Akeroyd/Stirling 94

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

- 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

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, $v_d^2 + v_u^2 + v_\ell^2 = v^2 = 246^2\text{GeV}^2$
- Theory: VV scattering unitarity, perturbativity, vacuum stability, EWSB with $h(125\text{ GeV})$ Keus/King/SM 14

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

Main constraints are from low energy process:

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

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

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

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

- In democratic 3HDM $H^\pm$ can be light since XY^* is arbitrary
- χ^2 to LHC data (loose contraints)

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

Scenario of large BR($H^\pm \to cb$)

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

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

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

Large BR($H^\pm \to cb$) Grossman 94, Akeroyd/Stirling 94

The necessary condition is: $|X| >> |Y|, |Z|$

- This condition is possible in the 2HDM-III (aka Flipped 2HDM) and 3HDM

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

2HDM-III

- $|X| >> |Y|, |Z|$ for $\tan\beta >> 1$ ($|X| = \tan\beta = 1/|Y| = 1/|Z|$)
- However, constraint from $b \to s\gamma$ leads to $m_{H^\pm} > 300$ 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 2HDM-III

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

3HDM

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

Magnitude of BR($H^\pm \to cb$) in 3HDM

- First numerical study of BR($H^\pm \to cb$) used

$m_s = 180$ MeV and $m_b = 5$ GeV Akeroyd/Stirling 94

- With these unrealistic values BR($H^\pm \to cb$)$_{\text{max}} = 55\%$
- Logan et al 09, Aoki at el 09 used $m_s = 80$ MeV at the scale of $m_{H^\pm}$

and obtained BR($H^\pm \to cb$)$_{\text{max}} = 70\%$

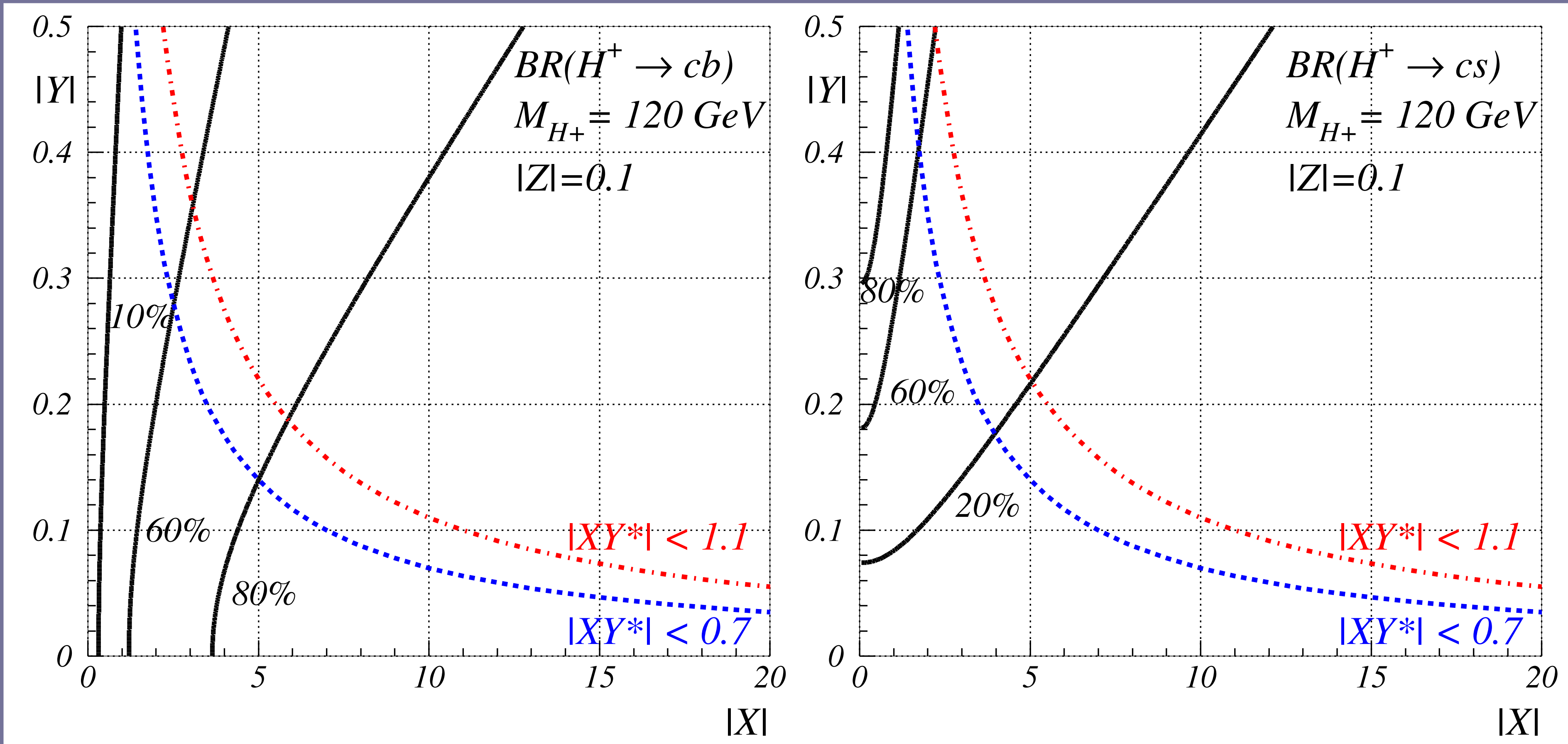
- We use the lattice result for m_s at $Q = 2$ GeV and run

it to $Q = m_{H^\pm}$, which gives $m_s = 55$ MeV

- We obtain BR($H^\pm \to cb$)$_{\text{max}} \sim 80\%$ Akeroyd/SM/Hernandez 12

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

Akeroyd/SM/Hernandez, arXiv:1203.5769



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

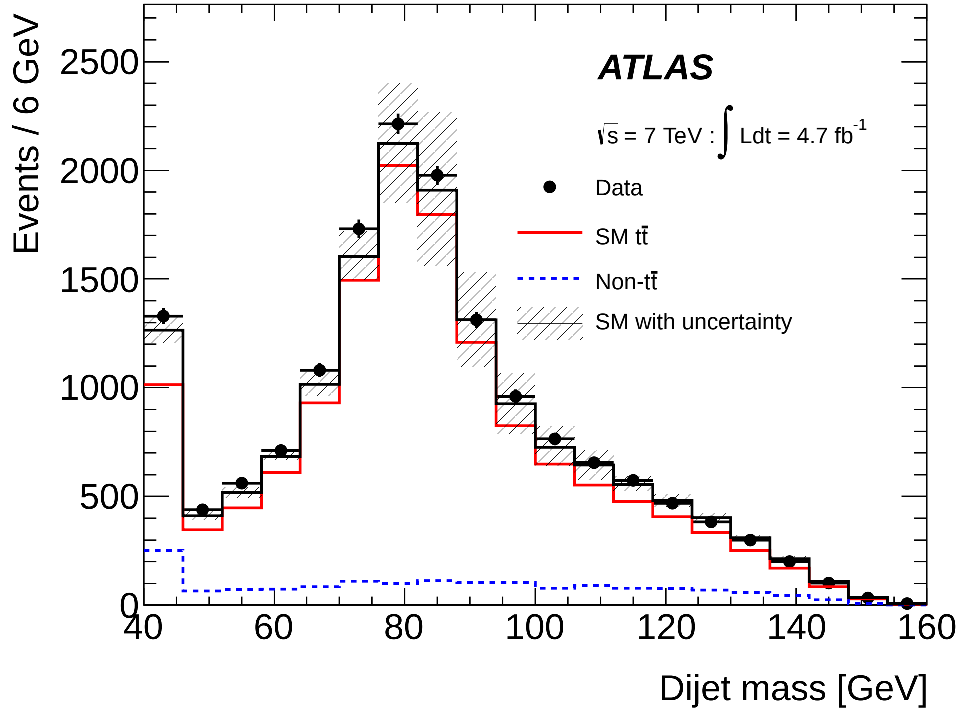
Direct searches for $t \to H^{\pm}b$ and $H^{\pm} \to cs$ at the LHC and application to case of $H^{\pm} \to cb$

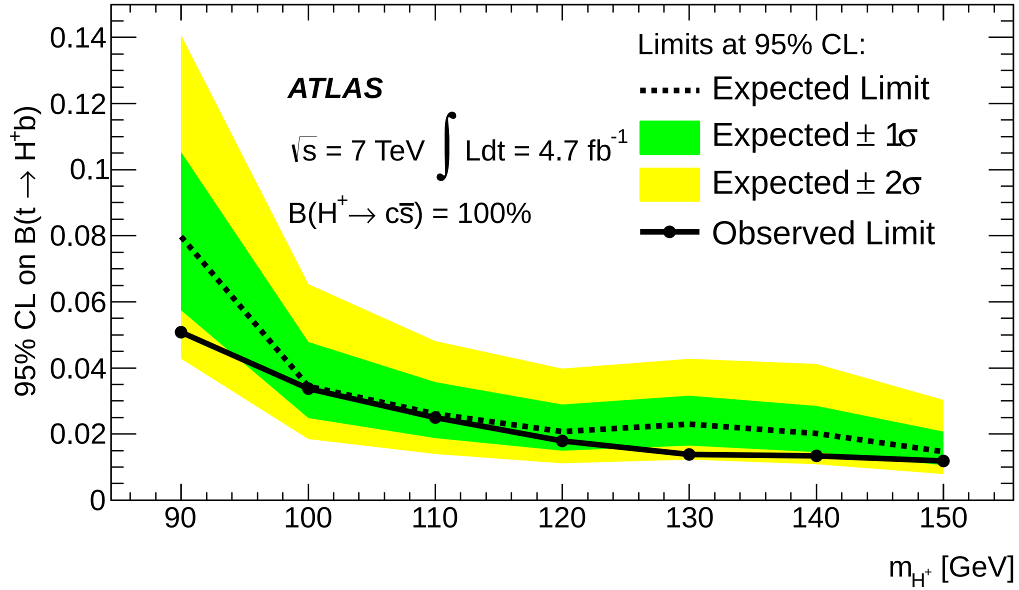
Direct searches for $t \to H^\pm b$ and $H^\pm \to cs$ at the LHC

- Both ATLAS & CMS have searched for $t \to H^\pm b$ and $H^\pm \to cs$
- Top quarks are produced in pairs e.g. $gg \to t\bar{t}$
- One top/anti-top decays via $t/\bar{t} \to Wb$, with $W \to e\nu$ or $\mu\nu$
- The other top/anti-top decays via $t/\bar{t} \to H^\pm b$
- $H^\pm \to cs$ 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

ATLAS limits on $t \to H^{\pm}b$ with BR$(H^{\pm} \to cs) = 100\%$ arXiv:1302.3694





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

See yesterday's talk by Gouranga Kole for CMS limits

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

- ATLAS/CMS search also applies to case of dominant $H^{\pm} \to cb$
- Main background from $W \to ud/cs$; $W \to cb$ 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:

$$\frac{[S/\sqrt{B}]_{\text{btag}}}{[S/\sqrt{B}]_{\not{b}\text{tag}}} \sim \frac{\epsilon_b \sqrt{2}}{\sqrt{(\epsilon_j + \epsilon_c)}} \sim \boxed{2.13}$$

Which b-quark came from where?

Of the three tagged b quarks, need to identify:

- Which orginates from $H^\pm \to cb$

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

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

(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 $t \to Wb$ and $t \to H^\pm b$ should reconstruct to m_t
- Then use third b quark and non-b quark to plot invariant mass

distribution, which should peak at $m_{H^\pm}$

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

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

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

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

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

i) BR$(t \to H^{\pm} b)$x[BR$(H^{\pm} \to cb)$+BR$(H^{\pm} \to cs)$]

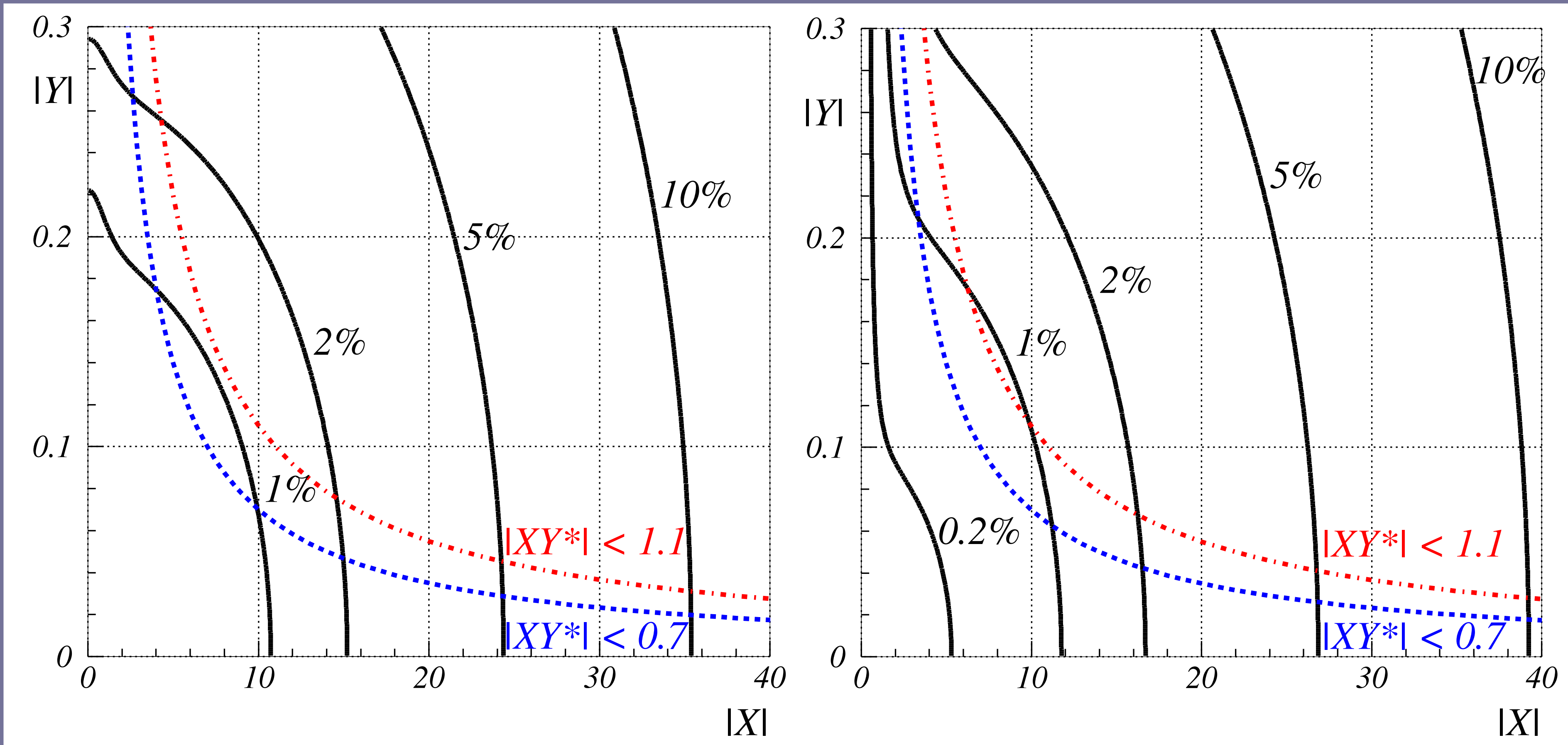
ii) BR$(t \to H^{\pm} b) \times$BR$(H^{\pm} \to cb)$

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

from $b \to s\gamma$ and $t \to H^{\pm} b$

BR($t \to H^\pm b$) with $m_{H^\pm} = 120$ GeV and $|Z| = 0.1$ in a 3HDM

Akeroyd/SM/Hernandez 12



Left: BR($t \to H^\pm b$)x[BR($H^\pm \to cb$)+ BR($H^\pm \to cs$)] (no b-tag); Right: BR($t \to H^\pm b$)xBR($H^\pm \to cb$) (b-tag)

Summary of results

- Constraints from $t \to H^{\pm}b$ on plane $[|X|, |Y|]$ are competitive with those from $b \to s\gamma$
- BR($t \to H^{\pm}b$) $< 2\%$ rules out two regions which cannot be excluded from $b \to s\gamma$: 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 $H^{\pm} \to cb$ would possibly allow sensitivity to BR($t \to H^{\pm}b$) $< 0.5\%$ or less
- $t \to H^{\pm}b$ and $H^{\pm} \to cb$ could provide stronger constraints on the $[|X|, |Y|]$ plane than $b \to s\gamma$ (or perhaps discover $H^{\pm} \to cb$...)

Conclusions

- A scalar particle found, maybe more scalars, including $H^{\pm}$
- $H^{\pm} \to cb$ can be the dominant decay in the 3HDM
- $H^{\pm} \to cb$ has a small branching ratio in most 2HDMs
- Large $H^{\pm} \to cb$ & $m_{H^{\pm}} < m_t$ points to 3HDM (also A2HDM)
- ATLAS search for $t \to H^{\pm}b$, $H^{\pm} \to cs$ is sensitive to $H^{\pm} \to cb$ (same for CMS)
- Tagging the b quark from $H^{\pm} \to cb$ could further improve sensitivity to the fermionic couplings of $H^{\pm}$ ($|X|$ and $|Y|$)
- A (possibly) straightforward extension of ongoing searches for $t \to H^{\pm}b$, $H^{\pm} \to cs$

BACKUP SLIDES

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)

$\rightarrow$ 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

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	$\tan\beta$	$\cot\beta$	$\tan\beta$
Type IV (Lepton-specific)	$-\cot\beta$	$\cot\beta$	$\tan\beta$
Type III (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 and are well studied; Model II is the structure in SUSY models
- Only a few studies on $H^{\pm}$ in Type IV (Lepton-specific) and Type III (Flipped) models prior to 2009, but now the phenomenology is well-studied

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) $\tan\gamma = \sqrt{v_d^2 + v_u^2}/v_\ell$ ($0 < v_d, v_u, v_\ell <$ 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 $|X|, |Y|, |Z|$.

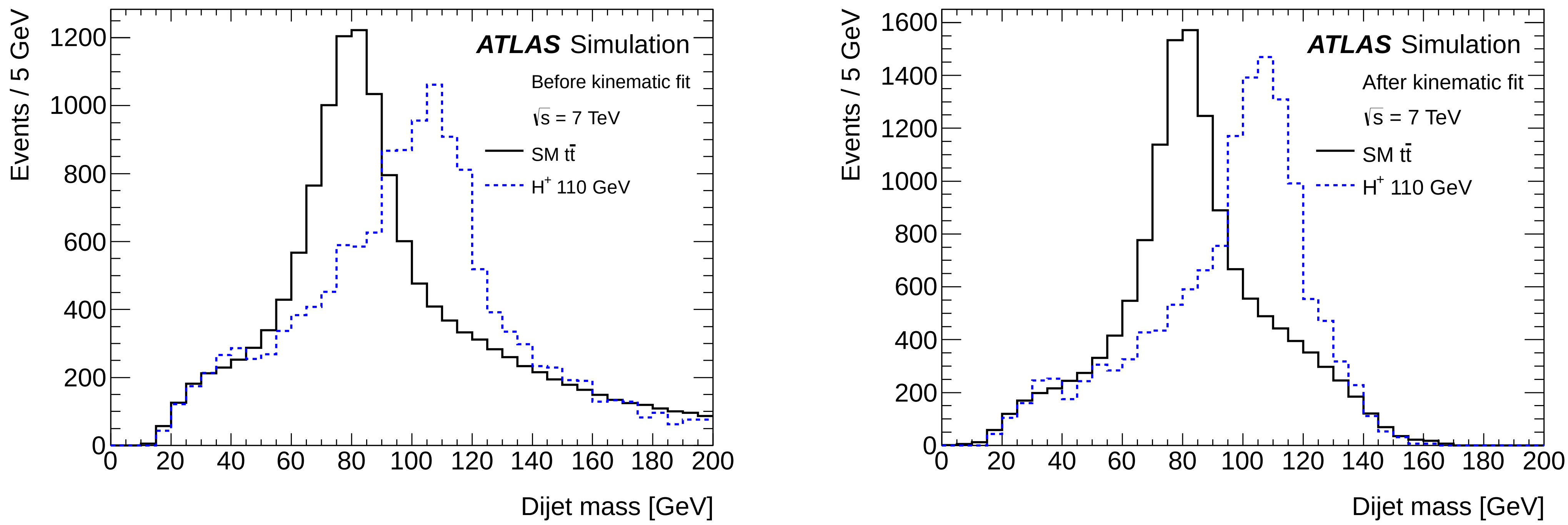
Magnitude of BR($H^\pm \to cb$) in 3HDM

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 in $H^\pm$ phenomenology
- Lattice QCD gives $m_s = 94 \pm 3$ MeV at scale $Q = 2$ GeV

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



Left: Before kinematic fit Right: After kinematic fit arXiv:1302.3694

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

Tree-level expressions:

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

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

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

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

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

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

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