Charged Higgs Decays

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Prospects for Charged Higgs Discovery at Colliders

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The Charged Higgs boson

- Charged Higgs bosons appear whenever the scalar sector responsible for EWSB is extended by fields transforming non-trivially under SU(2).

- In this talk: SU(2) doublet -> One charged Higgs pair
  - Minimal supersymmetry (MSSM, NMSSM, …)
  - General two-Higgs-Doublet models (2HDM)

- Charged Higgs bosons are important since the search results (exclusion limits, …) complements the neutral Higgs sector, and can often be discussed with fewer ambiguities:
  e.g. light/heavy SM-like Higgs question, CP-admixture, MSSM mass relations, scenarios …

  -> Don't disregard searches which appear to have low sensitivity in a particular scenario

Quick overview of H⁺ decay modes

Mode	MSSM	NMSSM	2HDM	EXP
$H^+ \to \tau^+ \nu_\tau$	X	X	X	ATL-CONF-2013-090 CMS [1205.5736]
$H^+ \to \mu^+ \nu_\mu$	X	X	X	
$H^+ \to t\bar{b}$	X	X	X	CMS-HIG-13-026
$H^+ \to c\bar{b}$	(X)	(X)	X	
$H^+ \to c\bar{s}$	X	X	X	ATLAS [1302.3694] CMS-HIG-13-035
$H^+ \to W^+ h$	(X)	X	X	
$H^+ \to W^+ H$	-	X	X	
$H^+ \to W^+ A$	-	X	X	
$H^+ \to \chi_i^+ \chi_j^0$	X	X	-	

Calculation of decay modes in MSSM

- Coupling to light quarks/leptons are suppressed by small masses, additional CKM suppression for flavor off-diagonal couplings

- From LHCHXSWG MSSM recommendations:

$$\Gamma_{H^\pm} = \Gamma^{FH}_{H^\pm\to\tau\nu_\tau} + \Gamma^{FH}_{H^\pm\to\mu\nu_\mu} + \Gamma^{FH}_{H^\pm\to hW} + \Gamma^{FH}_{H^\pm\to HW} + \Gamma^{FH}_{H^\pm\to AW}$$
$$+ \Gamma^{HD}_{H^\pm\to tb} + \Gamma^{HD}_{H^\pm\to ts} + \Gamma^{HD}_{H^\pm\to td} + \Gamma^{HD}_{H^\pm\to cb} + \Gamma^{HD}_{H^\pm\to cs} + \Gamma^{HD}_{H^\pm\to cd}$$
$$+ \Gamma^{HD}_{H^\pm\to ub} + \Gamma^{HD}_{H^\pm\to us} + \Gamma^{HD}_{H^\pm\to ud} ,$$

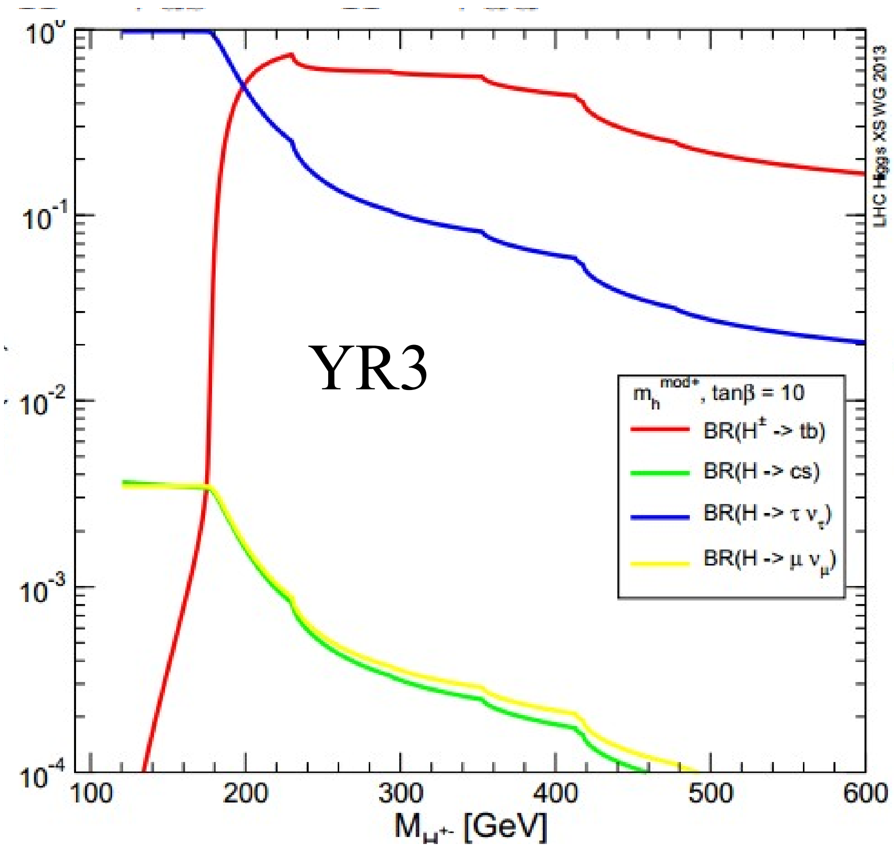
- Two programs are used by XSWG to calculate MSSM decays of H^+:
  FeynHiggs (FH) — S. Heinemeyer, W. Hollik, G. Weiglein, [hep-ph/9812320]
  HDECAY (HD) — A. Djouadi, J. Kalinowski, M. Spira, [hep-ph/9704448]

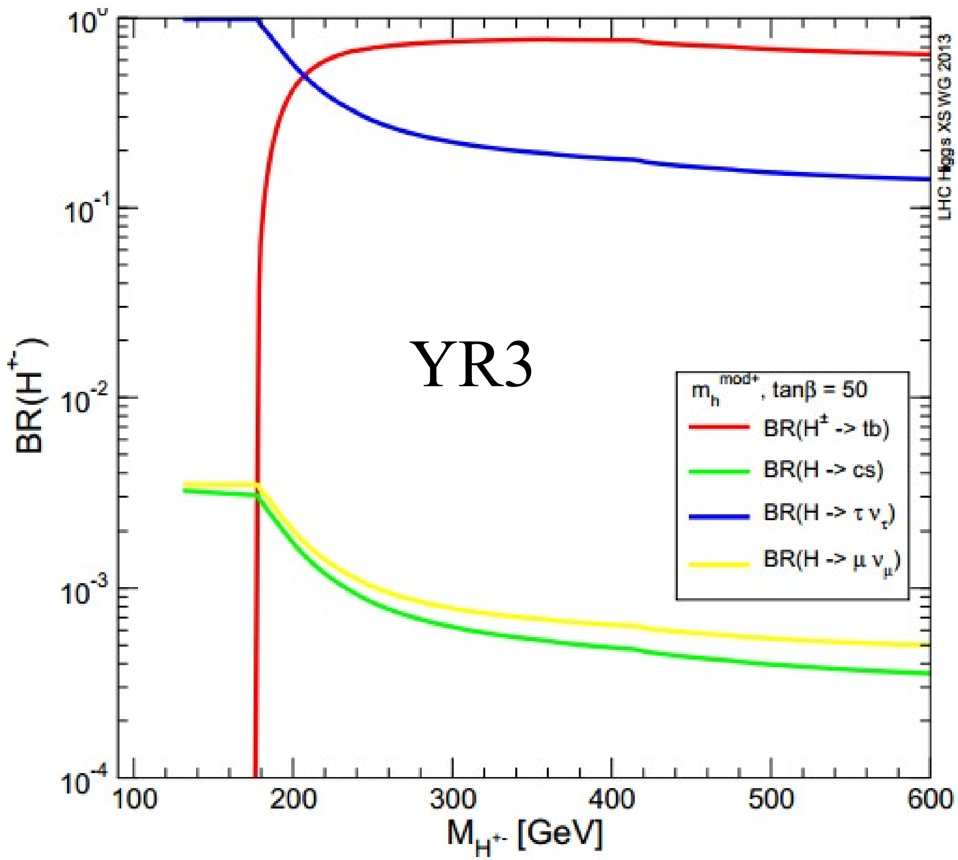
- QCD corrections important, including MSSM-specific contributions to bottom Yukawa coupling enhanced with tan β (“Δ_b effects”)
  Decays with gauge couplings typically sub-dominant in MSSM

MSSM H^+ decays to SM particles

- Example: M_h^{mod+} benchmark scenario

M. Carena, S. Heinemeyer, OS, C. Wagner, G. Weiglein, [1302.7033]

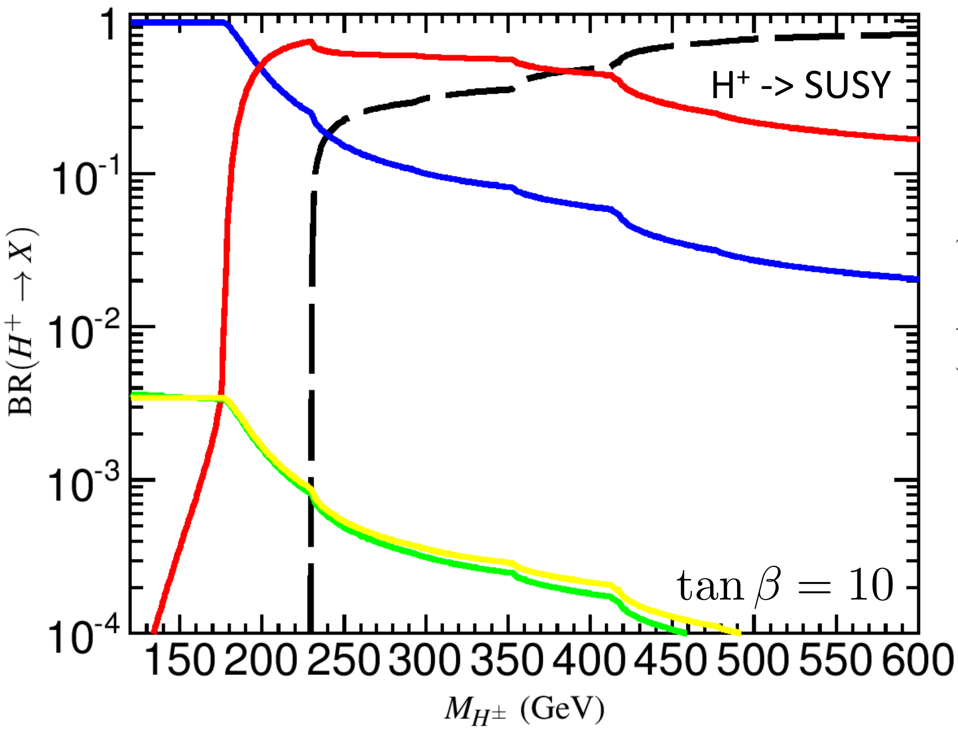


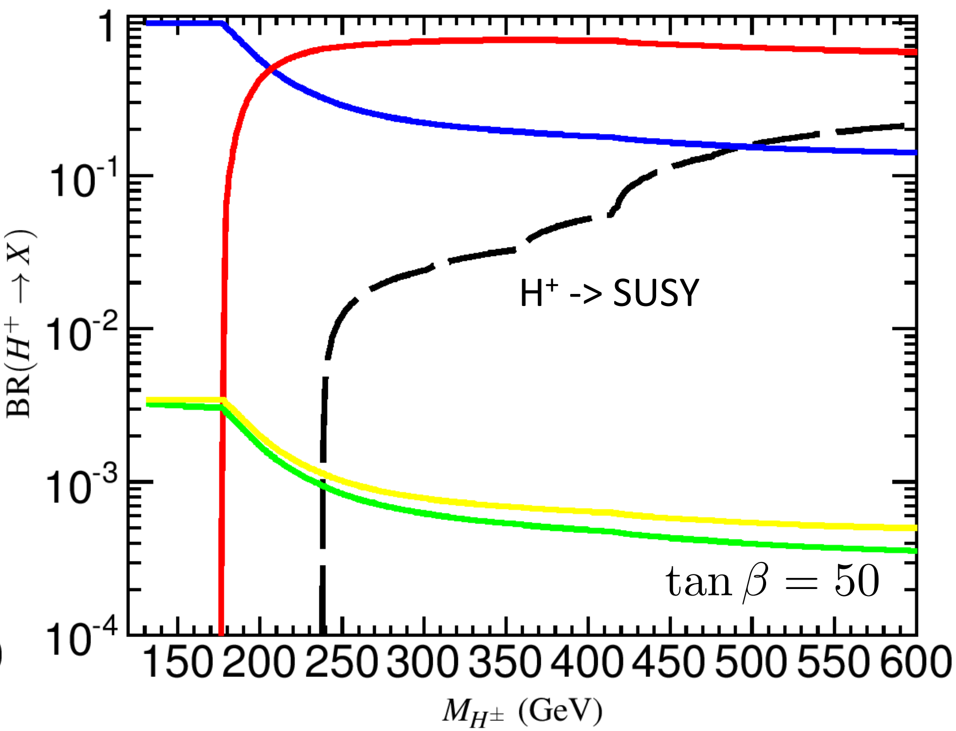


- Modes with light quarks could become more important for really low tan $\beta \sim 1$ (requires high M_{stop})

What is missing in this picture?

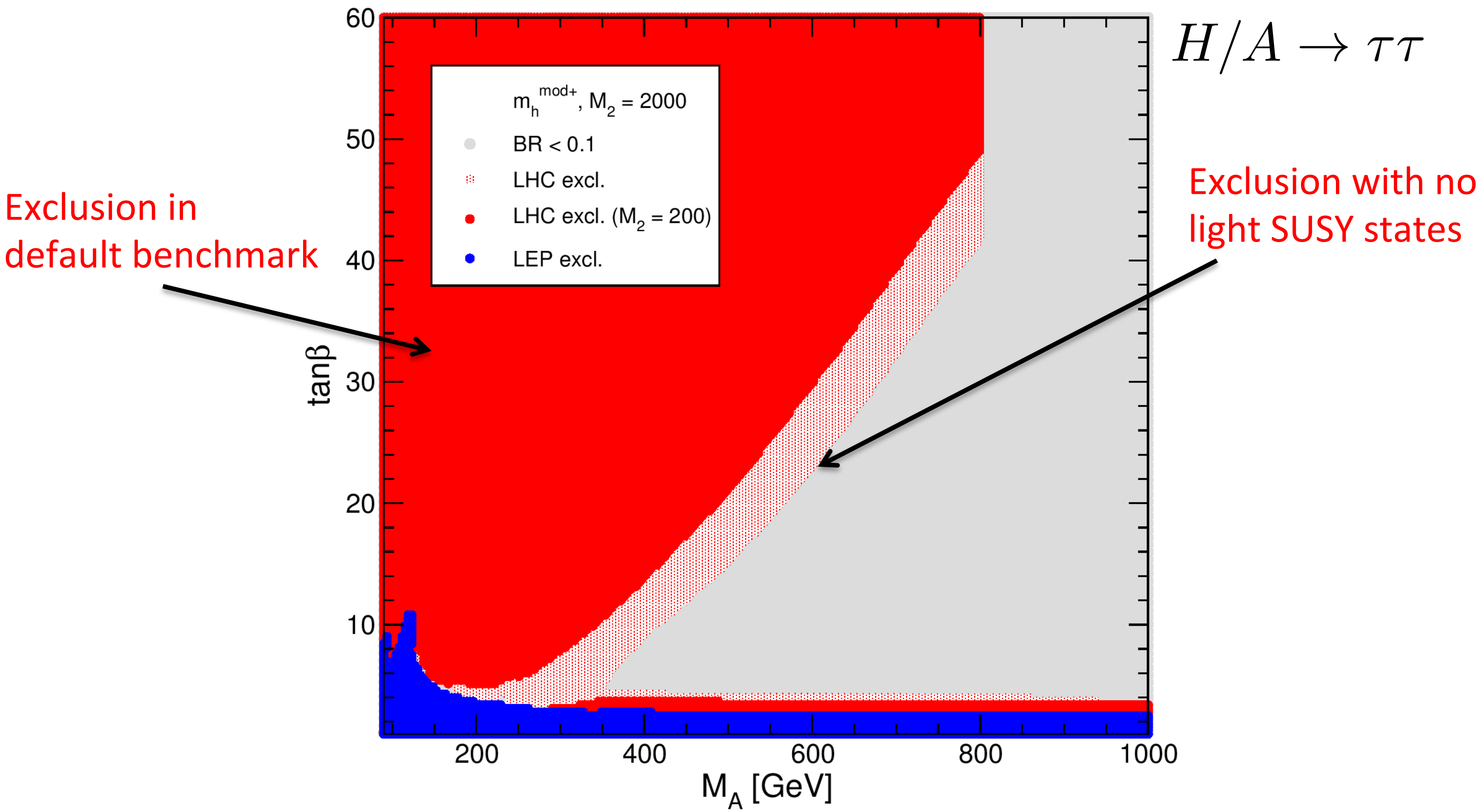
- Decays to SUSY states (chargino/neutralino pairs) can become dominant for heavy H^+





- Limits from $\tau\,\nu$ searches interpreted in this scenario are less excluding than the corresponding 2HDM Type-II (without SUSY)

SUSY Decays of Heavy MSSM Higgs bosons



- Light SUSY states is either considered a nuisance for "SM" searches
  - or an opportunity to improve sensitivity in the "wedge" region

Decays involving gauge couplings

- The couplings governing the decays

$$H^+ \to W^+ h \qquad H^+ \to W^+ H \qquad H^+ \to W^+ A$$

have generic form in *all* two-Higgs-doublet models:

$$g_{H^\pm W^\mp h} \propto \frac{g}{2}\cos(\beta-\alpha) \quad g_{H^\pm W^\mp H} \propto \frac{g}{2}\sin(\beta-\alpha) \quad g_{H^\pm W^\mp A} \propto \frac{g}{2}$$

- In the alignment limit, with h as the SM-like Higgs boson

$$\sin(\beta-\alpha) \to 1$$

- $H^+ \to H_{\rm SM} W^+$ is suppressed

- Sizeable rates for H^+ into lighter Higgs/vector final states requires
  - mass hierachies among scalars
  - suppression of H^+-fermion couplings

  Not common in the MSSM, but possible in 2HDM/NMSSM

General 2HDM: Yukawa Couplings

- The 2HDM with most general form of Yukawa couplings:

$$
\begin{aligned}
-\mathcal{L}_{\mathrm{Y}} = {} & \frac{1}{\sqrt{2}}\overline{D}\Big[\kappa^D s_{\beta-\alpha} + \rho^D c_{\beta-\alpha}\Big]Dh + \frac{1}{\sqrt{2}}\overline{D}\Big[\kappa^D c_{\beta-\alpha} - \rho^D s_{\beta-\alpha}\Big]DH + \frac{\mathrm{i}}{\sqrt{2}}\overline{D}\gamma_5\rho^D DA \\
& + \frac{1}{\sqrt{2}}\overline{U}\Big[\kappa^U s_{\beta-\alpha} + \rho^U c_{\beta-\alpha}\Big]Uh + \frac{1}{\sqrt{2}}\overline{U}\Big[\kappa^U c_{\beta-\alpha} - \rho^U s_{\beta-\alpha}\Big]UH - \frac{\mathrm{i}}{\sqrt{2}}\overline{U}\gamma_5\rho^U UA \\
& + \frac{1}{\sqrt{2}}\overline{L}\Big[\kappa^L s_{\beta-\alpha} + \rho^L c_{\beta-\alpha}\Big]Lh + \frac{1}{\sqrt{2}}\overline{L}\Big[\kappa^L c_{\beta-\alpha} - \rho^L s_{\beta-\alpha}\Big]LH + \frac{\mathrm{i}}{\sqrt{2}}\overline{L}\gamma_5\rho^L LA \\
& + \Big[\overline{U}\big(V_{\mathrm{CKM}}\rho^D P_R - \rho^U V_{\mathrm{CKM}} P_L\big)DH^+ + \overline{\nu}\rho^L P_R L H^+ + \mathrm{h.c.}\Big].
\end{aligned}
$$

- In principle full freedom to choose the 3x3 matrix ρ_F independently from κ_F (mass matrix)

- Charged Higgs couplings depend only on ρ_F

- Any model where ρ_F is not diagonal in the same basis as κ_F will have tree-level FCNC (-> strongly restricted from data)

Absence of tree-level FCNC –> 2HDM Types

- To get rid of FCNC in a natural way, implement a (softly broken) Z_2 symmetry in a specific basis for Φ_1 and Φ_2
  -> 2HDM "Types" depending on fermion Z_2 charges

$$\rho_F \propto \kappa_F = \frac{\sqrt{2}}{v} M_F$$

Barger, Hewitt, Philips, PRD41 (1990)

Type	U_R	D_R	L_R	ρ^U	ρ^D	ρ^L
I	$+$	$+$	$+$	$\kappa^U \cot\beta$	$\kappa^D \cot\beta$	$\kappa^L \cot\beta$
II	$+$	$-$	$-$	$\kappa^U \cot\beta$	$-\kappa^D \tan\beta$	$-\kappa^L \tan\beta$
III	$+$	$-$	$+$	$\kappa^U \cot\beta$	$-\kappa^D \tan\beta$	$\kappa^L \cot\beta$
IV	$+$	$+$	$-$	$\kappa^U \cot\beta$	$\kappa^D \cot\beta$	$-\kappa^L \tan\beta$

Type III = Type Y = "Flipped"   Type IV = Type X = "Lepton-specific"

- Tree-level MSSM -> Type-II Yukawa couplings
  Beyond tree-level this is broken by Δ_b -> More general couplings

Two-Higgs-doublet-Model Calculator (2HDMC)

- 2HDMC is a public C++ code for calculations in the general 2HDM

D. Eriksson, J. Rathsman (Lund), OS (Stockholm)

[0902.0851]

http://2hdmc.hepforge.org

- Official LHCHXSWG recommendations for the 2HDM Higgs cross sections and branching ratios

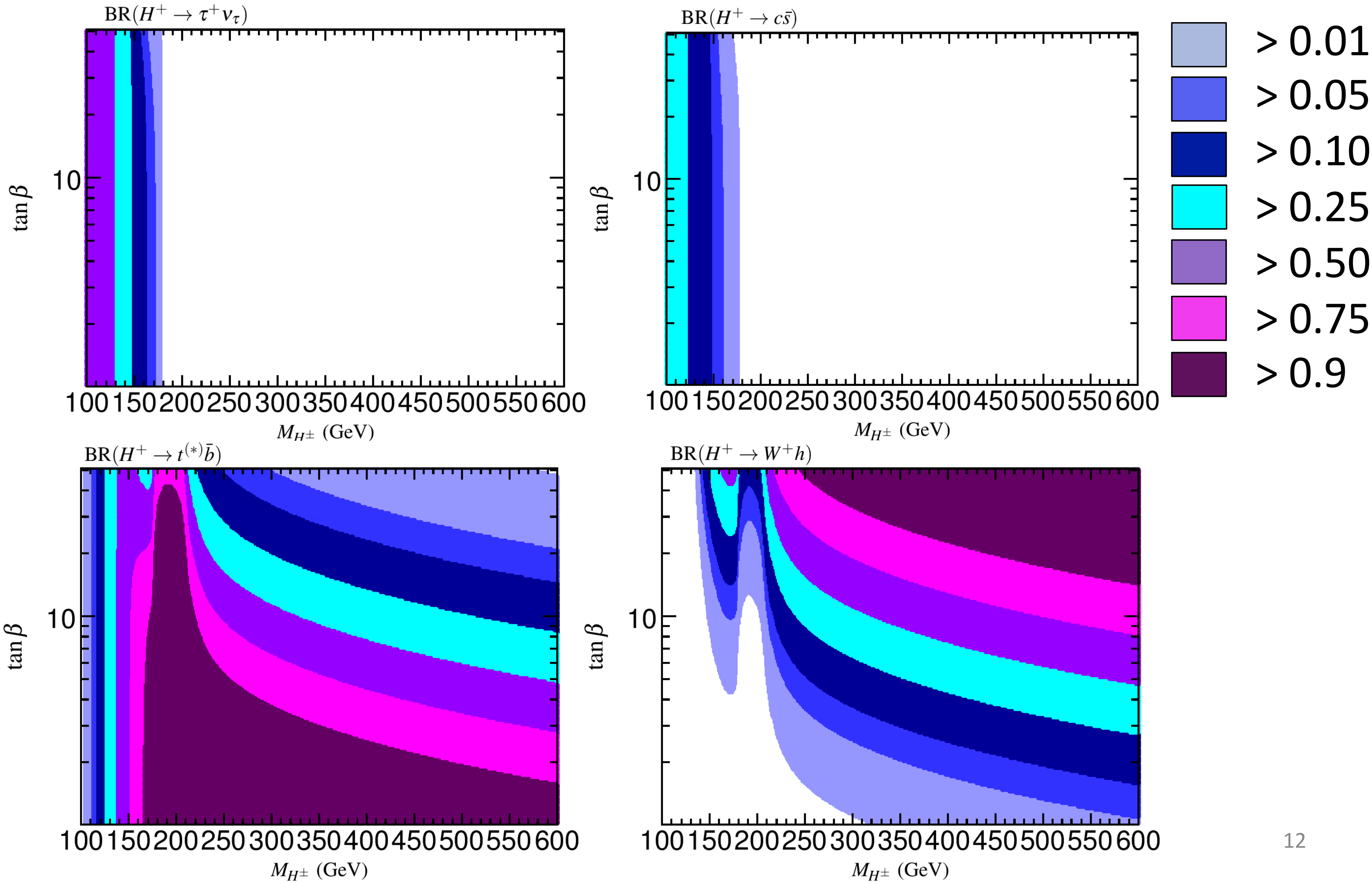
R. Harlander, M. Mühlleitner, J. Rathsman, M. Spira, OS, [1312.5571]

SusHi (xsection) + 2HDMC (decays)
HIGLU (xsection) + HDECAY (decays)

- Charged Higgs cross section not part of the recommendations, but H^+ decays are calculated both by 2HDMC and HDECAY

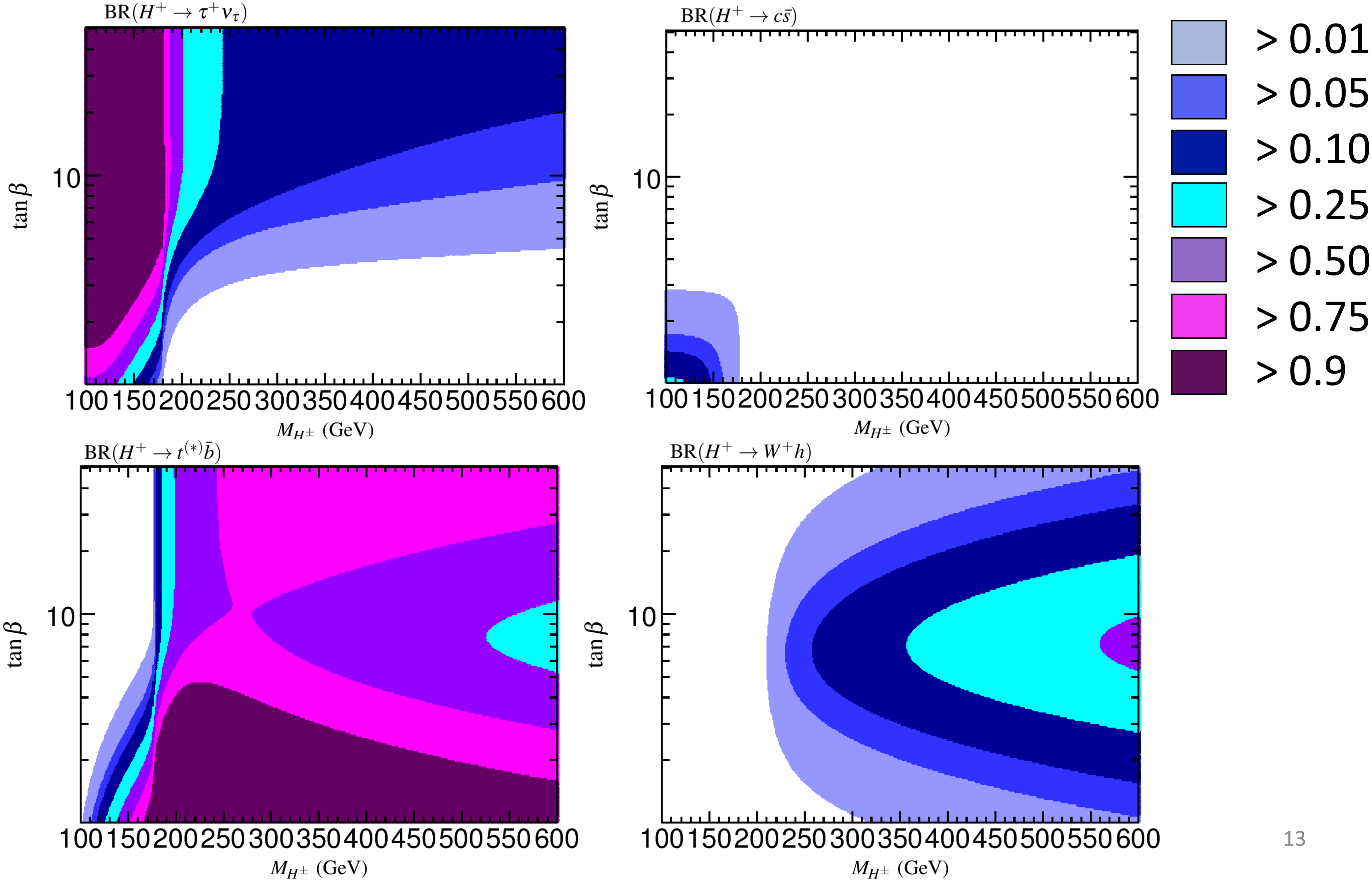
H⁺ decays in 2HDM Type-I

$$M_h = 125\,\mathrm{GeV},\ M_H = M_A = M_{H^\pm},\ \sin(\beta-\alpha) = 0.99,\ m_{12}^2 = M_A^2 c_\beta s_\beta$$



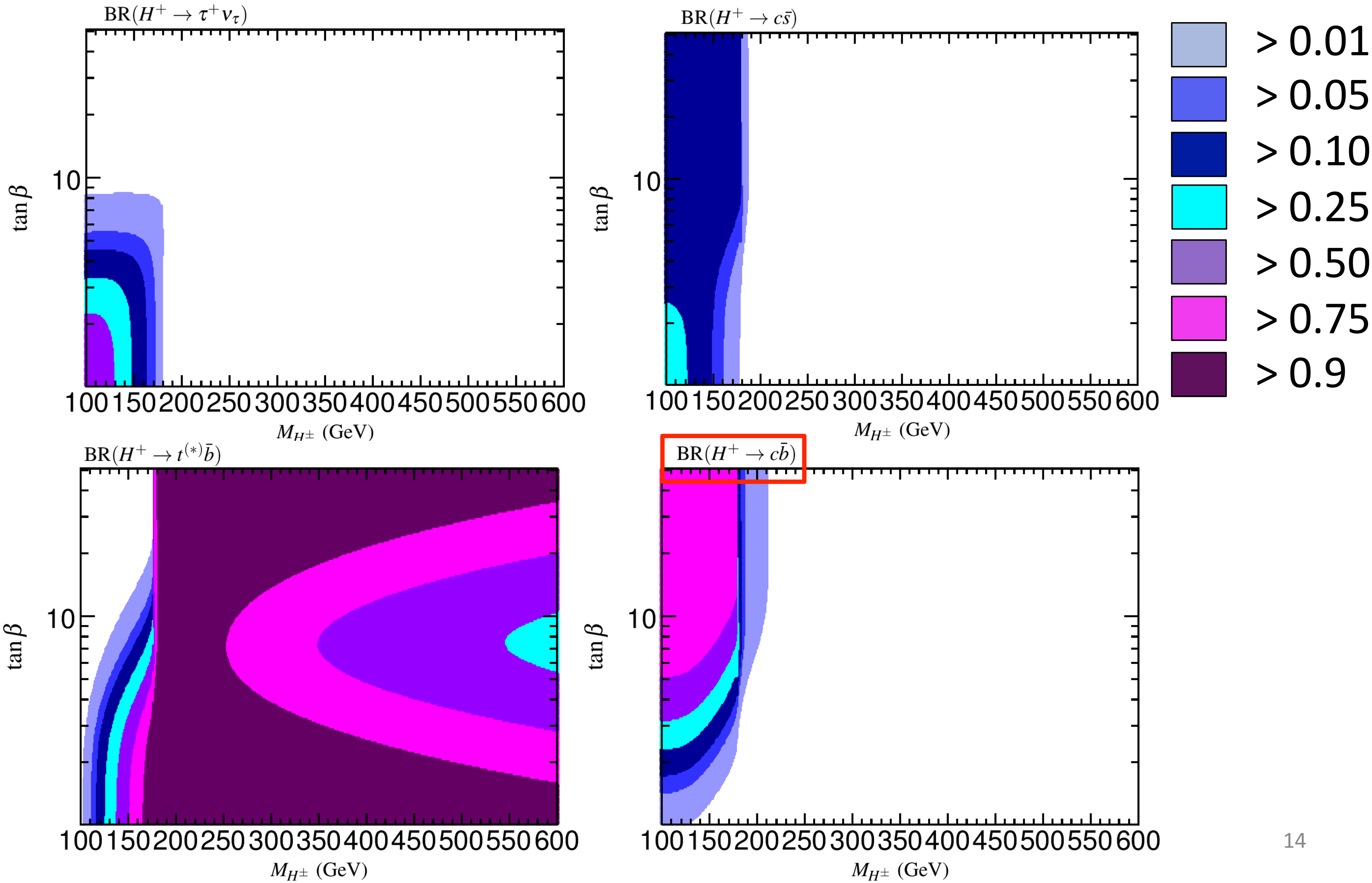
H+ decays in 2HDM Type-II

$$M_h = 125\,\text{GeV},\ M_H = M_A = M_{H^\pm},\ \sin(\beta-\alpha) = 0.99,\ m_{12}^2 = M_A^2 c_\beta s_\beta$$



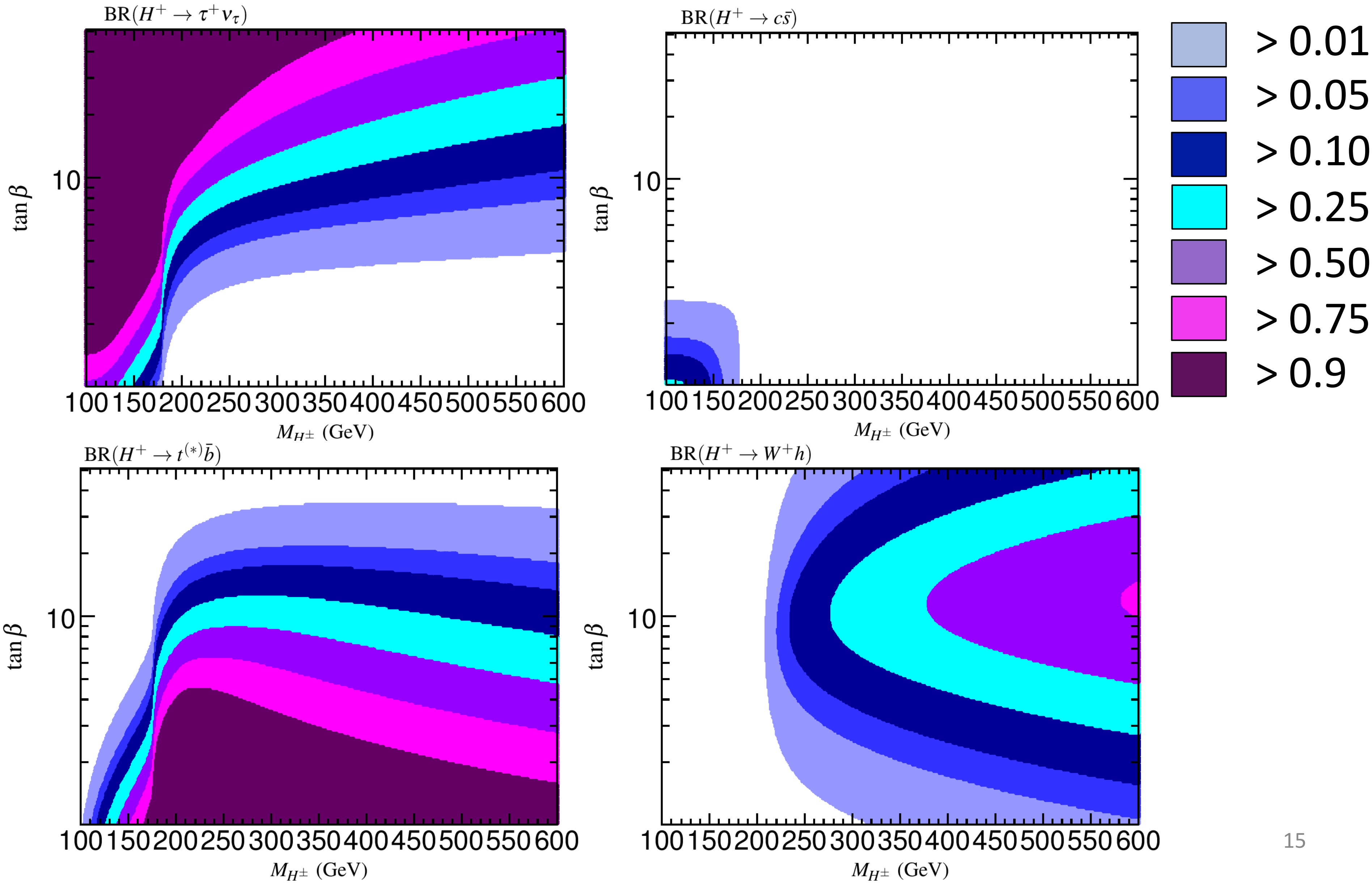
H^+ decays in 2HDM Type-III

$$M_h = 125\,\mathrm{GeV},\ M_H = M_A = M_{H^\pm},\ \sin(\beta-\alpha) = 0.99,\ m_{12}^2 = M_A^2 c_\beta s_\beta$$



H⁺ decays in 2HDM Type-IV

$$M_h = 125\,\mathrm{GeV},\ M_H = M_A = M_{H^\pm},\ \sin(\beta-\alpha) = 0.99,\ m_{12}^2 = M_A^2 c_\beta s_\beta$$



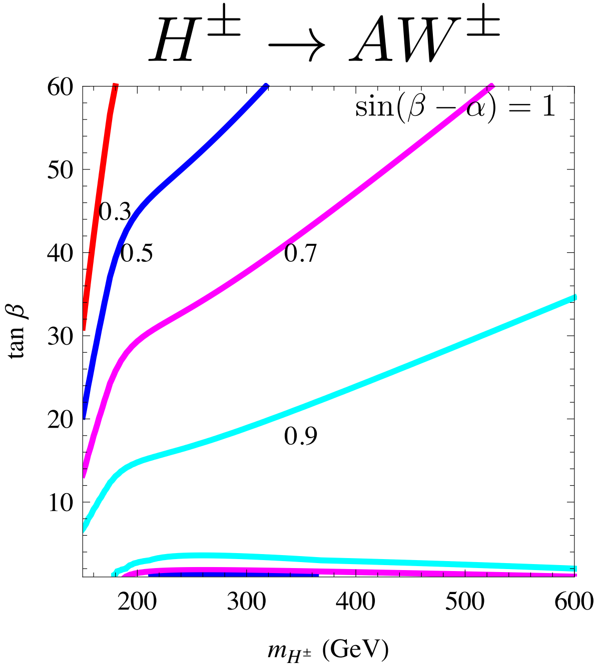
The H⁺ -> A/H W⁺ channel

B. Coleppa, F. Kling, S. Su, [1408.4119]

- The 2HDM pseudoscalar can also be light

$$M_A = 50\,\mathrm{GeV}\ (126\,\mathrm{GeV})$$

$$pp \to t\bar{b}H^- \to t\bar{b}AW^- \to W^+W^-b\bar{b}(b\bar{b}/\tau\tau)$$

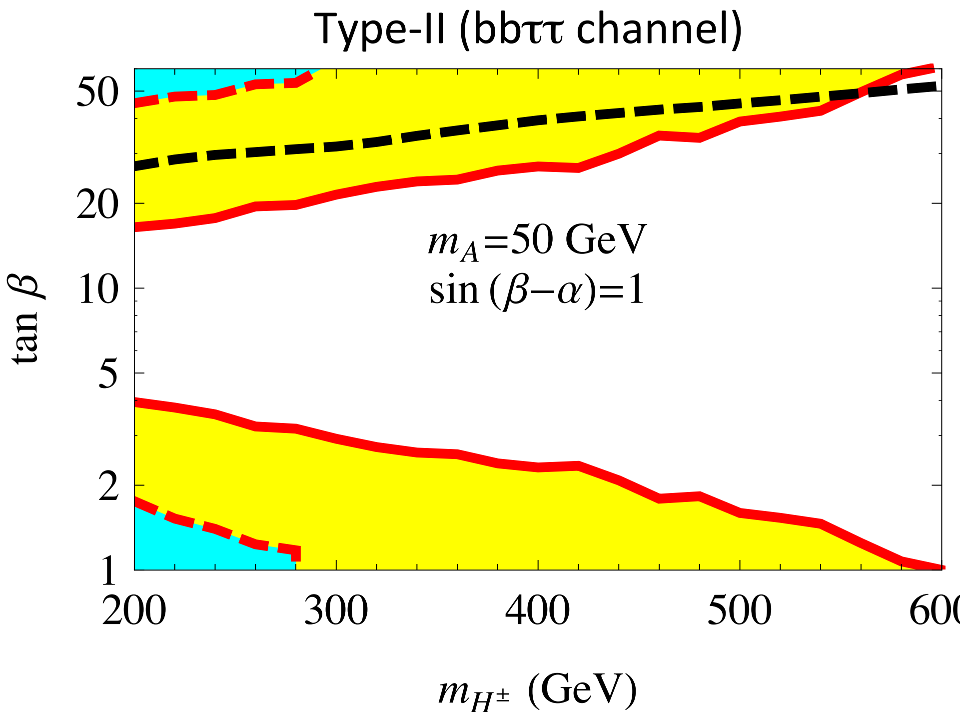


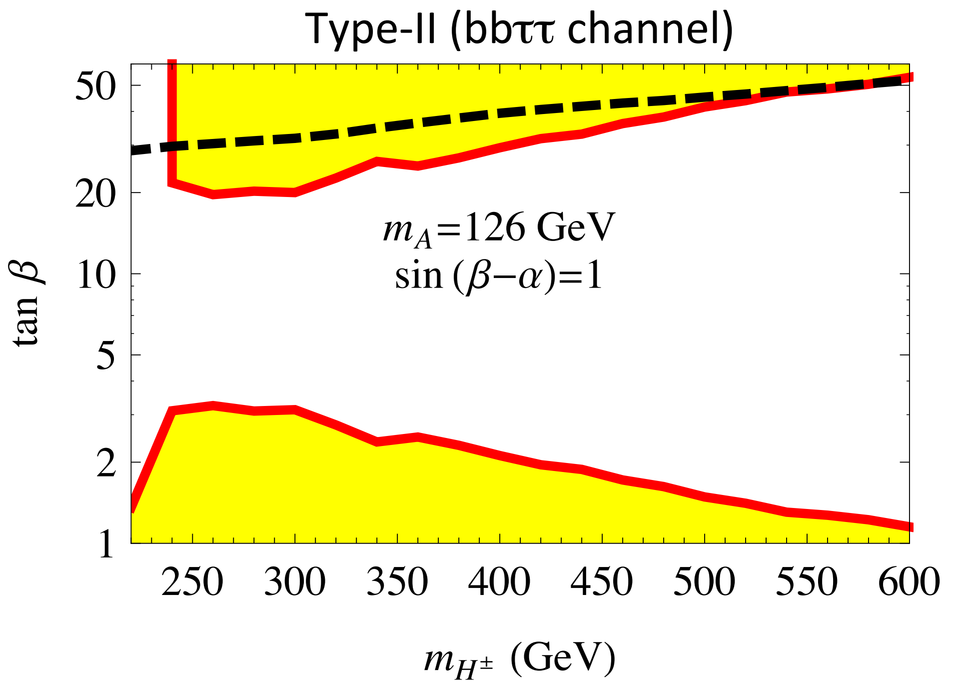
- MC fast detector-level analysis with MG5 + Pythia + Delphes taking into account dominant backgrounds

Cut	Signal [fb]	$t\bar{t}$ [fb]	$t\bar{t}\tau\tau$ [fb]	$W(W)\tau\tau$ [fb]	S/B	$S/\sqrt{B}$
σ	100	$6.3\cdot10^5$	247	2000	-	-
A: Identification [Eq.(4.1)]	0.45	23.4	0.58	0.078	0.02	1.62
$m_{\tau\tau}$ vs $m_{\tau\tau W}$ [Eq.(4.5)]	0.14	0.69	0.014	0.003	0.19	2.84
B: Identification [Eq.(4.2)]	0.39	0.35	0.697	0.072	0.35	6.49
$m_{\tau\tau}$ vs $m_{\tau\tau W}$ [Eq.(4.5)]	0.13	0.043	0.047	0.0062	1.35	7.31
C: Identification [Eq.(4.3)]	0.44	2.35	5.11	0.058	0.06	2.81
$m_{\tau\tau}$ vs $m_{\tau\tau W}$ [Eq.(4.5)]	0.12	0.30	0.31	0.0077	0.19	2.54

The H^+ -> A/H W^+ channel

- Results for exclusion / 5 σ discovery with 100 fb^{-1} at 14 TeV





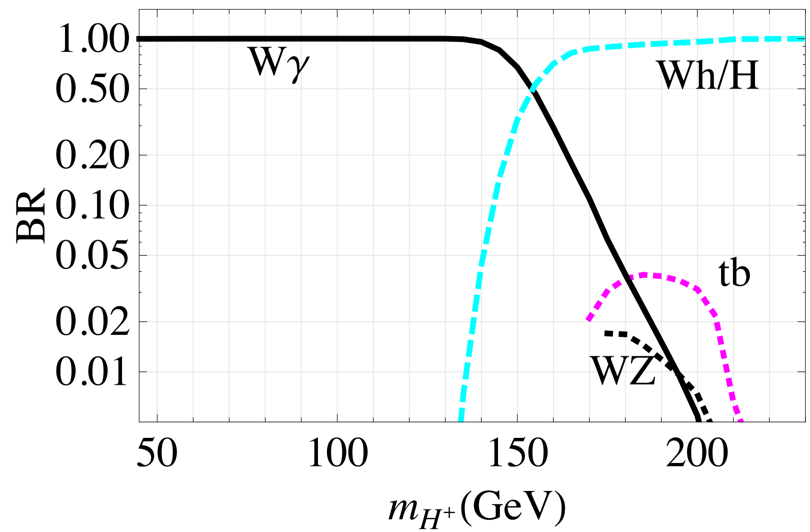
- Results complementary to other searches, in particular the τ ν channel, with additional sensitivity at low tan β

- Could also be relevant for light H^+ with very light A_1 in the NMSSM

J. Rathsman, T. Rössler [1206.1470]

Loop-induced H^+ decays

- With two Higgs doublets, there are no tree-level couplings of H^+W^-Z or $H^+W^-\gamma$, but the decays $H^+ \to W^+ Z/\gamma$ are induced at 1-loop -> Similar to $h \to \gamma\gamma$ or $h \to \gamma Z$
- In normal 2HDM and MSSM scenarios, both these decays have BR < 10^{-3} (typically much smaller)
- Can be enhanced in "stealth" model with suppressed tree-level couplings of second doublet to fermions



(c) $m_A = m_{H^\pm}$, $m_h = 125$ GeV, $m_H = 300$ GeV, $\sin\alpha = 0.9$.

R. Enberg, J. Rathsman, G. Wouda, [1311.4367]
See also: V. Ilisie, A. Pich, [1405.6639]

Conclusions

- Charged Higgs bosons remain important to search for as signs of physics beyond the SM

- Public codes for the calculation of the H^+ branching ratios in popular models (MSSM, 2HDM, …) are in an advanced stage

- Beyond the ''traditional'' fermionic decay modes, there are options for non-standard decays that can also be searched for:

  - Heavy H+ decays into SUSY particles
  - Non-standard decays of a light charged Higgs (cb / $W\gamma$)
  - H+ decays into 125 GeV Higgs / W (in remaining parameter space)
  - H+ decays into lighter scalars and W bosons, typically leading to different (complex) final states with multiple b/τ

BACKUP

MSSM Higgs sector

- Minimal SUSY (MSSM) -> two complex Higgs Doublets: H_u, H_d
  8 scalar degrees of freedom, 5 physical Higgs bosons (SM: 4, 1)

- CP conservation: h, H (CP-even), A (CP-odd), and $H^{\pm}$
  $m_H > m_h$

- At tree-level, the Higgs sector is determined by two parameters:
  $M_A, \tan\beta$ or $M_{H^{\pm}}, \tan\beta$

$$\tan\beta = \frac{v_u}{v_d}$$

- Other Higgs masses are *predictions*:

$$M^2_{h,H} = \frac{1}{2}\left[M_A^2 + M_Z^2 \mp \sqrt{(M_A^2 + M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta}\right]$$

$$M^2_{H^{\pm}} = M_A^2 + M_W^2$$

$$M^2_{h,\mathrm{tree}} \leq M_Z^2 \cos^2 2\beta \leq M_Z^2$$

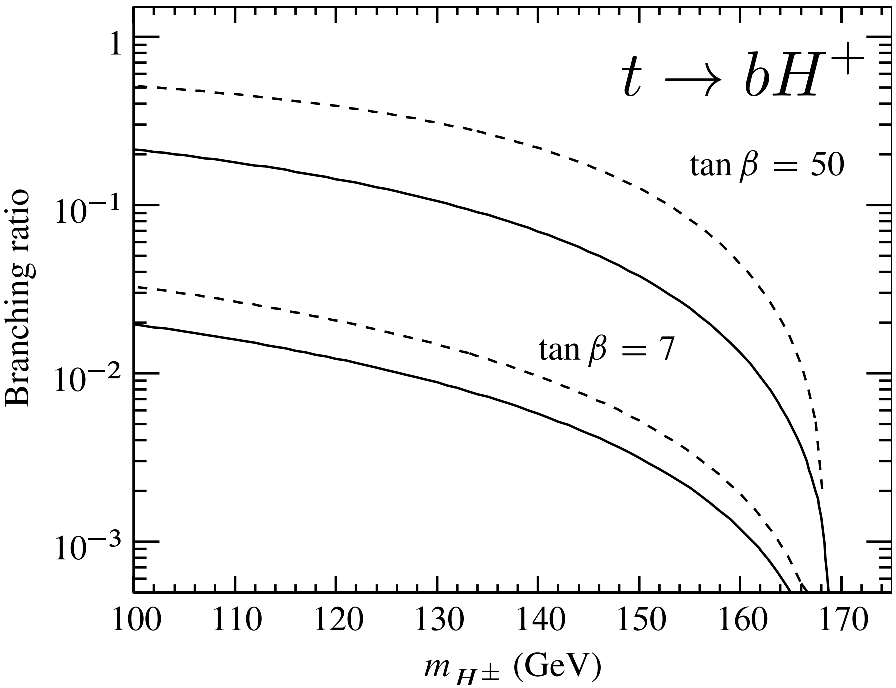
Charged Higgs bosons

- Two kinematic regions for charged Higgs production

- Light charged Higgs

$$M_{H^\pm} < m_t - m_b$$

$$pp \to t\bar{t} \qquad t \to bH^+$$



- Heavy charged Higgs

$$M_{H^\pm} > m_t - m_b$$

$$gg/gb \to \bar{t}bH^+$$

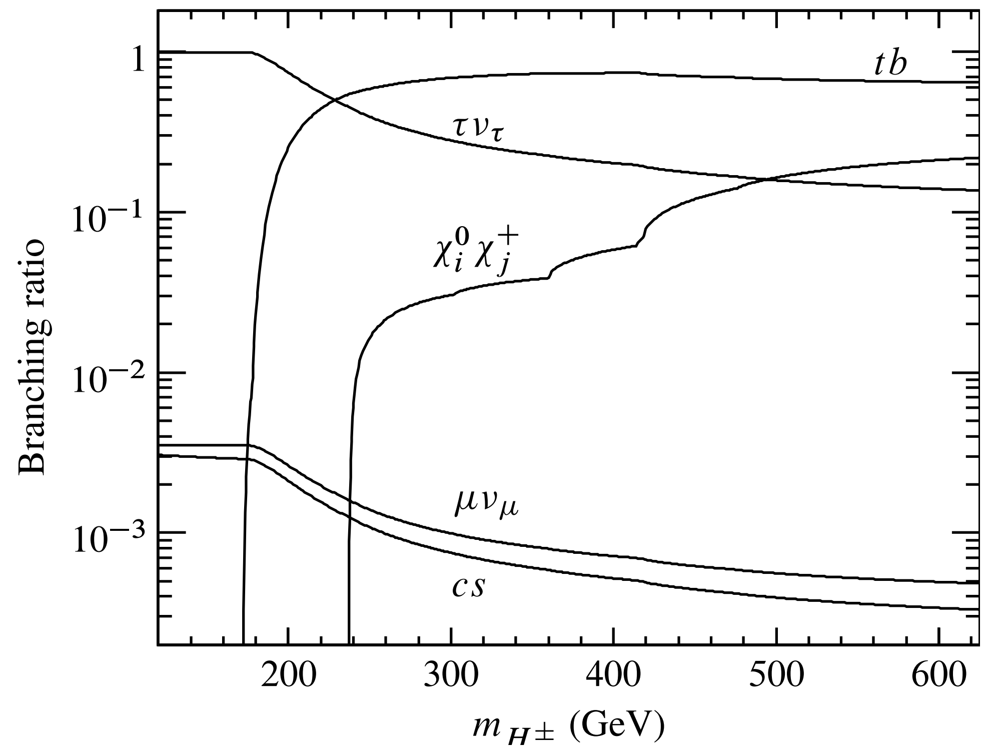
- Complementary production modes

$$pp \to H^\pm H^\mp \quad pp \to H^\pm W^\mp$$

Charged Higgs bosons: Decay modes

- MSSM Decay mode also 'fixed' by kinematics

$\tan\beta > 1$



- Light charged Higgs

$$\mathrm{BR}(H^+ \to \tau^+\nu_\tau) \simeq 1$$

- Heavy charged Higgs

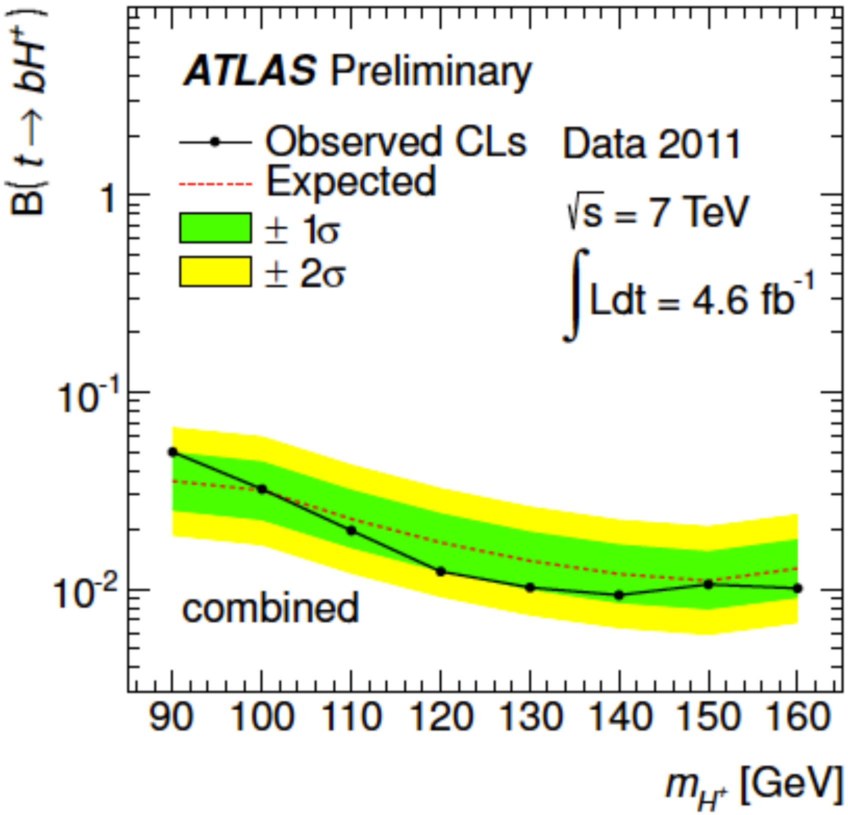
$$\mathrm{BR}(H^+ \to \tau^+\nu_\tau) \simeq 0.1$$

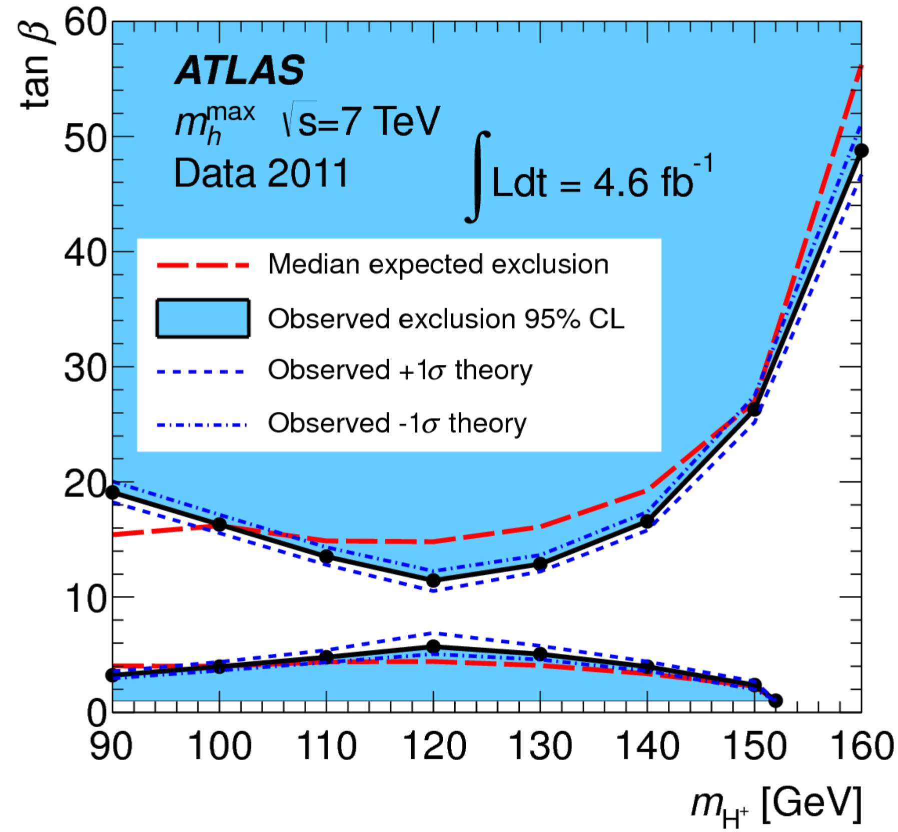
$$\mathrm{BR}(H^+ \to t\bar{b}) \simeq 0.9$$

- In the NMSSM should be complemented with searches for

$$H^\pm \to A_1 W^\pm \qquad H^\pm \to H_1 W^\pm$$

From branching ratios to MSSM parameter limits





$$g_{H^+\bar{t}b} = \sqrt{2}\,\mathrm{i}V_{tb}\left[P_L m_b \frac{\tan\beta}{1+\Delta_b} + P_R m_t \cot\beta\right]$$

$$\Delta_b = \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \mu \tan\beta I(M_{\tilde{b}_1}, M_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{y_t^2}{16\pi^2} A_t \mu \tan\beta I(M_{\tilde{t}_1}, M_{\tilde{t}_2}, \mu)$$