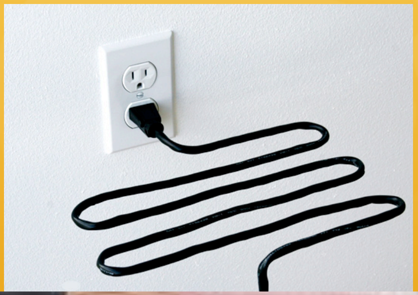
CHARGED HIGGS BOSONS AT THE LHC



Marc Sher, William and Mary, September, 2013

The charged Higgs has been extensively studied over the years. There is a conference CH20xx every two years in Uppsala dedicated to it, and the proceedings of that conference are pretty comprehensive. One can find most of the latest LHC constraints in the CH2012 proceedings. Prior to the LHC start, a long discussion and list of references can be found in a recent review article.

Branco, Ferreira, Lavoura, Rebelo, MS, Silva, Physics Reports, 1106.0034

In this talk, I'll review these constraints, but will then turn to a few new ideas regarding charged Higgs signatures.

Assumptions for this talk:

1. 2HDM, no supersymmetry
2. no CP violation in the Higgs sector
3. no tree-level flavor-changing neutral currents

Sadly, the Cheng-Sher ansatz appears to be dead....

Outline:

1. Models w/out FCNC
2. Constraints on charged Higgs lighter than the top.
3. Constraints on charged Higgs heavier than the top.
4. Decay of the charged Higgs that needs further study
5. Neutrinophilic models
6. Decays into "dark" Z's

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. This will be discussed later.

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

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

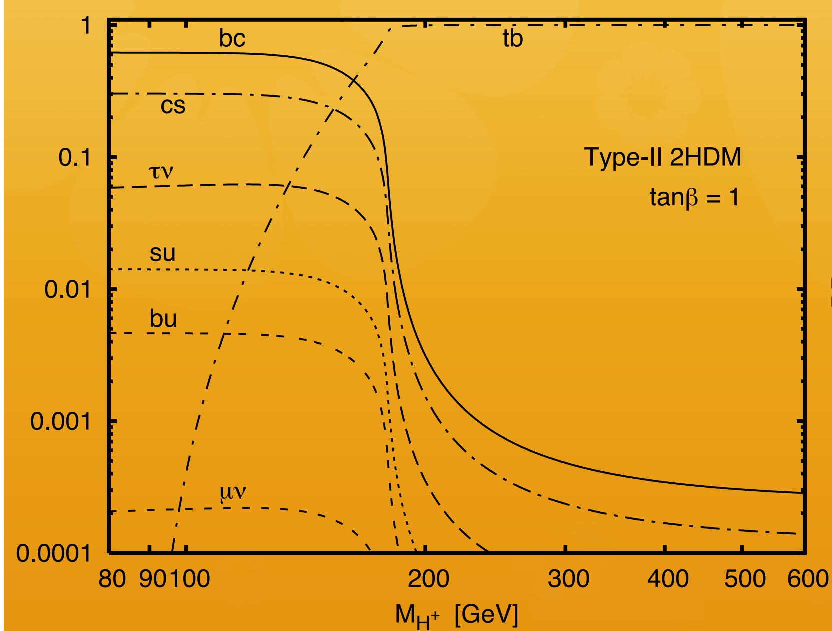
For top decays, one gets both lower and upper bounds for tan β in the Type II and Flipped, but only a lower bound in the Type I and Lepton-specific

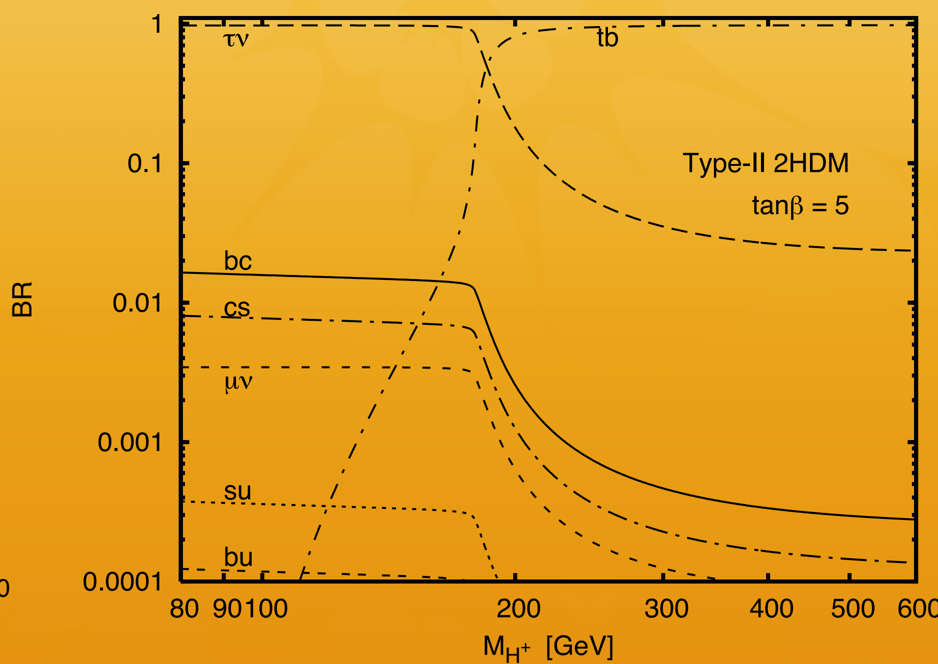
First, we consider the case in which the charged Higgs is lighter than the top quark. This is the most studied case, since significant bounds can already be obtained.

NOTE: In the Type II and flipped models, radiative B decays force the charged Higgs to be heavier than 350 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 $t \rightarrow H^+ b$, and then convert into a bound in the M – tan β plane. They use the MSSM, but abandoning this assumption makes quantitative, but not qualitative, differences.

TYPE II MODEL

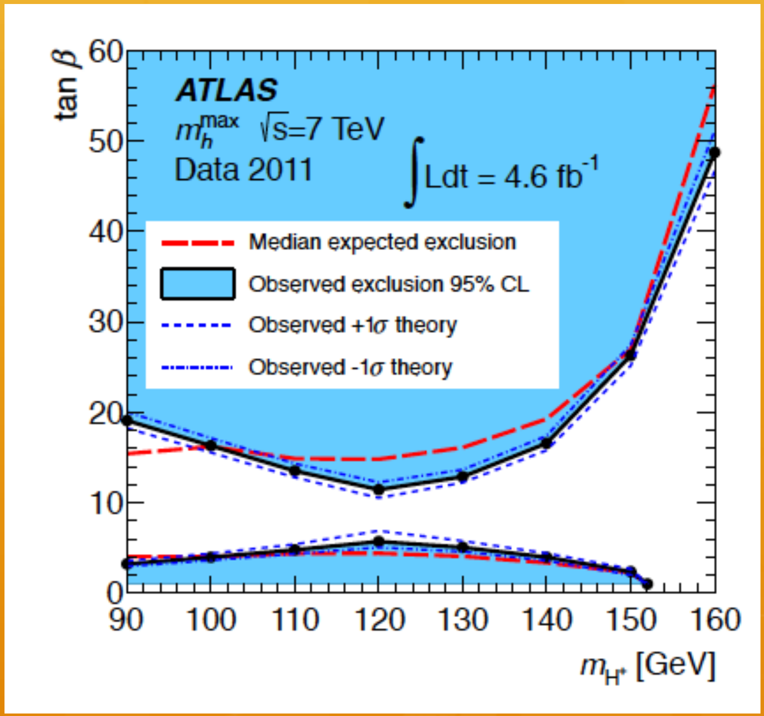




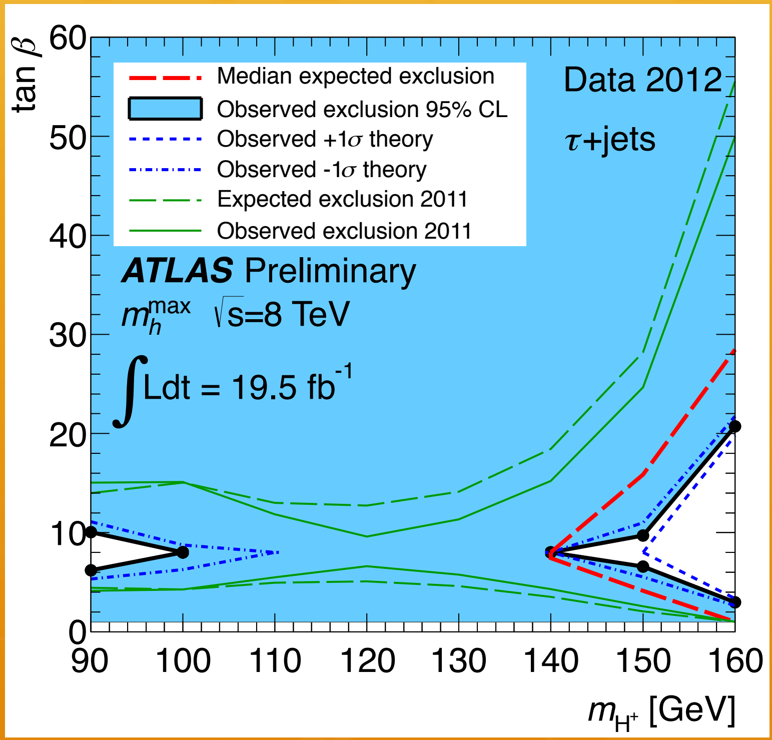
Note that except for tan β near 1, the dominant decay is into τ ν

This ignores $H^+ \to h\ W^+$, which can be substantial in some cases (more later)

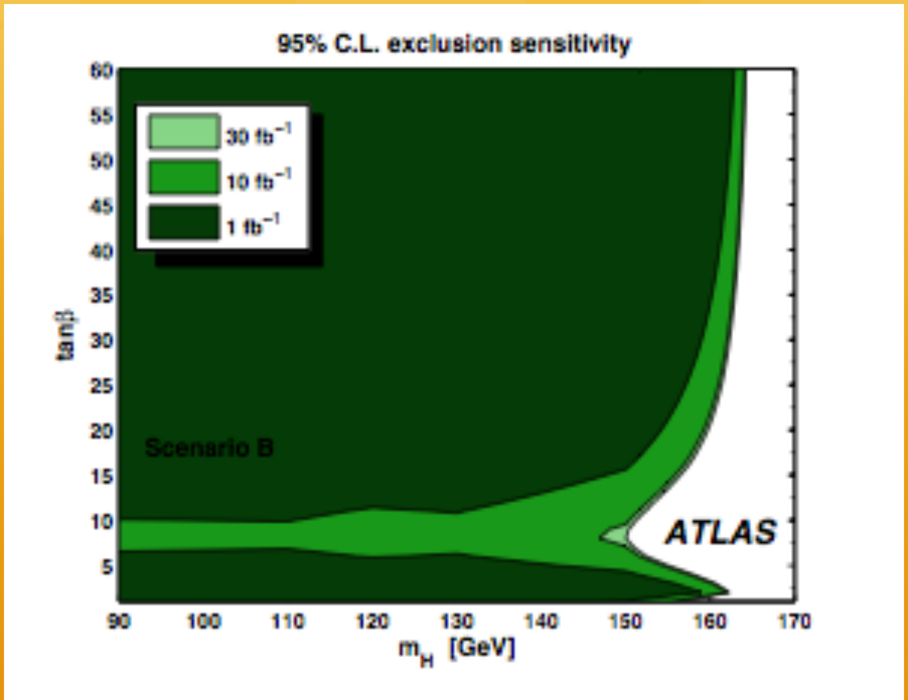
Results (from 2011 data)

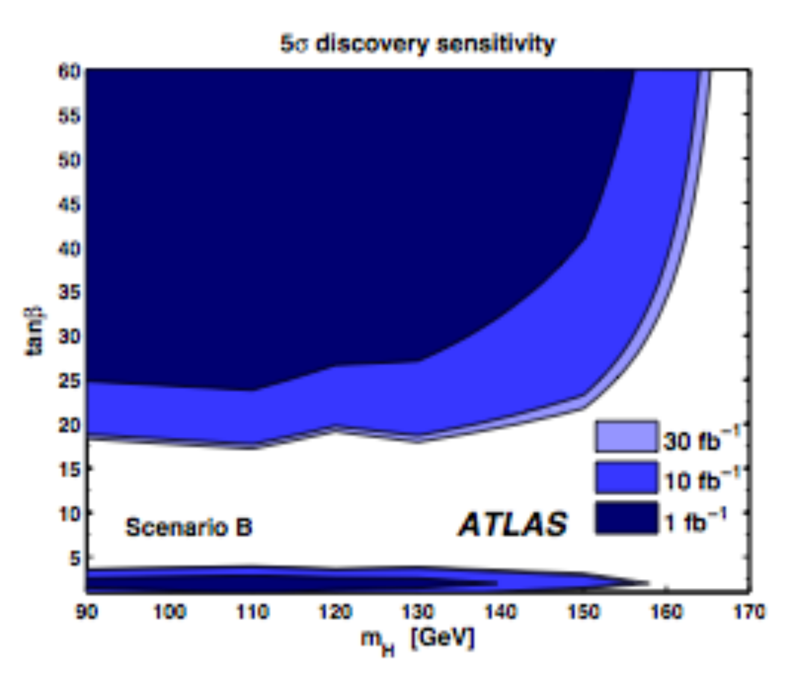


Results (from 2012 data – announced last week)



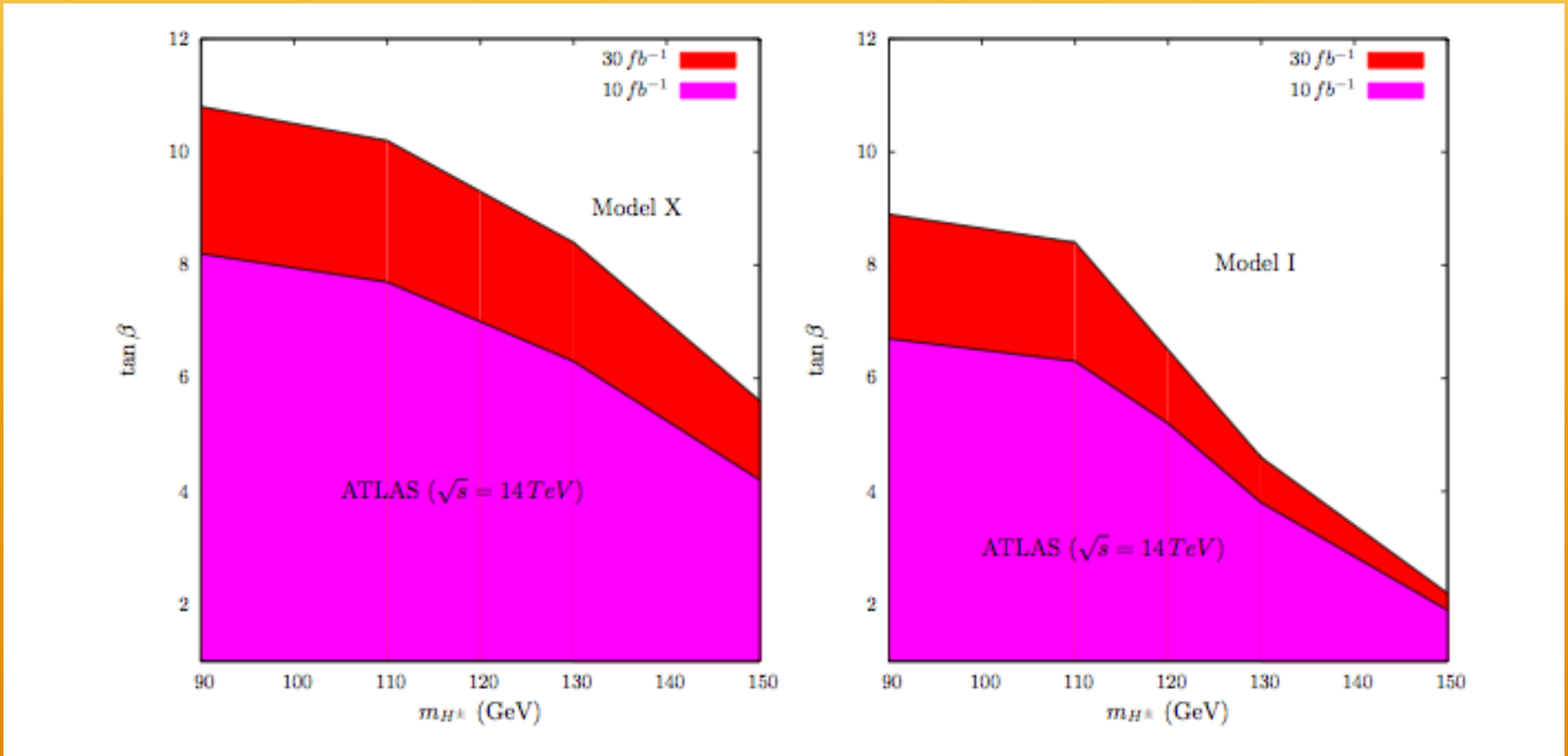
type II





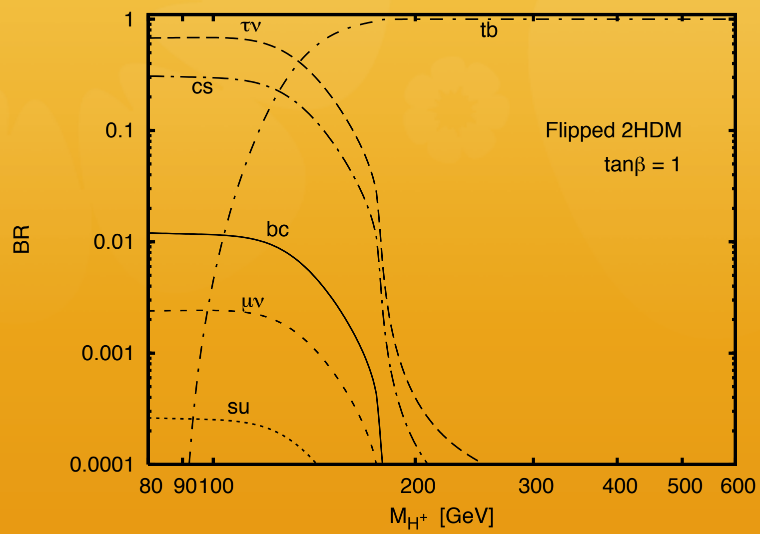
Thus, it will not be too long after start-up that the entire region up to 160 GeV could be excluded (or there could be evidence, of course).

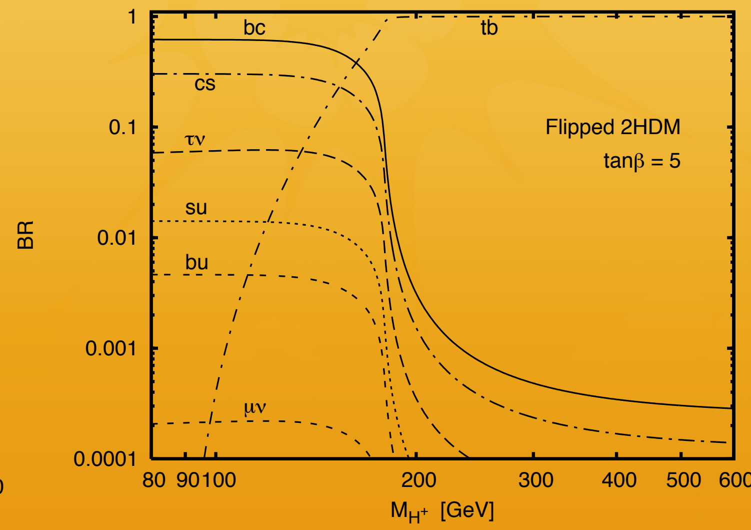
Aoki, Guedes, Kanemura, Moretti, Santos, Yagyu, 1104.3178



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.

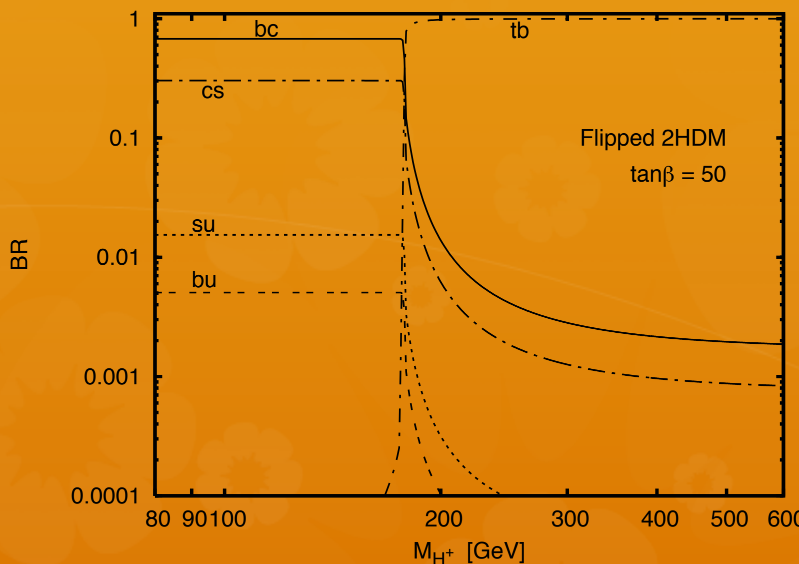
Flipped Model

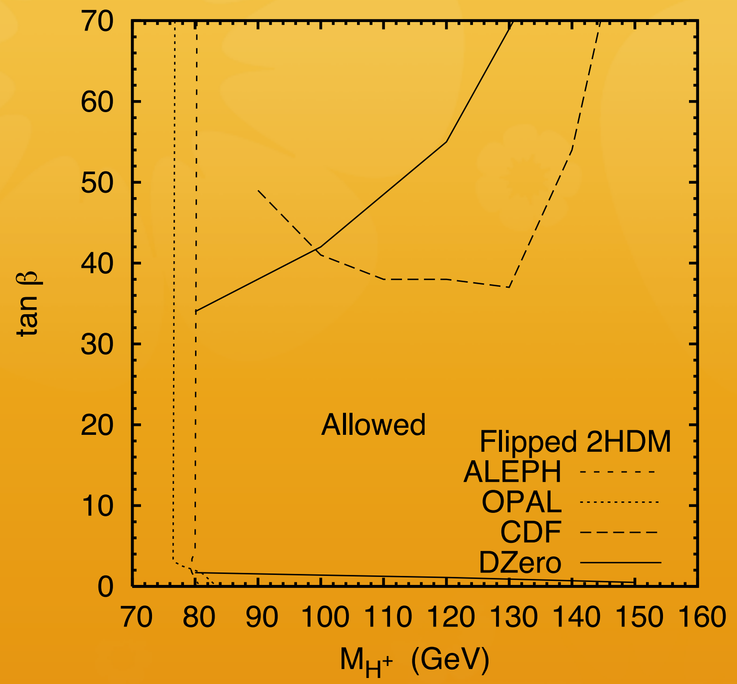


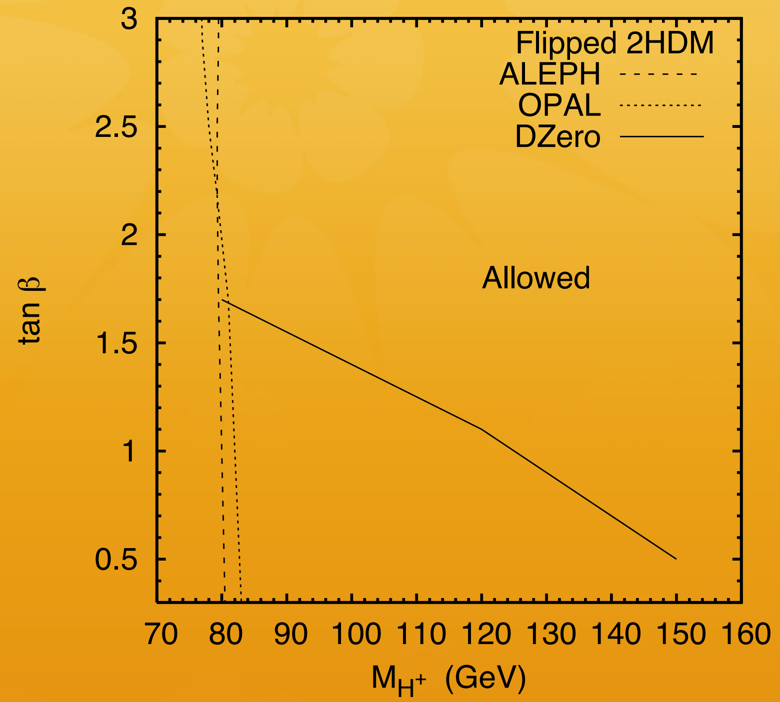


For most values of tan β , the dominant decay is into bc, and the subdominant decay is into cs.

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.

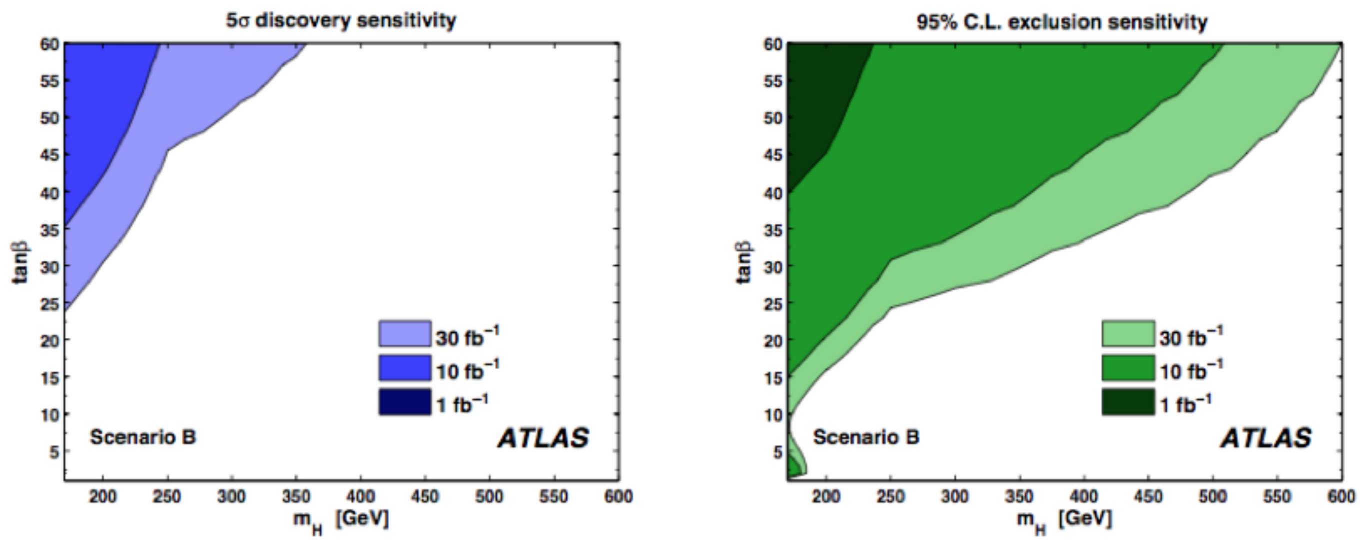
Now suppose the charged Higgs is heavier than the top quark.

For the moment, ignore decays of $H^+ \rightarrow h\ W^+$

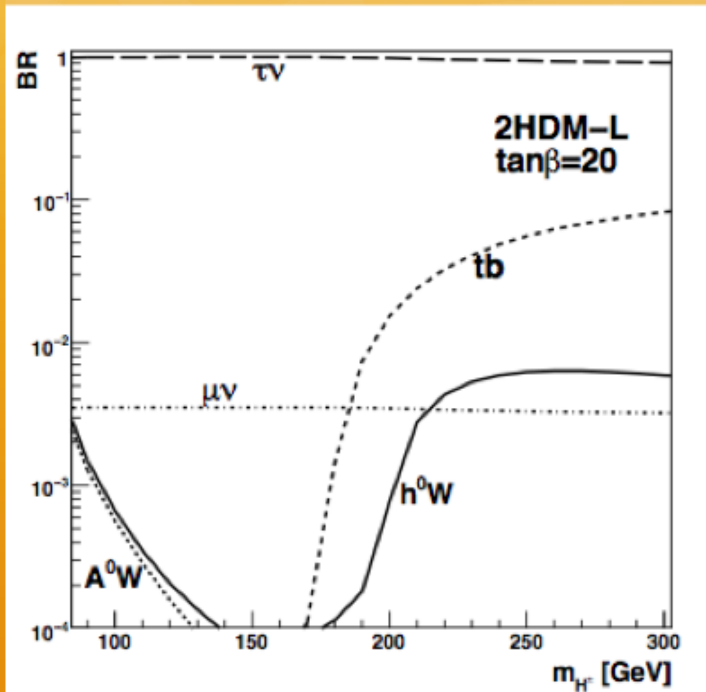
The dominant decay is into t b, which has large backgrounds, so most analyses focus on the $\tau\ \nu$ decay. In the type II model, this is a few percent for moderate tan β and 10% for large tan β .

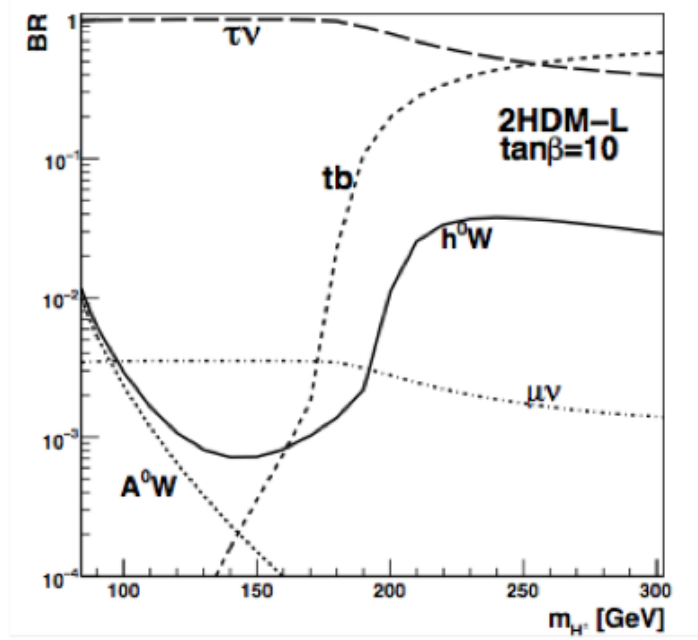
Type II model

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 $\tau\,\nu$



In the lepton-specific model, branch ing ratios look promising:





In the flipped model, there is no chance of detecting a charged Higgs with a mass above 200 GeV

Perhaps the best hope of detection is $H^+ \rightarrow H(125)\ W^+$

Studied in 2009 by Kanemura, Moretti, Mukai, Santos, Yagyu 0901.0204

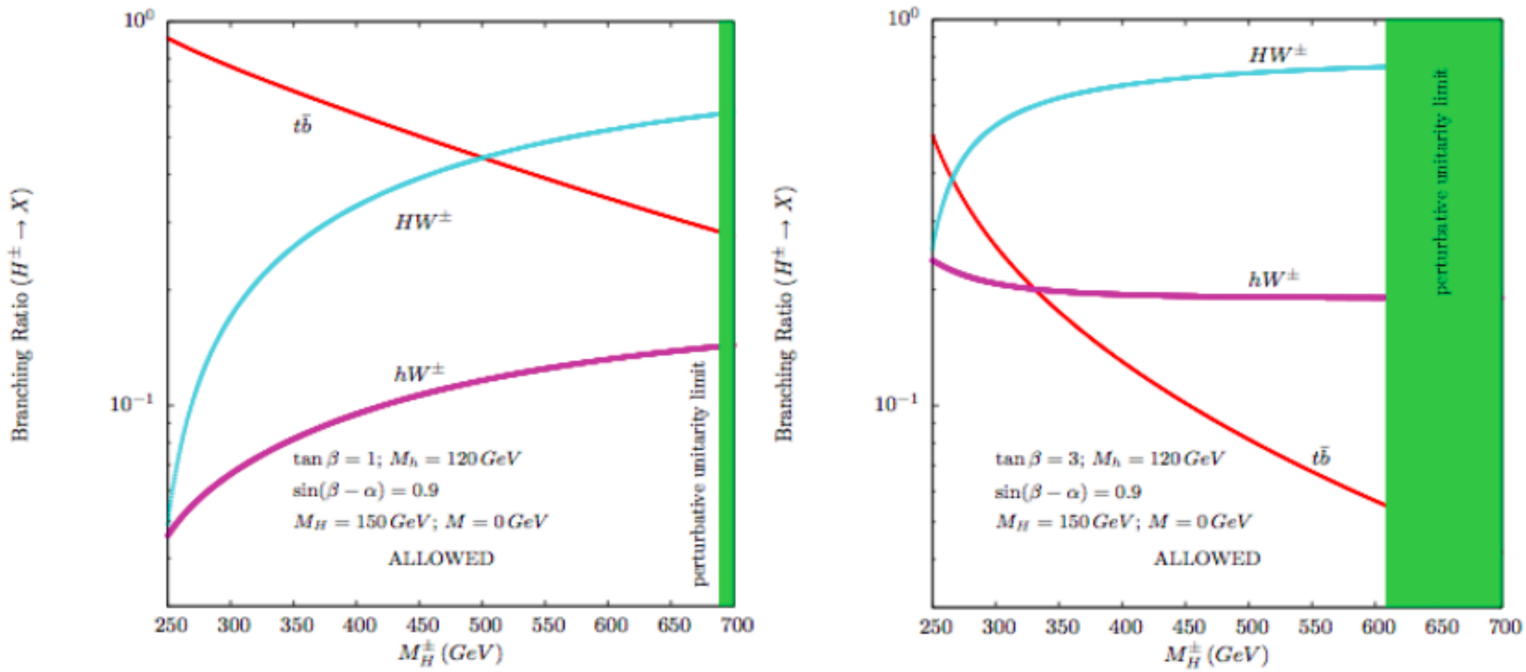
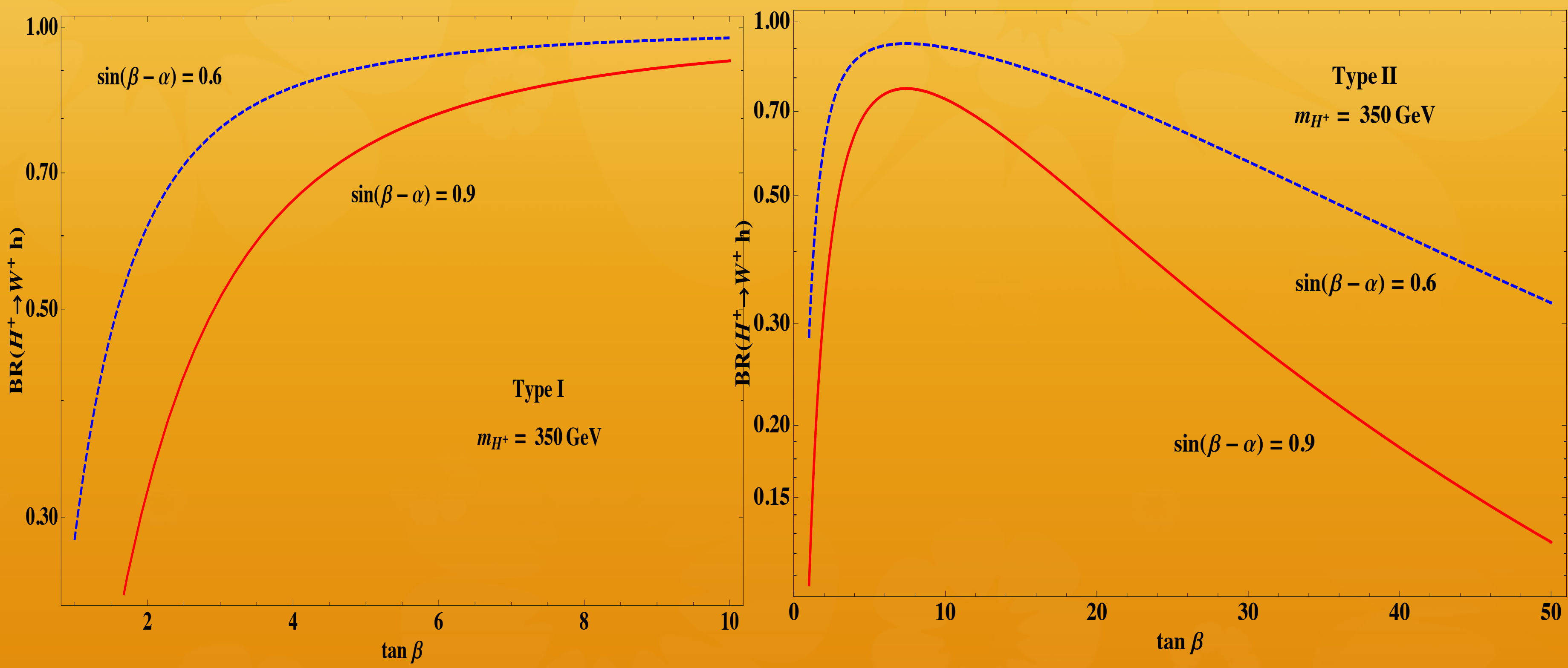


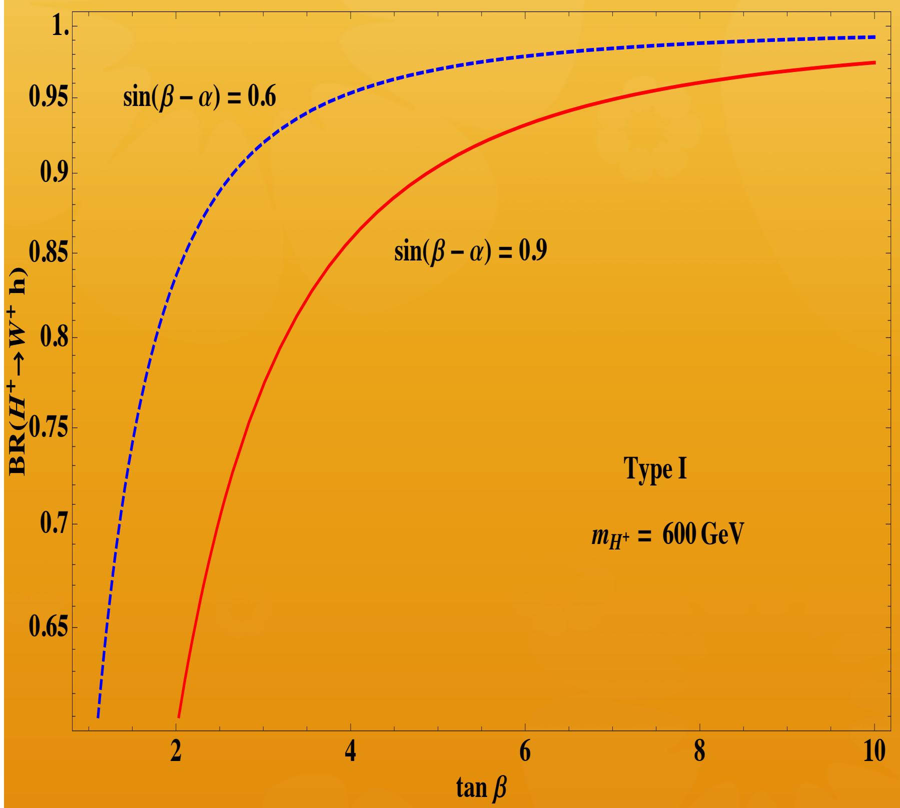
FIG. 7: $H^\pm$ decays for $M_h = 120\ GeV$, $M_H = 150\ GeV$, $M_A = M_{H^\pm}$ and $\sin(\beta - \alpha) = 0.9$. On the left is the plot for $\tan\beta = 1$ while on the right we set $\tan\beta = 3$. Perturbative unitarity limits are shown.

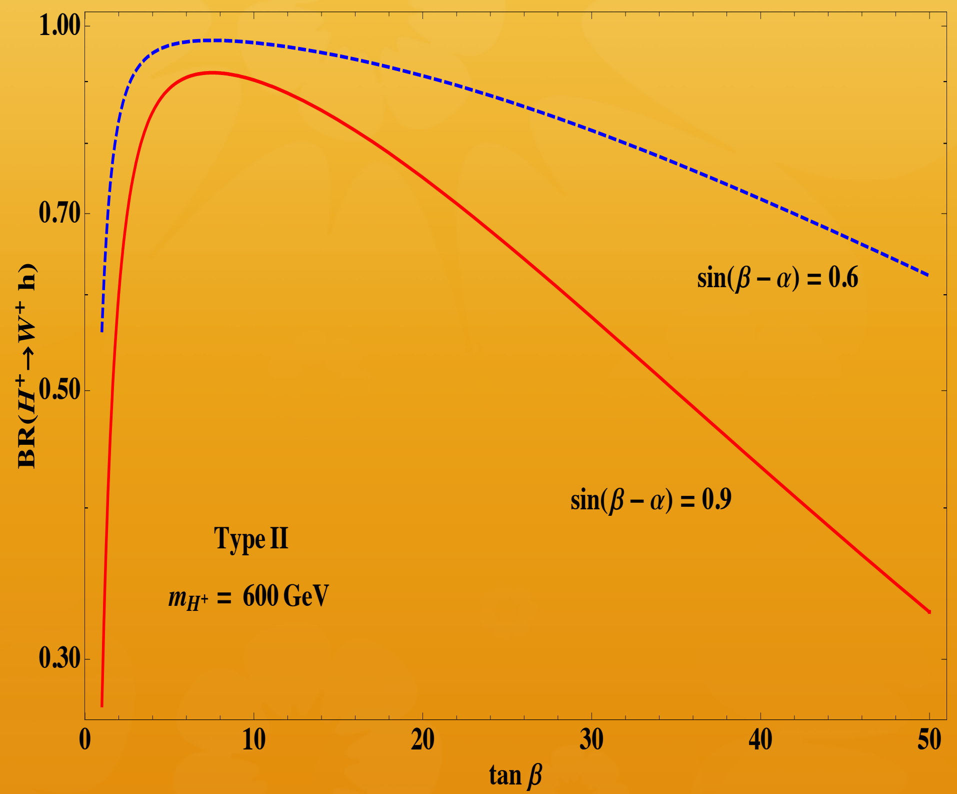
Chiang and Yagyu (1303.0168) studied $gb \rightarrow H^- t \rightarrow hW^- bW^+ \rightarrow l^+ l^- bbb$ + missing E_T at 8 TeV and found a signal rate in the type II model of 1-2 fb and a background of 0.05 fb . They assumed 100% b-jet identification efficiency.

For a similar signature in a type II model with CP violation, see Basso, Lipniacka, Mahmoudi, Moretti, Osland, Pruna, Purmohammedi, 1205.6569 with a follow-up in 1305.3219, and the inert model in Osland et al(1302.3713)

Is currently being studied by Rui Santos and MS, in collaboration with Pankaj Sharma and Shi-Chieh Hsu (ATLAS).



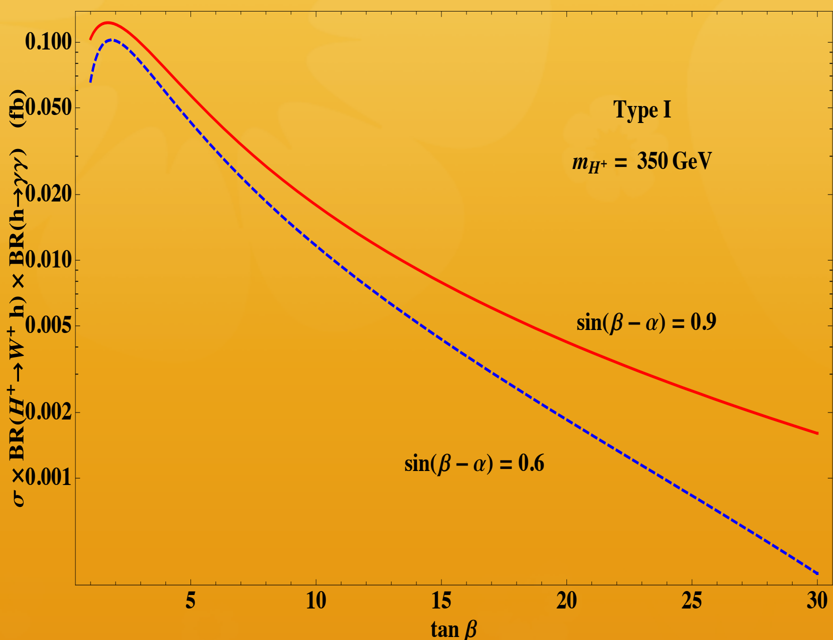


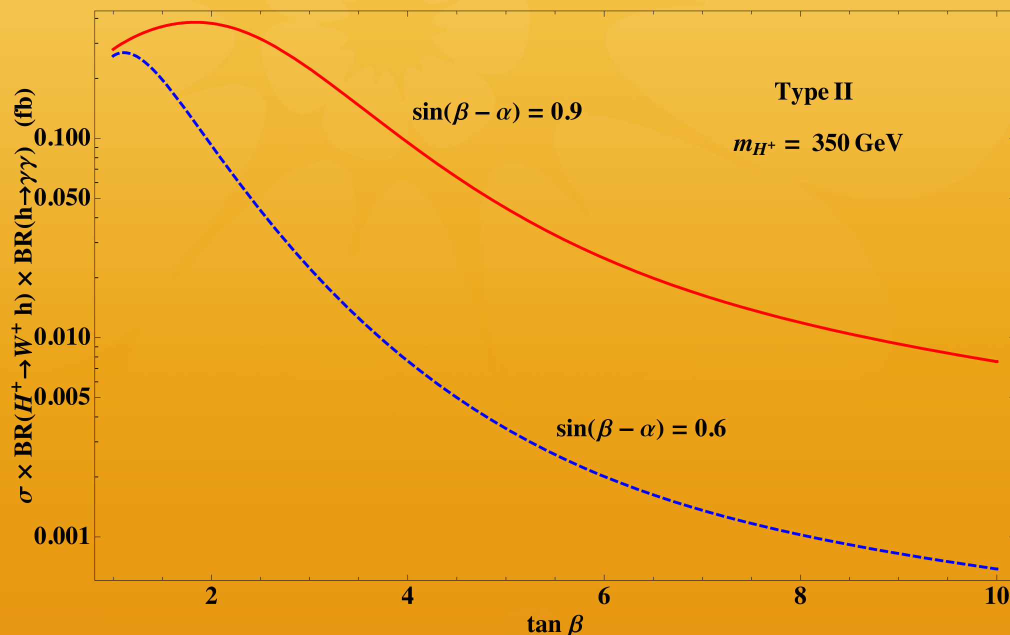


For a mass of 350 GeV, width is around 10 GeV; for a mass of 600 GeV, the width is tens of GeV.

Same pattern for mass of 900 GeV, but width becomes 100-200 GeV.

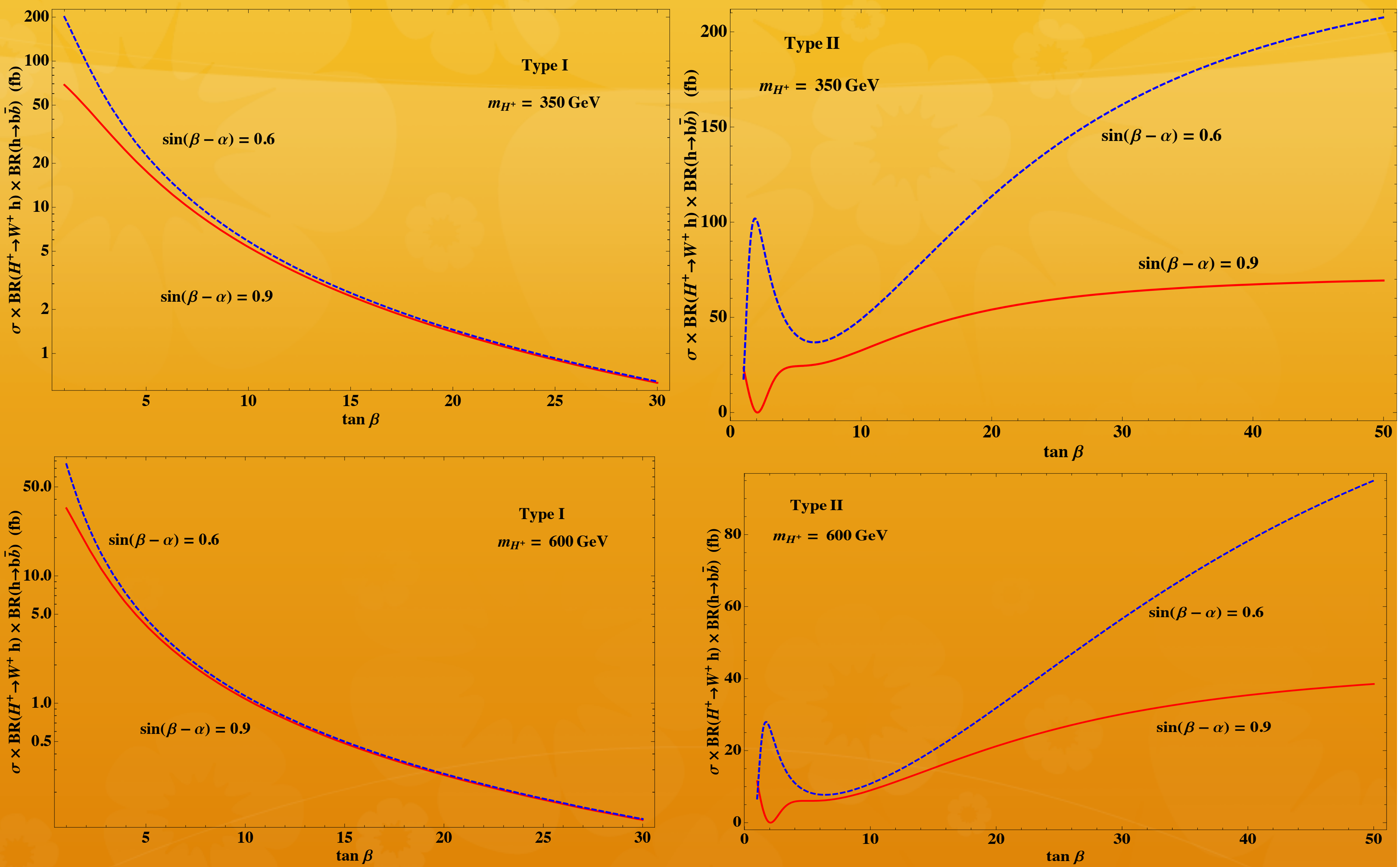
Really need production cross section times BR ($H^+ \rightarrow hW$) times BR($h \rightarrow xx$)





Very low rates. Similar for 600 GeV.

However, for large masses, $h \rightarrow bb$ might be more easily detectible since the b's are highly boosted.



A detailed analysis is currently under investigation.

Neutrinophilic Models

In 2001, Ma introduced the idea of neutrinophilic models. One Higgs couples to the SM fermions (as in the Type I model) and the other couples to right-handed neutrinos. A Z_2 symmetry in which the right-handed neutrinos and one Higgs doublet are odd can enforce this. Note that the Z_2 symmetry allows RH neutrino Majorana masses.

Later, Gabriel and Nandi, and Wang, Wang and Yang did not include Z_2 breaking and did not include Majorana masses. This required v_2 to be O(.1) eV and leads to a very light scalar (which could manifest as invisible Higgs decays.

If one breaks the Z_2 with a quadratic Higgs m_{12} term, then one needs m_{12} to be O(0.1) MeV. It can be even higher, O(10) MeV, with RH Majorana neutrino masses. Haba and Horita showed that these models do not have a vacuum stability problem.

Finally, Davidson and Logan promoted the Z_2 to a global U(1), which automatically eliminates Majorana masses. This is broken **explicitly** by an m_{12} term of O(1) MeV. It yields a vev of O(1) eV and no very light scalar (which helps with BBN).

The charged Higgs phenomenology in these models is quite unusual….

The charged Higgs phenomenology was studied in the Dirac case by Davidson and Logan (0906.3335) and in the Majorana case by Haba and Tsumura (1105.1409)

The most interesting decay of the charged Higgs is

$$H^+ \to \ell^+ \nu$$

Note that the charged lepton is left-handed, unlike the usual leptonic decay

$$\Gamma = \frac{M_{H^+}}{8\pi v^2}\langle m_\nu^2\rangle_\ell \qquad \langle m_\nu^2\rangle_\ell = \sum_i m_{\nu_i}^2 |U_{\ell i}|^2$$

Normal hierarchy: $\mu\nu$, $\tau\nu$ dominate
Inverse hierarchy: eν is 50%, $\mu\nu$ 30%, $\tau\nu$ 20% (assuming lightest neutrino is very light).

Thus, observation of the charged Higgs will quickly determine the hierarchy.

Production is electroweak pair production. Davidson and Logan find that a charged Higgs up to 300 GeV can be discovered at 5 sigma with 30-300/fb, depending on the spectrum and lightest neutrino mass

Last month, Akeroyd, Moretti and Sugiyama 1308.0230 updated all of these results, including the θ_{13} discovery, and found that measuring the charged Higgs decays would yield information of the sign of Δm^2_{31} and the octant ambiguity of θ_{23} even earlier than the neutrino oscillation experiments.

In the case with Majorana RH neutrinos, Haba, Tsumura 1105.1409 considered charged Higgs decays into Majorana neutrinos and looked at the possibility of observable tracks from long-lived charged Higgs and secondary vertices.

Dark charged Higgs decays

HS Lee, MS
1303.6653

Assume there is an extra U(1), under which all SM fields are singlets.
The gauge sector Lagrangian is

$$-\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta_W}B_{\mu\nu}Z'^{\mu\nu} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu}$$

If there is only one Higgs doublet and a Higgs singlet to give mass to the Z', then Z' couples to the electromagnetic current, and is called a dark photon.
If there are two doublets, then there will be Z-Z' mixing, and the coupling is to both the electromagnetic and weak current, and it is called a dark Z.

In either event, the mass range that has been of enormous interest recently is O(1) GeV, and the decay is mostly into lepton pairs.

We considered the dark Z and the case in which the 125 GeV state is the heavier of the two neutral scalars. The case in which the 125 GeV is the lighter was discussed by Davoudiasl et al 1304.4935.

We found that for all allowed values of the lighter Higgs mass, the decay $H^+ \rightarrow h W^+$ dominates for the entire charged Higgs mass range. The h will then almost always decay into Z' Z', each of which decays into lepton pairs (roughly 1/3 of the time). Since the Z' is light, these will be heavily boosted, and will give a "lepton jet". Given that the H^+ may be pair produced, this will give two W's and four lepton jets.

ATLAS has looked for prompt "lepton jets" at 7 TeV, and got a bound on events with 2 or more lepton jets of 20 fb. This is beginning to put constraints on the parameter space.

Very recently, Chang, Ma, Yuan 1308.6071 studied a similar model with a dark photon, rather than a dark Z.

What about $H^+ \to W^+ Z'$?

For charged Higgs masses between 90 and 180 GeV, it is the only two body decay other than $\tau\nu$, which is suppressed by m_τ^2 and by $1/\tan^2\beta$.

Signature is $W + (e^+e^-, \mu^+\mu^-)$.

Branching ratio and LHC detection currently under investigation with Raymundo Ramos.

SUMMARY

There are many, many studies of charged Higgs bosons in 2HDMs. In the next LHC run, the mass range below 160 GeV will be excluded in Type II, and excluded for tan β below 10-15 in type I (unless it is discovered). Heavier masses are much more challenging.

However, there are several possibilities that have not yet been explored by experimentalists

1. $H^+ \rightarrow h\,W$ is only now being looked at by ATLAS/CMS

2. In neutrinophilic models, leptonic decays dominate, and for the inverse hierarchy, the leading decay mode is into $e + \nu$

3. One needs to keep in mind the possibility of decays into dark photons or dark Z's, which would give W + Z' $\rightarrow$ W + lepton jet.