‘Charged 2008’, Uppsala, 16 Sep 2008

NON MINIMAL MODELS WITH CHARGED HIGGS BOSONS

Stefano Moretti (NExT Institute)

Outline

Introduction

- SUSY beyond the Minimal Supersymmetric Standard Model:

1. MSSM+Singlets: Next-to-MSSM (NMSSM, see Arhrib's talk)
2. MSSM+Triplets: MSSM+1CHT

- Non-SUSY models (mainly updates on Katri's talk in 2006):

1. General 2HDMs
2. Fermiophobic Higgses
3. Models with Triplets

Introduction

EWSB dynamics in SM unsatisfactory.

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

Experiment: no Higgs evidence so far

Hence, it is quite appropriate to explore implications of more complicated Higgs models !

Two major constraints to go beyond the SM:

1. The experimental fact that

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

2. Limits on the existence of FCNCs

NB: 1&2 are not a problem in the SM and for any additional singlets !

Electroweak ρ parameter is experimentally close to 1

→ constraints on Higgs representations

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

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

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

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

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

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

Absence of (tree-level) FCNCs

➡ constraints on Higgs couplings

In SM FCNC automatically absent as same operation diagonalising the mass matrix automatically diagonalises the Higgs-fermion couplings.

Again, there are again two ways fwd:

1. Make Higgs masses large (1 TeV or more) so that tree-level FCNCs mediated by Higgs are suppressed to comply with experimental data.

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.

   (MSSM is an example: Y=-1(+1) doublet couples to down(up)-type fermions, as required by SUSY.)

From MSSM to the NMSSM

The Higgs sector of the MSSM contains a soft SUSY breaking term $\sim \mu H_u H_d$ - μ exists in the Superpotential before EWSB so natural value would be either 0 or M_P - both phenomenologically unfeasible

This 'μ-problem' is elegantly addressed in the Next-to-Minimal Supersymmetric Standard Model (NMSSM), described by

$$W = \hat{Q}\hat{H}_u \mathbf{h_u} \hat{U}^C + \hat{H}_d \hat{Q} \mathbf{h_d} \hat{D}^C + \hat{H}_d \hat{L} \mathbf{h_e} \hat{E}^C + \lambda \hat{S}(\hat{H}_u \hat{H}_d) + \frac{1}{3}\kappa \hat{S}^3$$

(Do not consider here nMSSM, MNSSM – $\kappa = 0$ and linear terms are present instead.)

A new singlet Higgs field S is introduced and $B\mu H_u H_d$ gets replaced by an interaction term $\lambda A_\lambda S(H_u H_d)$, so that EWSB yields a VEV to S naturally of the order of M_{SUSY} or M_W along with the other two Higgs fields; generating an 'effective μ-parameter':

$$\boxed{\mu_{\mathrm{eff}} = \lambda < S >}$$

$$-\mathcal{L}_{\text{soft}} \supset m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + \left(\lambda A_\lambda S H_u H_d + \frac{1}{3} \kappa A_\kappa S^3 + \text{h.c.} \right) ,$$

where, like A_λ, A_κ is a dimensionful coefficient of order $\sim M_{\text{SUSY}}$.

After employing the minimization conditions for the Higgs potential and demanding the known value of the Z mass, the parameters specifying the Higgs sectors in the $\boxed{\text{NMSSM}}$ are as follows.

$$\boxed{\lambda, \quad \kappa, \quad A_\lambda, \quad A_\kappa, \quad \mu = \mu_{\text{eff}}, \quad \tan\beta\ .}$$

The upper limit on the lightest Higgs mass is now:

$$M_{H_1}^2 \leq M_Z^2 \cos^2(2\beta) + \frac{2\lambda^2 M_W^2}{g^2} \sin^2(2\beta) + \epsilon,$$

The NMSSM relaxes the LEP bound on M_{H_1}. Due to the second term in red above.

Effect pronounced at moderate $\tan\beta$

$$M_{H^+}^2 = M_A^2 + M_W^2\left(1 - \frac{2\lambda^2}{g^2}\right)$$

A limit on $M_{H^\pm}$ is possible **only** a limit on λ is possible.

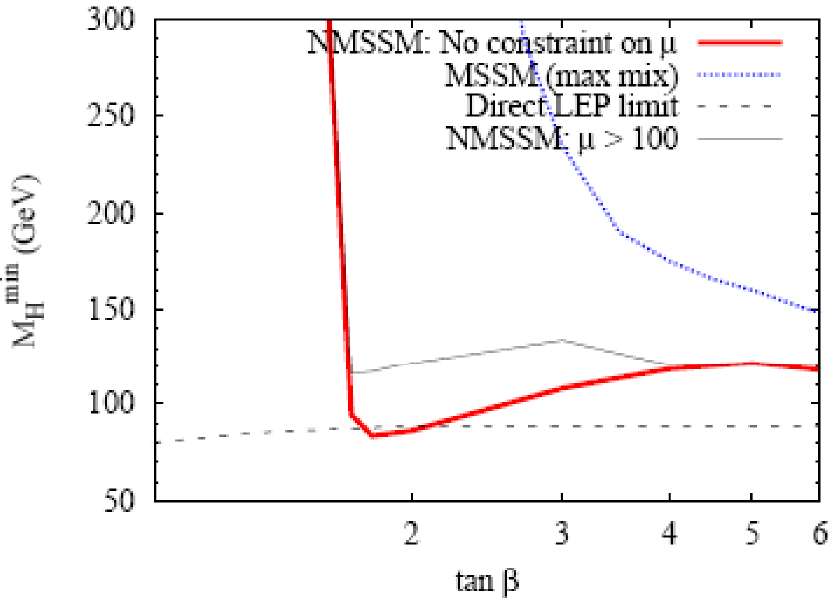
Such a limit obtained by demanding that all couplings remain perturbative upto some high scale.

Apart from λ, κ and x, one also has the soft SUSY breaking parameters: A_λ, A_κ.

We obtain a limit by varying all these parameters of the NMSSM potential, imposing LEP constraints.

Direct LEP bound is also shown.

For $\tan\beta \leq 6(4)$ $M_{H^+} > 150(175)$ GeV for MSSM. In NMSSM a $H^\pm$ with mass less than 120 GeV allowed over this range.



Godbole/Roy, 2005

Conventions: $\mu = \lambda x$ $\quad x = \langle S \rangle$

1. If ($M_{H^+} \simeq 120$ GeV) one has a dominantly singlet H_1 with ($M_{H_1} \simeq 50$ GeV). Thus this H_1 will evade LEP searches and will be difficult to produce at LHC as well. There is a light (50 GeV) pseudoscalar A_0 with significant doublet component. Such $H^\pm$ can be searched through $H^+ \to \tau^+ \nu$.

2. ($M_{H^\pm} > 130$ GeV), (in this $\tan\beta$ range), decays dominantly via the $H^+ \to W^+ A_1^0$. This is a good channel for the $H^\pm$ as well as A_1^0 search.

$\tan\beta$	M_{H^+} (GeV)	M_{A_1} (GeV)	B_{A_1} (%)	λ, κ	$x = v_s/\sqrt{2}, A_\lambda, A_\kappa$ (GeV)
2	147	38	94	.45,-.69	224,-8,2
3	159	65	83	.33,-.70	305,40,38
4	145	48	89	.28,-.70	563,170,85
5	150	10	91	.26,-.54	503,109,38

Interesting new phenomenology for a light charged Higgs boson at the LHC

MSSM+1CHT

The Higgs triplet is described in terms of a 2×2 matrix representation; ξ^0 is the complex neutral field, and ξ_1^-, ξ_2^+ denote the charged scalars.

$$(1) \qquad \Phi_1 = \begin{pmatrix} {\phi_1}^0 \\ {\phi_1}^- \end{pmatrix} \ , \quad \Phi_2 = \begin{pmatrix} {\phi_2}^+ \\ {\phi_2}^0 \end{pmatrix}$$

$$(2) \qquad \sum = \begin{pmatrix} \sqrt{\frac{1}{2}}\xi^0 & -\xi_2^+ \\ \xi_1^- & -\sqrt{\frac{1}{2}}\xi^0 \end{pmatrix} \ .$$

- For the MSSM we have at tree/level

$$(4) \qquad m_{H^\pm}^2 = m_W^2 + m_W^2$$

- While in this model we have

$$(5) \qquad Trm_{H_i^\pm}^2 > m_W^2 + Trm_{A_k}^2$$

- Thus, we could have one charged Higgs lighter than the W boson.

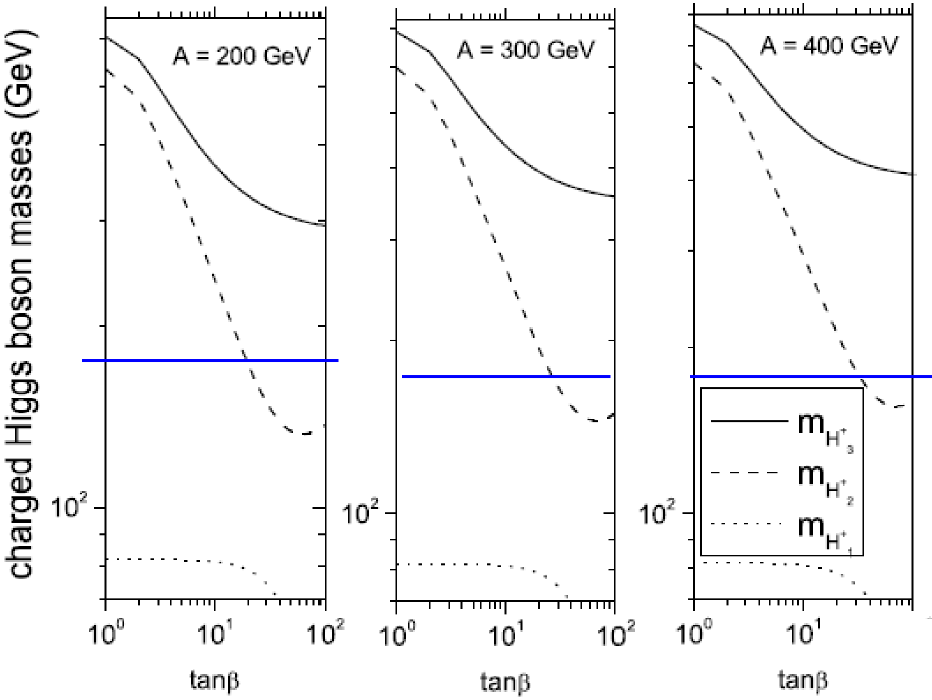
MSSM+1CHT Higgs Sector

A total of 14 d.o.f to start with, minus 3 longitudinal modes for W's & Z leaves 11 d.o.f which corresponds to:

- 3 CP-even neutral Higgs states
- 2 CP-odd neutral Higgs states
- 6 C.C. charged Higgs states (3 masses)

- The parameters of the Higgs sector include:
  -gauge: $r = v_T/v_D$ and $\tan\beta = v_2/v_1$
  - superpoptential: $\lambda,\ \mu_D,\ \mu_T$
  - soft: $A,\ B_D,\ B_T$
- In our numerical analysis we shall fix:
  $r = 0.012,\ 1.5 < \tan\beta < 70$, and
  $\lambda = 0.1, 0.5, 1.$,
- Then we shall define several scenarios according to:
  Scenario A: $B_D = \mu_D = 0$, $B_T = -A$, $\mu_T = 100$ GeV,
  Scenario B: $B_T = \mu_T = 0$, $B_D = -A$, $\mu_D = 100$ GeV,

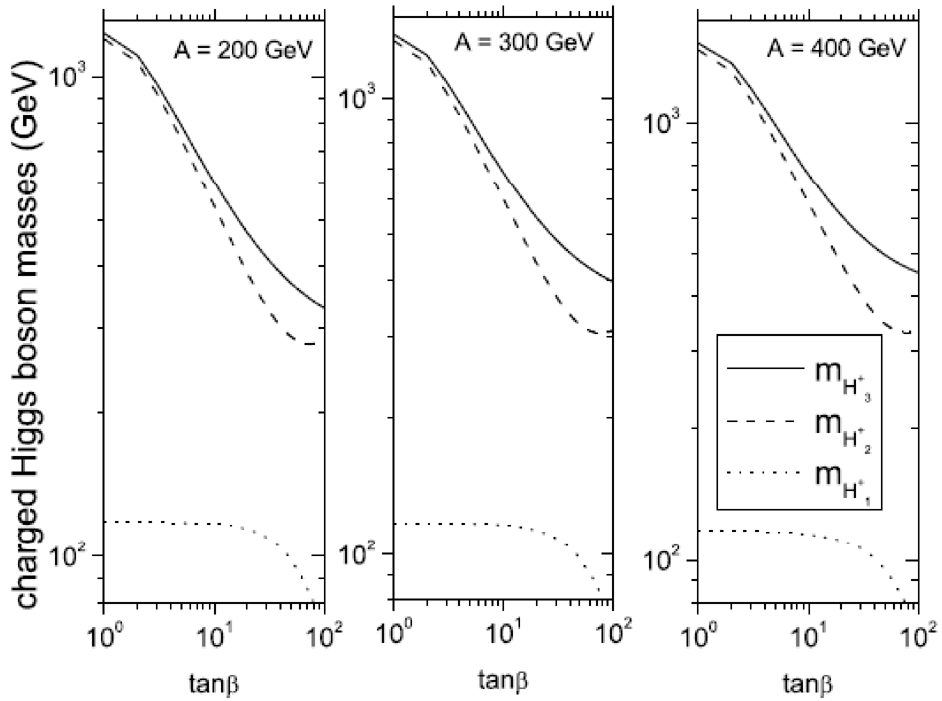
Diaz/Hernandez/Moretti/Rosado, 2007



Scenario A, λ=0.1

Two Higgs states below top mass

Scenario A, λ=0.5



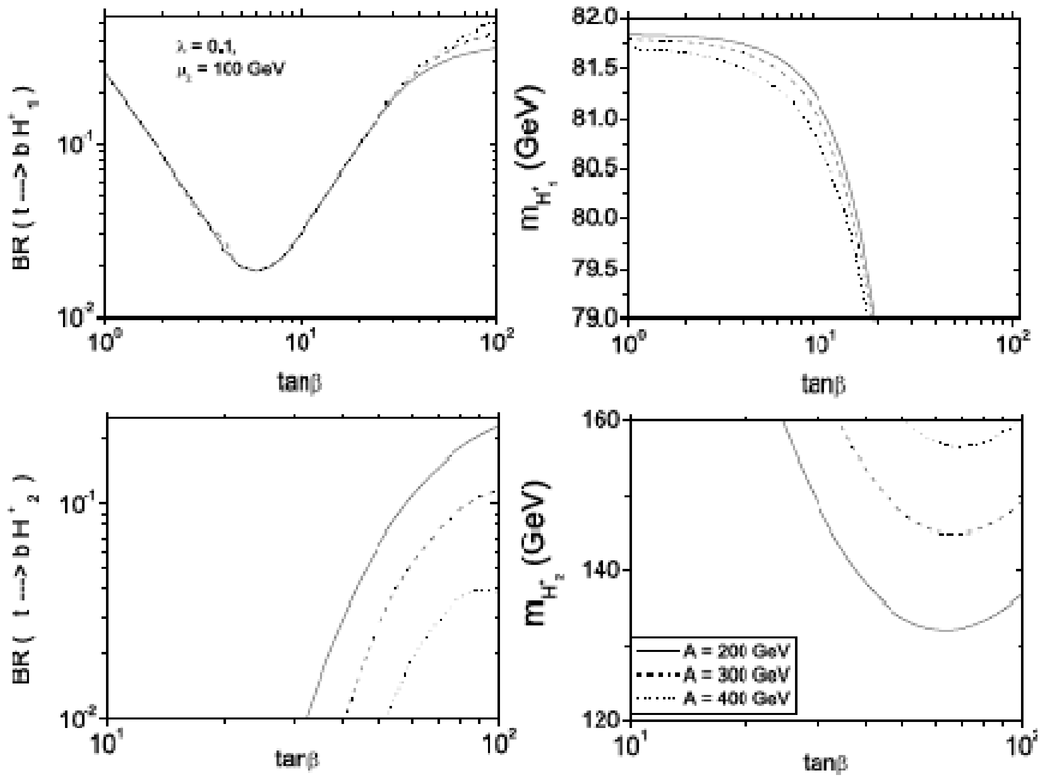
Top decay $t \to b + H^+$

As Tevatron has obtained bound on charged Higgs using top decays, we like to evaluate such decay within the MSSM+1CHT.
The decay width of these modes, takes the following form:

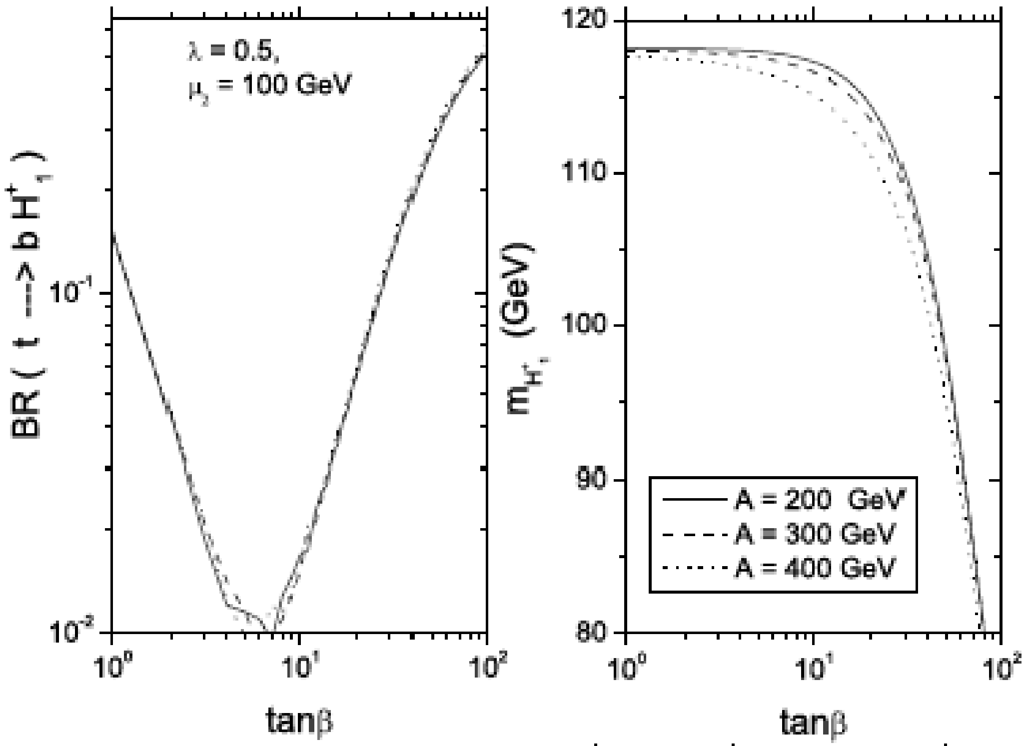
$$\begin{aligned} \Gamma(t \to H_i^+ b) &= \frac{g^2}{64\pi m_W^2}|V_{tb}|^2 m_t^3 \lambda^{1/2}(1, q_{H_i^+}, q_b) \\ & \Big[(1 - q_{H_i^+} + q_b)\Big(\frac{U_{1,i+1}^2}{s_\beta^2} + q_b \frac{U_{2,i+1}^2}{c_\beta^2}\Big) \\ & -4q_b \frac{U_{1,i+1}U_{2,i+1}}{s_\beta c_\beta}\Big] \end{aligned} \tag{6}$$

Possible benchmarks (Diaz-Cruz/Hernandez-Sachez/Moretti/Rosado, 2007)

B1. The point mu2=100 GeV, lambda=0.1, A=200 GeV for say tan(beta)=30 or 50 as represented in Fig. 1 (left panel). This is an interesting situation, in which one has both MH+/-(1) and both MH+/-(2) below mt, so that one could have two charged Higgs decays of a top quark that may be accessible (see Fig. below) at Tevatron and/or LHC.



B2. The point mu2=100 GeV, lambda=0.5, A=200 GeV for say tan(beta)=50, see Fig. below. Here, there seems to be scope to access H+/-(1) in top decays as well as H+/-(2) in either tb or W+/-A0(1)/H0(1) or both, see row 3 of Tab. below, at least for the LHC.



Assumes 100 inverse fb

λ	$(A, \tan\beta)$	$m_{H_i^+}$ in GeV	$\sigma(pp \to H_2^+ tb)$ in pb	Relevant BR's	Nr. Events
0.5	(200,50)	(98,290,370)	8.7×10^{-1}	$\mathrm{BR}\left(H_2^+ \to \tau^+\nu_\tau\right) \approx 8.2 \times 10^{-2}$	7134
				$\mathrm{BR}\left(H_2^+ \to tb\right) \approx 8.4 \times 10^{-1}$	73080
				$\mathrm{BR}\left(H_2^+ \to W^+A_1^0\right) \approx 2.4 \times 10^{-2}$	2088
				$\mathrm{BR}\left(H_2^+ \to W^+H_1^0\right) \approx 4.8 \times 10^{-2}$	4176

General 2HDM

The Standard Model with two Higgs doublets ϕ_1 and ϕ_2 ➡ ρ=1.

The simplest extension of the SM with charged Higgs bosons.

As in the MSSM five physical Higgs bosons: h, H, A, $H^{\pm}$

The scalar potential

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

Hermiticity: λ_i are real $\langle\phi_1\rangle = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \langle\phi_2\rangle = \begin{pmatrix} 0 \\ v_2 e^{i\xi} \end{pmatrix}, \quad \tan\beta = \frac{v_2}{v_1}$

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

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

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

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.

Barger/Hewett/Phillips, 1990

TABLE I. Summary of which doublet, ϕ_1 or ϕ_2, gives mass to each type of fermion and the values of the coefficients A_f in the charged Higgs coupling to fermions in Eq. (1.1) for models I–IV.

Models	I		II		III		IV	
	VEV	A_f	VEV	A_f	VEV	A_f	VEV	A_f
u	2	$\cot\beta$	2	$\cot\beta$	2	$\cot\beta$	2	$\cot\beta$
d	2	$-\cot\beta$	1	$\tan\beta$	1	$\tan\beta$	2	$-\cot\beta$
$\begin{pmatrix} \nu \\ l \end{pmatrix}$	2	$-\cot\beta$	1	$\tan\beta$	2	$-\cot\beta$	1	$\tan\beta$

$$L = \frac{g}{2\sqrt{2}m_W} H^{\pm}[V_{ij} m_{u_i} A_u \bar{u}_i (1-\gamma_5) d_j + V_{ij} m_{d_j} A_d \bar{u}_i (1+\gamma_5) d_j + m_l A_l \bar{\nu} (1+\gamma_5) l] + h.c.$$

NB: Types III, IV not discussed in HHG, poor attention over the years except that type IV advocated by Aoki/Kanemura/Seto (see Shinya’s talk)

Barger/Hewett/Phillips, 1990

The branching ratios can be very different from the SM.

tan β is important for phenomenology!

For processes which depend only on quark sector, models I and IV are similar, as well as models II and III.

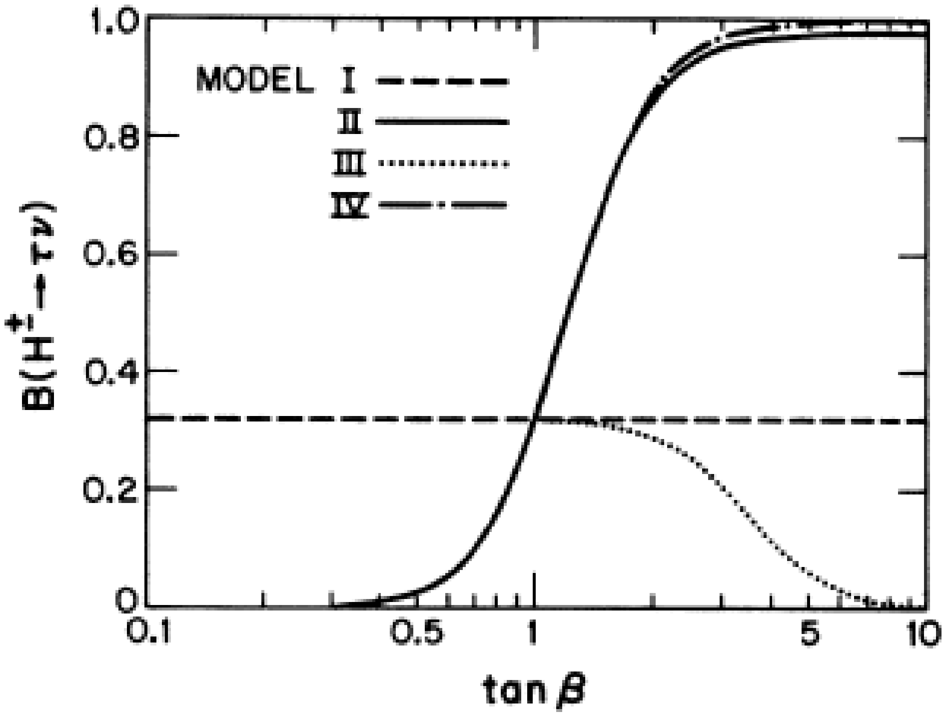


FIG. 1. The branching fraction $B(H^{\pm} \to \tau\nu)$ vs $\tan\beta$ in models I–IV. We take $m_c = 1.5$ GeV, $m_s = 0.15$ GeV, $m_\tau = 1.784$ GeV, $|V_{cs}| = 1.0$, and $m_{H^{\pm}} < m_t - m_b$.

How to distinguish 2HDM type II from MSSM using charged Higgs sector ?

1. Mass relations enforced by SUSY and experimental limits on the MSSM (Mh<<MH~MA~MH+) need not be true in the 2HDM

2a. Couplings H+/- H0/h0 W+/- enabling H+ -> W+H0/h0:

$$g_{H^+W^-h^0} = \frac{g}{2}\cos\left(\beta-\alpha\right), \; g_{H^+W^-H^0} = \frac{g}{2}\sin\left(\beta-\alpha\right)$$

where α is the neutral Higgs mixing angle :

$$h^0 = \sqrt{2}\left[-\left(\mathrm{Re}\,\phi_1^0 - v_1\right)\sin\alpha + \left(\mathrm{Re}\,\phi_2^0 - v_2\right)\cos\alpha\right]$$

α is derived in MSSM whilst is free parameter in the 2HDM !

2b. Couplings H+/- A0 W+/- enabling H+ -> W+A0 is pure gauge

2c. Other charged Higgs decay modes are MSSM-like:

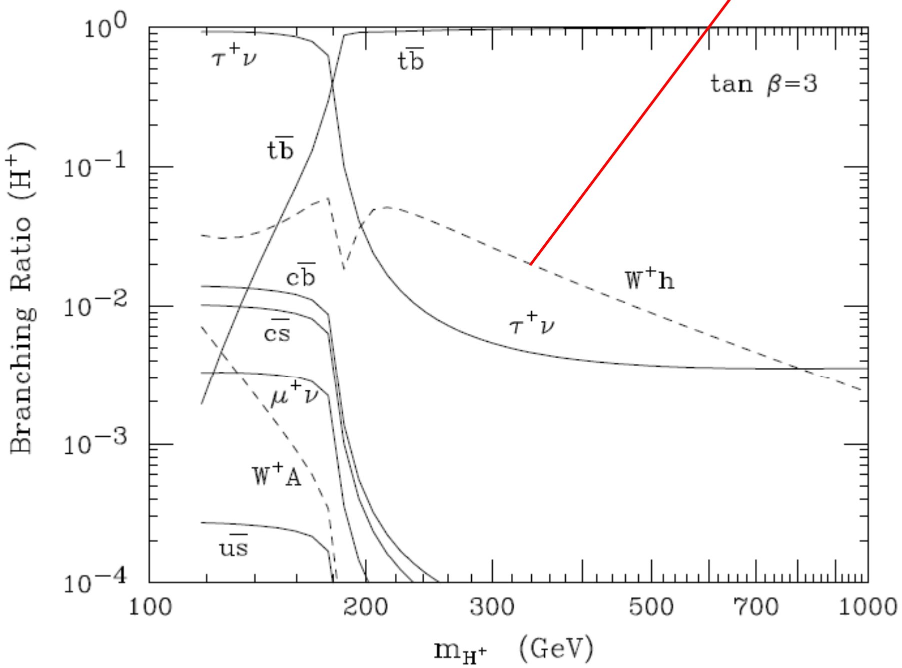
$$H^\pm \to cs, \tau\nu,$$

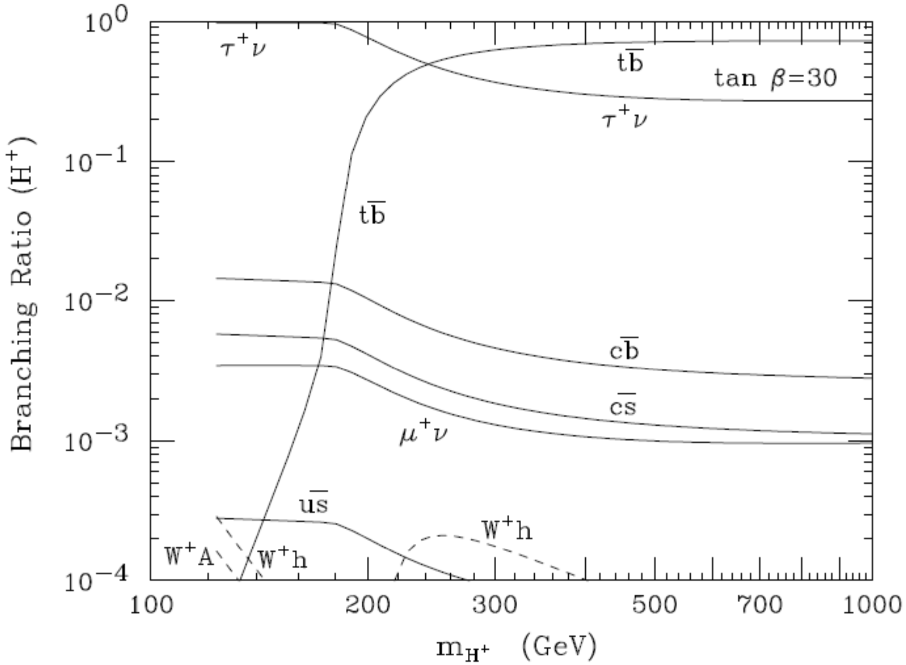
$$H^\pm \to tb, \text{ if kinematically possible}$$

Branching ratios of charged Higgses in 2HDM model II

Can be larger than MSSM !
(Only small tanβ though.)

Carena/Haber, 2003





Note that there is no $H^+W^-\gamma$ or H^+W^-Z coupling in 2HDMs at tree-level

➡ No tree-level gauge boson fusion in production at hadron colliders

Singly charged Higgs mass limit from LEP:

Assumed decay channels

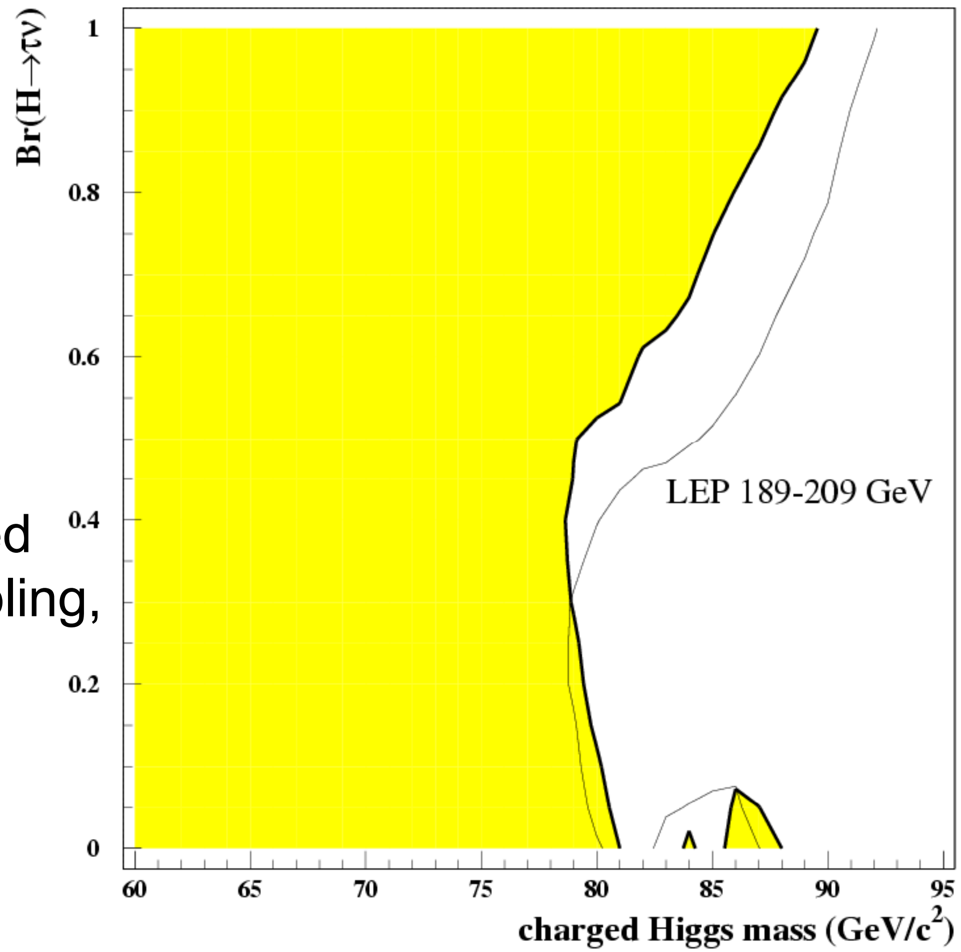
$H^+ \to c\bar{s}, \tau^+\nu$

➡ 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

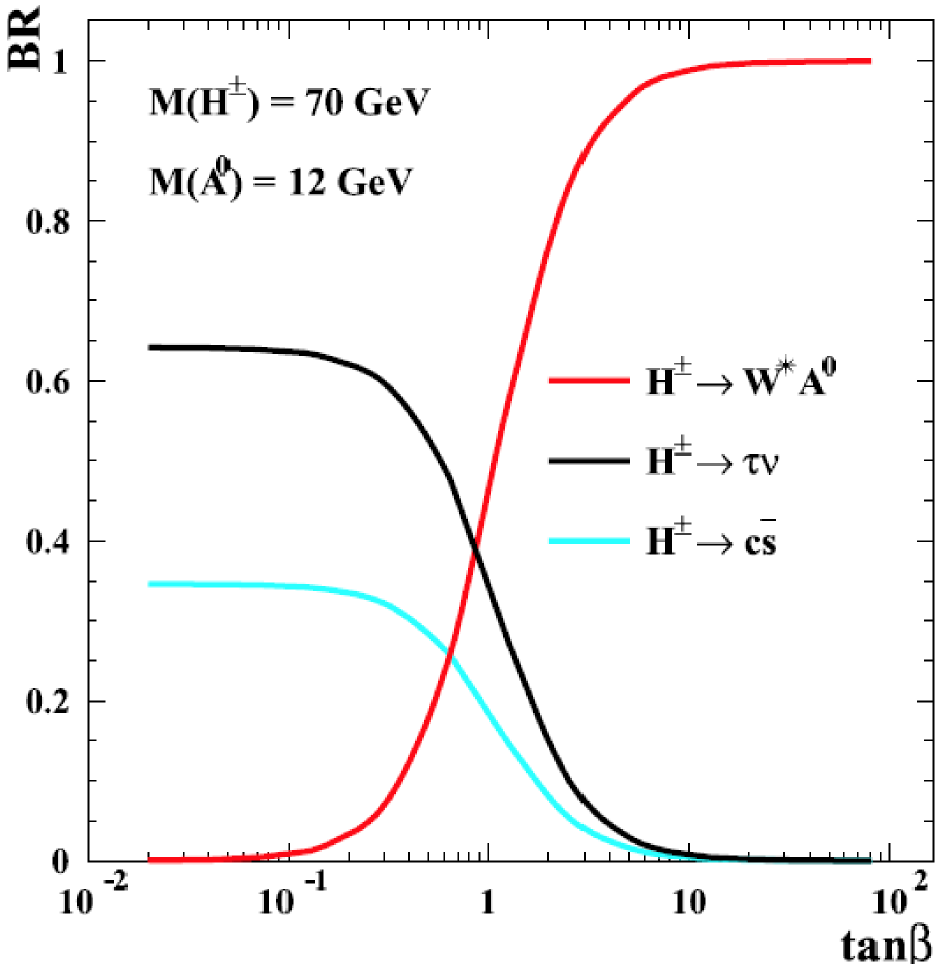


LEP Higgs working group, LHWG note 2001-05.

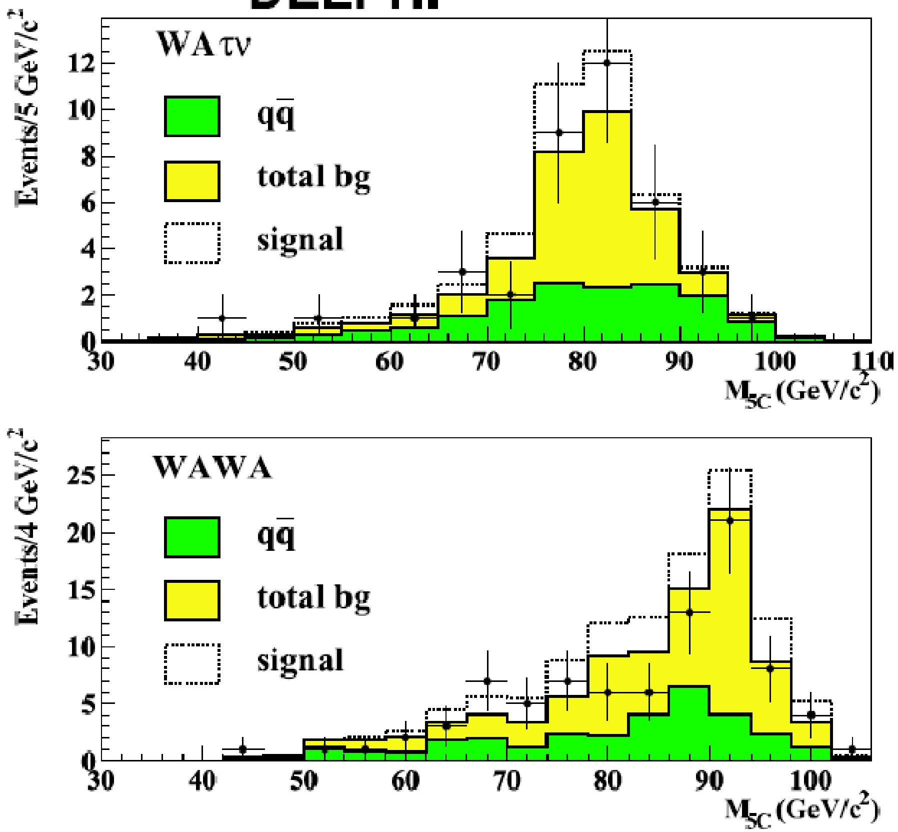
Less well known is the LEP search for the decay mode H+ to AW* (with A to bb) by DELPHI, 2004.

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

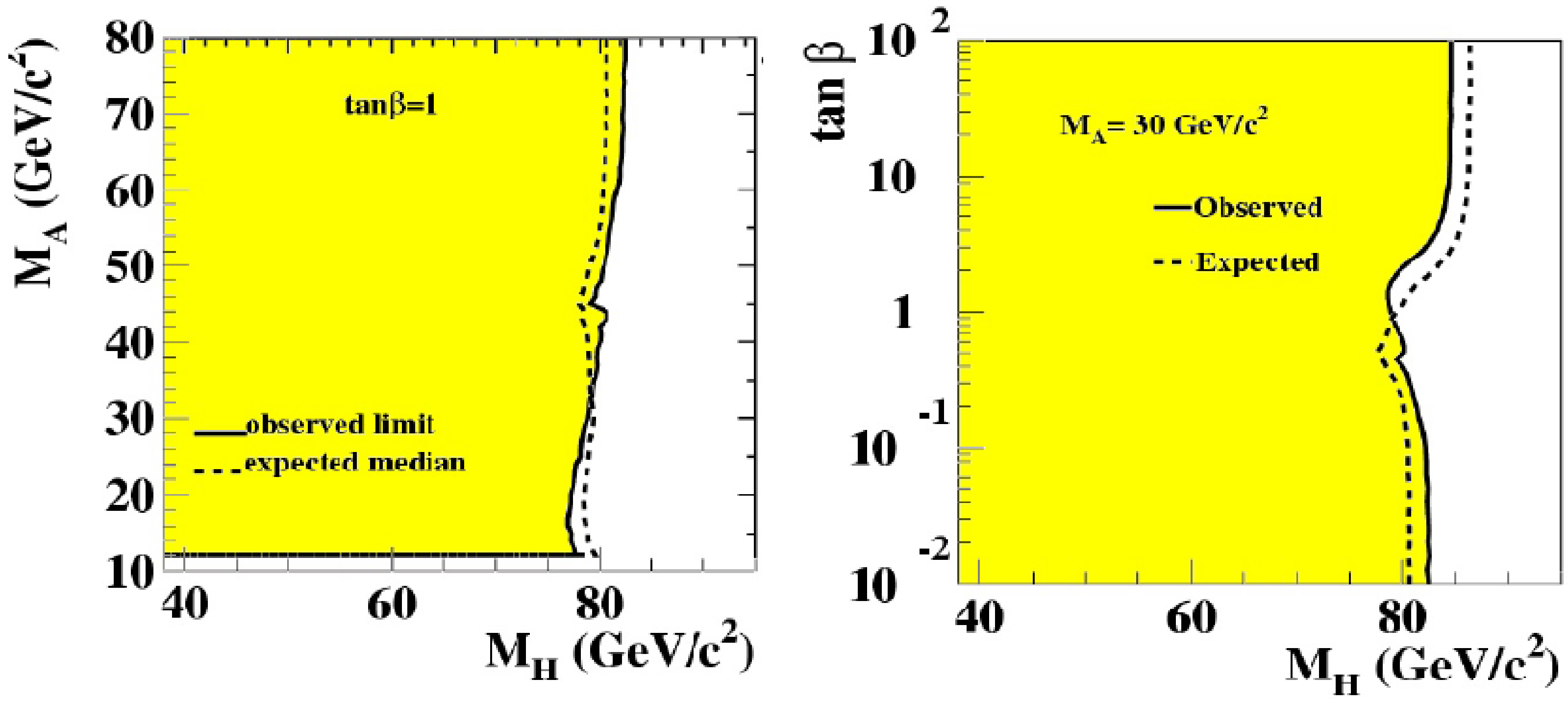
(In type II ruled out by b→sγ at such small charged Higgs mass.)



DELPHI PLB 552 (2003)



DELPHI Limits from $H^+ \rightarrow WA$



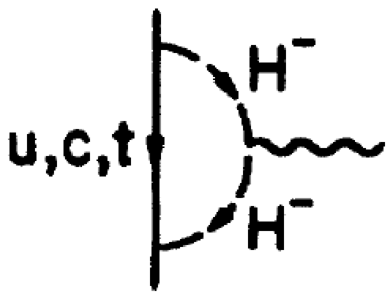
- Type-1 limit at 95% CL: $mH^+ > 76.7$ (77.1) GeV for any tanβ and mA > 12 GeV.

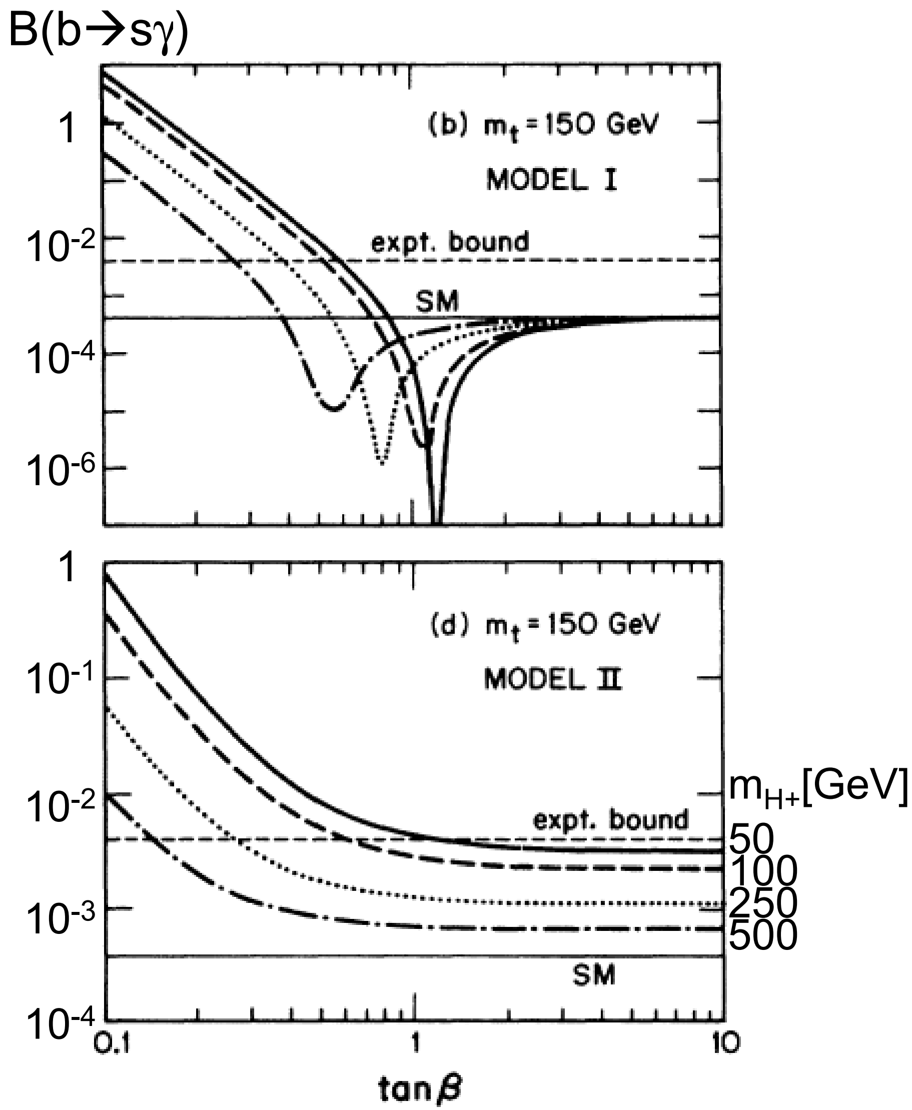
NB: Dermisek, 2008 claims H+ to AW* with A to cc or ττ could have a large BR and thus escape the above search which was only for A to bb decays.

Limits from $b \rightarrow s\gamma$ in 2HDM

Barger/Hewett/Phillips, 1990

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

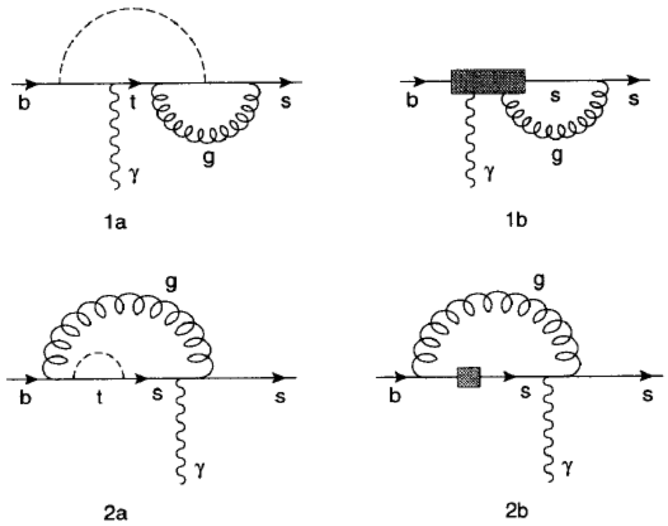


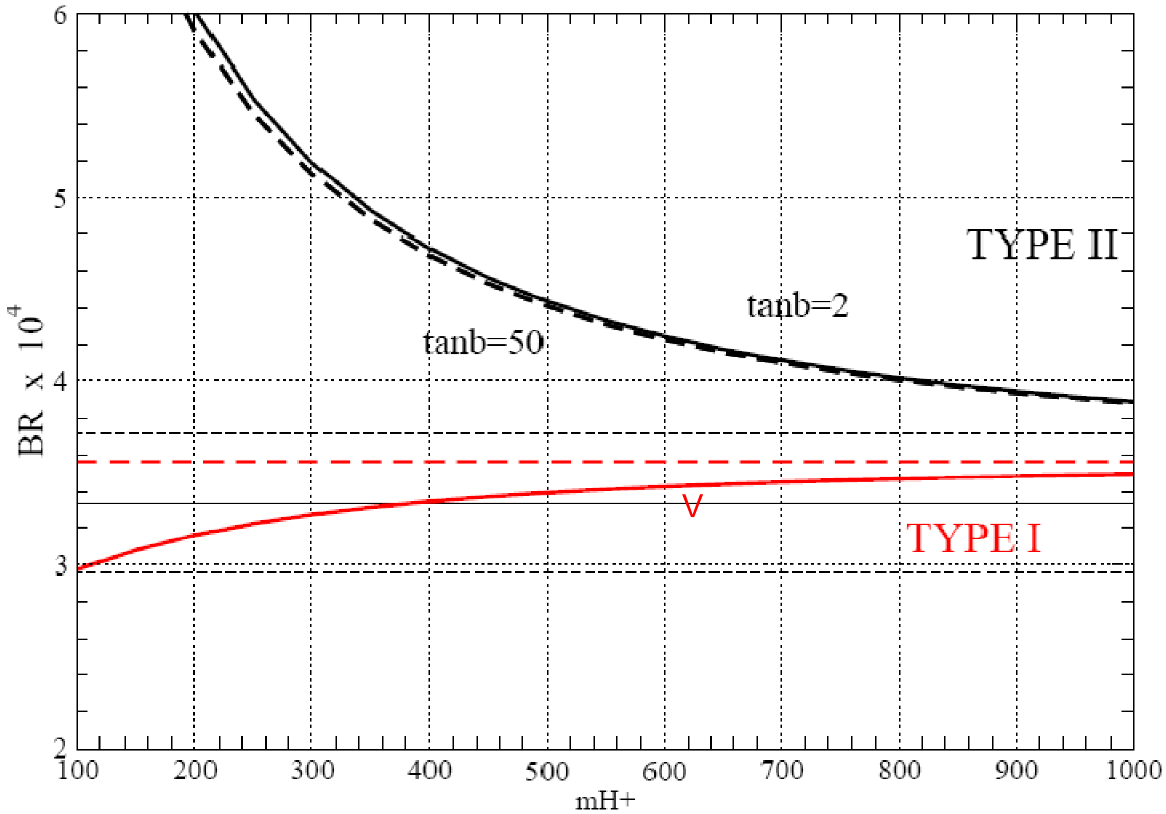


THDM II: $m_{H+} > (244 + 63/\tan\beta)$ GeV@LO

(Grinstein/Springer/Wise, 1990)

For type IV:
Aoki/Kanemura/Tsumura/Yagyu, 2008





Full NLO QCD results

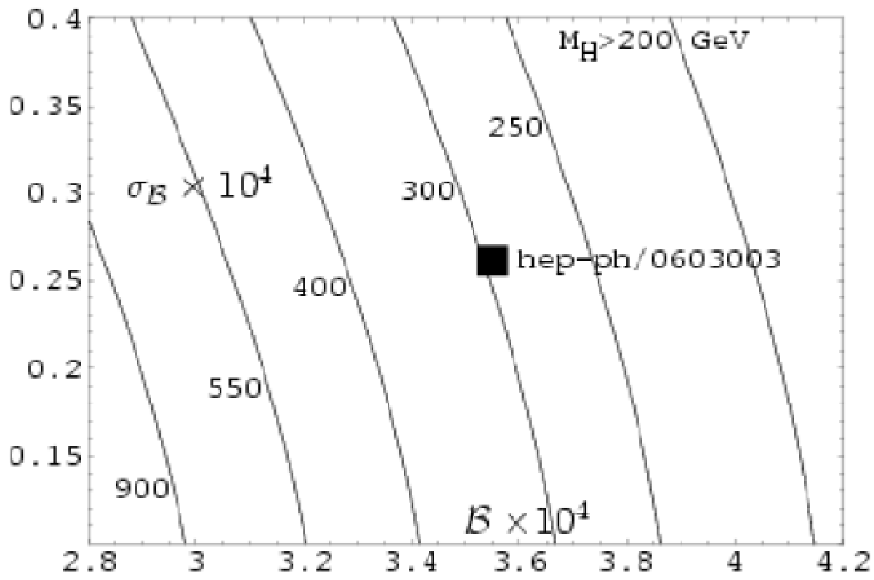
Uncertainty range of theoretical predictions (Ciuchini et al, 1998) is such that mH+>250-300 or so GeV is required in type II

Type IV much alive (see Kanemura's talk)

Latest NNLO (see Ali's talk later)

95% C.L. Lower Bound on M_{H+} in 2HDM from $\mathcal{B}(\bar{B} \to X_s \gamma)$

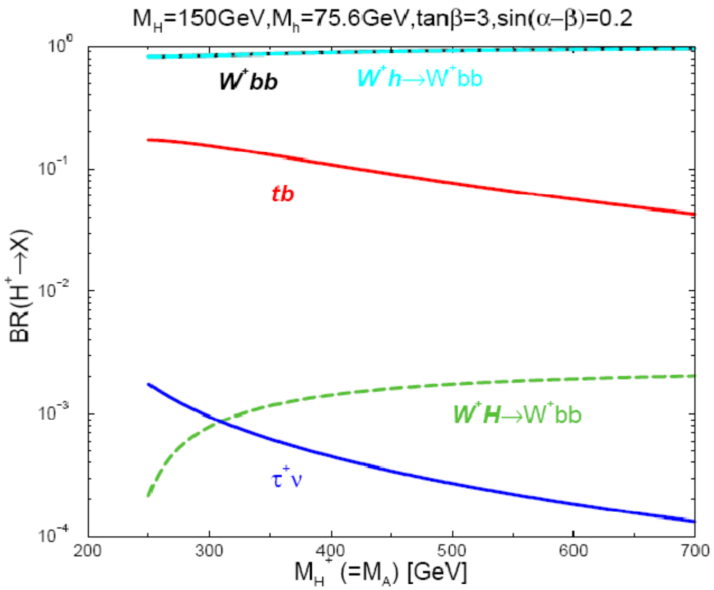
[Misiak et al., hep-ph/0609232]

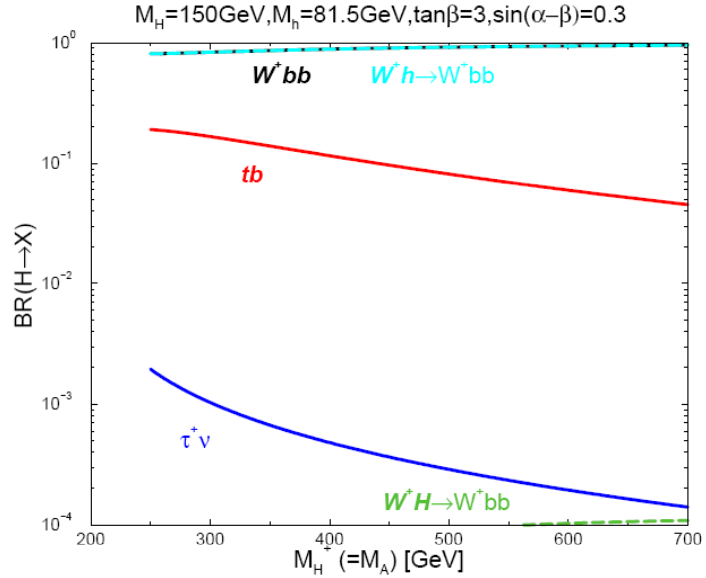


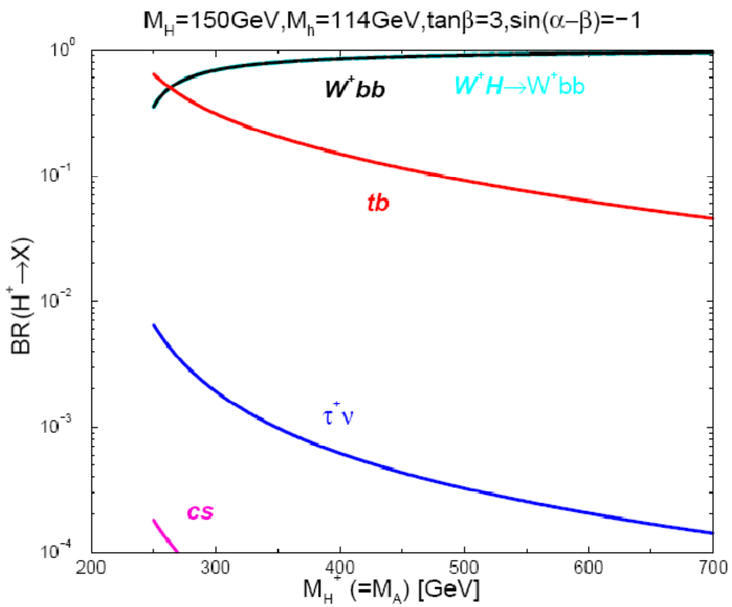
- 95% C.L. lower bound is around 295 GeV

Also limits from B+ -> tau nu, Bs -> mu mu, etc.

Possible 2HDM Benchmarks for H+/- (I): H+ -> W+ bb







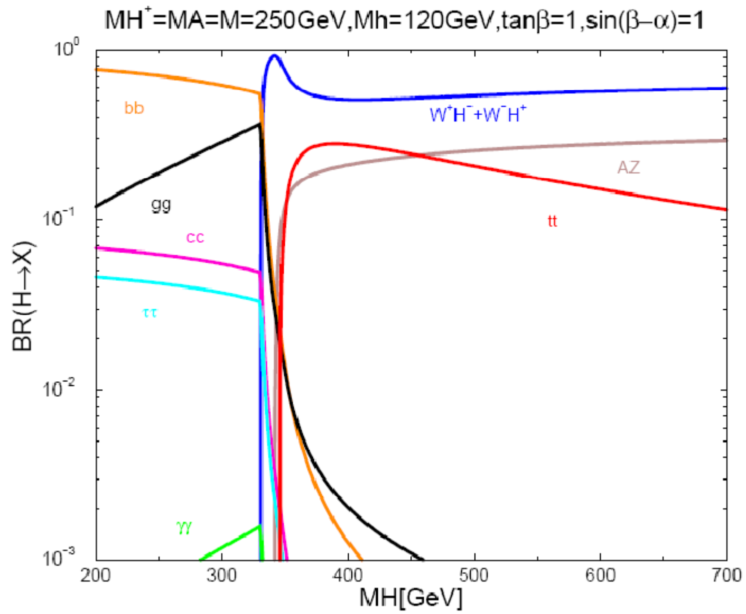
Branching of Wbb with A mediation is smaller than 10^-4 as mH+=mA is kept to avoid the ρ parameter constraints.

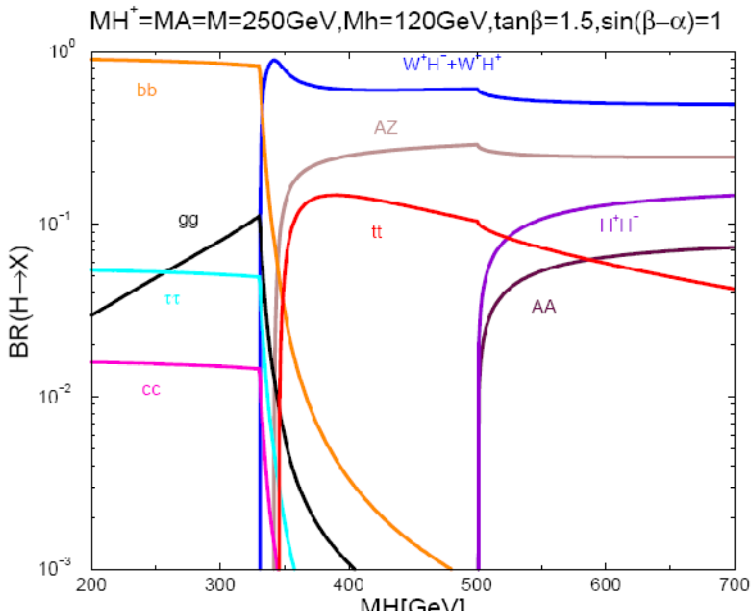
LEP search limits enforced, B-> sγ compliant & Unitarity respected.

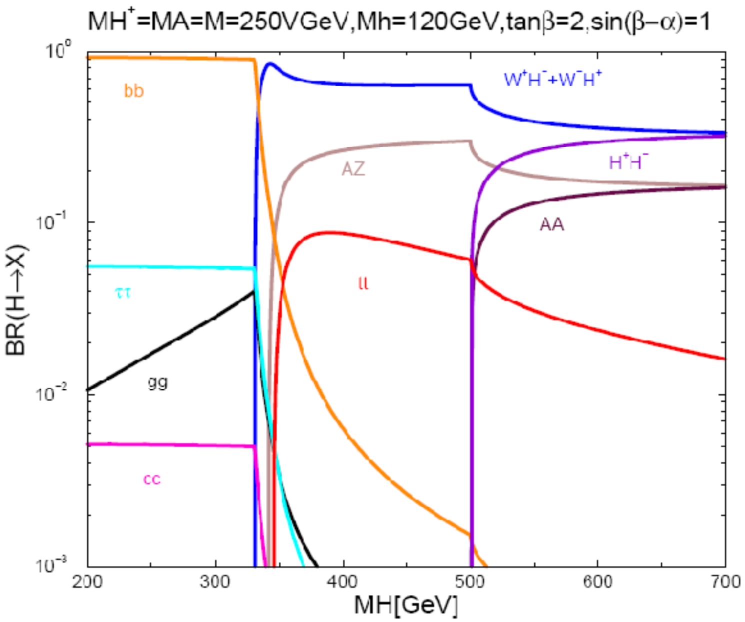
Kanemura/Moretti/Mukai/Santos/Yagyu, preliminary (also following figures).

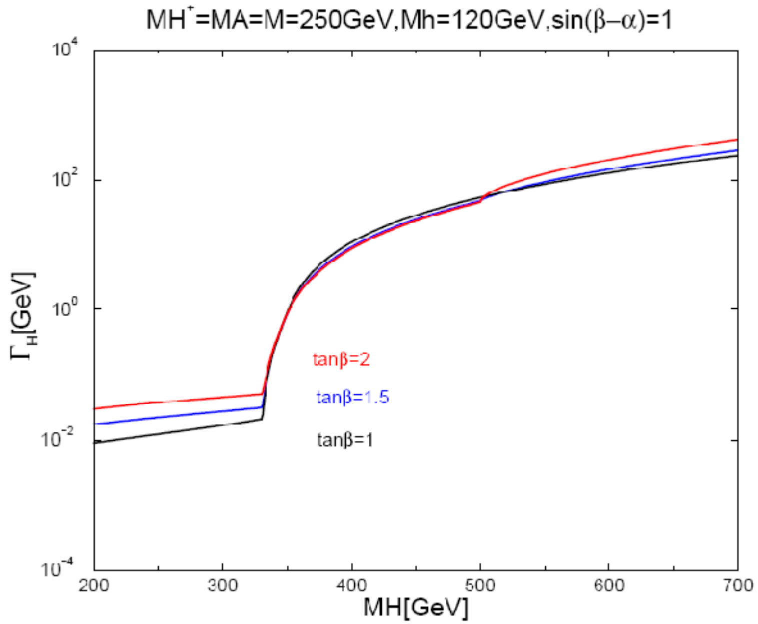
CPV in progress (with P. Osland)

Possible 2HDM Benchmarks for H+/- (II): H -> H+H- & W+H-

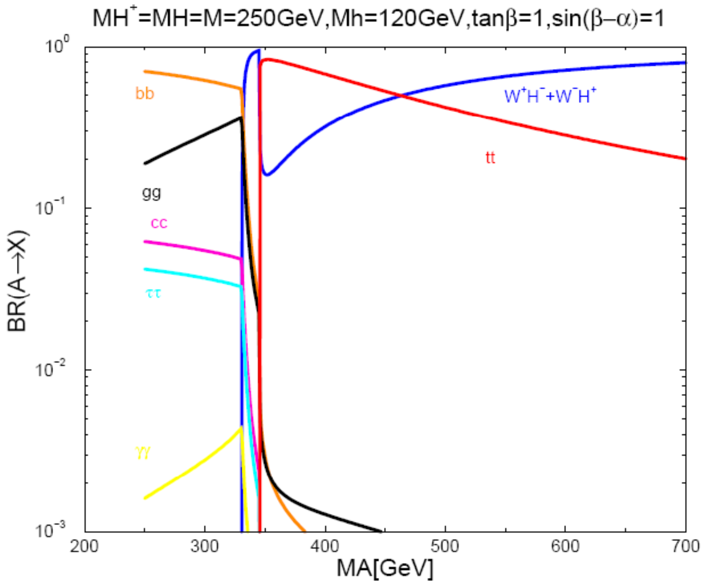


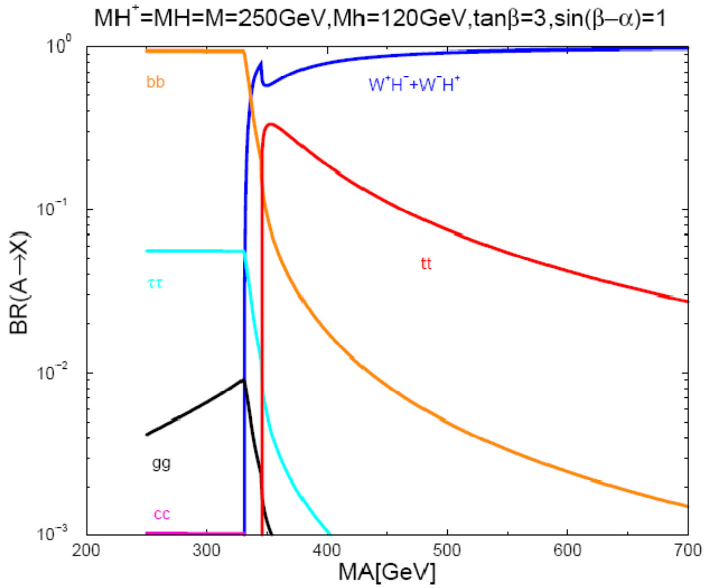


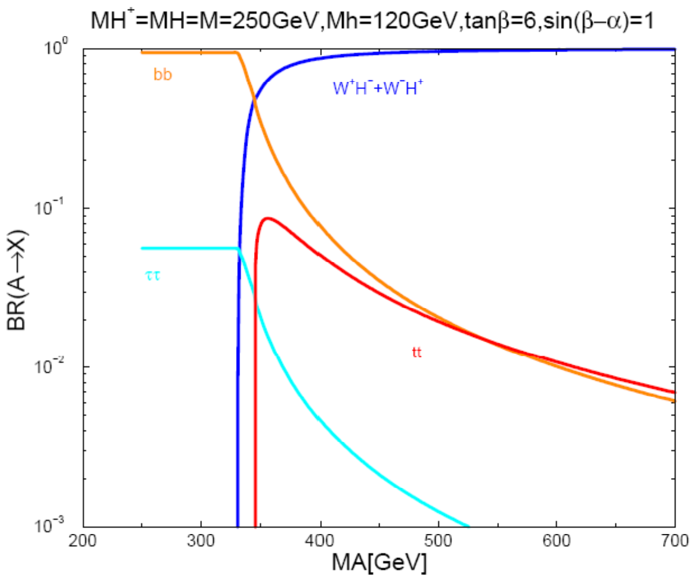


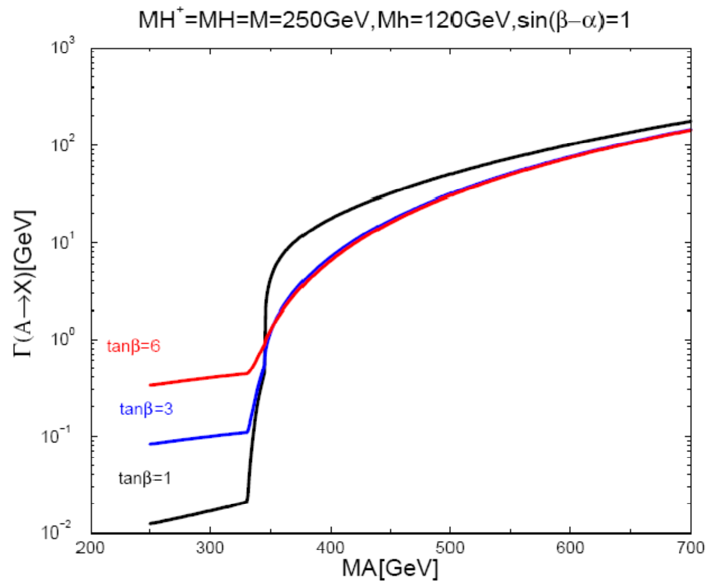


Possible 2HDM Benchmarks for H+/- (III): A -> W+H-





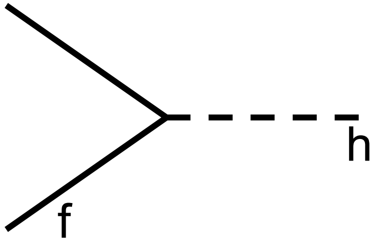




Fermiophobic Higgs bosons

Coupling to fermions very suppressed or zero, e.g. 2HDM type I or a triplet model (to be discussed).

Signal for Higgs decay is enhanced h → $\gamma\gamma$ or h → *VV* (*V*=*W*,*Z*)

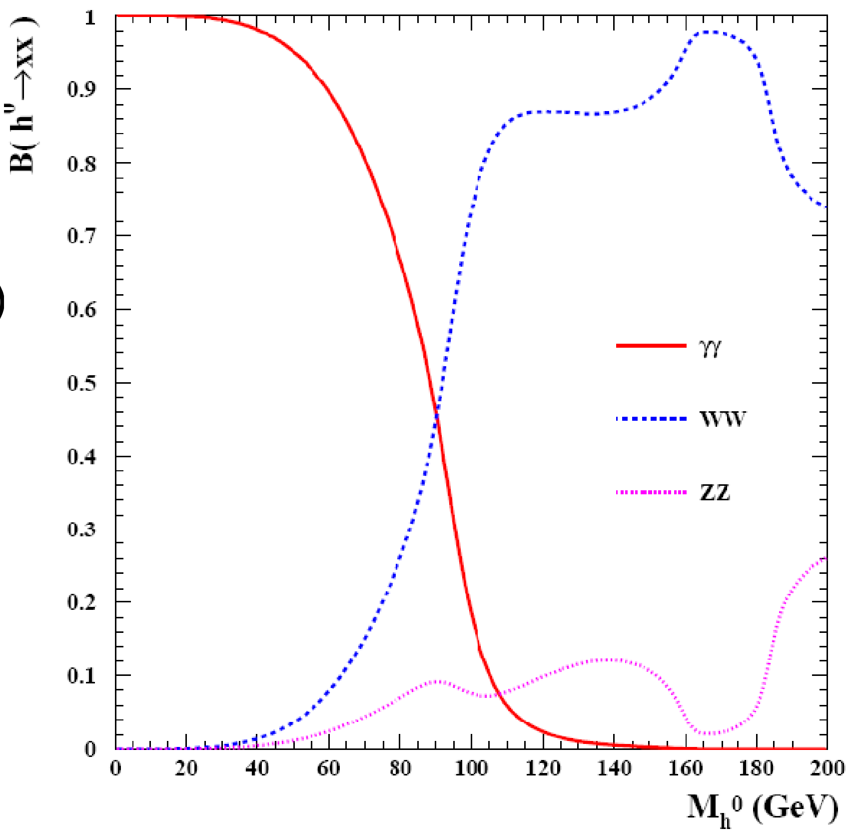


= cos α / sin β → 0

(even if exactly zero

a coupling can arise

in loop corrections !)



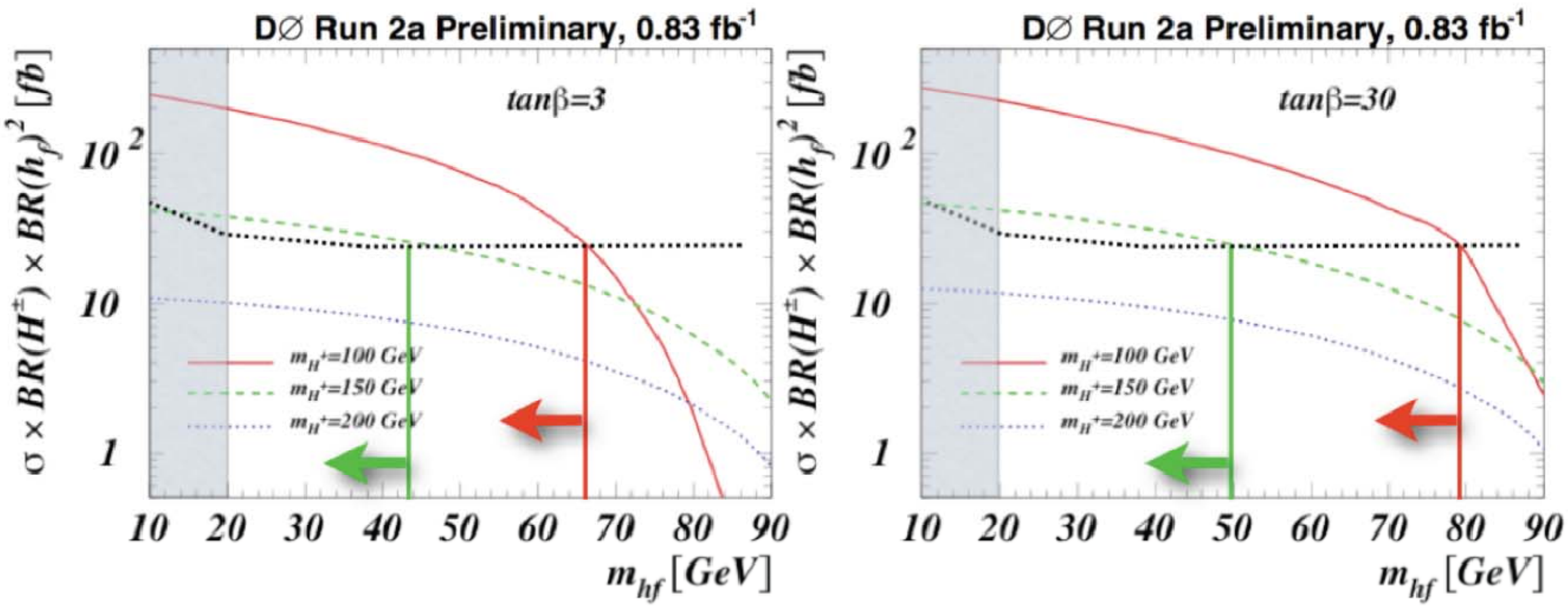
Enables $H^{+/-}$ production at LHC:

$pp \rightarrow H^{+/-}$h,

with the decays

$H^{+/-} \rightarrow$ hW^{*}, h→ $\gamma\gamma$

The double h_f production via pp to H+h_f to Wh_fh_f to l miss ET & 4 gamma was searched for in D0



The mechanism was actually proposed in: Akeroyd/Diaz, 2003

Models with triplet Higgses

The simplest model contains one complex triplet $Y \neq 0$

The minimal Higgs content is

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}; \quad \phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

Seesaw mechanism provides masses for neutrinos:

$$L = y_{ll'} L_l^T C i \tau_2 \Delta L_{l'} + h.c.$$

Constraints on the Yukawa coulings

from $\mu \to \bar{e}ee, \;\; \mu \to e\gamma$: $\begin{cases} y_{e\mu} y_{ee} < 3.2 \times 10^{-11} \text{ GeV}^{-2} \; M_{++}^2, \\ y_{e\mu} y_{\mu\mu} < 2 \times 10^{-10} \text{ GeV}^{-2} \; M_{++}^2, \end{cases}$

from Bhabha scattering: $y_{ee}^2 < 9.7 \times 10^{-6} \text{ GeV}^{-2} \; M_{++}^2$

from muonium-antimuonium transition: $y_{ee} y_{\mu\mu} < 5.8 \times 10^{-5} \text{ GeV}^{-2} \; M_{++}^2$

NB: The processes tau to 3l (six distinct decays) give useful constraints on the Yukawa couplings y_{3i}y_{jk} and these limits are improving at the B factories.

A vertex $ZH^{\pm}W^{\mp}$ possible at tree-level only in models with larger than doublet representations.

In a model with triplets, proportional to the triplet VEV.

The coupling comes from the kinetic term:

$\sum_k \left(D^{\mu}\phi_k\right)^* D_{\mu}\phi_k$, with the covariant derivative $D_{\mu} = \partial_{\mu} + igW_{\mu}^{a}T^{a} + \frac{1}{2}g' B_{\mu}Y$

The $ZH^{\pm}W^{\mp}$ vertex is given by

$$L_{H^{\pm}W^{\mp}Z} = -gm_Z\xi\left[W_{\mu}^{+}Z^{\mu}H^{-} + h.c.\right],$$

where $$\xi^2 = \left(1 - \frac{1}{\rho}\right)\frac{1}{T(T+1) - \frac{3}{4}Y^2}\left[\left[T(T+1) - \frac{1}{4}Y^2\right]\left(Y^2 + \frac{1}{\rho}\right) - \frac{1}{2}Y^2\left(1 + \frac{1}{\rho}\right)\right]$$

$$\xi \neq 0 \quad \Rightarrow \quad \rho \neq 1$$

A charged Higgs boson can be produced from gauge boson fusion,

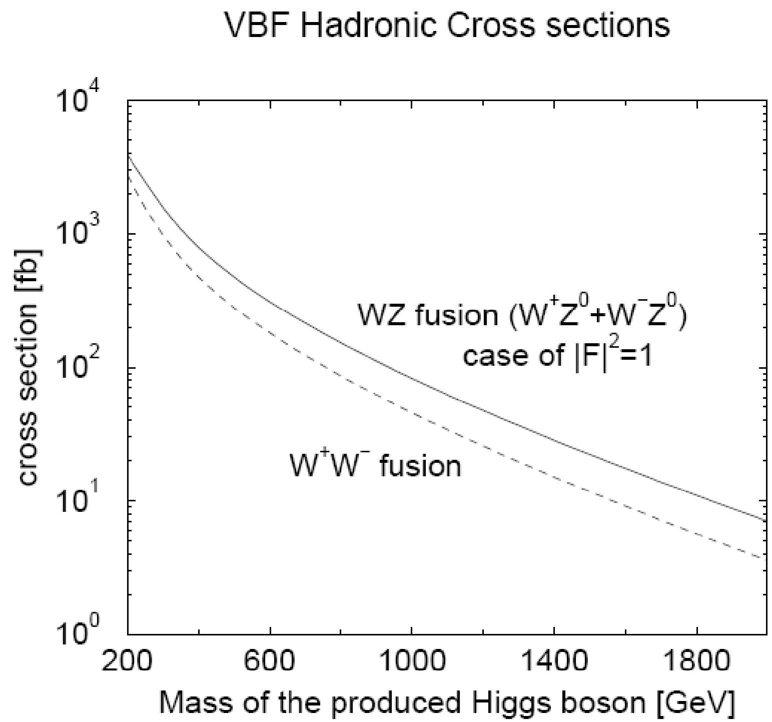
$$pp \to H^{\pm} X$$

High p_T jets to the forward and backward directions from the scalar boson;

No color flow in the central region;

Use kinematic cuts to isolate signal

LHC



Asakawa/Kanemura,2005.

Doubly charged Higgs in triplet models

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}; \quad \phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad L = y_{ll'} L_l^T i C \tau_2 \Delta L_{l'} + h.c.$$

Doubly charged Higgs does not mix with anything and it does not couple to quarks.

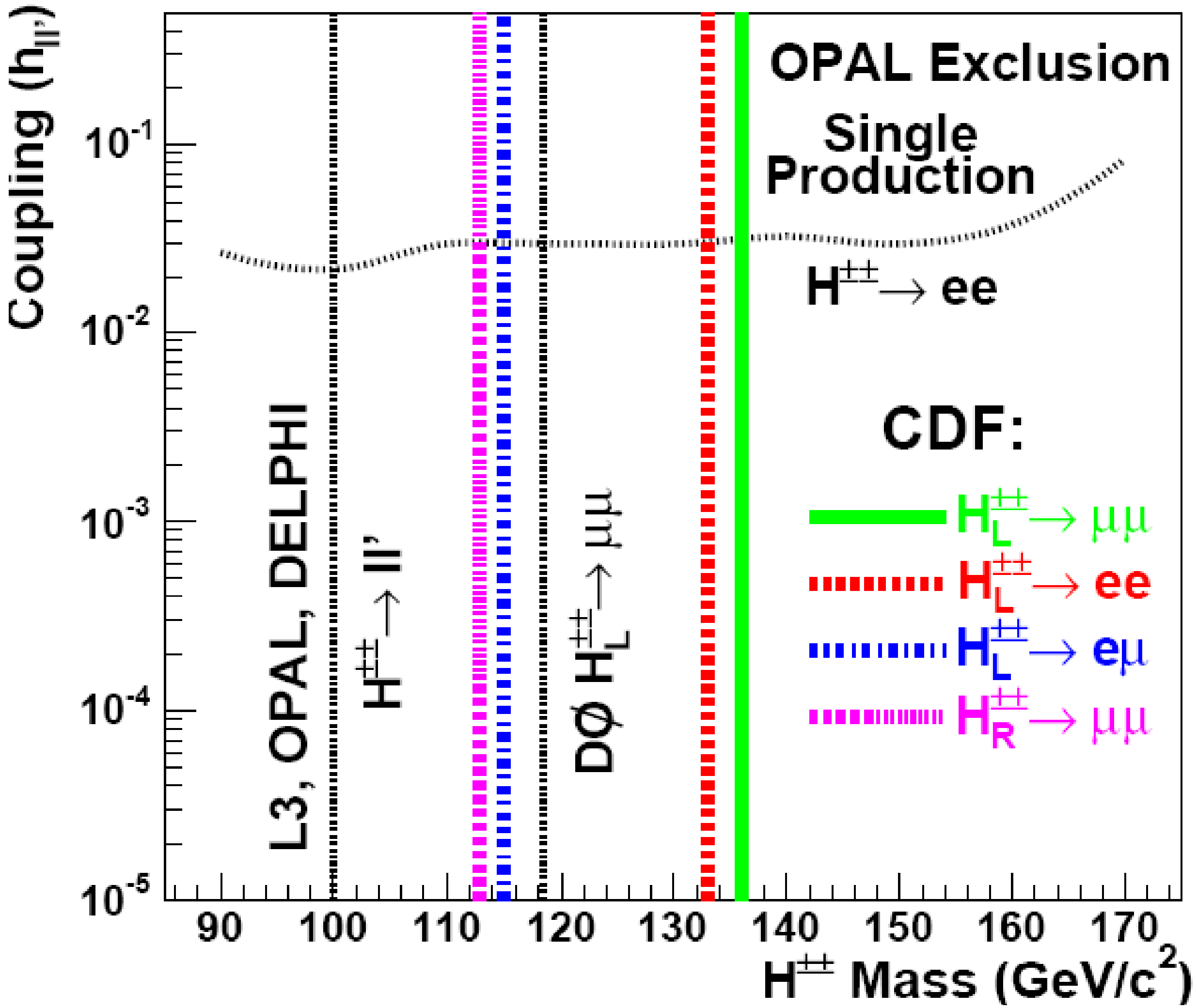
Doubly charged Higgs is a clear evidence of triplet representations.

Recently main development has been the study of the prediction for H++ to ll as a function of neutrino parameters.

This is the case if neutrino mass solely comes from triplet vev times Yukawa coupling (called the "Higgs Triplet Model").

Discussed in Chun at al, 2003 and then in Garayoa, 2007, Akeroyd/Aoki/Sugiyama, 2007, Raidal et al, 2007

Doubly charged Higgs mass limit

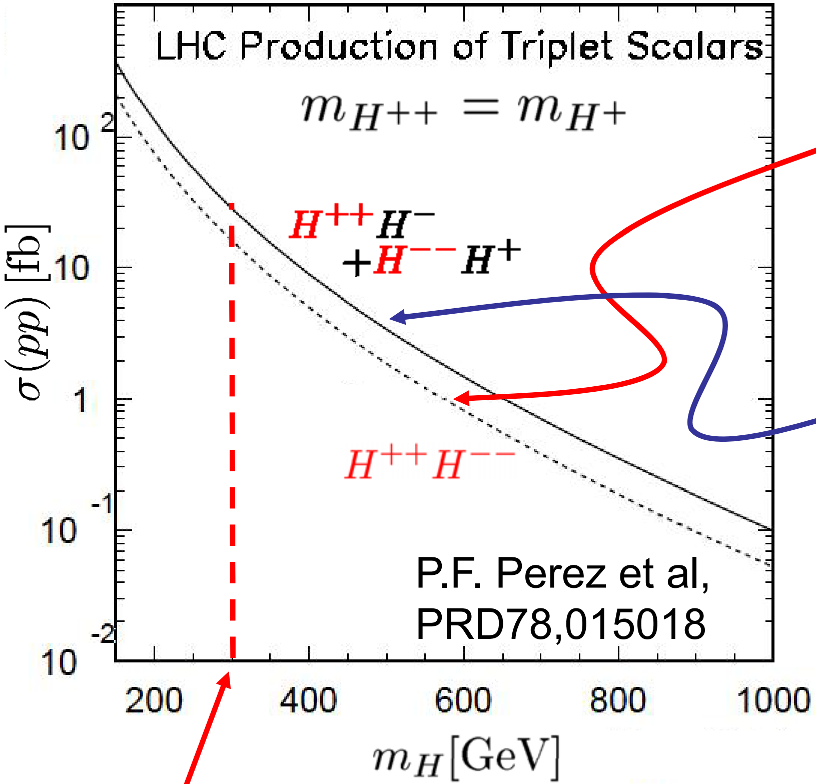


There is a D0 search with a mass limit of 150 GeV of which I can't find a figure !!!

$H^{\pm\pm}$ Production

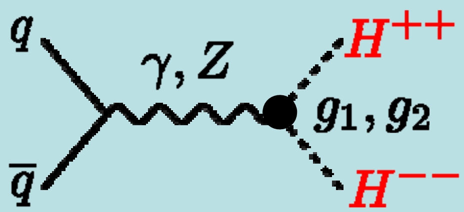
$$\underbrace{\underline{H^{\pm\pm} = \Delta^{\pm\pm}}, \quad H^{\pm} \simeq \Delta^{\pm}, \quad H^0 \simeq \mathrm{Re}(\Delta^0), \quad A^0 \simeq \mathrm{Im}(\Delta^0)}_{\text{mass splittings} \lesssim 100\text{GeV } (\rho\text{-param.})}, \quad h^0 \simeq \mathrm{Re}(\phi^0)$$

Production at hadron collider :

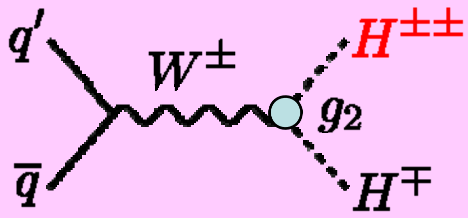


$m_{H^{\pm\pm}} = 300\text{GeV}$

$\Rightarrow \quad \sigma(pp) \simeq 20\text{-}30\text{fb}$

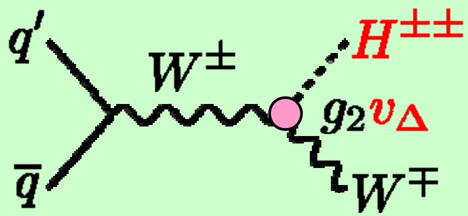


conventional mode



$SU(2)_L$-charged $H^{\pm\pm}$
(c.f. $SU(2)_L$ singlet with $Y = 4$)

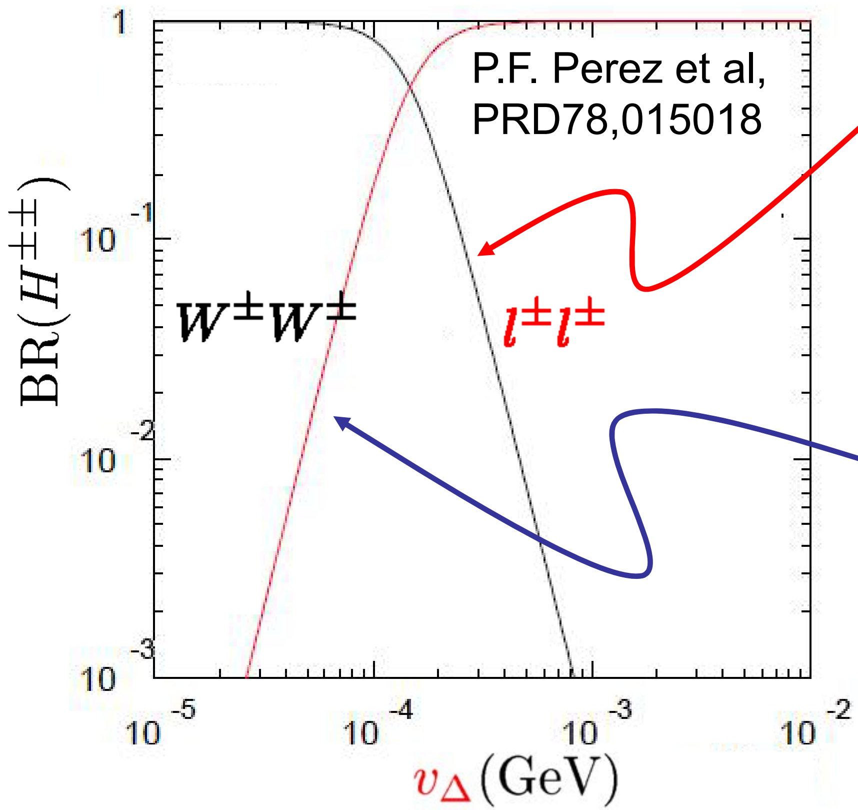
stressed in A.G. Akeroyd, M. Aoki, PRD72,035011



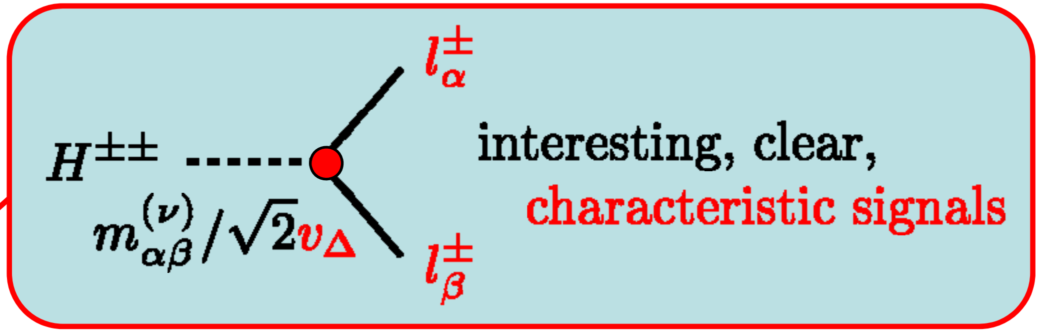
suppressed by v_Δ

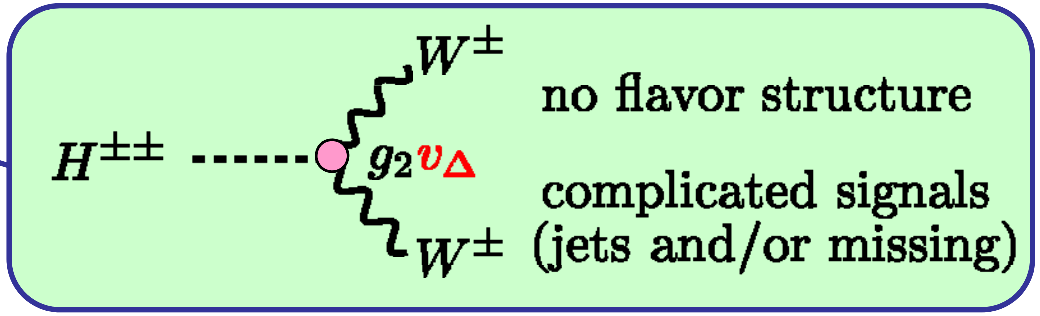
$H^{\pm\pm}$ Decay

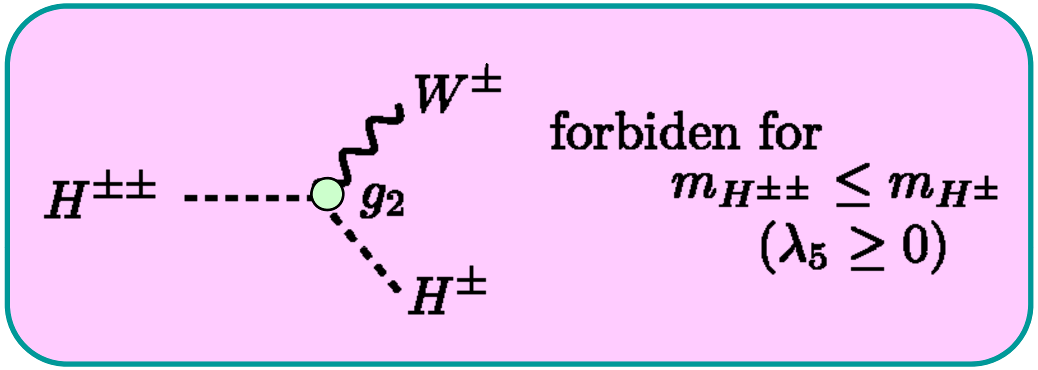
$$m_{H^{\pm\pm}} = m_{H^{\pm}} = 300\text{GeV}$$
$$(\sigma(pp) \simeq 20\text{-}30\text{fb})$$



$(1\text{eV} \lesssim v_\Delta \lesssim 10\text{GeV})$







$v_\Delta \lesssim 10^{-5}$GeV
$\Rightarrow$ simple and interesting

Summary

Differences to MSSM:

New couplings $H^{\pm}W^{\mp}Z$ (triplet model)

H^+ mass can in general be lower than in the MSSM

New particles: Other (two) H^+'s (MSSM+1CHT)

H^{++} (triplet model [with seesaw])

Branching ratios different:

- $H^+ \to \nu\tau$ (2HDM, triplet)
- $H \to H^+ H^-$ (2HDM, type II & NMSSM)
- $H \to W^+ H^-$ (2HDM, type II & NMSSM)
- $A \to W^+ H^-$ (2HDM, type II & NMSSM)
- $H^+ \to W^*h$, $h \to bb$ (2HDM, type II & NMSSM)
- $H^+ \to W^*A$, $A \to bb$ (NMSSM)
- $H^+ \to W^*h$, $h \to \gamma\gamma$ (fermiophobic)
- $H^+ \to W^+Z$ (triplet)

BACKUP SLIDES

Some interesting NMSSM scenarios for the Charged Higgs sector (to be discussed in Benchmark Break-out Session)

Must be different from MSSM:

1) H+ -> W+A1 (a la Godbole/Roy) but also WH1 & WH2
2a) H3/A2 -> W-H+
2b) H3 -> H+H- (by CPC, A cannot decay to 2 charged Higgses!)
3) m+ ≠ mA (mH+ just above mH2 and mA1, H3, A2 heavy and singlet)
4) m+ << mt-mb (a la Godbole/Roy)
5) m+ > mt-mb, all other Higgses < mt

	no constraints			SUSY, Higgs + theory			all constraints		
	# points	$\tan(\beta)$	m_{H+}	# points	$\tan(\beta)$	m_{H+}	# points	$\tan(\beta)$	m_{H+}
BMP1	100k	1	90	30k	1.4	170	15k	15	250
BMP2a	380k	1	70	170k	1.4	160	80k	15	210
BMP2b	90k	1	70	24k	1.6	170	7k	16	210
BMP3	44k	1	70	6k	3	160	2k	18	215
BMP4	13k	1	70	3	18	160	-	-	-
BMP5	3	10	180	-	-	-	-	-	-

NMSSM (weak scale). Soft masses for sleptons at 1 TeV, 2.5 TeV for trilinears and 150 GeV, 300 GeV, 1TeV for M1, M2, M3 risp. I then randomly scanned on lambda, kappa, Alambda, Akappa, mu and tan(beta), taking 10^9 points. Positive mass squared for all scalars, all exp. constraints (LEP/Tevatron limits, b->sγ, g–2, etc.)

We can combine the VEVs of the doublet Higgs fields through the relation $v_D^2 \equiv v_1^2 + v_2^2$ and define $\tan\beta \equiv v_2/v_1$. Furthermore, the parameters v_D, v_T, m_W^2 and m_Z^2 are related as follows:

$$\begin{aligned} m_W^2 &= \tfrac{1}{2} g^2 (v_D^2 + 4 v_T^2), \\ m_Z^2 &= \frac{\tfrac{1}{2} g^2 v_D^2}{\cos^2\theta_W} \, , \end{aligned}$$

which implies that the ρ-parameter is different from 1 at the tree level, namely,

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1 + 4R^2, \quad R \equiv \frac{v_T}{v_D} \; . \tag{6}$$

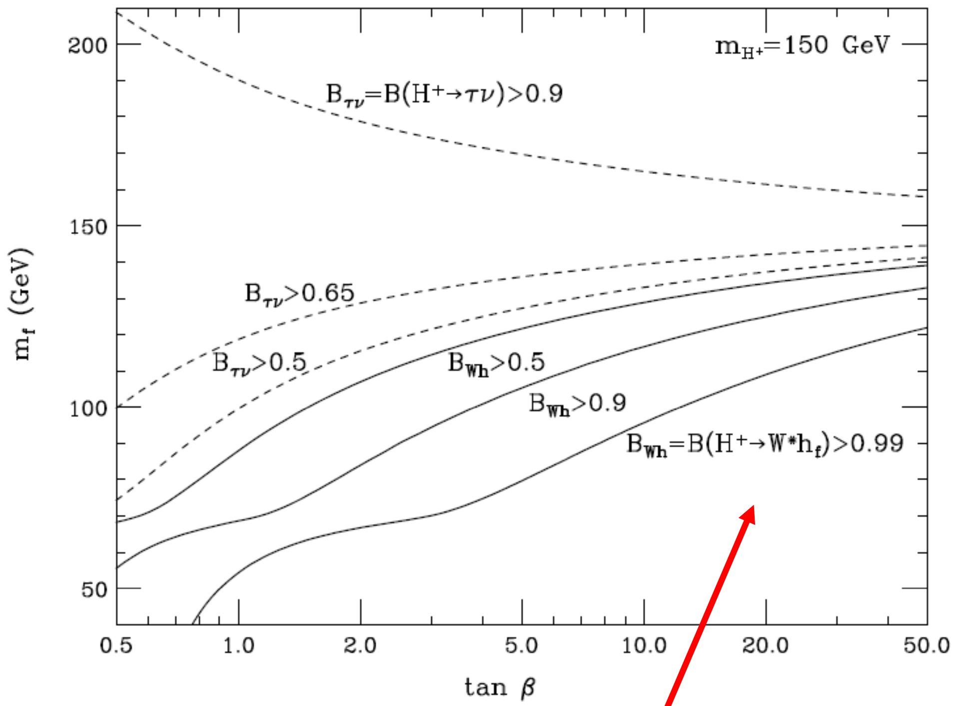
The bound on R is obtained from the ρ parameter measurement, which presently lies in the range 0.9993–1.0006, from the global fit reported in Refs. [6, 23]. Thus, one has $R \leq 0.012$ and $v_T \leq 3$ GeV. We have taken into account this bound in our numerical analyses.

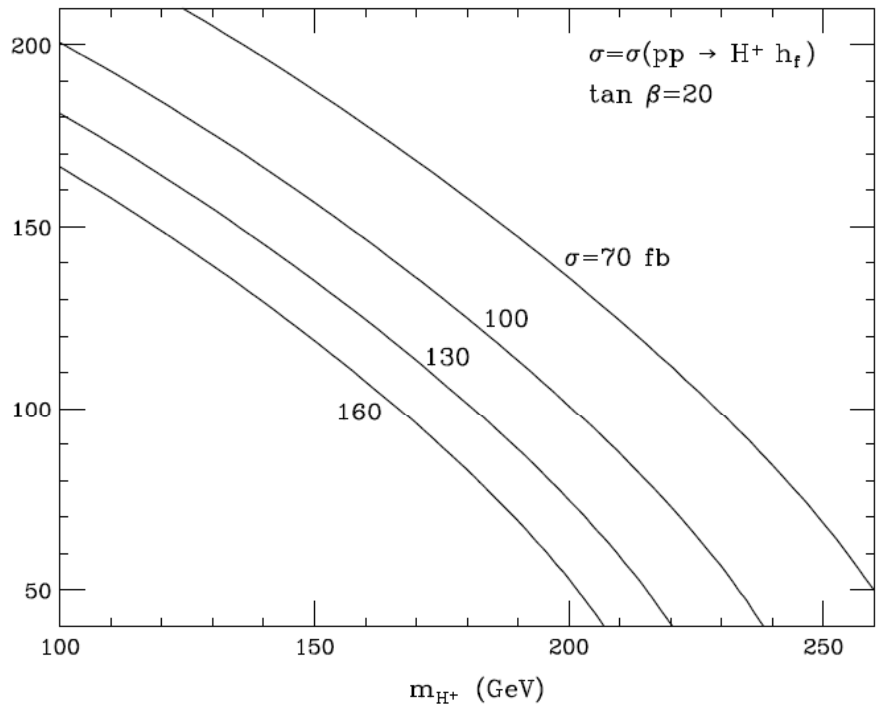
Thus, the Higgs sector of this model depends of the following parameters: (i) the gauge-related parameters (g, g', v, R, $\tan\beta$); (ii) the Yukawa couplings (λ, μ_1, μ_2) and (iii) the soft Supersymmetry-breaking parameters (A, B_1, B_2). The gauge-related parameters can be replaced by the quantities (G_F, α, m_W, ρ, $\tan\beta$). For the numerical analysis to be realized in the remainder of this paper, we must make sure that the following theoretical conditions of the MSSM+1CHT are satisfied: (a) the global stability condition of the potential; (b) the necessary condition for having a global minimum and (c) the positivity of the mass eigenvalues of the full spectrum of charged, pseudoscalar and scalar Higgs bosons [10].

Top decay $t \to b + H^+$

- The factors $U^2_{j,i+1}$ denote the diagonalizing matrix for the charged Higgs states.
- Note that if one replaces $U_{2,i+1} \to s_\beta$ and $U_{1,i+1} \to -c_\beta$ the formulae of decay width reduces to the MSSM case.
- Furthermore, we will assume $|V_{tb}| \simeq 1$ and neglect light fermion generations.
- $\lambda(a, b, c) = (a - b - c)^2 - 4bc$ and $q_{b,H^+} = m^2_{b,H^+}/mt^2$.

Akeroyd/Diaz/Pacheco,2004



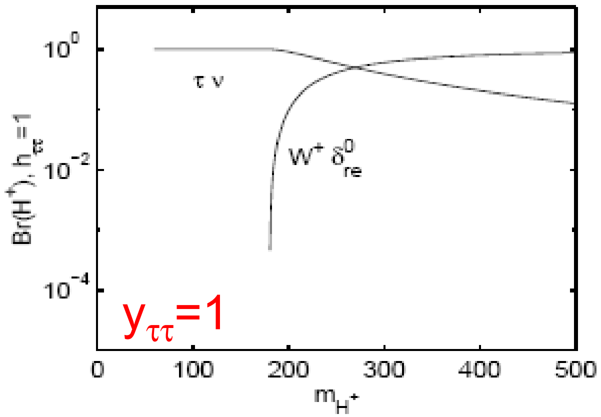


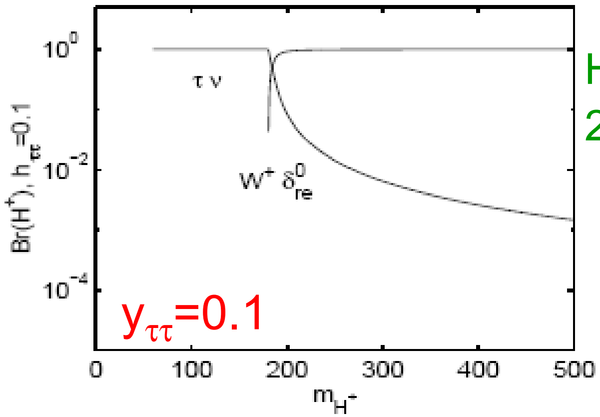
Double h production,
h → γγ

$M_{\text{charged Higgs}}$=150 GeV

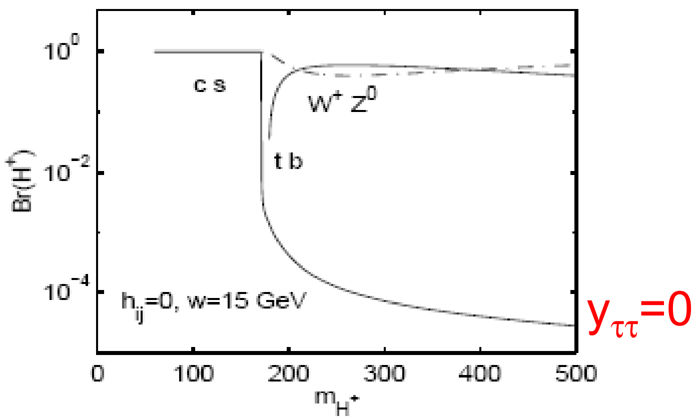
Singly charged Higgs is a mixture of doublet and triplet charged Higgs ➡ decay modes

Modes common with 2HDMs: $H^+ \rightarrow \bar{l}\,\nu_l, u_i\bar{d}_i, W^+H^0$





Huitu/Laitinen/Maalampi, 2001.



Branching ratios different due to tree-level H^+W^-Z-coupling.

Can also suppress tb.

Higgs Triplet Model

no ν_R

"Yukawa" int. with a complex Higgs triplet

H^{++} : doubly charged Higgs

$$h_{\alpha\beta}\left(-\overline{(l_{\alpha L})^C}, \overline{(\nu_{\alpha L})^C}\right)\underbrace{\begin{pmatrix} \Delta^-/\sqrt{2} & \Delta^{--} \\ \Delta^0 & -\Delta^-/\sqrt{2} \end{pmatrix}}_{\Delta\,:\,SU(2)_L\text{ triplet},\ Y=2,\ L=-2}\begin{pmatrix} \nu_{\beta L} \\ l_{\beta L} \end{pmatrix} + \text{h.c.}$$

Higgs potential

$\Phi \equiv (\phi^+, \phi^0)^T$: $SU(2)_L$ doublet, $Y=1$, $L=0$

$M^2 > 0$ (no Majoron)

$$V = -m^2(\Phi^\dagger\Phi) + \lambda_1(\Phi^\dagger\Phi)^2 + M^2\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_2[\mathrm{Tr}(\Delta^\dagger\Delta)]^2 + \lambda_3\mathrm{Det}(\Delta^\dagger\Delta)$$
$$+ \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5(\Phi^\dagger\tau_i\Phi)\mathrm{Tr}(\Delta^\dagger\tau_i\Delta) + \left(\frac{1}{\sqrt{2}}\mu(\Phi^T i\tau_2\Delta^\dagger\Phi) + \text{h.c}\right)$$

$v \equiv \sqrt{2}\langle\phi^0\rangle$: spontaneous breaking of $SU(2)_L$

$v_\Delta \equiv \sqrt{2}\langle\Delta^0\rangle \simeq \dfrac{\mu v^2}{2M^2}$: explicit breaking of L

$1\,\text{eV}(\text{LFV decay}, m_\nu) \lesssim v_\Delta \lesssim 10\,\text{GeV}(\rho\text{-param.})$

Majorana ν_L mass

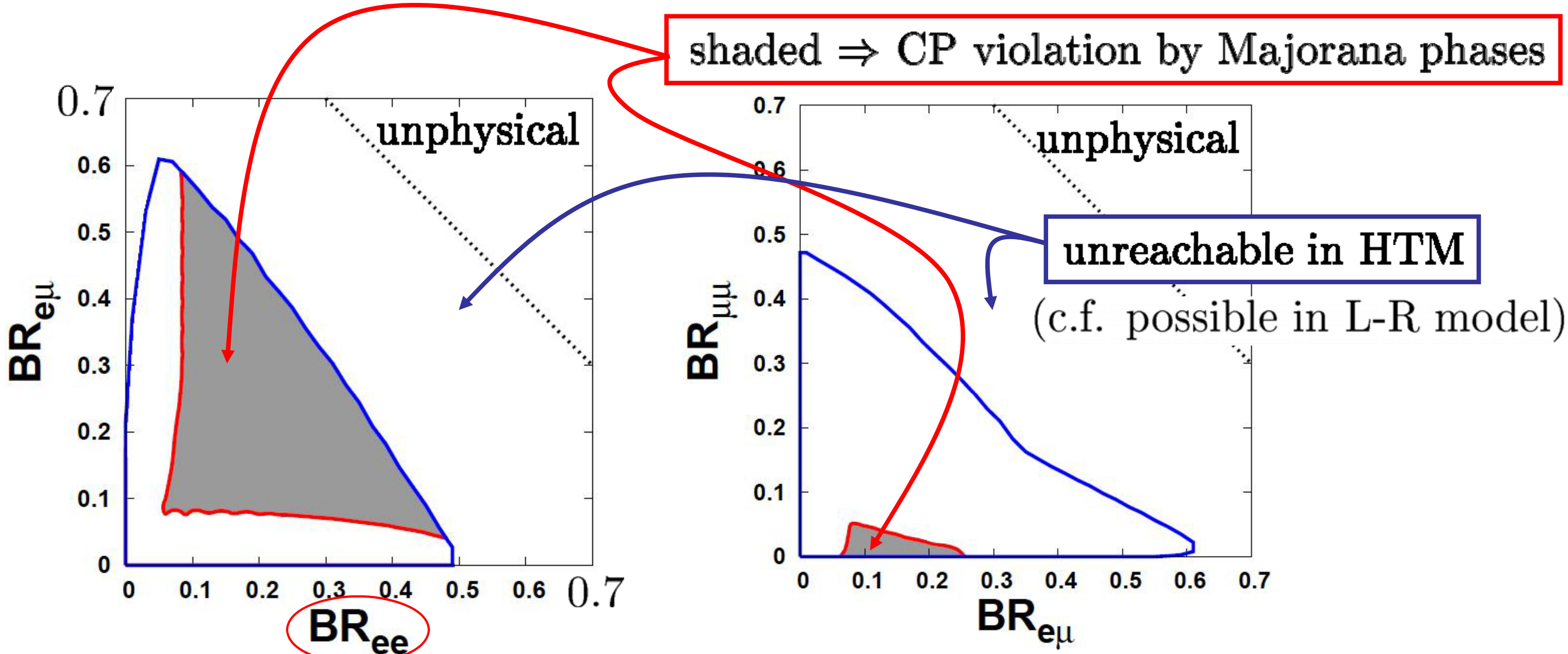
$$m_{\alpha\beta}^{(\nu)} = \sqrt{2}\, v_\Delta\, h_{\alpha\beta}$$

ν exp. $\leftrightarrow$ LFV decay

Utilization of $\mathrm{BR}(H^{\pm\pm} \to l_\alpha^\pm l_\beta^\pm)$ Measurement

- test of models
- information about neutrino mixing matrix in the Higgs triplet model

  (ex. CP violation due to nonzero Majorana phases)



ee seems important

A.G. Akeroyd, M. Aoki, H. Sugiyama, PRD 77,075010

See also J. Garayoa, T. Schwetz, JHEP 0803,009
M. Kadastki, M. Raidal, L. Rebane, PRD 77, 115023