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Prospect for Charged Higgs Boson Searches at Colliders

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Introduction

EWSB dynamics based on Higgs mechanism in SM unsatisfactory

Theory: Higgs boson mass is unstable under radiative corrections (hierarchy problem)

Experiment: Higgs boson discovered in 2012@LHC

Mass (125 GeV) requires NP below Plank scale (vacuum not stable)

Appropriate to explore implications of more complicated Higgs models

Doublet Higgs nature: 2HDMs (see K Yagyu's & I Ivanov's talks for 3HDMs)

Three major constraints to go BSM:

1. EWPTs:

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} \approx 1$$

2. Limits on the existence of FCNCs
3. BSM Higgses (notably charged ones) may alter (heavy) flavour data
4. Properties of h(125 GeV) state (SM-like) & limits on companions

Electroweak ρ parameter is experimentally close to 1

→ constraints on Higgs representations

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \frac{\sum_{T,Y}\left[4T(T+1)-Y^2\right]\left|V_{T,Y}\right|^2 c_{T,Y}}{\sum_{T,Y} 2Y^2 \left|V_{T,Y}\right|^2} \approx 1 \ ,$$

$$V_{T,Y} = \left\langle \phi(T,Y) \right\rangle, \quad c_{T,Y} = \begin{cases} 1, & (T,Y) \in \text{complex representation} \\ \frac{1}{2}, & (T,Y) \in \text{real representation} \end{cases}$$

Real representation: consists of a real multiplet of fields with integer weak isospin and zero hypercharge

Take c(T,Y)=1

$\rho=1 \Rightarrow (2T+1)^2-3Y^2=1.$

Thus doublets (T=1/2, Y=+1 or -1) can be added without problems with ρ. Other representations possible (T=3, Y=4) but rather complicated.

For `bad' Higgs representations, there are two ways fwd:

1. Take a model with multiple `bad' Higgs representations and arrange a `custodial' SU(2) symmetry among the copies (i.e., VEVs arranged suitably), so that $\rho=1$ at tree-level. This can be done for triplets (see MA Diaz' talk).

2. One can choose arbitrary Higgs representations and fine tune the Higgs potential parameters to produce ρ=1. This may appears unnatural and we won't consider it here either.

General 2HDM

Take SM with exactly two Higgs doublets ϕ_1 and ϕ_2 $\Rightarrow$ ρ=1.

The simplest extension of the SM with charged Higgs bosons

Five physical Higgs bosons: h, H, A, $H^{\pm}$

The scalar potential

$$V(\phi_1,\phi_2)=\lambda_1(\phi_1^+\phi_1-v_1^2)^2+\lambda_2(\phi_2^+\phi_2-v_2^2)^2+\lambda_3\left[(\phi_1^+\phi_1-v_1^2)+(\phi_2^+\phi_2-v_2^2)\right]^2$$
$$+\lambda_4\left[(\phi_1^+\phi_1)(\phi_2^+\phi_2)-(\phi_1^+\phi_2)(\phi_2^+\phi_1)\right]+\lambda_5\left[\mathrm{Re}(\phi_1^+\phi_2)-v_1v_2\cos\xi\right]^2$$
$$+\lambda_6\left[\mathrm{Im}(\phi_1^+\phi_2)-v_1v_2\sin\xi\right]^2$$

Take λ_i's real, ξ=0, $\langle\phi_1\rangle=\begin{pmatrix}0\\ v_1\end{pmatrix}$, $\langle\phi_2\rangle=\begin{pmatrix}0\\ v_2e^{i\xi}\end{pmatrix}$, $\tan\beta=\dfrac{v_2}{v_1}$

Goldstone $G^{\pm}=\phi_1^{\pm}\cos\beta+\phi_2^{\pm}\sin\beta,$

Charged Higgs $H^{\pm}=-\phi_1^{\pm}\sin\beta+\phi_2^{\pm}\cos\beta,$

with $m_{H^{\pm}}^2=\lambda_4(v_1^2+v_2^2),$ $m_W^2=g^2(v_1^2+v_2^2)/2,$

Absence of (tree-level) FCNCs → constraints on Higgs couplings

In SM FCNC automatically absent as same operation diagonalising the mass matrix diagonalises the Hff couplings. Not so in 2HDMs.

Again, there are two ways fwd:

1. Make responsible Higgs masses large (1 TeV or more) so that tree-level FCNCs mediated by Higgs are suppressed to comply with experimental data (unattractive phenomenologically).
2. Glashow & Weinberg theorem more elegant: FCNCs absent in models with more than one Higgs doublet if all fermions of a given electric charge couple to no more than one Higgs doublet.

$\mathbb{Z}_2$ symmetry (Natural Flavour Conservation)

Type I: one Higgs doublet provides masses to all quarks (up- and down-type quarks) (~SM).

Type II: one Higgs doublet provides masses for up-type quarks and the other for down-type quarks (~MSSM).

Type III,IV: different doublets provide masses for down type quarks and charged leptons.

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

Type III also Type Y
Type IV also Type X

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

- 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

If the $\mathbb{Z}_2$ symmetry of the Yukawas holds in the Higgs potential, entire model symmetric: absence of CP-Violation (CPV)

Consider softly broken $\mathbb{Z}_2$-symmetric 2HDM for CPV: $m_{12}^{*}(\phi_1^{\dagger}\phi_2) + h.c.$

Barger/Hewett/Phillips, 1990

How to recognise a 2HDM realisation?

H+/- BRs can be very different from type to type (eg, $\tau\nu$) →

tan β is important for phenomenology!

For processes which depend only on quark sector, types II and IV are similar, more than types I and III are

Gauge/Higgs (self-) interactions blur the distinction

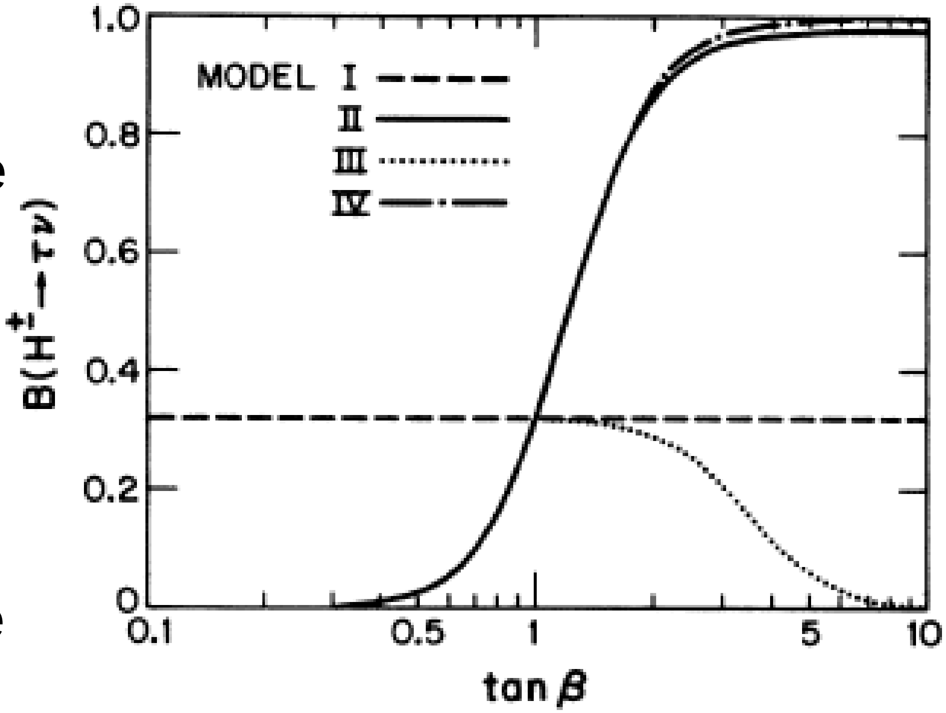


FIG. 1. The branching fraction $B(H^{\pm} \to \tau\nu)$ vs tanβ in models I–IV. We take $m_c = 1.5$ GeV, $m_s = 0.15$ GeV, $m_\tau = 1.784$ GeV, $|V_{cs}| = 1.0$, and $m_{H^{\pm}} < m_t - m_b$.

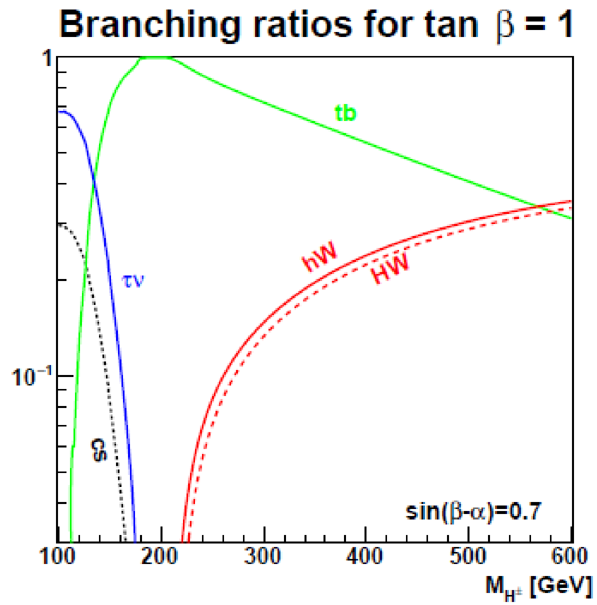
Gauge couplings

$$H^{\mp}W^{\pm}h: \quad \frac{\mp ig}{2}\cos(\beta-\alpha)(p_\mu - p_\mu^{\mp}),$$

$$H^{\mp}W^{\pm}H: \quad \frac{\pm ig}{2}\sin(\beta-\alpha)(p_\mu - p_\mu^{\mp}),$$

$$H^{\mp}W^{\pm}A: \quad \frac{g}{2}(p_\mu - p_\mu^{\mp}).$$

Can be large at any $\tan\beta$ especially at large masses away from top-bottom threshold



$(M_H, M_A) = (130\ \mathrm{GeV}, M_{H^\pm})$

(tanβ=1: all 2HDM types are the same)

Charged-Higgs branching ratios vs $M_{H^\pm}$, for $\tan\beta = 1$ and $\sin(\beta-\alpha) = 0.7$.

Charged Higgs boson decays

1.Fermionic:

$$H^+ \to c\bar{s},$$
$$H^+ \to c\bar{b},$$
$$H^+ \to \tau^+\nu_\tau,$$
$$H^+ \to t\bar{b},$$

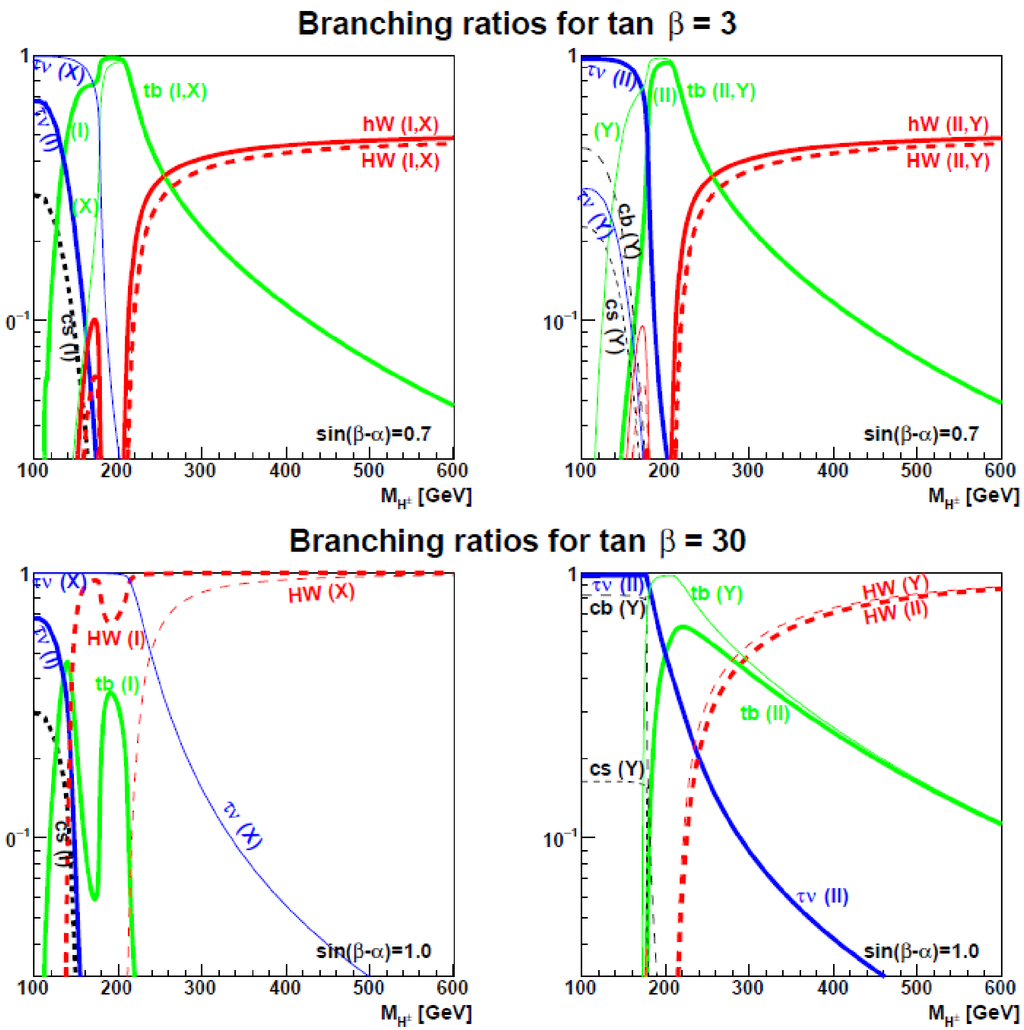
2.To gauge bosons (only one-loop):

$$H^+ \to W^+\gamma,$$
$$H^+ \to W^+Z,$$

3. To other Higgs bosons too:

$$H^+ \to H_j W^+$$

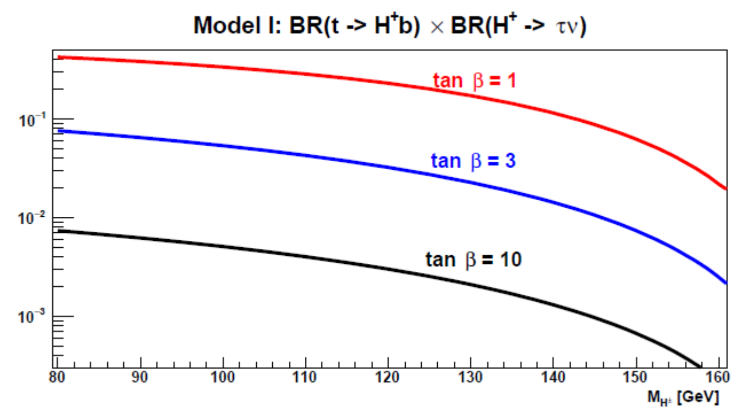
Branching ratios vs $M_{H^\pm}$



Left: I & X
Right: II & Y

Top: $\sin(\beta-\alpha) = 0.7$
Bottom: $\sin(\beta-\alpha) = 1$

Top decay to H^+b



$(M_H, M_A) = (130 \text{ GeV}, M_{H^\pm})$

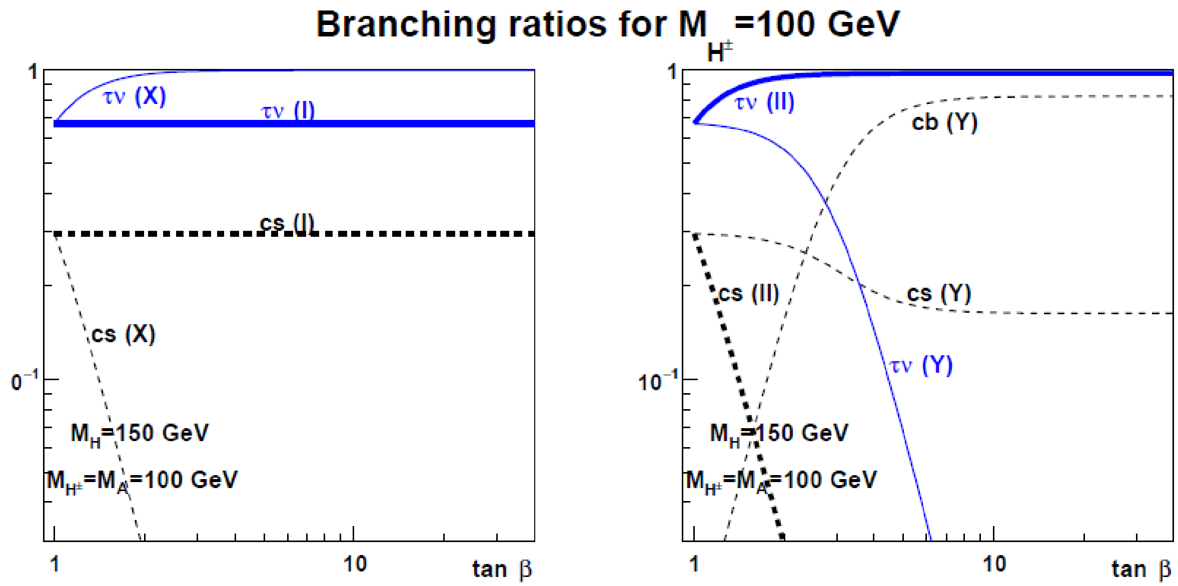
Model II: min @tan β=6–7

$$H^+ b \bar{t} : \quad \frac{ig}{2\sqrt{2}\, m_W} V_{tb}[m_b(1+\gamma_5)\tan\beta + m_t(1-\gamma_5)\cot\beta],$$

$$H^- t \bar{b} : \quad \frac{ig}{2\sqrt{2}\, m_W} V_{tb}^*[m_b(1-\gamma_5)\tan\beta + m_t(1+\gamma_5)\cot\beta].$$

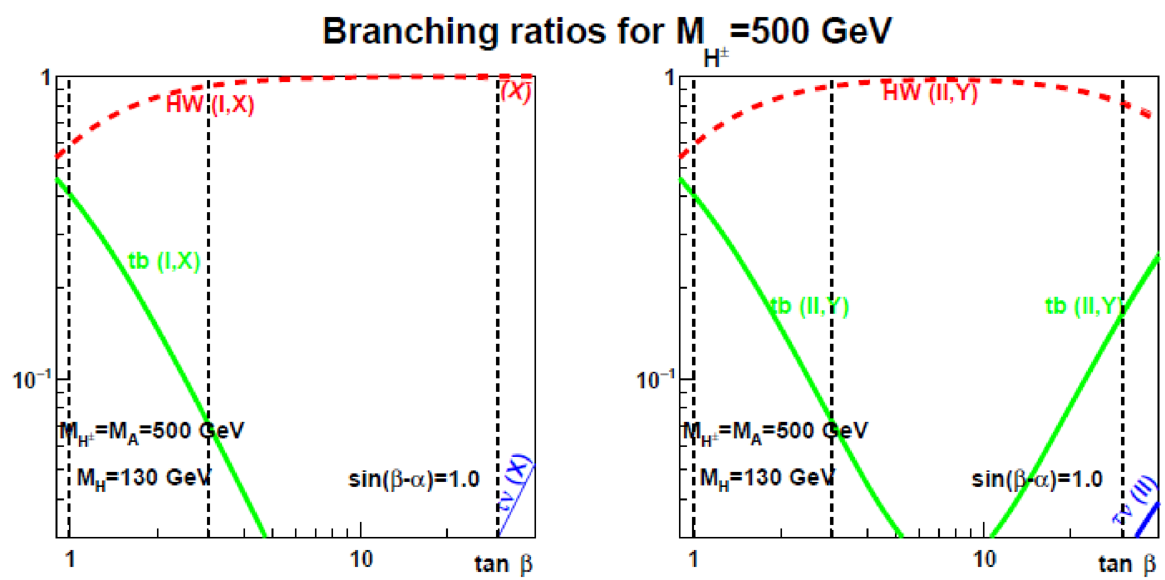
Branching ratios vs $\tan\beta$

Light H^+ $(M_{H^\pm} < m_t)$



Heavy H^+ $(M_{H^\pm} > m_t)$

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



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

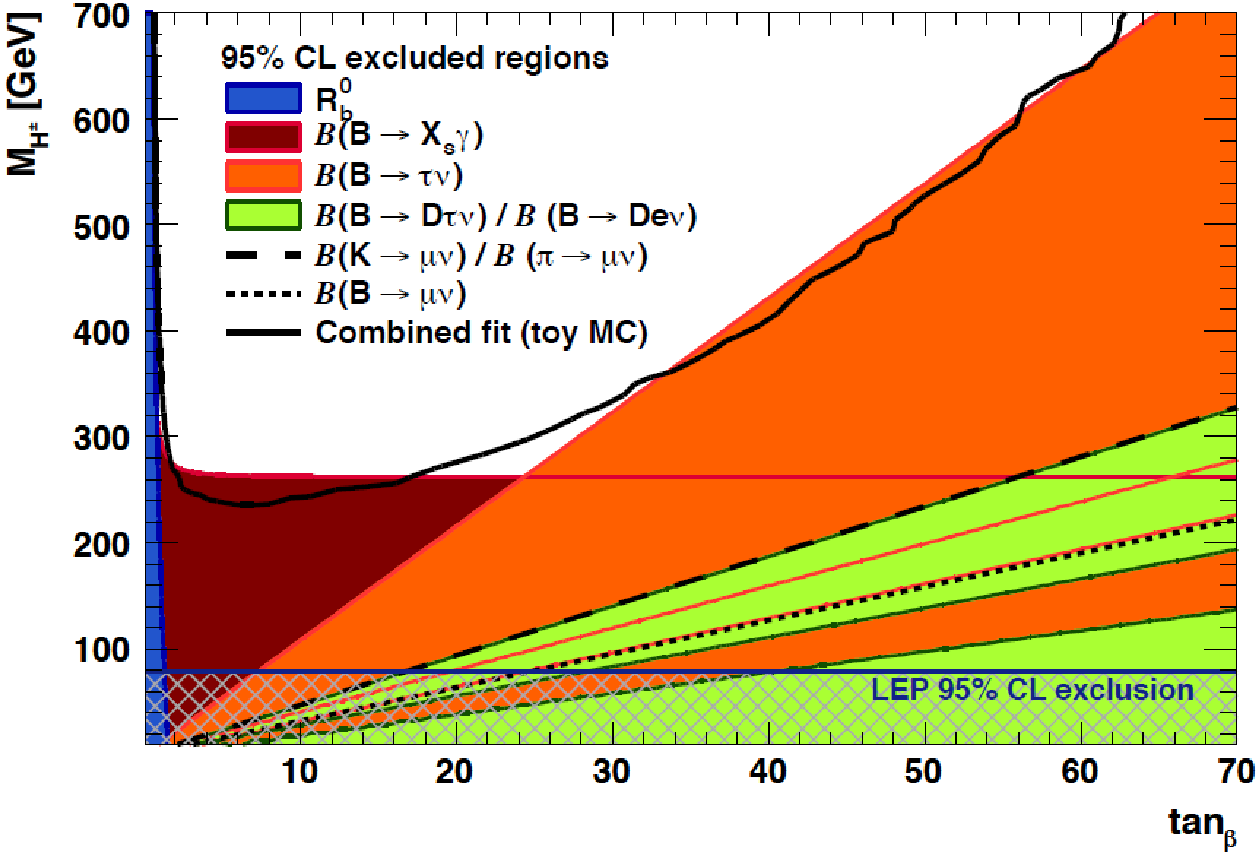
The necessary condition is: $|X| >> |Y|, |Z|$

- This condition is possible in the 2HDM-III (aka Flipped 2HDM)
- ATLAS/CMS $H^\pm \to cs$ → applies to case of dominant $H^\pm \to cb$
- Estimate gain in sensitivity as:

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

Low-energy constraints

Model II 95% CL exclusion regions in the ($\tan\beta$, $M_{H^\pm}$) plane.



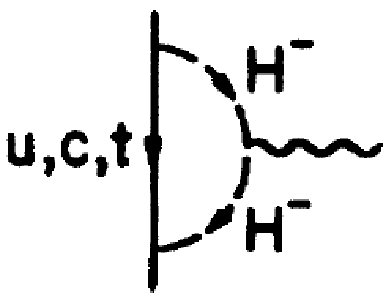
Also:

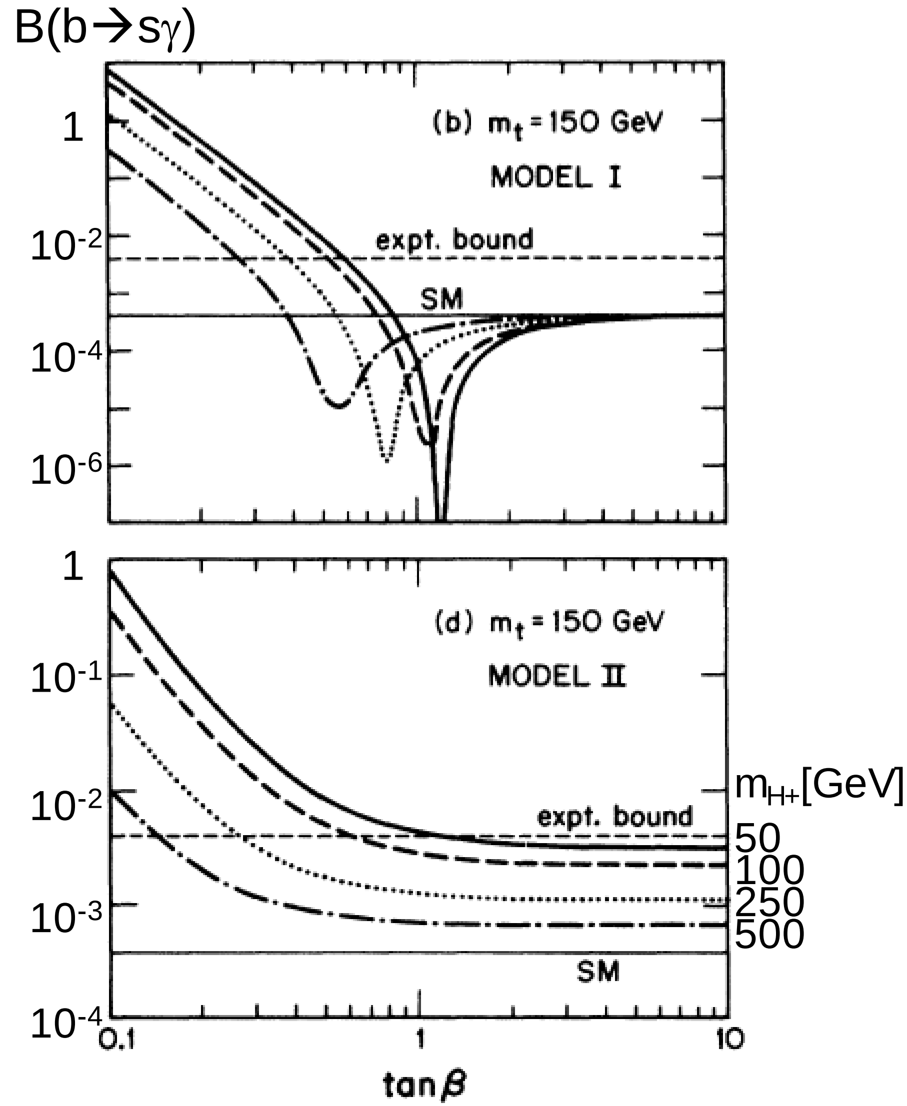
B0/B0(bar) mixing, muon anomalous magnetic moment, electron EDM, S & T parameters

Barger/Hewett/Phillips, 1990

Limits from b→sγ in 2HDM

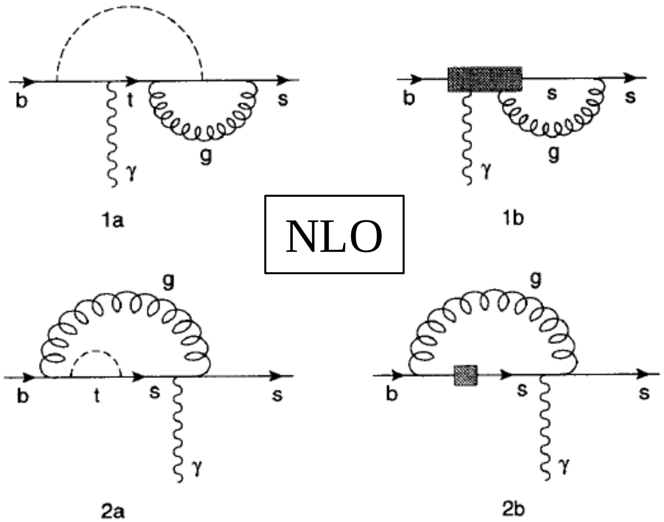
In model II the contribution is always bigger than in the SM, while in model I one can have strong cancellations due to –cot β in the coupling.





THDM II: $m_{H+} > (244 + 63/\tan\beta)$ GeV@LO

(Grinstein/Springer/Wise, 1990)



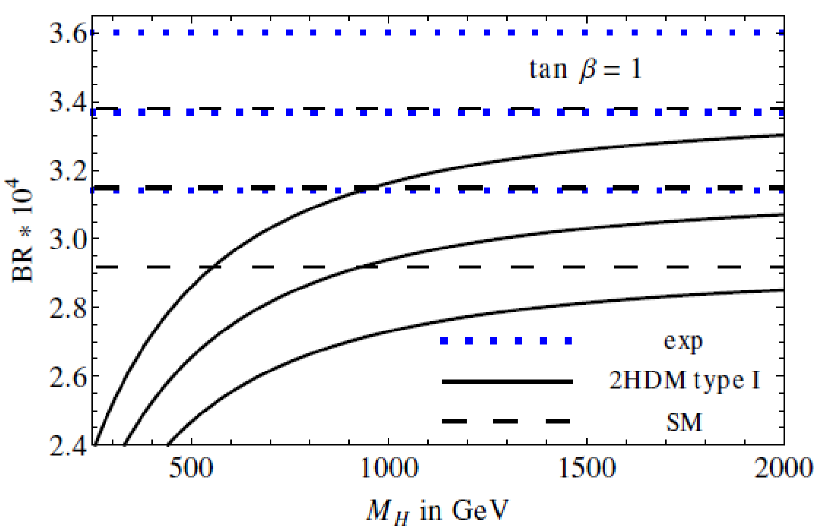
NLO

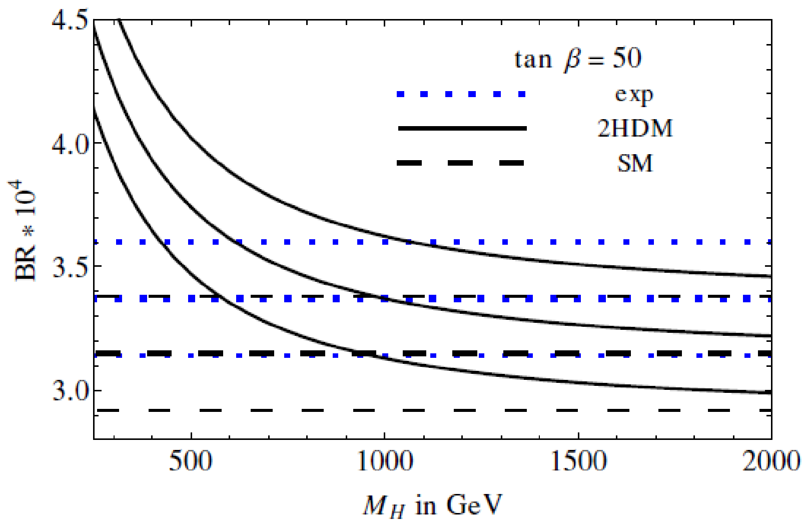
Now <u>NNLO</u> QCD results for SM and 2HDM (Misiak et al)

2HDM-II (tanβ→ infinity):

$$M_{H^\pm} > 480\,\mathrm{GeV} \quad \text{at } 95\%\ \text{C.L.}\,,$$
$$M_{H^\pm} > 358\,\mathrm{GeV} \quad \text{at } 99\%\ \text{C.L.}$$

Models II and Y $m_{H^\pm} \gtrsim 360\ GeV$ **Best available bound on the charged Higgs mass** Any tanβ





(Shown are central values with $\pm 1\sigma$ shifts.)

High-energy constraints

Charged Higgs mass limit from LEP: pair production is model independent

Assumed decay channels

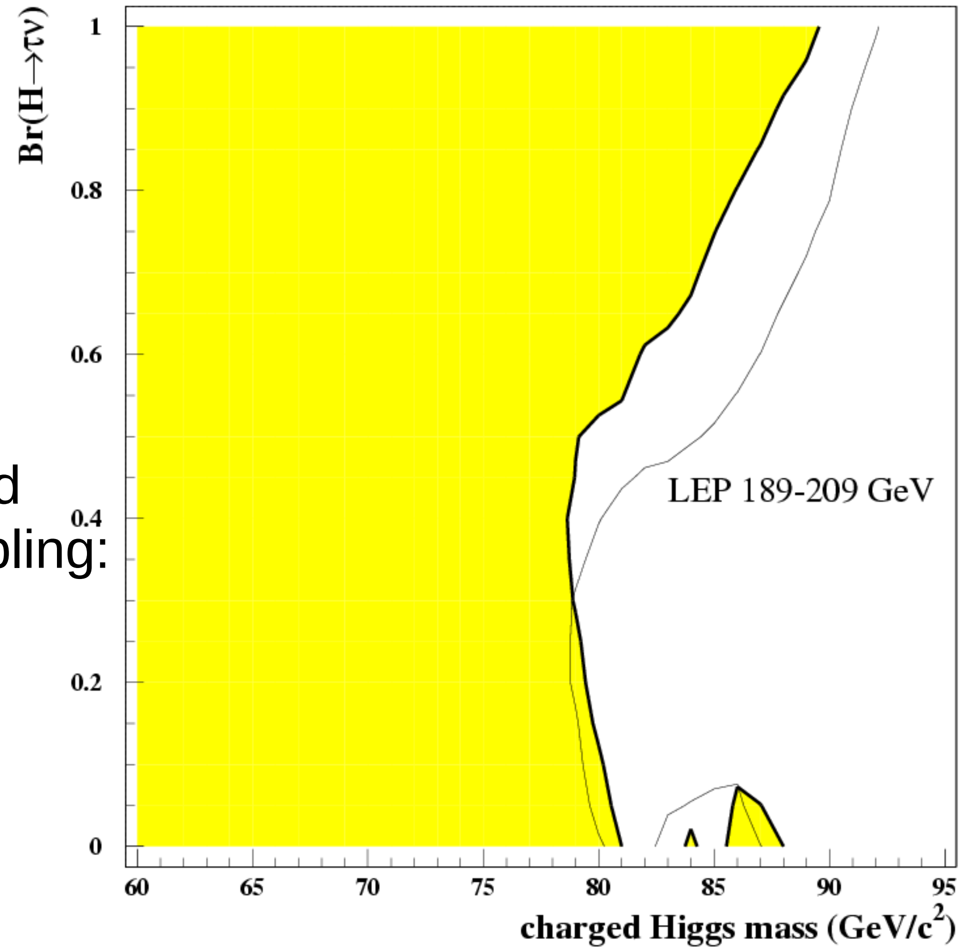
$H^{+} \to c\bar{s}, \tau^{+}\nu$

➡ Saturate BRs

$m_{H^{+}} > 78.6$ GeV

Note that photon/Z to charged Higgs coupling is gauge coupling: (ie, no model dependence)

Irreducible WW background overwhelming above 80 GeV

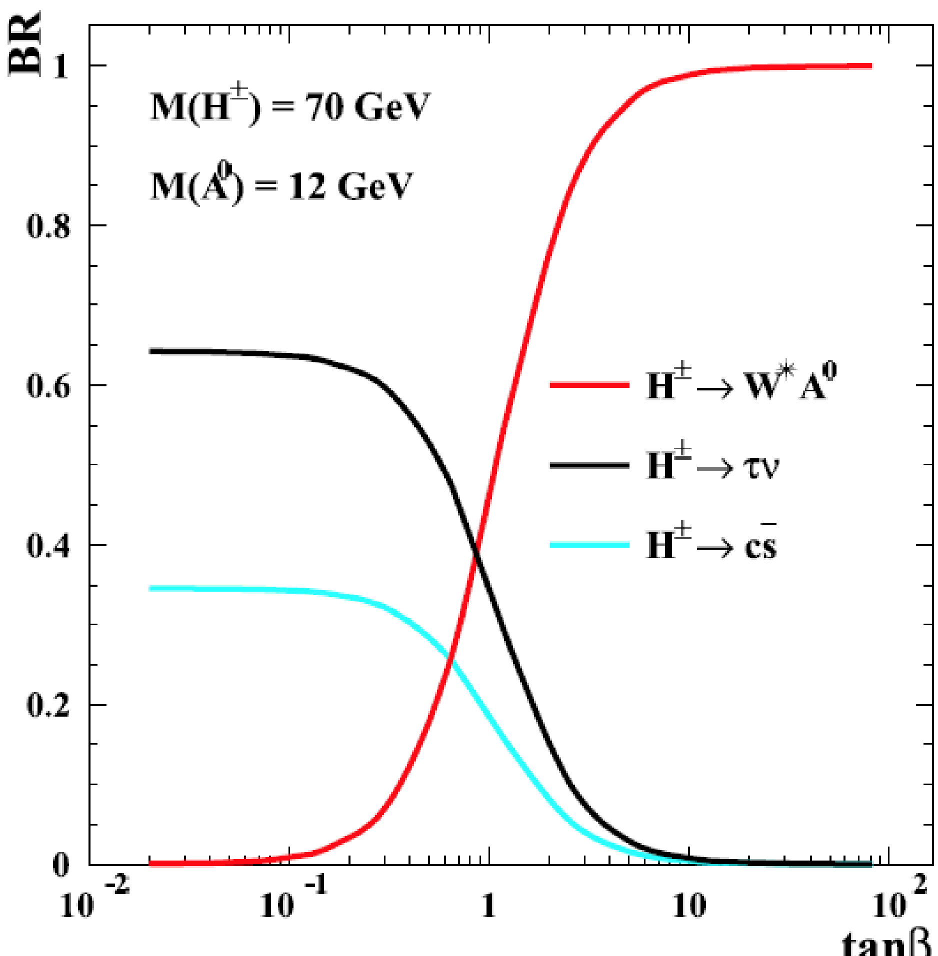


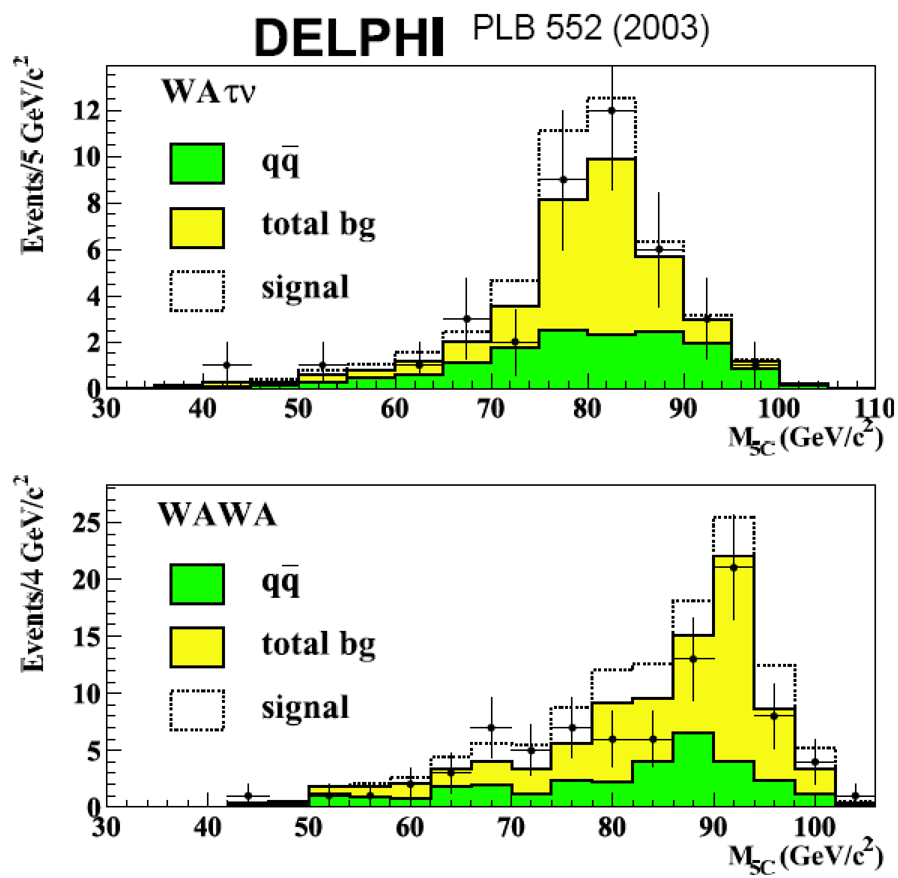
LEP Higgs working group, LHWG note 2001-05.

Less well known is the LEP search for the decay mode H+ to AW*
(with A to bb) by DELPHI, 2004.

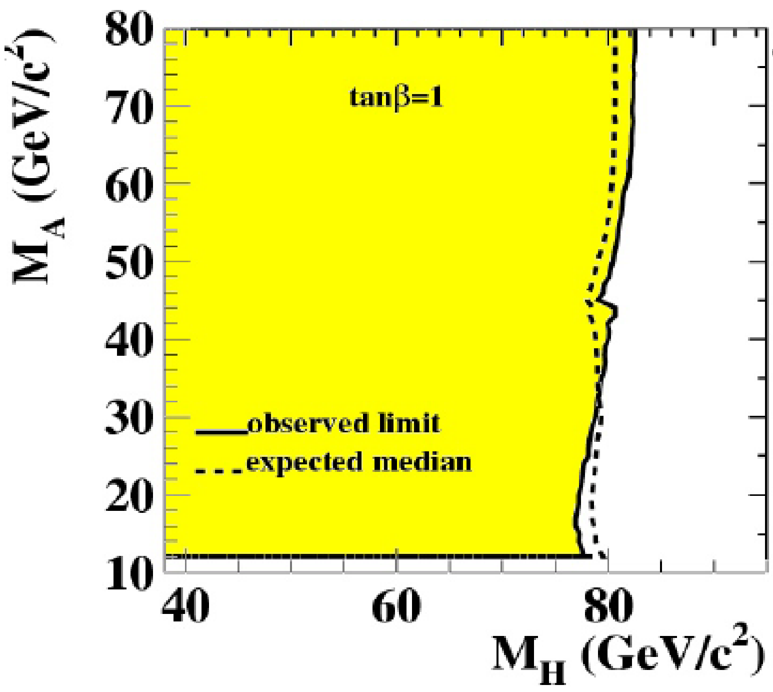
In the 2HDM (type I) this decay mode can be dominant: Akeroyd, 1999 & Borzumati/Djouadi, 2002.

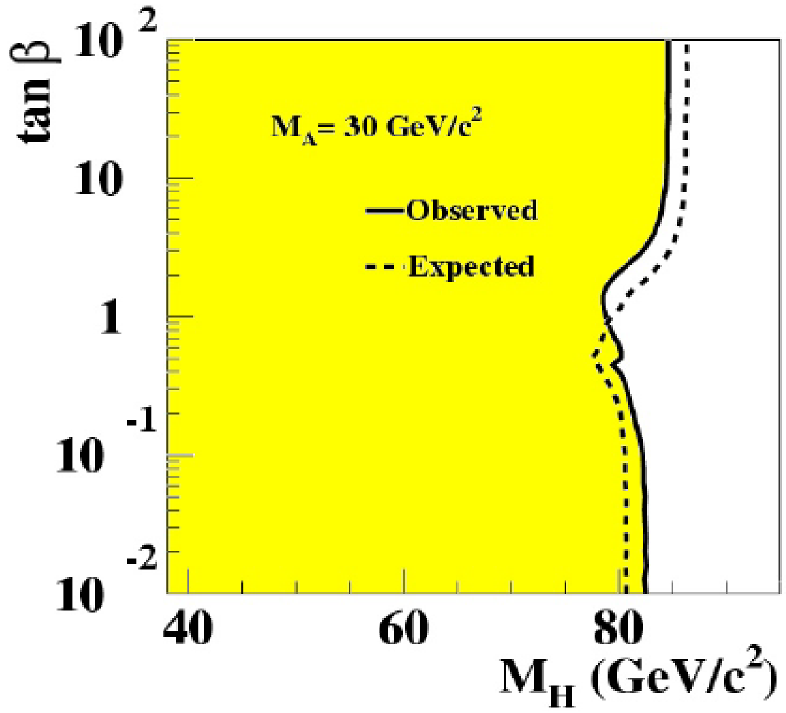
(In Type II ruled out by b→sγ at such small charged Higgs mass.)





DELPHI Limits from $H^+ \to WA$





- Type-1 limit at 95% CL: $mH^+ > 76.7$ (77.1) GeV for any tanβ and mA > 12 GeV.

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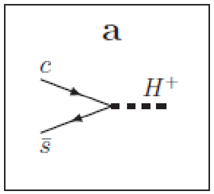
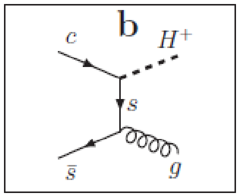
* Limit in Model I weakened somewhat
* Still only limit which is (largely) model independent

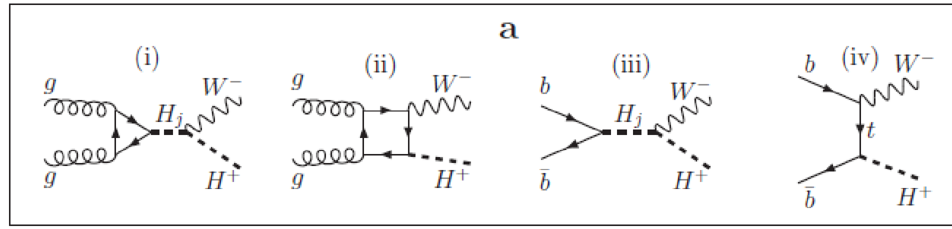
H^+ production mechanisms at the LHC

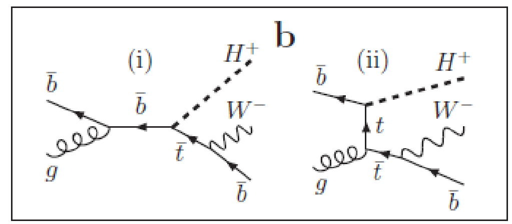
$$c\bar{s} \to H^+,$$
$$c\bar{s} \to H^+ g.$$



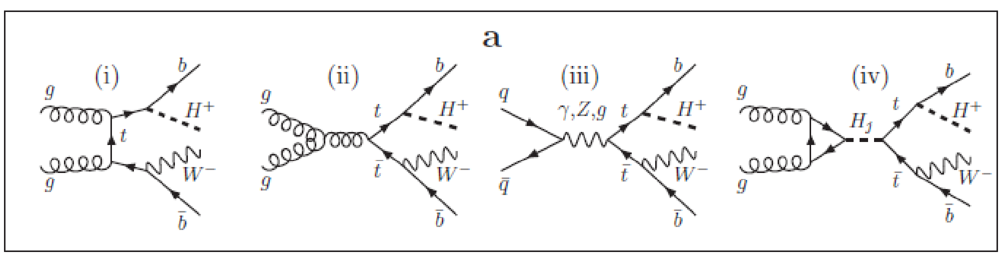


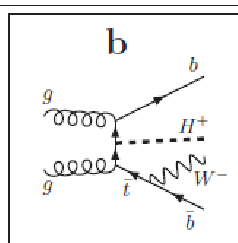
$$gg, b\bar{b} \to W^- H^+,$$
$$g\bar{b}\ (\to \bar{t}H^+) \to \bar{b}W^- H^+.$$



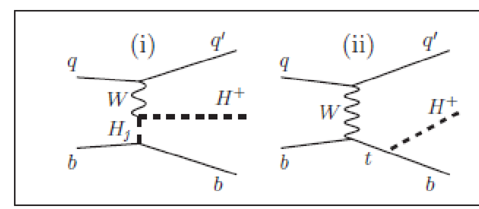


$$gg, q\bar{q}, b\bar{b}\ (\to t\bar{t} \to b\bar{t}H^+) \to b\bar{b}W^- H^+,$$
$$gg\ (\to b\bar{t}H^+) \to b\bar{b}W^- H^+.$$

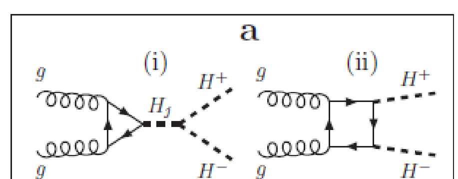


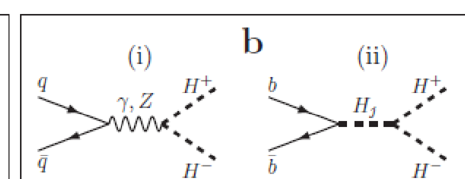


$$qb \to q' H^+ b$$



$$gg, q\bar{q}, b\bar{b} \to H^+ H^-$$



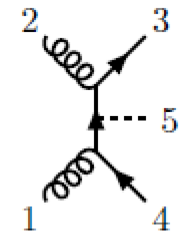


Production cross sections

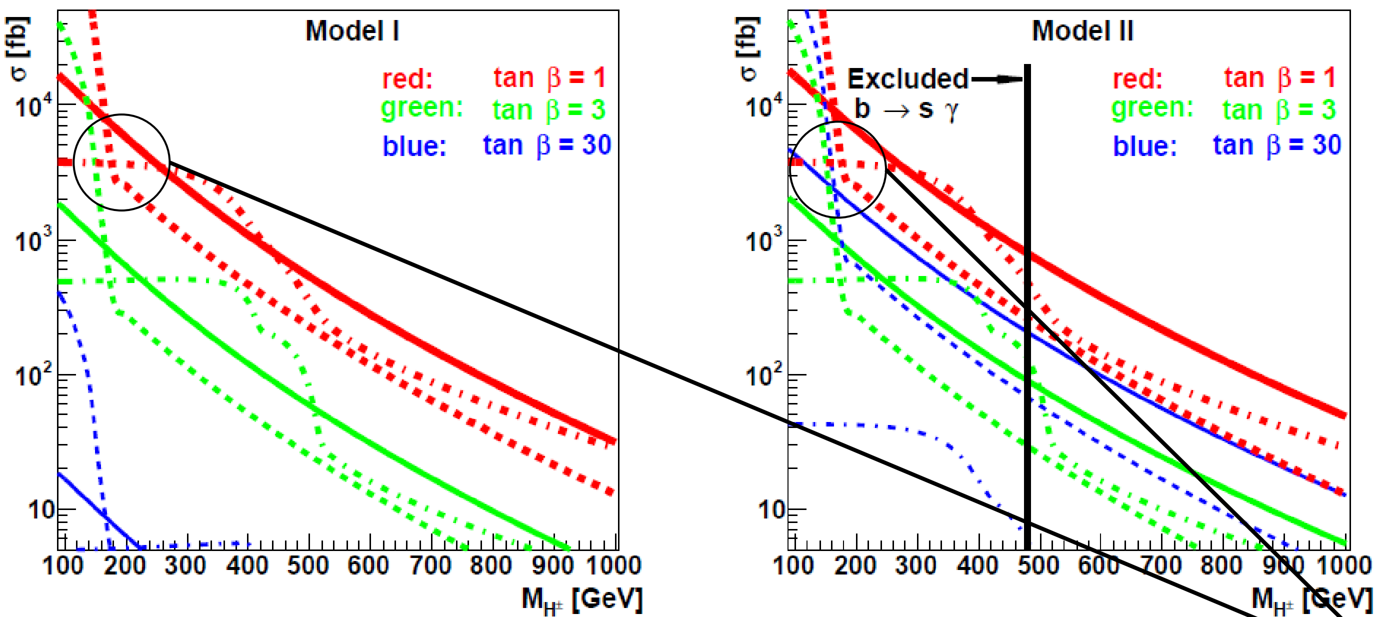
- "fermionic": $g\bar{b} \to H^+\bar{t}$, Solid
- "fermionic": $gg \to H^+ b\bar{t}$, Dotted
- "bosonic": $gg \to H_j \to H^+W^-$ Dot-dashed

These are actually the same process

$$g_1 g_2 \longrightarrow t_3 \bar{b}_4 H_5^-$$



Cross sections pp $\to$ H$^\pm$ X



LHC:
σ=O(100 pb)
at small mass,
yet rapidly
decreasing

t->bH+/- up to
MH+/-<mt

$$(M_H, M_A) = (500, 600) \text{ GeV}$$

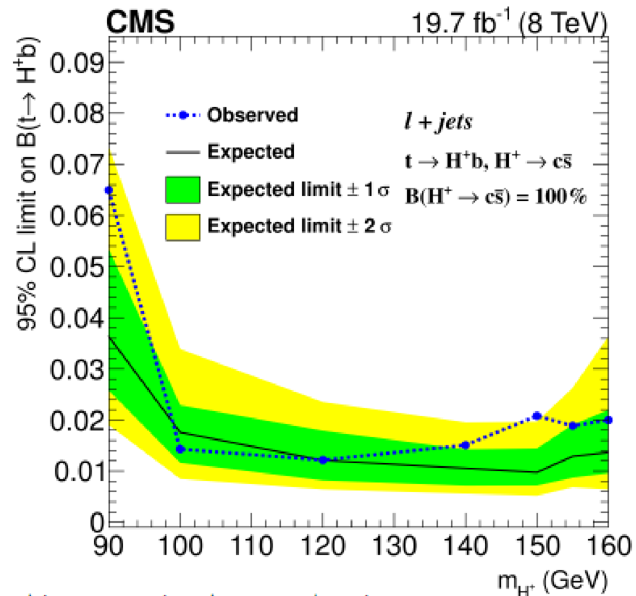
$$\sin(\beta - \alpha) = 1$$

Model X is ~ like II
Model Y is ~ like I

LHC constraints (already Run 1's supersede Tevatron ones)

CMS

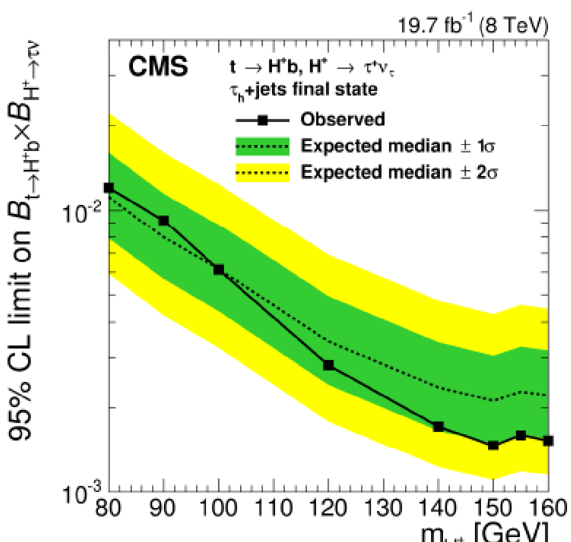
Limits from cs

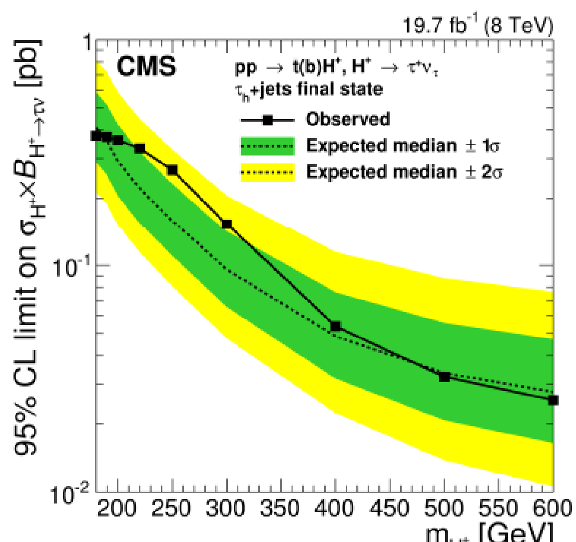


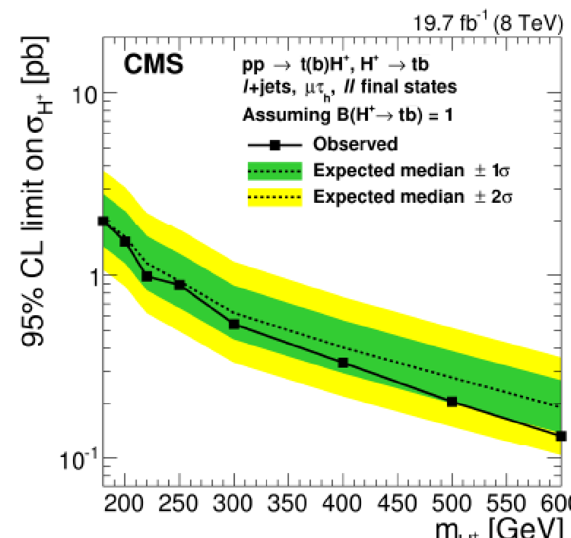
Limits from tau-nu

Limits from tb

$$\mathrm{BR}(t \to H^+ b) \times \mathrm{BR}(H^+ \to \tau^+ \nu_\tau) \quad \sigma(pp \to t(b)H^+) \times \mathrm{BR}(H^+ \to \tau^+ \nu_\tau)$$

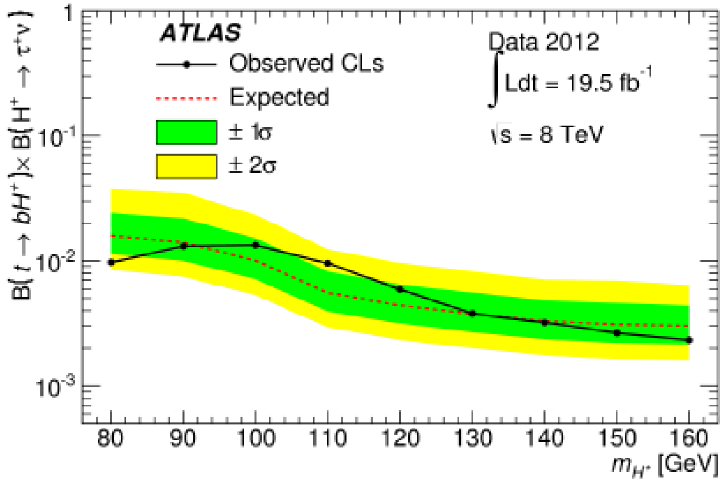


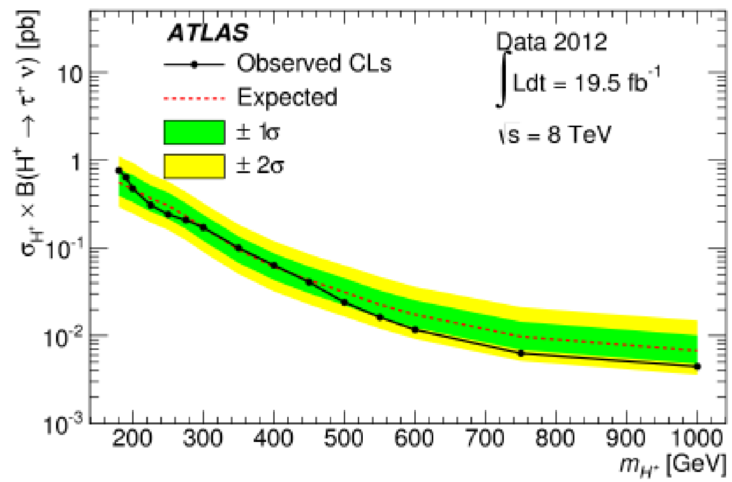




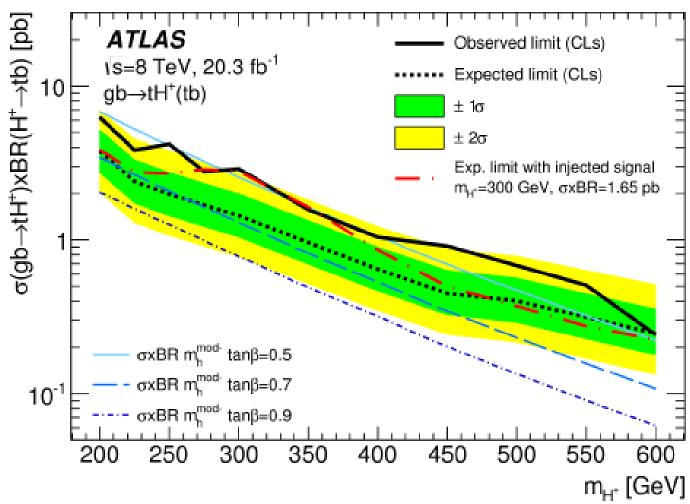
Limits from tau-nu

ATLAS

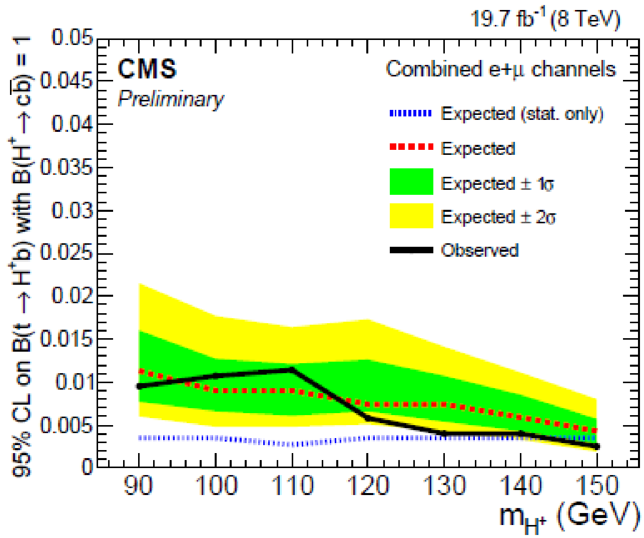




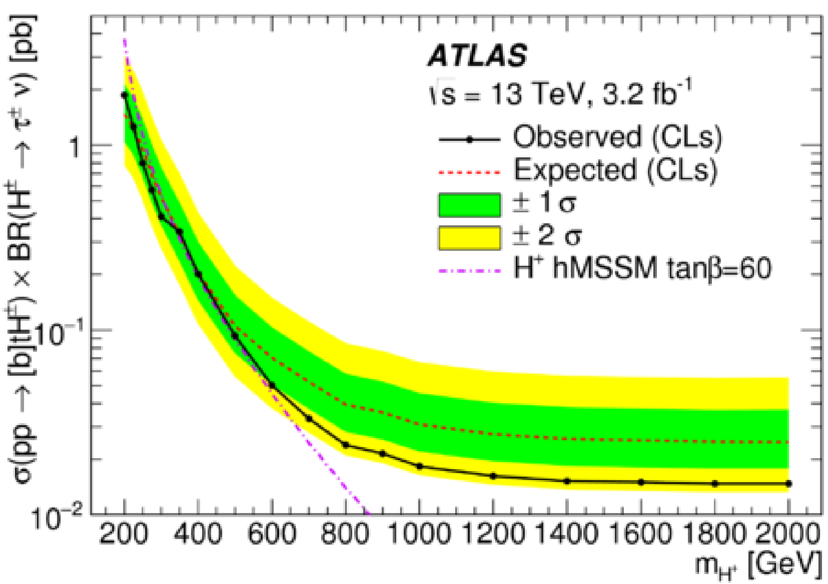
Limits from tb

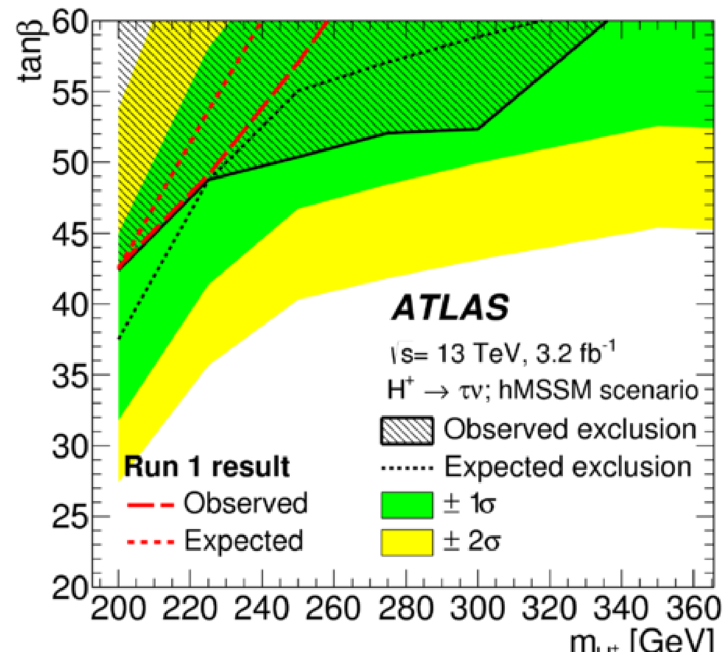


Limits from cb



Results from Run 2 (τν) with interpretation

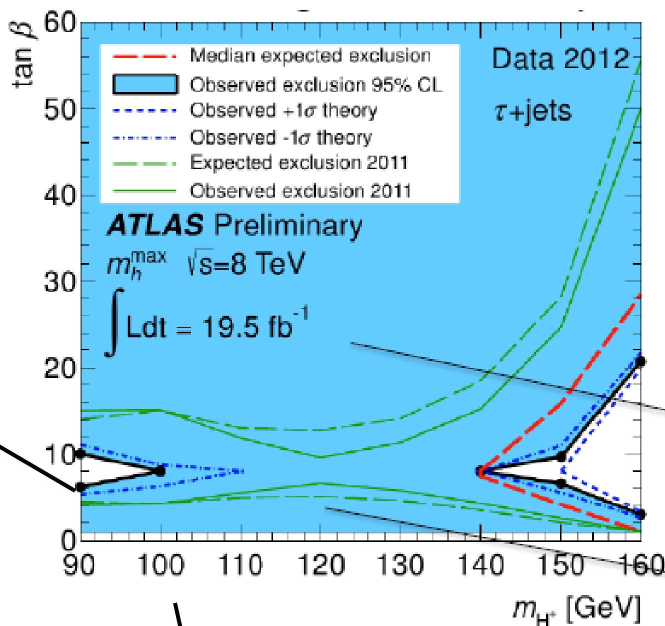




Interpreting exclusion plots (for 7,8 TeV)

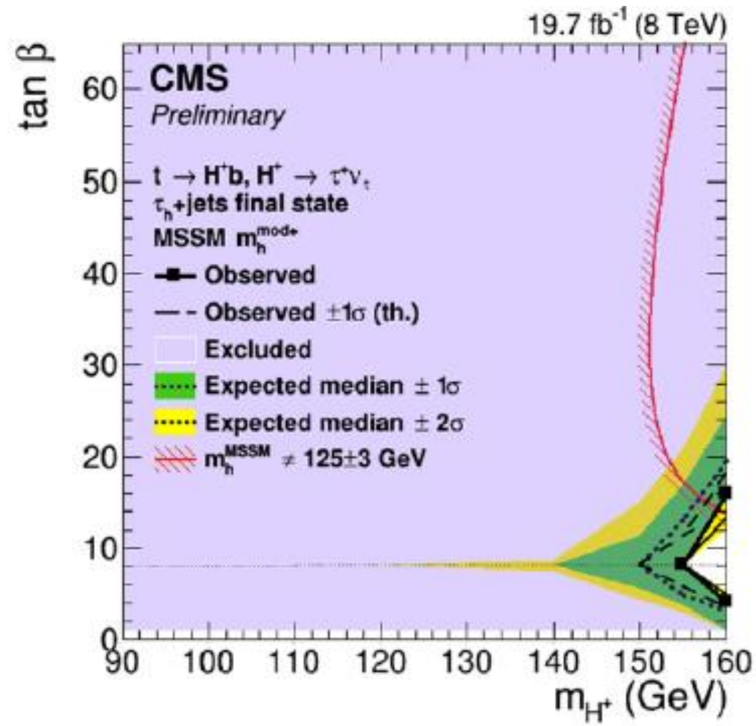
Take tau-nu search & assume 2HDM Type II

6.4



$m_b \tan\beta$

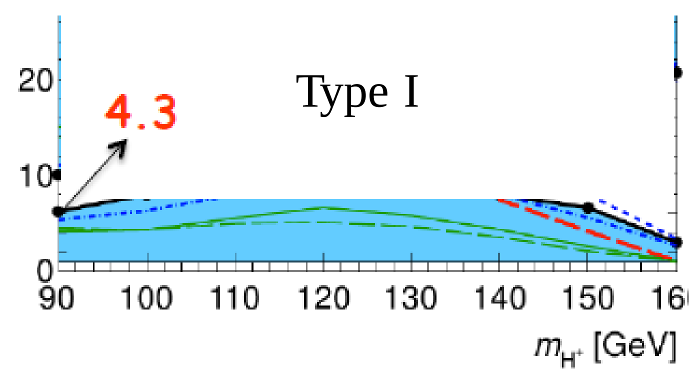
$\frac{m_t}{\tan\beta}$



Corrected for

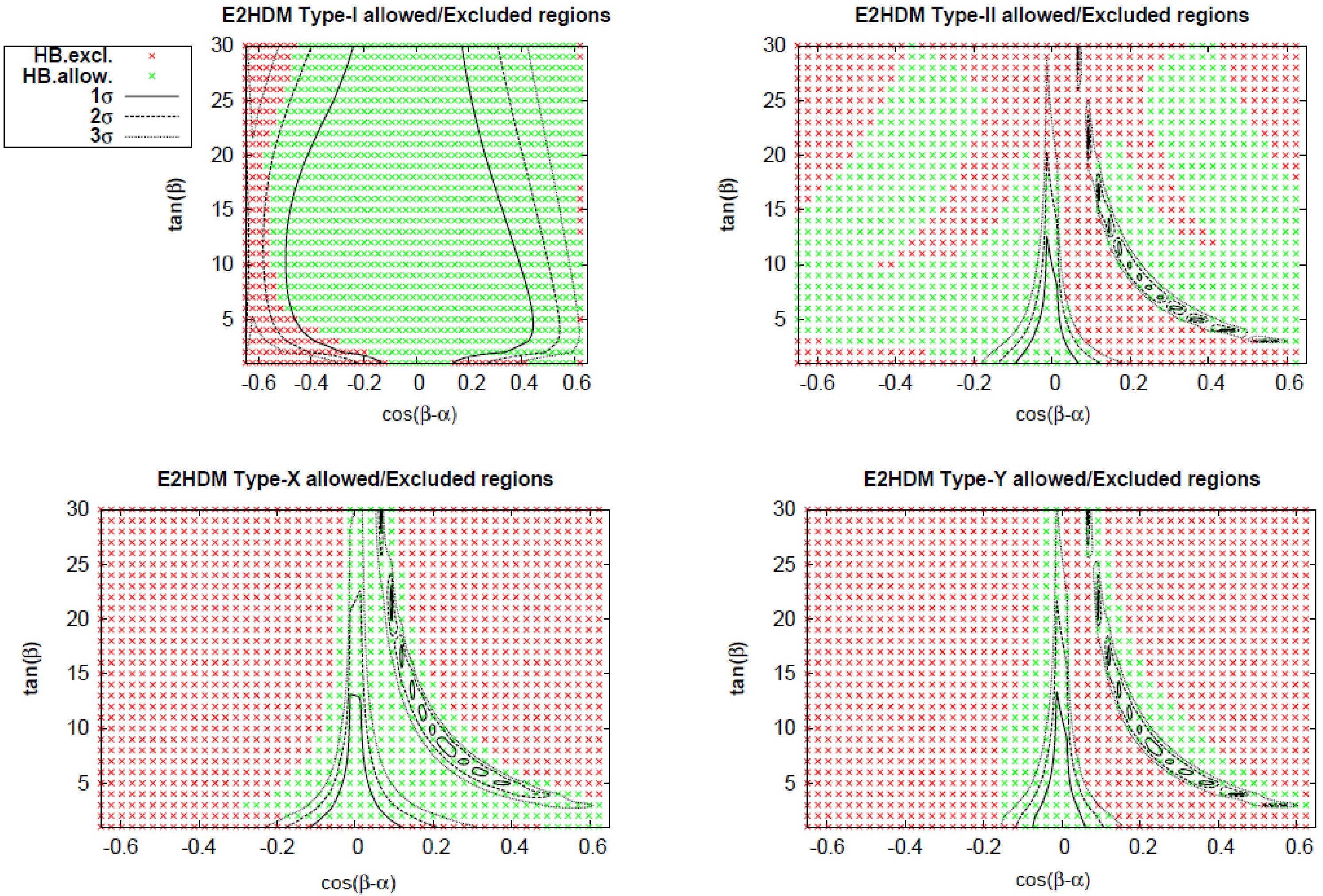
$BR(H^- \to \tau\bar{\nu})$

$m_{H^+} = 90$ GeV	I	II	F	LS
tanβ	4.3	6.4	3.2	5.2



Indirect constraints from h(125) properties ($\gamma\gamma$ & γZ, h(SM)H+H- coupling)

$$m_h = 125 \text{ GeV}, m_H = m_{H^+} = m_A = 500 \text{ GeV}$$



Additional prospects at the LHC (as lumi increases)

Channels for $M_{H^\pm} \lesssim m_t$

Single H^+ production

$M_{H^\pm}$	100 GeV		150 GeV	
$\tan\beta$	3	10	3	10
$H^+W^-b\bar{b}$ (6.3b)	$\surd$	$\surd$	$\surd$	
H^+bq (6.4)	$\surd$	$(\surd)$	$\surd$	

H^+H^- pair production

$M_{H^\pm}$	100 GeV			150 GeV		
$\tan\beta$	3	10	30	3	10	30
H^+W^- (6.2a)	$\surd$	$(\surd)$		$\surd$	$(\surd)$	
H^+H^- (6.7a)	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$
$H^+H^-q'Q'$ (6.7b)	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$	$\surd$

Models I and X

Four new production channels coming on line in Run 2

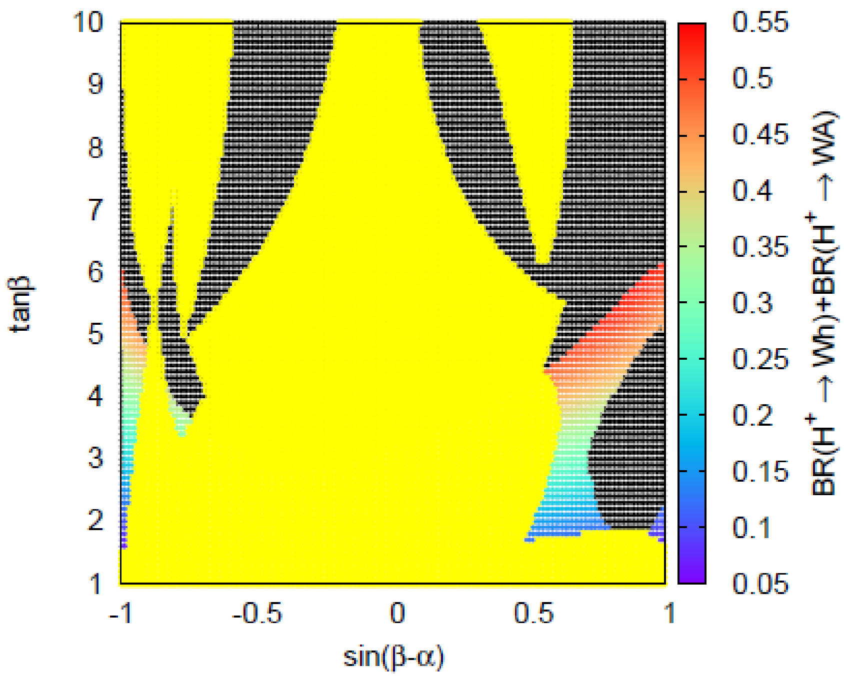
LEP equivalent @ the LHC

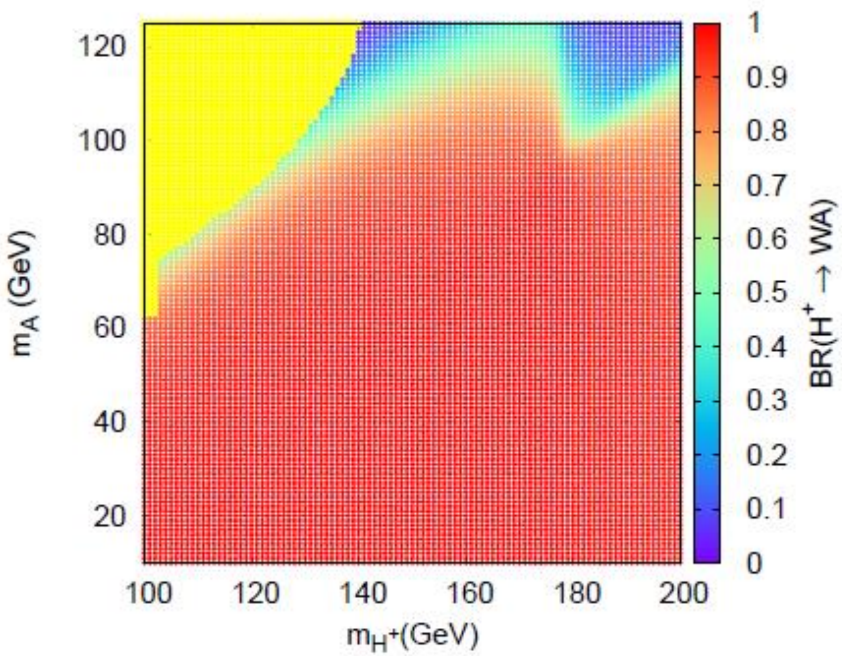
Channels for $M_{H^\pm} > m_t$

$H^+ \to W^+ H_j \to W^+ b\bar{b}$ would start playing a role (in most types), eg:

$$pp \to H^+ W^- X \to H_1 W^+ W^- X \to b\bar{b}\ell\nu jjX$$

Take Type I, also for light charged Higgs bosons if A is light (same culprit as at LEP):





Conclusions

Light SM-like Higgs boson discovered in 2012 incompatible with high scale survival/naturalness of SM

Higgs mechanism established in *doublet* form

Consider then MHDMs in going BSM: 2HDM offers minimal realisation

Three new Higgs states appear in the particle spectrum, one is charged

Several charged Higgs production and decay channels afford sensitivity to various Yukawa structures of a 2HDM

Current limits from direct searches of charged Higgs states exclude significant portions of parameter spaces, yet additional sensitivity is enabled by higher luminosities

Combination of fermionic and bosonic decays of charged Higgs states should afford one with the possibility of both discovery and separation of 2HDM scenarios

Other phenomenology: 1. Can make a doublet inert (DM candidate)
2. Type II can be embedded is SUSY (MSSM, etc.)