CHARGED HIGGS 2012

Review of prospects for the charged Higgs in non-SUSY multi-Higgs models in view of ATLAS and CMS results.

Marc Sher, William and Mary, October 10, 2012

"in view of ATLAS and CMS results", i.e. how have things changed since CH2010

1. Models without tree-level FCNC (four versions)

   latest updates for light Higgs ($t \rightarrow H^+b$) -- expectations for 13 TeV era

   possibilities for heavier Higgs ($m > m_{top}$) - expectations for 13 TeV era

2. Models with tree-level FCNC

3. Inert doublet models and others

Recent review article: Branco, Ferreira, Lavoura, Rebelo, MS, Silva, Physics Reports, 1106.0034

To avoid tree level FCNC, all fermions of a given charge must couple to the same Higgs multiplet (Glashow-Weinberg-Paschos theorem).

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

Note that four additional models could exist if there is a right-handed neutrino and a Dirac coupling to the Higgs.   We won't consider those here.

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

Barger, Hewett, Phillips, PRD 1990

	Type I	Type II	Lepton-specific	Flipped
X	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
Y	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Z	$\cot\beta$	$-\tan\beta$	$-\tan\beta$	$\cot\beta$

For top decays, one gets both lower and upper bounds for tan β in the Type II and Flipped, but only a lower bound in the Type I and Lepton-specific

First, we consider the case in which the charged Higgs is lighter than the top quark. This is the most studied case, since significant bounds can already be obtained.

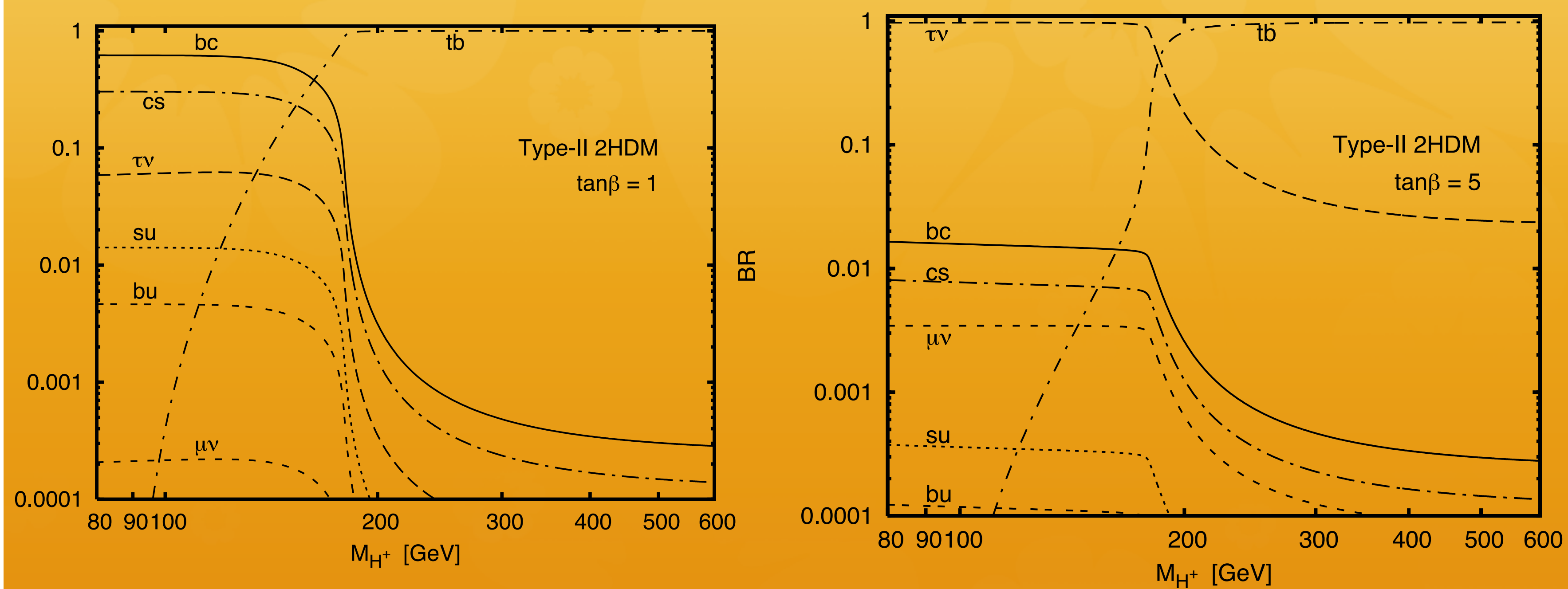
NOTE: In the Type II and flipped models, radiative B decays force the charged Higgs to be heavier than 300 GeV, IF there is no new physics. But many possible versions of new physics can weaken this bound.

Experimenters determine the limit for the branching ratio for t -> H^+ b, and then convert into a bound in the M – tan β plane, saying things like:

Interpreted in the context of the mmax h scenario of the MSSM, tan β above 12–26, as well as between 1 and 2–6, can be excluded in the mass range 90 GeV < mH+ < 150 GeV.

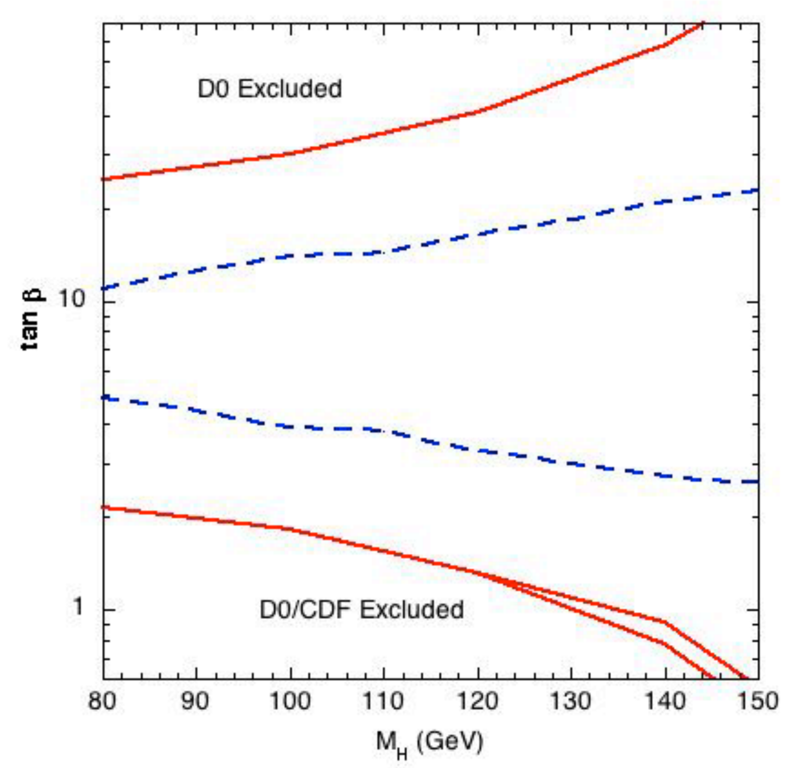
This is far too restrictive and unnecessary.

TYPE II MODEL

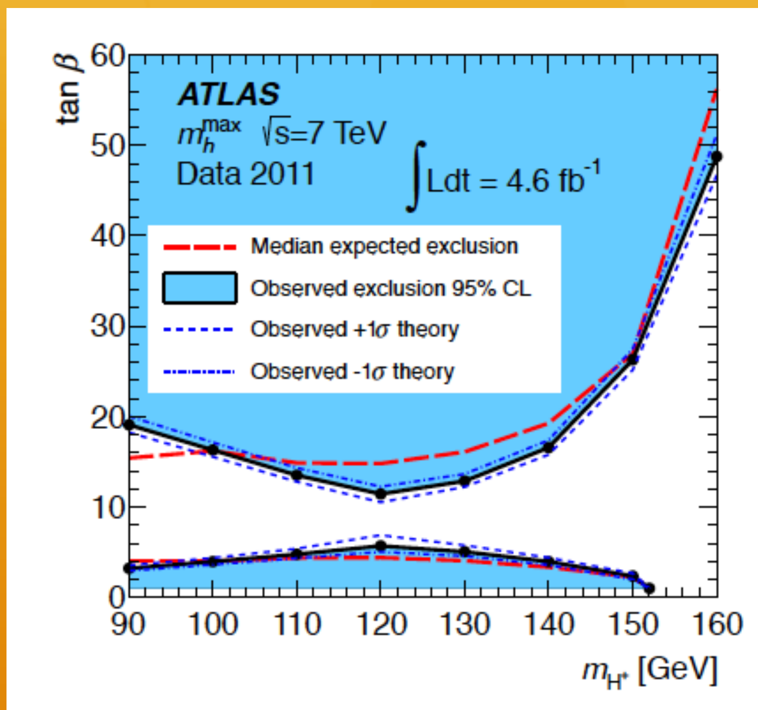


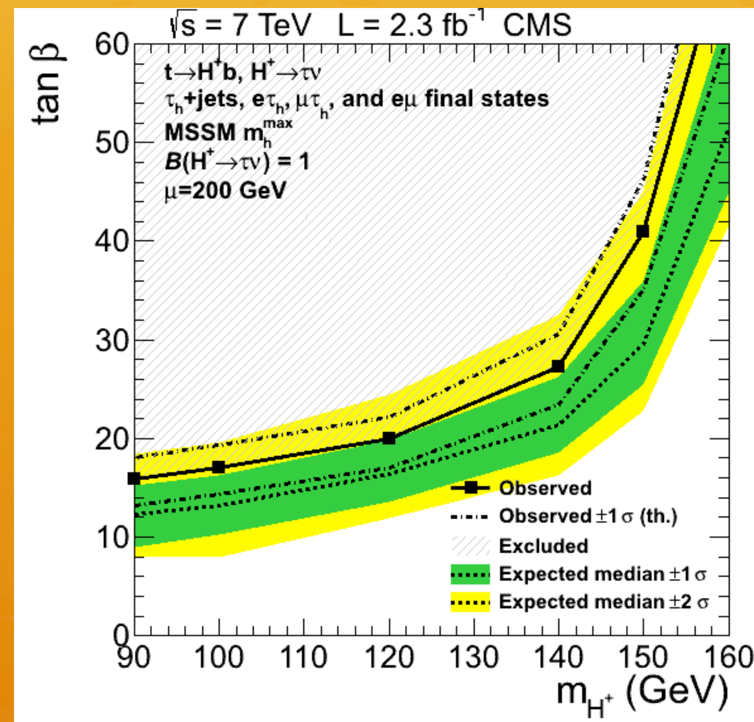
Note that except for tan β near 1, the dominant decay is into τ ν

RESULTS BEFORE THE LHC STARTUP

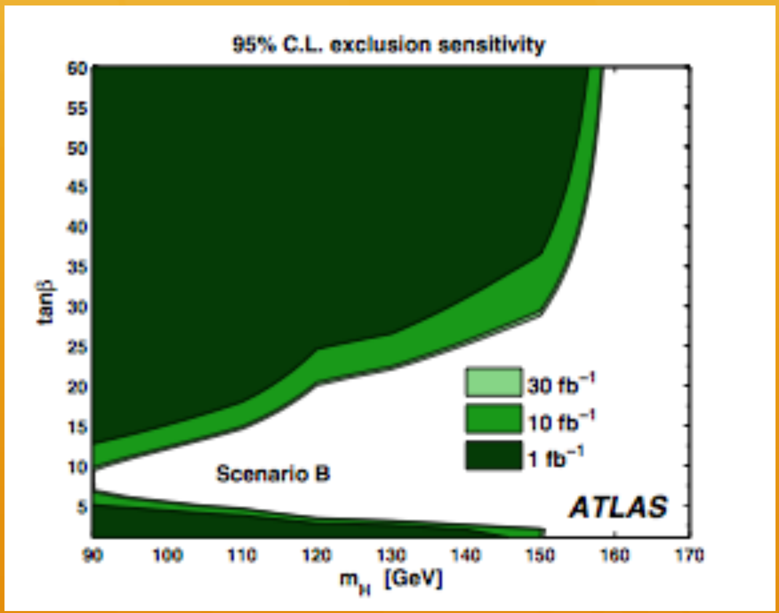


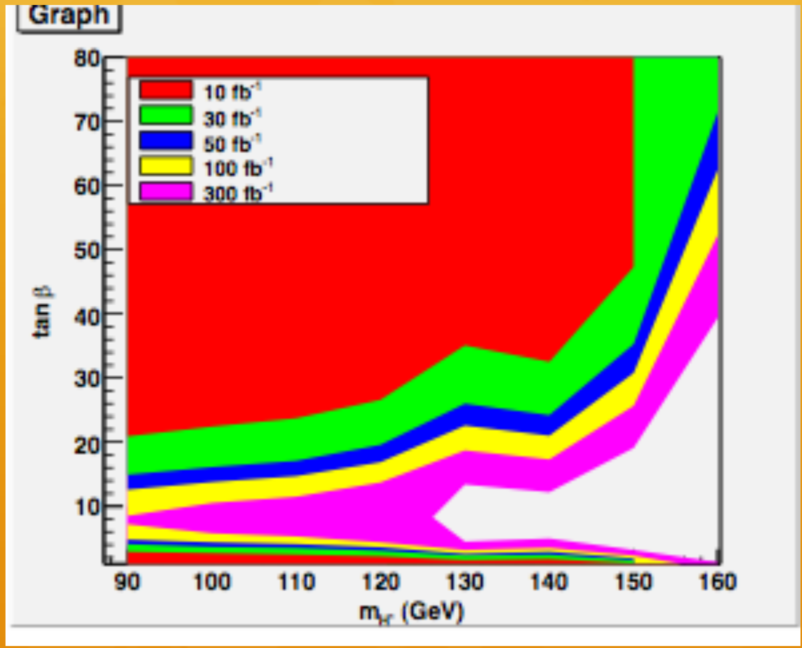
Latest results (from 2011 data)





Including the 2012 data will improve the reach somewhat, possibly even excluding masses around 120-130 for all tan β, but the biggest improvement will happen shortly after 13 TeV is started.



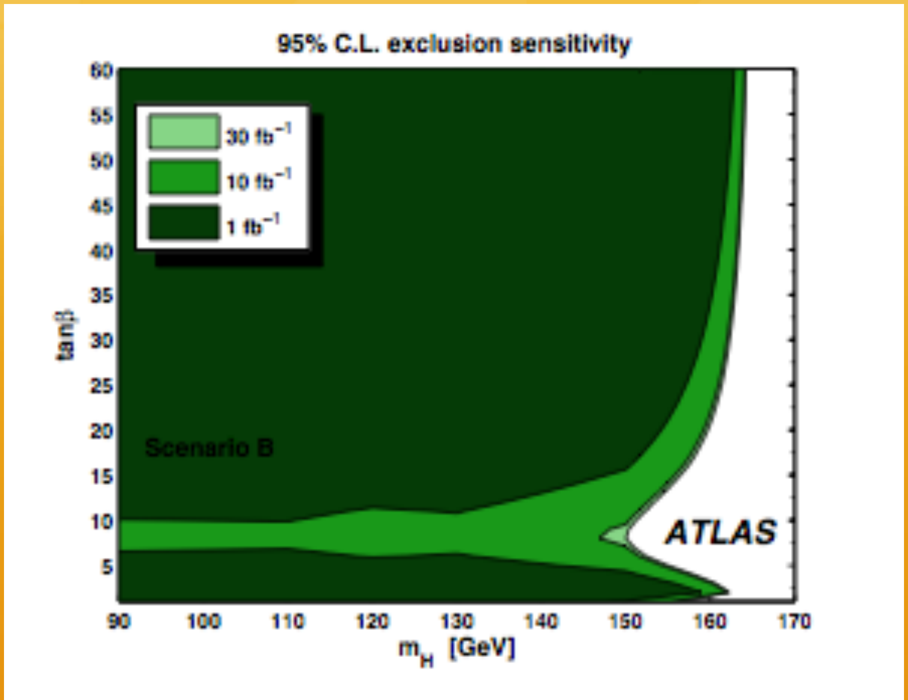


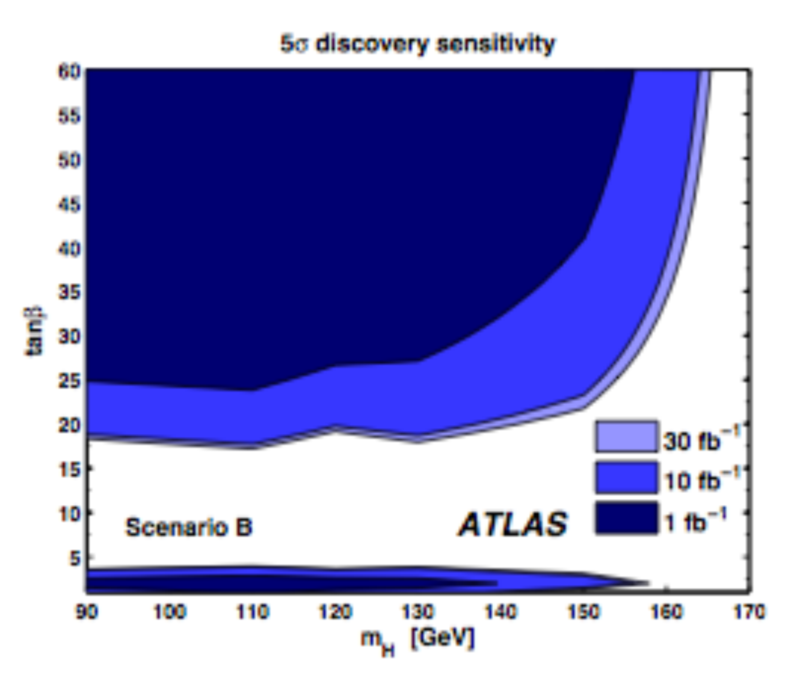
This is for 14 TeV with tt → bHbW, the W decaying to hadrons and the τ to leptons.

This is for single top

Guedes, Moretti, Santos (1207.4071)

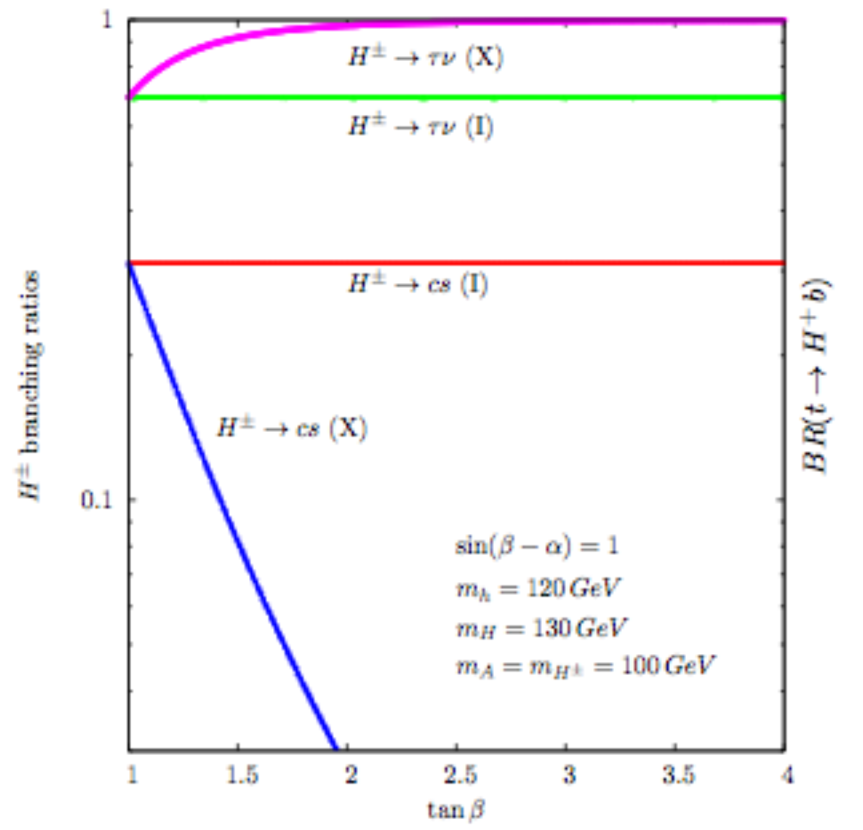
But one can do much better if hadronic τ decays are included.



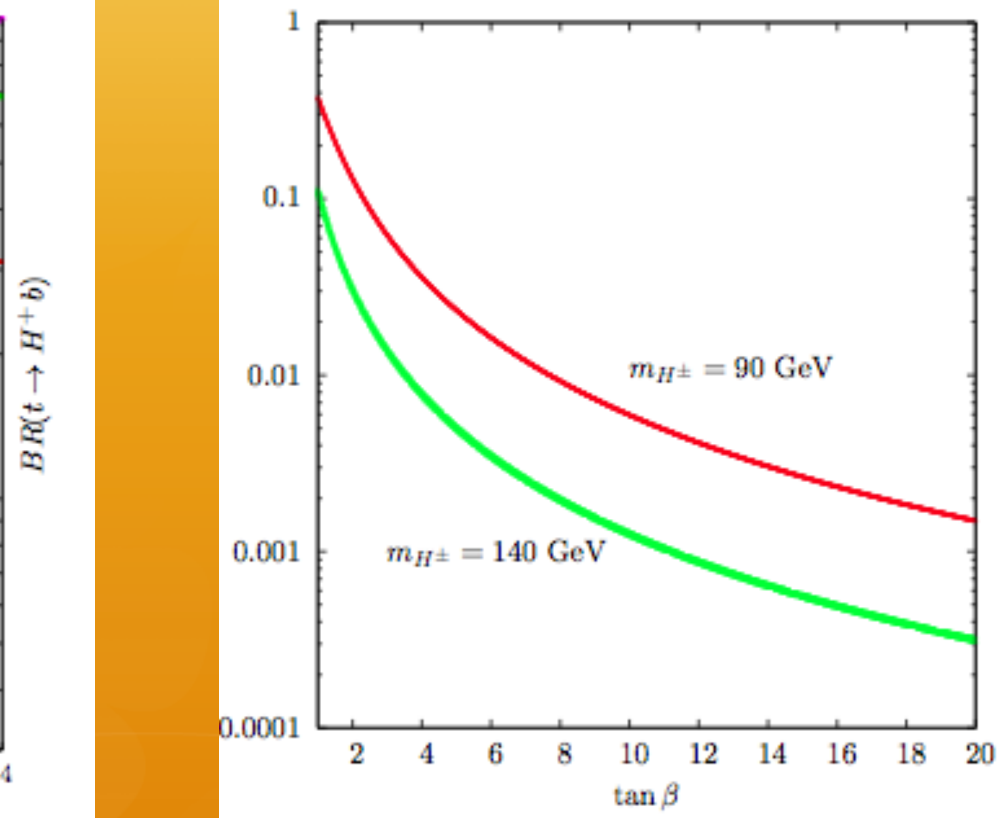


Thus, it will not be too long after start-up that the entire region up to 150 GeV could be excluded (or there could be evidence, of course).

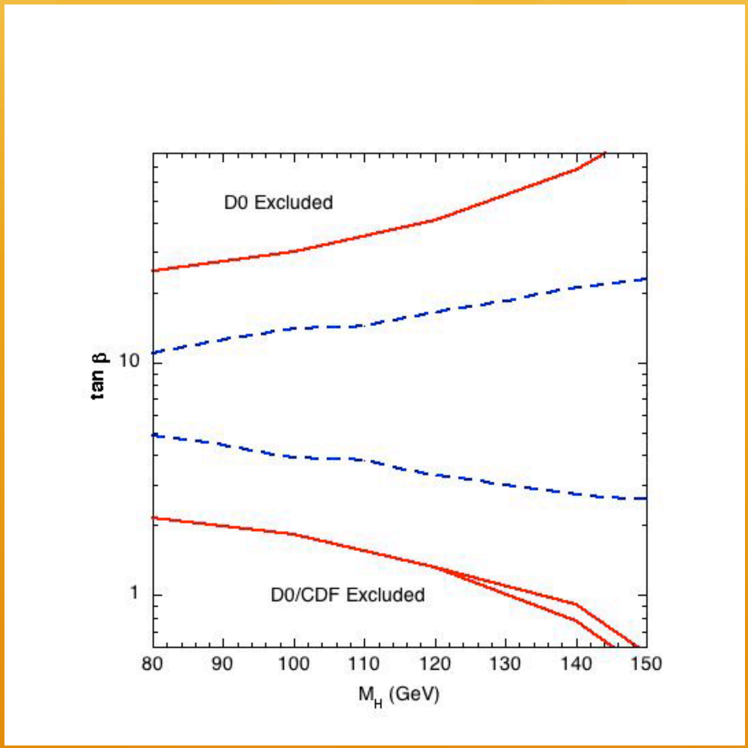
Type I and Lepton-Specific (type X)

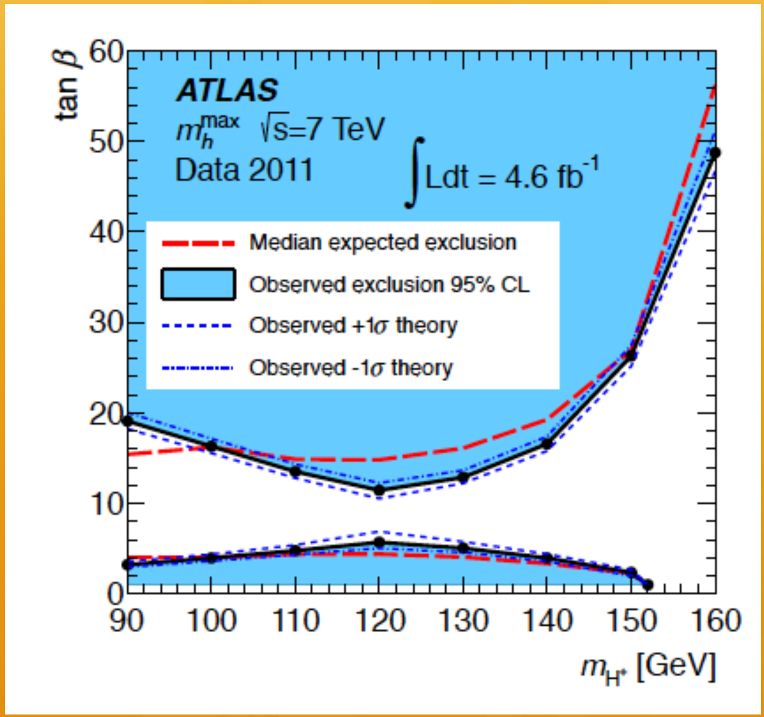


Branching ratio t->Hb



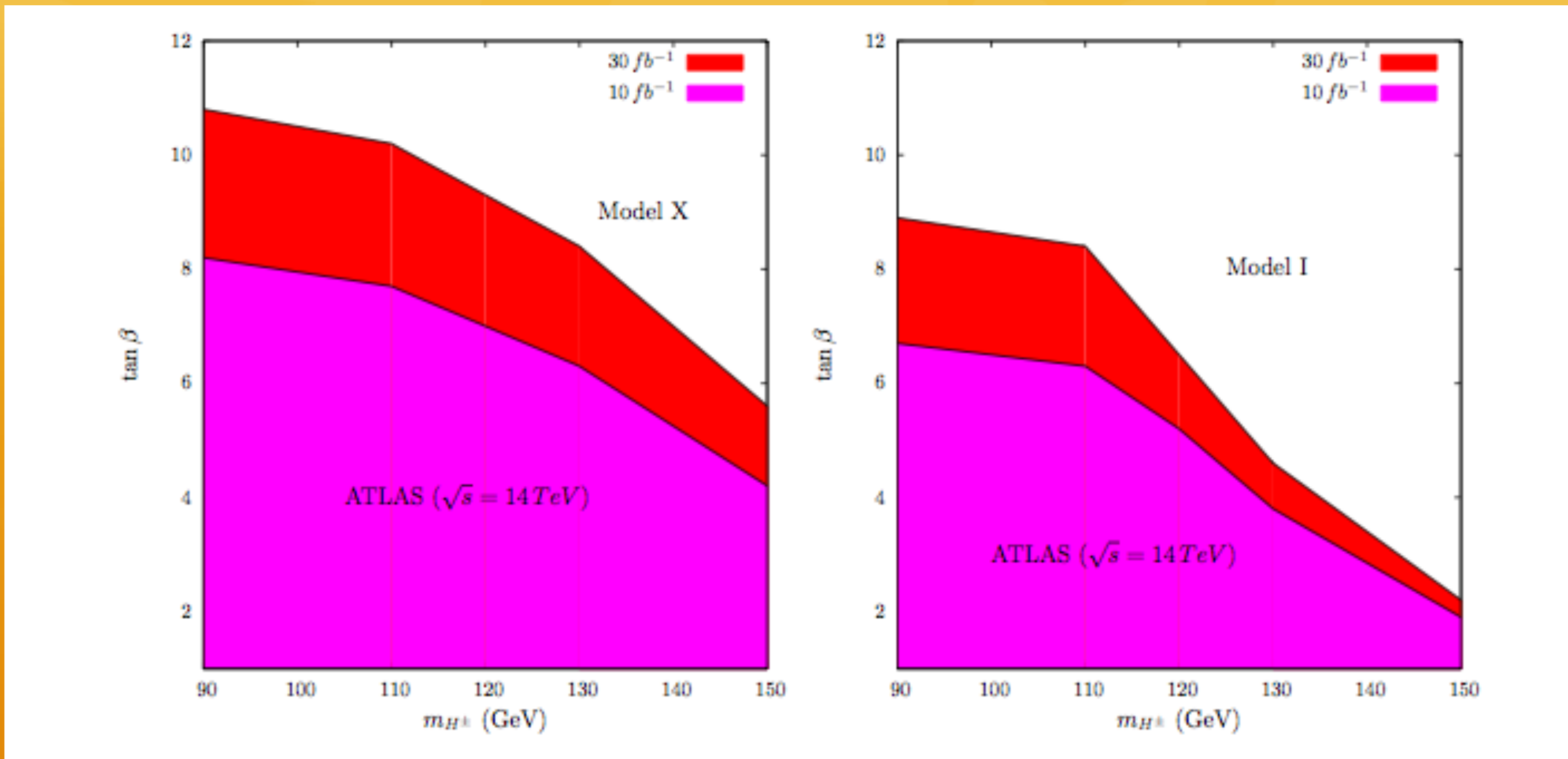
Current bounds are very close to the lower line in previous plots





This was known long ago. The discovery of a light Higgs at 125 GeV opens up another possibility for very light charged Higgs masses.

Aoki, Guedes, Kanemura, Moretti, Santos, Yagyu, 1104.3178



Guedes, Moretti, Santos (1207.4071) show that single top production will also give bounds that are somewhat weaker, but strong enough that it should be included in the analysis.

Mader, Park, Pruna, Stockinger and Straessner (1205.2692) point out that if the charged Higgs is very light, then associated production of a charged Higgs and the 125 GeV Higgs would lead to an excess of τ ν b b events for a wide range of tan β in the type I (and presumably the lepton-specific) models. The rate is much more parameter dependent. Rates can be higher with CP violation. They assume the charged Higgs mass is M_W (which might explain the anomaly of W → τν being somewhat larger than W →μν, eν)

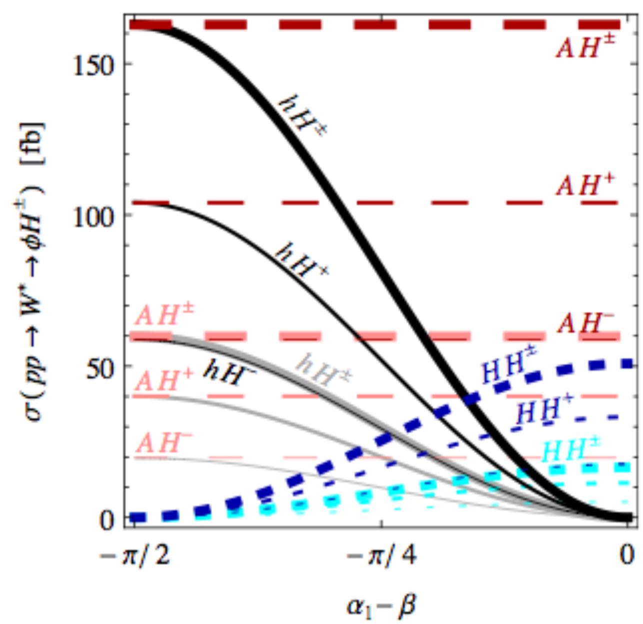
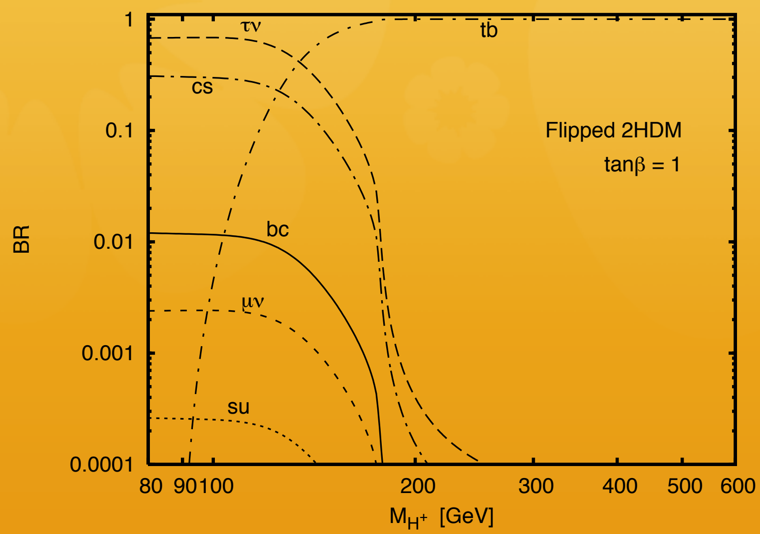
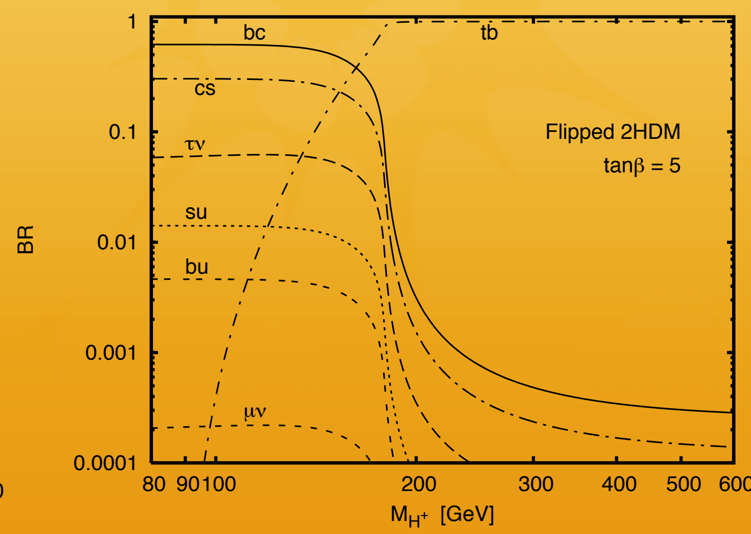


FIG. 4. Production cross-section of each neutral Higgs in association with a charged Higgs via a virtual W-boson in the CP-conserving case. The masses are $M_h = M_A = 125$ GeV, $M_H = 200$ GeV. For each channel, the darker and the lighter curves represent $\sqrt{s} = 7$ TeV, 14 TeV, respectively.

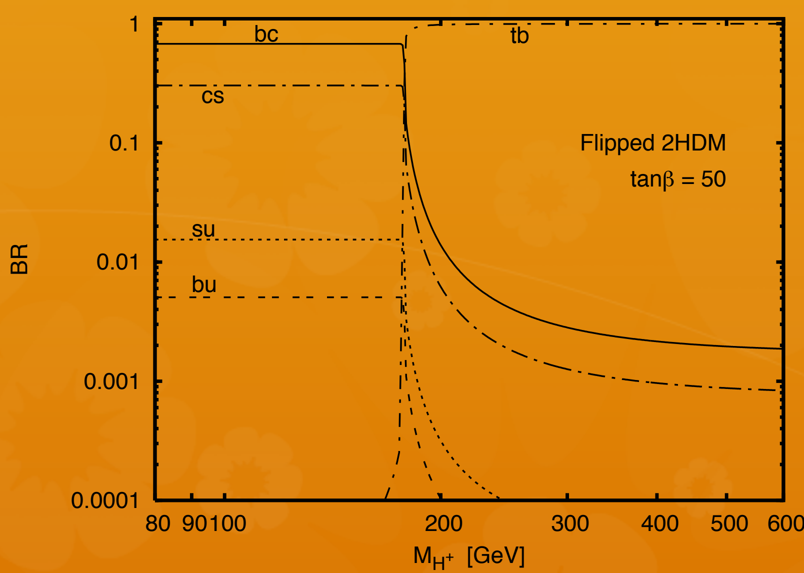
Flipped Model

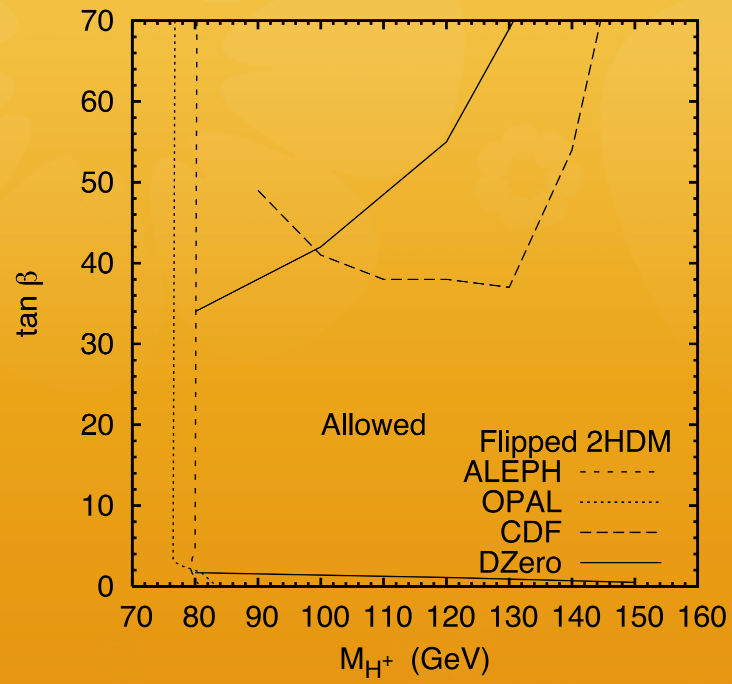


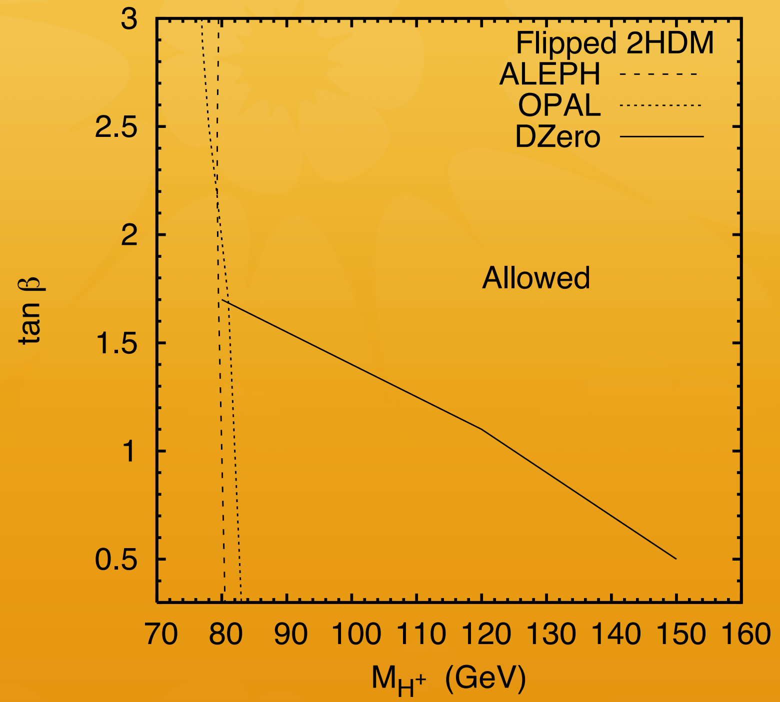


For most values of tan β , the dominant decay is into bc, and the subdominant decay is into cs.

Logan, MacLennan, 1002.4916







Logan, MacLennan got the above bounds from the Tevatron by arguing that, although CDF/D0 explicitly search for cs decays, the results would not be appreciably changed if the decay was into bc.

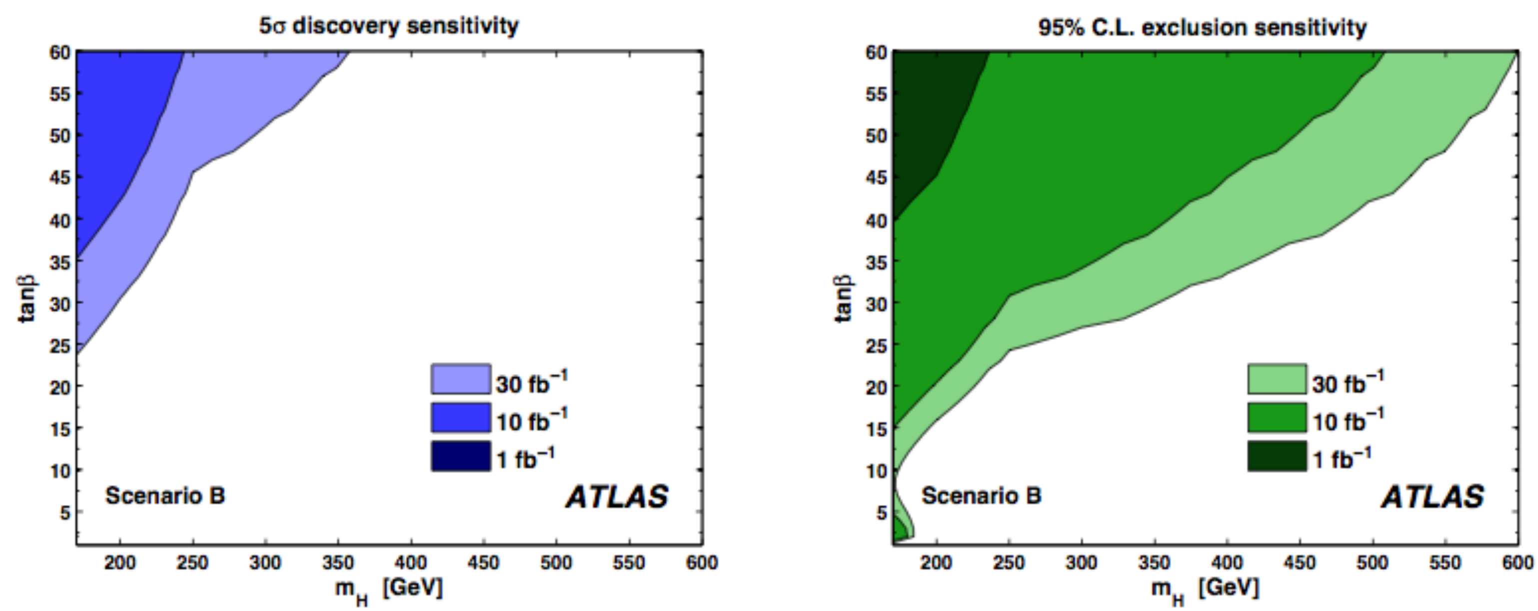
However, Akeroyd, Moretti and Hernandez-Sanchez (1203.5769) have argued that b-tagging could improve the signal-to-background by somewhat more than a factor of two.   A more detailed analysis, even for the Tevatron and the 7/8 TeV LHC run would be helpful.   Although their analysis was done in the context of the "Aligned" 2HDM and models with more than two doublets, it would apply here as well.

Now suppose the charged Higgs is heavier than the top quark.
For the moment, ignore decays of $H^+ \rightarrow h\ W^+$

The dominant decay is into t b, which has large backgrounds, so most analyses focus on the $\tau\ \nu$ decay. In the type II model, this is a few percent for moderate tan β and 10% for large tan β .

Type II model

ATLAS results for MSSM, which will not be very different from the type II model. Main production mechanism is g b → t H^-, with the H^- decaying into $\tau\,\nu$



Note that Eriksson, Hesselbach and Rathsman (hep-ph/0612198), pointed out that if the mass of the H or A is heavier than $M(H^+) + M(W)$, then the H or A can be resonantly produced leading to a huge enhancement (by as much as a factor of 100) in the production cross section for associated production of a charged Higgs and a W. The possibility of such an enhancement needs further analysis. This can occur in the 2HDMs, but does not generally occur in the MSSM.

What about the decay $H^+ \rightarrow W^+ h$? We now know the mass of the h….

Detailed analysis by Kanemura, Moretti, Mukai, Santos and Yagyu 0901.0204

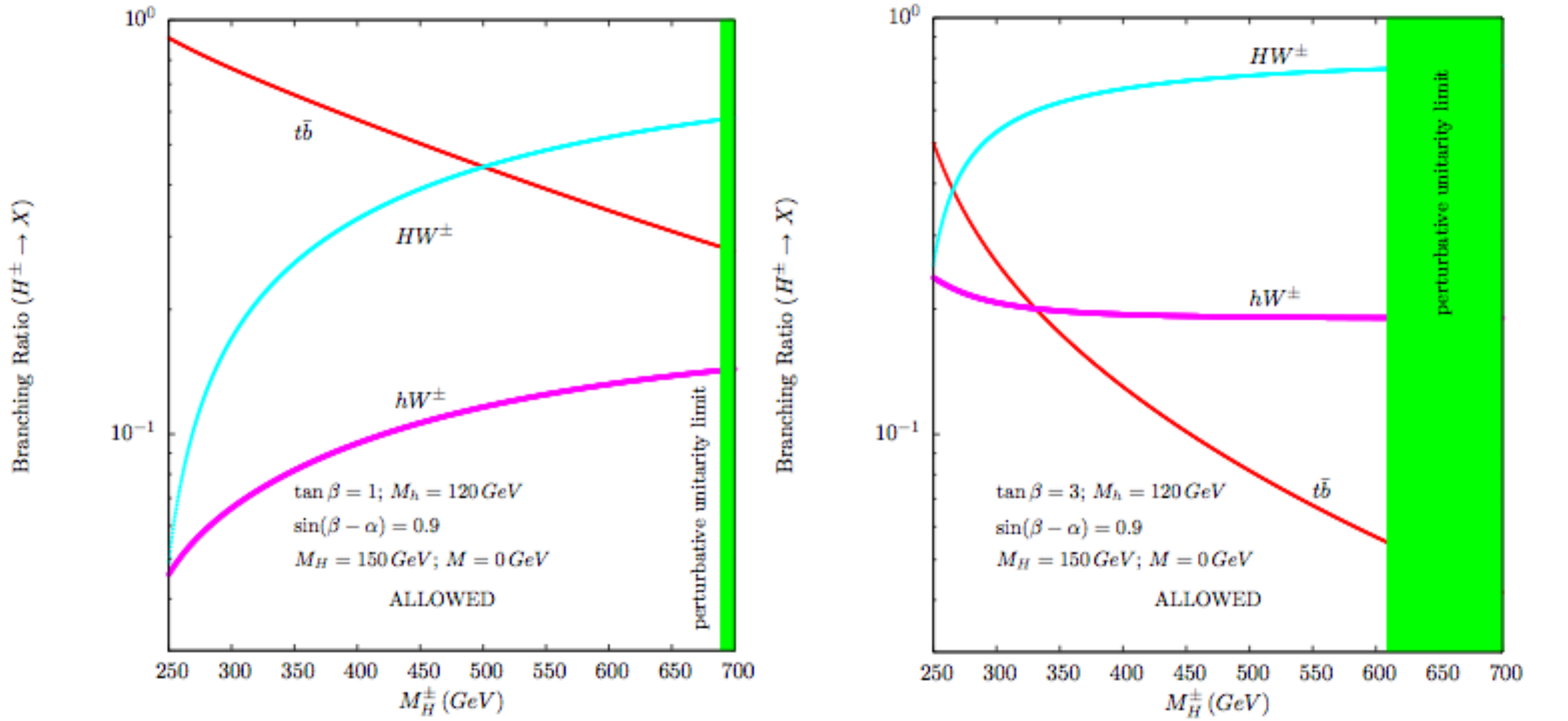


FIG. 7: $H^\pm$ decays for $M_h = 120\ GeV$, $M_H = 150\ GeV$, $M_A = M_{H^\pm}$ and $\sin(\beta-\alpha) = 0.9$. On the left is the plot for $\tan\beta = 1$ while on the right we set $\tan\beta = 3$. Perturbative unitarity limits are shown.

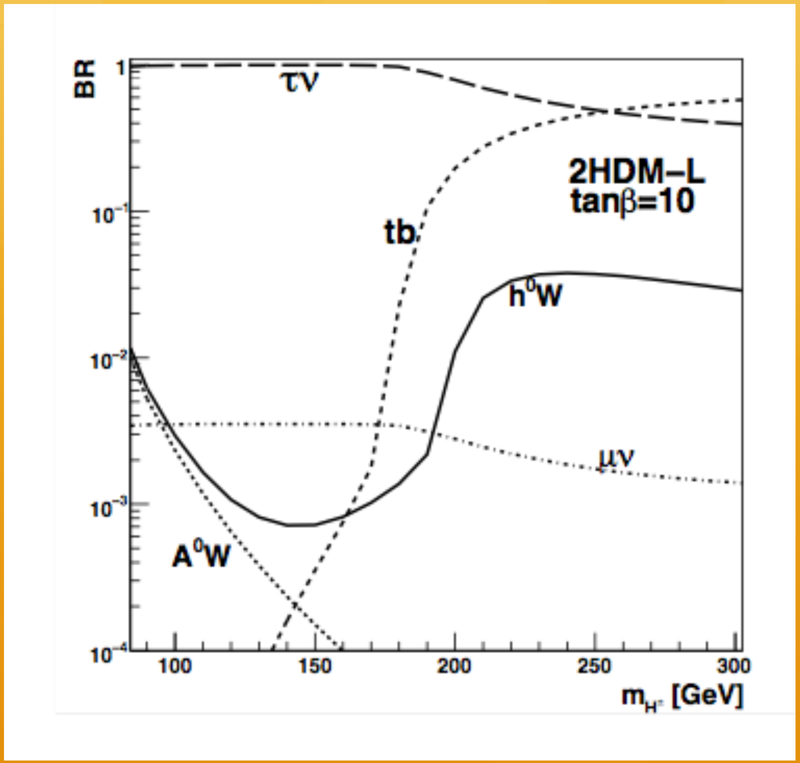
The decay was studied by Assamagan, Coadou, Deandrea (hep-ph/0203121) and by Drees, Guchait and Roy (hep-ph/9909266).

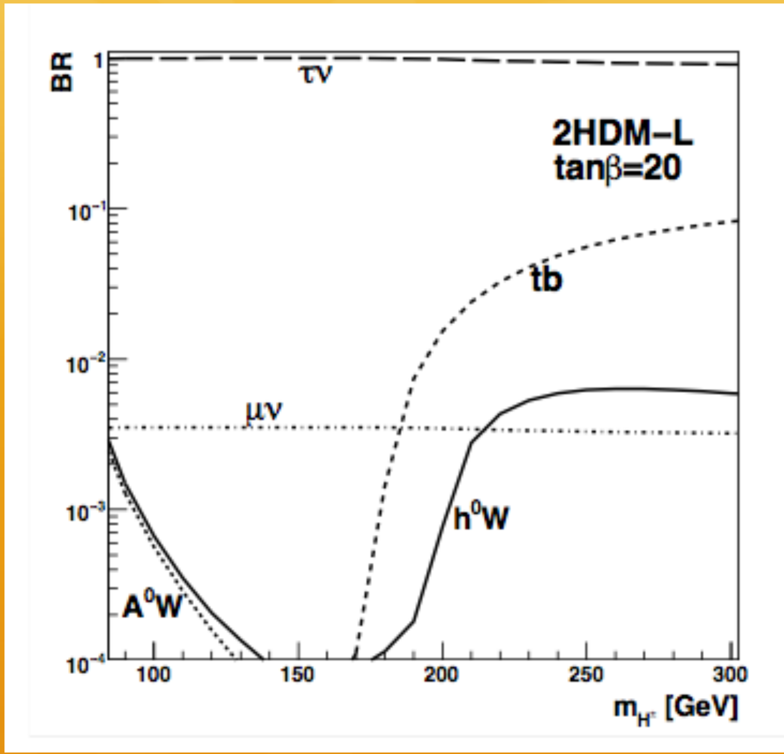
They considered g b → t H, with t → Wb and H → W h, with h → bb. The backgrounds are severe, and for fairly light (200 GeV) charged Higgs one can get a signal after years of running.

But these papers are old, and only studied the hadronic decays of the light Higgs. H → Wh may be the most promising decay signature of a heavy charged Higgs in the type II model, and a much more detailed analysis is needed.

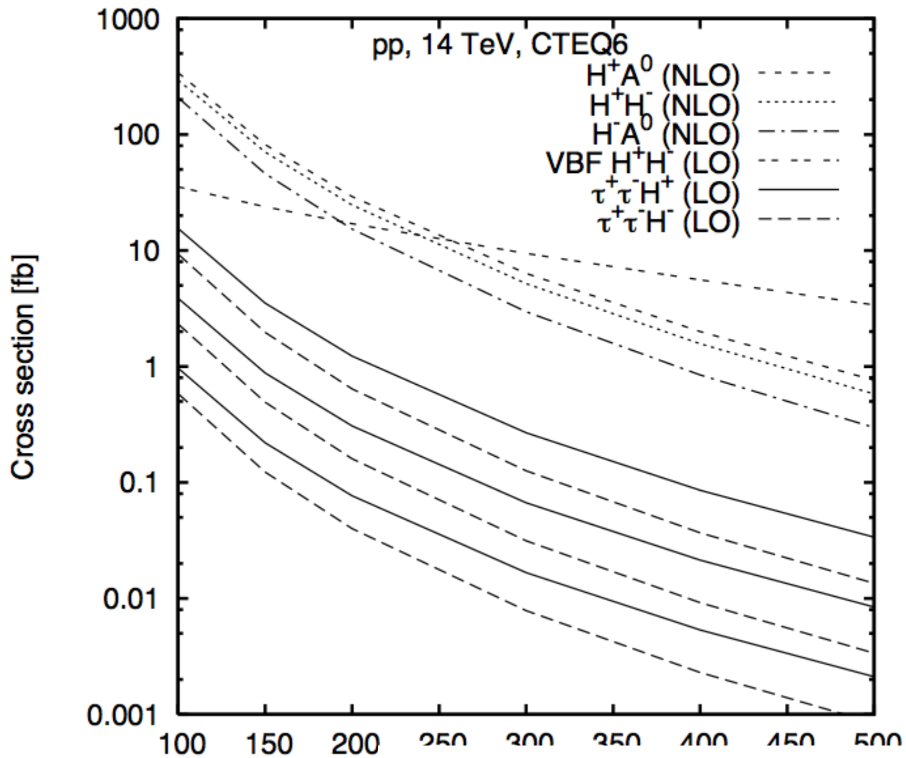
Note also that the charged Higgs in type I model will have a much lower branching ratio into $\tau\,\nu$ and thus the W h signal will offer the only hope for detection. Unfortunately, production through g b → t H is suppressed at large tan β and thus one might need to produce the charged Higgs via pair production. Analysis of these signatures is currently underway.

In the lepton-specific model, branching ratios look promising:





However, all quark induced production mechanisms are suppressed, and other production mechanisms are necessary.



Logan and Maclennan
0903.2246

Aoki, Kanemura,Tsumura,
Yagyu, 0902.4665

	$AH^\pm, HH^\pm(m_\Phi = 130$ GeV)	$AH^\pm, HH^\pm(m_\Phi = 150$ GeV)	$ZW^\pm$
$\tau^+\tau^-\tau\nu$	8.4×10^4	5.0×10^4	3.2×10^4
$\mu^+\mu^-\tau\nu$	3.0×10^2	1.8×10^2	3.1×10^4

TABLE IV: Events for the $\tau^+\tau^-\tau\nu$ and $\mu^+\mu^-\tau\nu$ final states from the Higgs boson pair production and $ZW^\pm$ background. The signal events are summed over $AH^\pm$ and $HH^\pm$. The integrated luminosity is taken to be 300 fb^{-1}. Values for the decay branching ratios are taken to be $\mathcal{B}(A/H \to \tau^+\tau^-) = 0.99$, $\mathcal{B}(A/H \to \mu^+\mu^-) = 0.0035$, and $\mathcal{B}(H^\pm \to \tau\nu) = 0.99$, which correspond to the values for $\tan\beta \gtrsim 7$. The cross section of $pp \to ZW^\pm$ is evaluated as $\sigma_{ZW} = 27.7$ pb by

Main points:

For the type II model, the charged Higgs decay into h + W is the most promising, especially now that we know the h mass.

For type I, this is also true, but production may have to go through non-fermionic production (such as associated or pair production.

For the lepton-specific, non-fermionic production is also needed, and one has the possibility of multi-tau decays (even h → $\mu\mu$ may play a role.

Further analysis in all of these cases is needed.

In the flipped model, for a charged Higgs above 200 GeV, the decay will always (>0.99) be into tb. Studies show that systematic uncertainties in top pair production will swamp any signal. I know of no prospects for detection at the LHC.

Logan, MacLennan, 1002.4916

MODELS WITH TREE-LEVEL FCNC

$$\bar{Q}_L \eta_1^U U_R \tilde{\Phi}_1 + \bar{Q}_L \eta_1^D D_R \Phi_1 + \bar{Q}_L \eta_2^U U_R \tilde{\Phi}_2 + \bar{Q}_L \eta_2^D D_R \Phi_2$$

$$M^F = \frac{v}{\sqrt{2}} \left(\eta_1^F \cos\beta + \eta_2^F \sin\beta \right)$$

Defining

$$\kappa^F \equiv \eta_1^F \cos\beta + \eta_2^F \sin\beta$$

$$\rho^F \equiv -\eta_1^F \sin\beta + \eta_2^F \cos\beta$$

Notation is that of
Mahmoudi and Stal, 0907.1791

Then one Higgs has a vev and diagonal Yukawa couplings, κ^F, and the other has no vev and couples with ρ^F. If one uses the discrete symmetry to suppress FCNC, then some of the η's vanish and ρ is proportional to κ

The charged Higgs couplings are $H^+ \bar{U} \left(V \rho^D P_R - \rho^U V P_L \right) D$

Couplings are all arbitrary.
The Cheng-Sher ansatz (Cheng, MS, PRD35,3484 (1987):

$$\rho_{ij}^F = \lambda_{ij}^F \frac{\sqrt{2m_i m_j}}{v}$$

Davidson, Greiner, 1001.0434

where the λ_{ij} are O(1), although some argue that O(1/tan β) is more appropriate. After 25 years, this model is under serious challenge---current bounds are

$$(\lambda_{ds}, \lambda_{uc}, \lambda_{bd}, \lambda_{bs}) \leq (0.1, 0.2, 0.06, 0.06)$$

(If the A mass is increased from 120 GeV to 400 GeV, these bounds increase by a factor of three)

Golowich et al, 0705.3650

Dominant charged Higgs vertex will be into $c_R b_L$, unlike $c_L b_R$ in the type I and II models. The vertex is larger though, of O(1)%. This leads (He, Yuan, hep-ph/9810367) to the possibility of s-channel charged Higgs production. This will substantially increase the rate of single top production, and hW production. For masses below 350 GeV, this should be observable. This work is definitely in need of updating.

The Inert Doublet Model

Here a Z_2 symmetry eliminates all of the couplings of a Higgs doublet to fermions and also does not allow any vev for the doublet. The lightest state is then a dark matter candidate. Most studies of the model focus on the neutral component. The charged Higgs will only decay via H W and A W (the lightest of H or A is then stable). Cao, Ma and Rajasekaran (0708.2939) studied the phenomenology and found production cross sections. A later analysis of Miao, Su and Thomas (1005.0090) concluded that charged Higgs masses above 120 GeV or so can't be detected due to large backgrounds.

Pich Tuzon 0908.1554,1001.0293

The Aligned 2HDM

This model simply assumes that the ρ^F and κ^F matrices are proportional leading to no tree-level FCNC. This assumption is not radiatively stable. The parametrization can be convenient and leads to the standard four models as special cases (see Mahmoud, Stal (0907.1791) for a discussion and limits from low-energy processes).

The Neutrino-Specific Model

Davidson, Logan 0906.3335

In this model, one Higgs only couples to neutrinos, giving them a Dirac mass. The vev of the Higgs is O(eV). The only decay mode of the charged Higgs is into a lepton and a neutrino. For a normal hierarchy, it is primarily into $\tau\,\nu$, $\mu\,\nu$ and for an inverted hierarchy into primarily $e\,\nu$. The signature for $pp \rightarrow H^+H^- \rightarrow l^+l^-\,\nu\nu$ is quite dramatic. Study of various cuts shows a 5σ discovery range up to 300 GeV for 100/fb at 14 TeV.

Conclusions

LIGHT HIGGS

Type II - some mass ranges will be ruled out in the current run, but the entire range up to a mass of 150 GeV will be covered shortly after the 2014 start up

Type I and lepton-specific – lower bounds on tan β will be obtained from top decays. For larger tan β, discovery may not be possible at the LHC.

Flipped--- Dominant decay is into cb, subdominant into cs. b-tagging could increase efficiencies---more studies (even at 7-8 TeV) are needed.

HEAVY HIGGS

Type II -- can get upper bound on tan β by looking at $\tau\nu$ but the most promising decay might be h W, and detailed analyses have not yet been done.

Type I -- Same, but need non-fermionic production for large tan β . More studies needed. Same for lepton-specific, where one might get multi – tau events.

Flipped-- appears to be hopeless.