Charged Higgs phenomenology beyond the MSSM

Heather Logan
Carleton University

TRIUMF
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Based on:

H.E.L. and D. MacLennan, Phys. Rev. D79, 115022 (2009)

H.E.L. and D. MacLennan, arXiv:100x.xxxx

S.M. Davidson and H.E.L., Phys. Rev. D80, 095008 (2009) + in progress

Outline

Introduction: the Higgs sector

Charged Higgs in the MSSM and experimental studies

Other models:
- Lepton-specific two Higgs doublet model
- Flipped two Higgs doublet model
- Two-doublet model for neutrino masses

Conclusions

Introduction: the Standard Model Higgs mechanism on one slide

Introduce a single complex SU(2)-doublet scalar field Φ.
Scalar potential $V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$ triggers electroweak symmetry breaking:

$$\Phi = \begin{pmatrix} \phi^+ \\ (v + \phi^{0,r} + i\phi^{0,i})/\sqrt{2} \end{pmatrix} \qquad \text{with } v = \sqrt{\frac{\mu^2}{\lambda}}.$$

Physical Higgs is $h^0 = \phi^{0,r}$.
Would-be Goldstone bosons are $G^0 = \phi^{0,i}$, $G^+ = \phi^+$ and can be gauged away ("eaten by the W and Z").
Covariant derivative term $(\mathcal{D}^\mu \Phi)^\dagger (D_\mu \Phi)$ gives weak boson masses $M_W^2 = \frac{g^2 v^2}{4}$, $M_Z^2 = \frac{(g^2+g'^2)v^2}{4}$.
Yukawas $\mathcal{L} = -y_{ij}^d \bar{d}_{Ri} \Phi Q_{Lj} - y_{ij}^u \bar{u}_{Ri} \tilde{\Phi} Q_{Lj} - y_{ij}^\ell \bar{e}_{Ri} \Phi L_{Lj} + h.c.$ give fermion mass matrices $m_{ij}^f = y_{ij}^f v/\sqrt{2}$; diagonalizing gives fermion masses (with y_{ij}^f diagonalized automatically); CKM matrix from mismatch between u_L and d_L rotations.

Two automatic features of the Standard Model:

1) Custodial symmetry preserved at tree level:

$$\frac{M_W}{M_Z \cos\theta_W} = 1 \qquad \text{where } \cos\theta_W \equiv \frac{g}{\sqrt{g^2 + g'^2}}.$$

Maintained in extended Higgs sectors if they contain only doublets (and singlets).

Two-doublet models: covariant derivative terms become

$$\mathcal{L} \supset (\mathcal{D}^\mu \Phi_1)^\dagger (D_\mu \Phi_1) + (\mathcal{D}^\mu \Phi_2)^\dagger (D_\mu \Phi_2)$$

Gauge boson masses become

$$M_W^2 = \frac{g^2 v_1^2}{4} + \frac{g^2 v_2^2}{4}, \qquad M_Z^2 = \frac{(g^2 + g'^2) v_1^2}{4} + \frac{(g^2 + g'^2) v_2^2}{4}$$

Preserves $\frac{M_W}{M_Z \cos\theta_W} = 1$; requires $v_1^2 + v_2^2 = v_{\rm SM}^2$.

With two doublets we have four more scalar degrees of freedom:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (v_1 + \phi_1^{0,r} + i\phi_1^{0,i})/\sqrt{2} \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ (v_2 + \phi_2^{0,r} + i\phi_2^{0,i})/\sqrt{2} \end{pmatrix}$$

with $v_1^2 + v_2^2 = v_{\rm SM}^2 = 4M_W^2/g^2$ and $v_2/v_1 \equiv \tan\beta$.

Mass eigenstates:

$$\begin{aligned} h^0 &= -\sin\alpha\,\phi_1^{0,r} + \cos\alpha\,\phi_2^{0,r}, & H^0 &= \cos\alpha\,\phi_1^{0,r} + \sin\alpha\,\phi_2^{0,r} \\ A^0 &= -\sin\beta\,\phi_1^{0,i} + \cos\beta\,\phi_2^{0,i}, & G^0 &= \cos\beta\,\phi_1^{0,i} + \sin\beta\,\phi_2^{0,i} \\ H^+ &= -\sin\beta\,\phi_1^{+} + \cos\beta\,\phi_2^{+}, & G^+ &= \cos\beta\,\phi_1^{+} + \sin\beta\,\phi_2^{+} \end{aligned}$$

Can rotate by angle β to "Higgs basis": $s \equiv \sin(\beta-\alpha)$, $c \equiv \cos(\beta-\alpha)$

$$\begin{pmatrix} G^+ \\ (v_{\rm SM} + (sh^0 + cH^0) + iG^0)/\sqrt{2} \end{pmatrix} \qquad \begin{pmatrix} H^+ \\ ((ch^0 - sH^0) + iA^0)/\sqrt{2} \end{pmatrix}$$

Gauge couplings:

γH^+H^-, ZH^+H^-, $W^-H^+A^0$, $W^-H^+(ch^0 - sH^0)$

Two automatic features of the Standard Model:

2) No flavor-changing neutral Higgs couplings.

Generic multi-Higgs-doublet model:

$$\mathcal{L}_{\text{Yuk}} \supset -y^d_{ij}\bar{d}_{Ri}\Phi_1 Q_{Lj} - \tilde{y}^d_{ij}\bar{d}_{Ri}\Phi_2 Q_{Lj} + h.c.$$

Mass matrix for down-type quarks: $m^d_{ij} = (y^d_{ij}v_1 + \tilde{y}^d_{ij}v_2)/\sqrt{2}$. Diagonalizing m^d_{ij} does *not* in general diagonalize y^d_{ij} and $\tilde{y}^d_{ij}$ separately; leads to flavor-changing neutral Higgs couplings.

Flavor-changing neutral Higgs couplings are forbidden if each type of fermion (u, d, ℓ) gets its mass from exactly one Higgs doublet: called "natural flavor conservation." [Glashow & Weinberg; Paschos; 1977]

One doublet: $\mathcal{L} = -y^d_{ij}\bar{d}_{Ri}\Phi Q_{Lj} - y^u_{ij}\bar{u}_{Ri}\tilde{\Phi} Q_{Lj} - y^\ell_{ij}\bar{e}_{Ri}\Phi L_{Lj} + h.c.$

Two doublets: four ways to assign fermion couplings (u, d, ℓ):

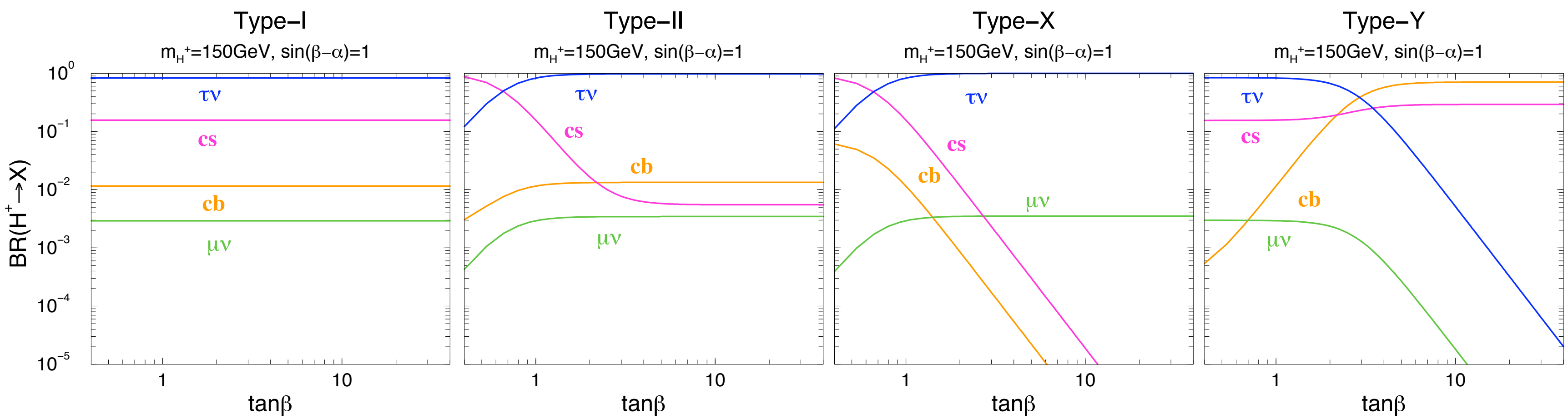
	Type I	Type II	Leptonic	Flipped
Φ_1	$-$	d, ℓ	ℓ	d
Φ_2	u, d, ℓ	u	u, d	u, ℓ

Charged Higgs couplings to fermions (all $\times \frac{ig}{\sqrt{2}M_W}$):

Model	$H^+\bar{u}_i d_j$	$H^+\bar{\nu}_i \ell_i$
Type I	$V_{ij}(\cot\beta\, m_{ui} P_L - \cot\beta\, m_{dj} P_R)$	$\cot\beta\, m_{\ell i} P_R$
Type II	$V_{ij}(\cot\beta\, m_{ui} P_L + \tan\beta\, m_{dj} P_R)$	$\tan\beta\, m_{\ell i} P_R$
Leptonic	$V_{ij}(\cot\beta\, m_{ui} P_L - \cot\beta\, m_{dj} P_R)$	$\tan\beta\, m_{\ell i} P_R$
Flipped	$V_{ij}(\cot\beta\, m_{ui} P_L + \tan\beta\, m_{dj} P_R)$	$\cot\beta\, m_{\ell i} P_R$

Physics controlled by $\tan\beta$ and M_{H+}.
Most experimental studies: Type II model (same as in MSSM).

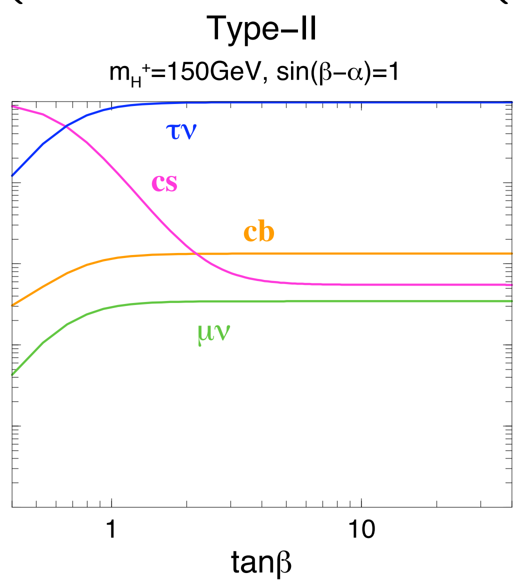
Model	$H^+\bar{u}_i d_j$	$H^+\bar{\nu}_i\ell_i$
Type I	$V_{ij}(\cot\beta\, m_{ui}P_L - \cot\beta\, m_{dj}P_R)$	$\cot\beta\, m_{\ell i}P_R$
Type II	$V_{ij}(\cot\beta\, m_{ui}P_L + \tan\beta\, m_{dj}P_R)$	$\tan\beta\, m_{\ell i}P_R$
Leptonic	$V_{ij}(\cot\beta\, m_{ui}P_L - \cot\beta\, m_{dj}P_R)$	$\tan\beta\, m_{\ell i}P_R$
Flipped	$V_{ij}(\cot\beta\, m_{ui}P_L + \tan\beta\, m_{dj}P_R)$	$\cot\beta\, m_{\ell i}P_R$



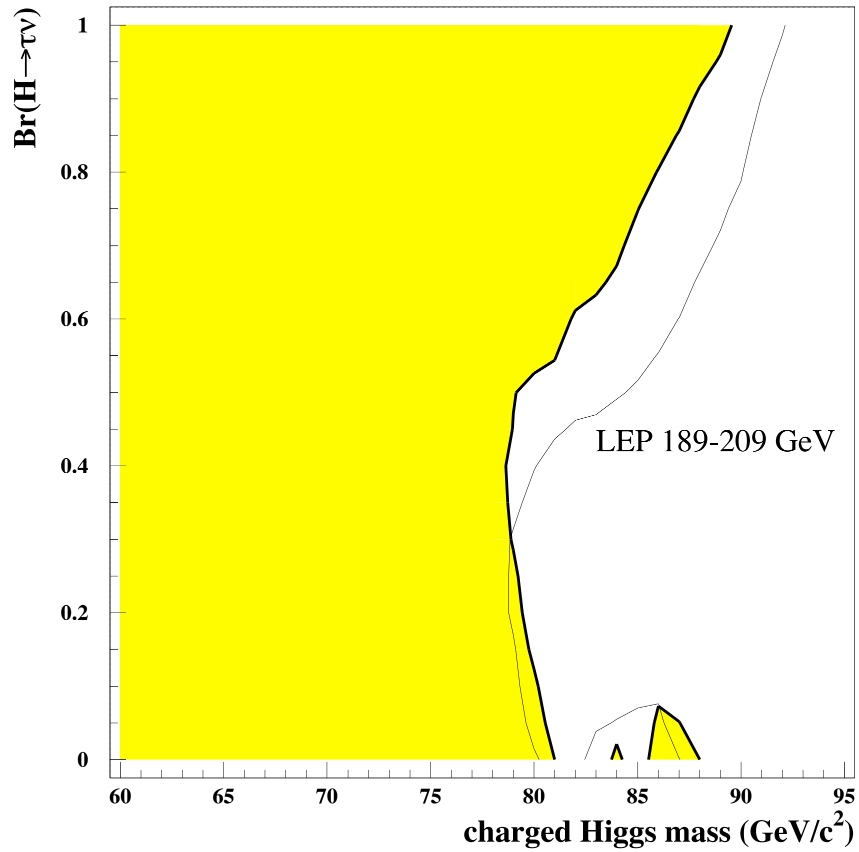
Aoki et al, Phys. Rev. D80, 015017(2009)

LEP, Tevatron, and LHC

LEP combined limit, assuming
$\mathrm{BR}(H^+ \to \tau\nu) + \mathrm{BR}(H^+ \to c\bar{s}) = 1$:
$M_{H^+} > 78.6$ GeV
(89.6 GeV for $\mathrm{BR}(H^+ \to \tau\nu) = 1$)



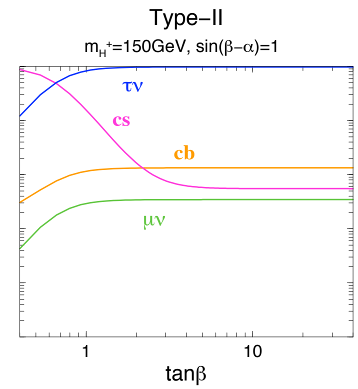
Aoki et al, Phys. Rev. D80, 015017(2009)



ADLO, hep-ex/0107031

Separate OPAL analysis for $\mathrm{BR}(H^+ \to \tau\nu) = 1$:
$M_{H^+} \geq 92.0$ GeV Abbiendi et al [OPAL], Eur. Phys. J. C32, 453 (2004)

LEP, Tevatron, and LHC



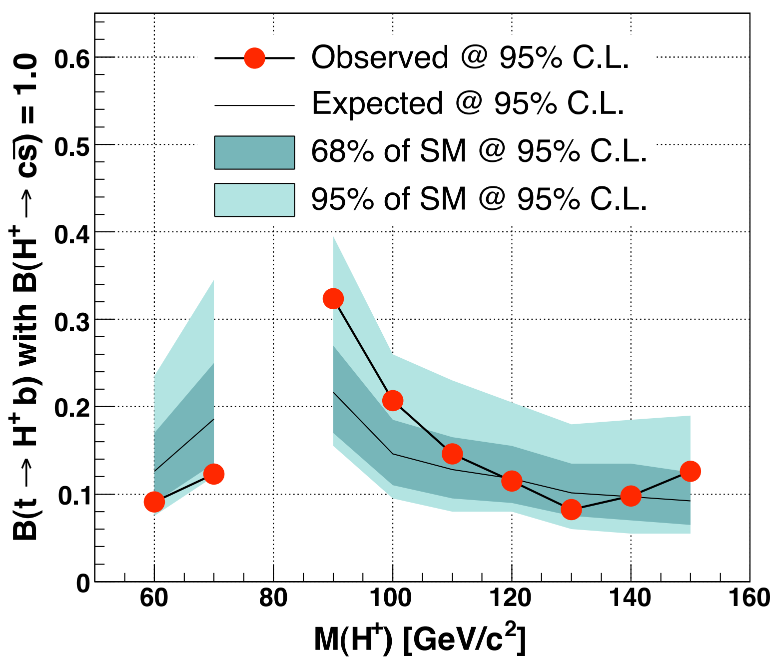
Aoki et al (2009)

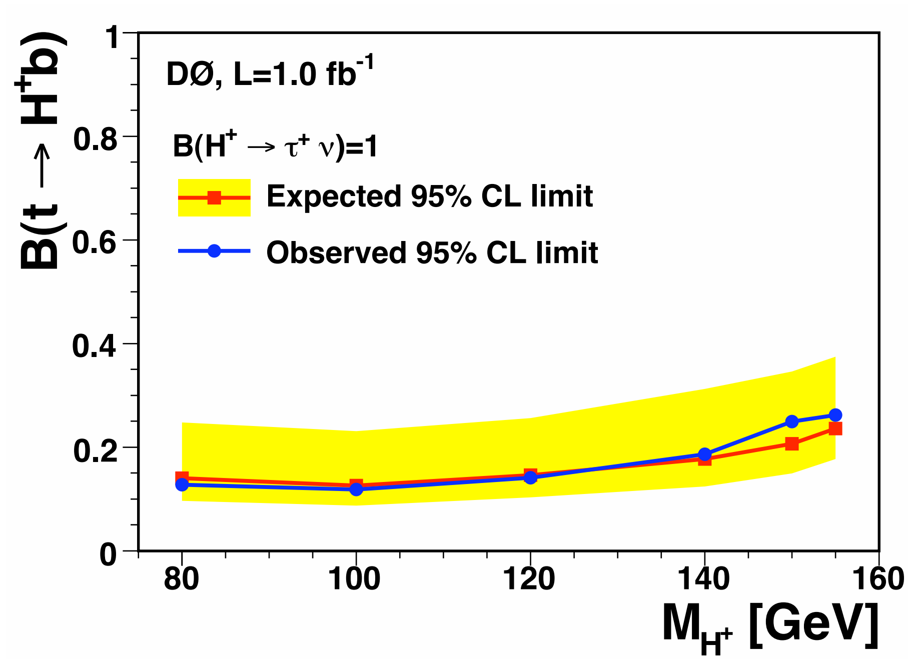
Tevatron search for charged Higgs in top decay

Type-II model: coupling for $t \to bH^+$ is
$\frac{ig}{\sqrt{2}M_W} V_{tb}(\cot\beta\, m_t P_L + \tan\beta\, m_b P_R)$

BR$(H^+ \to c\bar{s}) = 1$
Look for $M_{jj} \neq M_W$

BR$(H^+ \to \tau\nu) = 1$



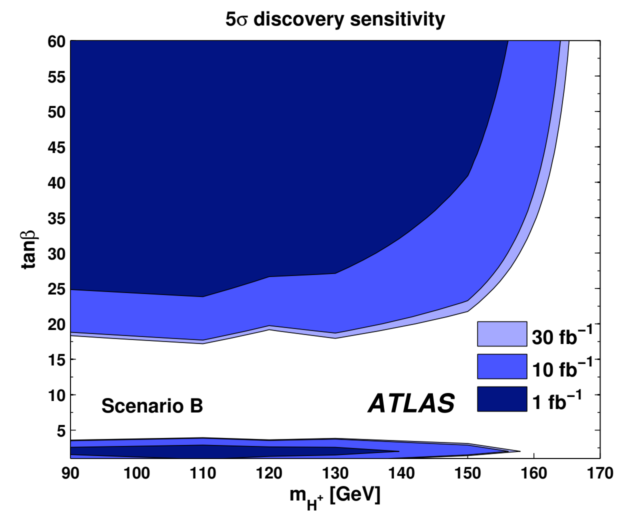


CDF, PRL103, 101803 (2009)

DZero, arXiv:0908.1811

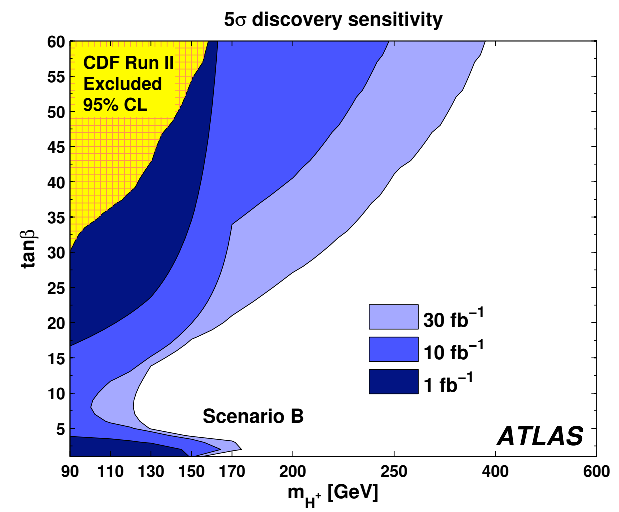
LEP, Tevatron, and LHC

LHC search prospects: Type II 2HDM



Light charged Higgs:
top decay $t \to H^+ b$ with $H^+ \to \tau\nu$

ATLAS CSC book, arXiv:0901.0512



Heavy charged Higgs:
associated production tH^+ with $H^+ \to tb$

Lepton-specific two Higgs doublet model

Model	$H^+\bar{u}_i d_j$	$H^+\bar{\nu}_i \ell_i$
Type II	$V_{ij}(\cot\beta\, m_{ui} P_L + \tan\beta\, m_{dj} P_R)$	$\tan\beta\, m_{\ell i} P_R$
Leptonic	$V_{ij}(\cot\beta\, m_{ui} P_L - \cot\beta\, m_{dj} P_R)$	$\tan\beta\, m_{\ell i} P_R$

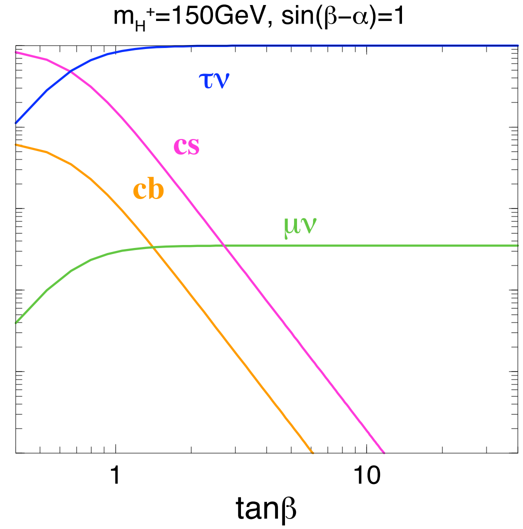
Couplings to quarks: $\propto \cot\beta$, same pattern as Type I 2HDM.
- Constraint from $b \to s\gamma$ same as in Type-I model: $\tan\beta \gtrsim 4(2)$ for $M_{H+} = 100(500)$ GeV. [Su & Thomas, PRD79, 095014 (2009)]
- Production rates in $t \to H^+ b$, tH^+ associated production suppressed by $\cot^2\beta$.

Couplings to leptons: $\propto \tan\beta$
- Decays to taus usually dominate
- Model used as "messenger" of dark matter for PAMELA/ATIC positron excess [Goh, Hall & Kumar, JHEP 05 (2009) 097]

Lepton-specific two Higgs doublet model: constraints

Below the tb threshold:
decays almost entirely to $\tau\nu$.

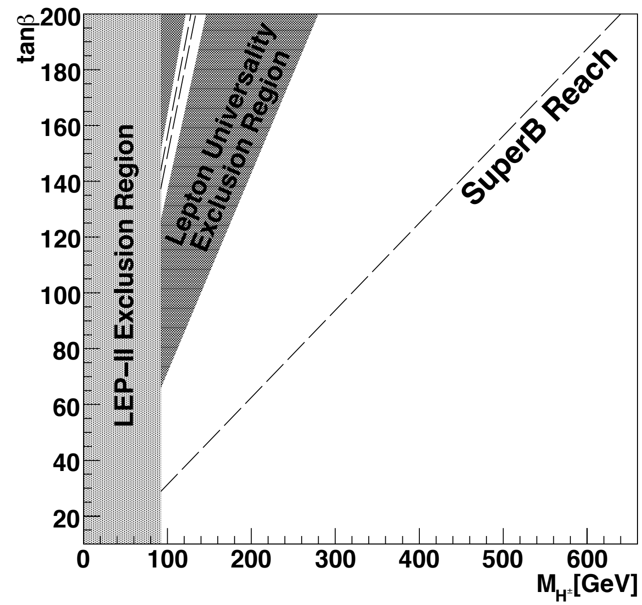
[Plot: Aoki et al, PRD80, 015017(2009)]



Use LEP limit from OPAL:
$M_{H+} \geq 92.0$ GeV
Abbiendi et al [OPAL], EPJC32, 453 (2004)

$\tau \to e\nu\bar{\nu}$ vs $\tau \to \mu\nu\bar{\nu}$:
Tree-level charged Higgs exchange affects lepton universality.

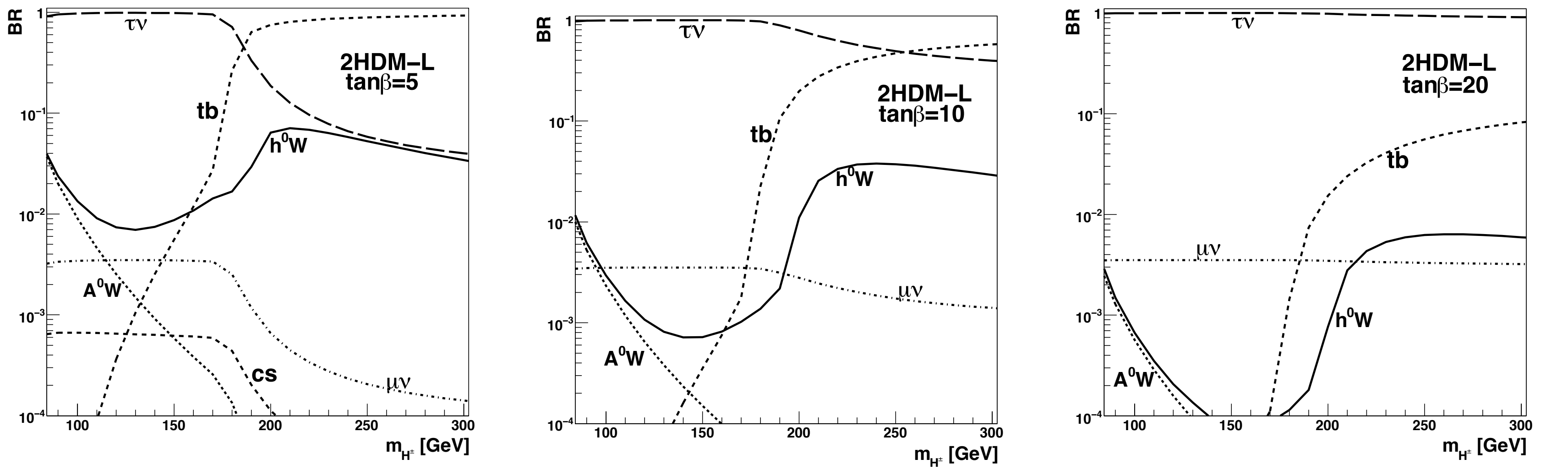
[Plot: HEL & D. MacLennan, PRD79, 115022 (2009)]



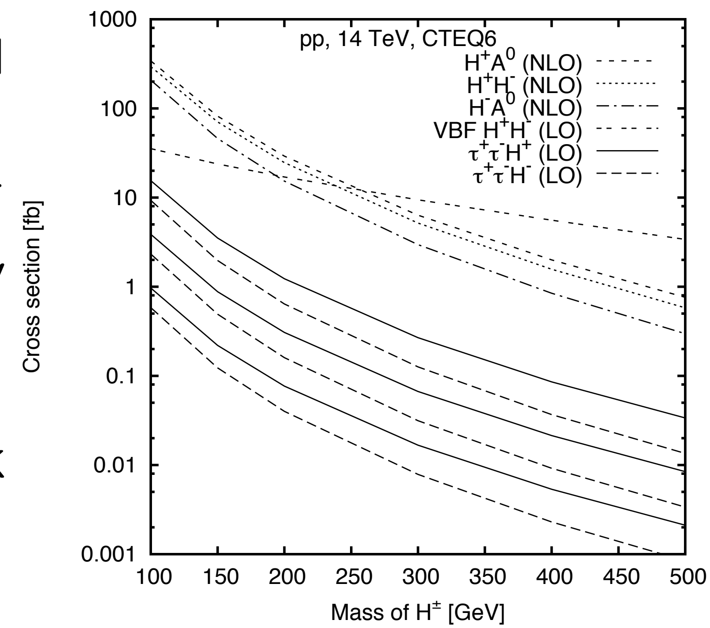
$M_{H+} \geq 1.4 \tan\beta$ GeV
(plus allowed sliver: 0.61–0.73 $\tan\beta$ GeV)

Lepton-specific two Higgs doublet model: LHC prospects

Decays are to $\tau\nu$; also tb above threshold for $\tan\beta$ not too large.



[Plots: HEL & D. MacLennan, PRD79, 115022 (2009)]



Production rates in $t \to H^+b$, tH^+ associated production suppressed by $\cot^2\beta$.

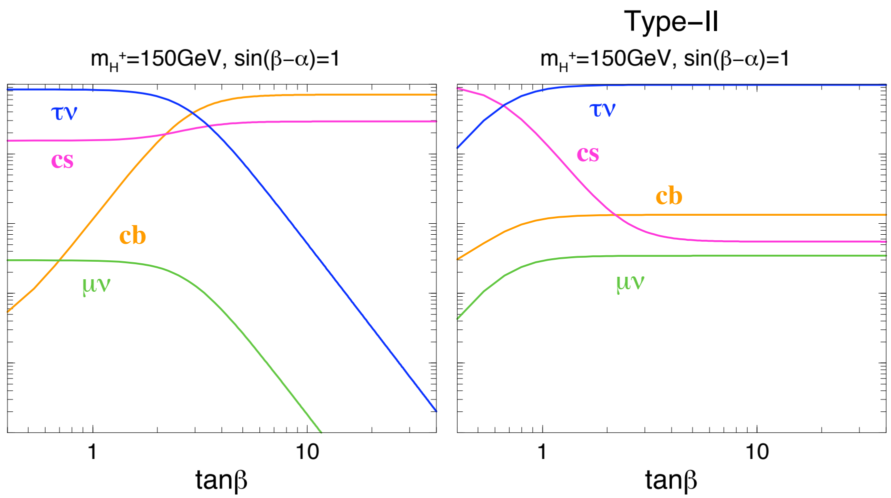
Have to rely instead on electroweak production: $H^+H^- \to \tau^+\tau^- p_T^{\rm miss}$, $H^\pm A^0/H^0 \to \tau^\pm p_T^{\rm miss}\tau\tau$ $(\mu\mu)$

Flipped two Higgs doublet model

Model	$H^+\bar{u}_i d_j$	$H^+\bar{\nu}_i \ell_i$
Type II	$V_{ij}(\cot\beta\, m_{ui} P_L + \tan\beta\, m_{dj} P_R)$	$\tan\beta\, m_{\ell i} P_R$
Flipped	$V_{ij}(\cot\beta\, m_{ui} P_L + \tan\beta\, m_{dj} P_R)$	$\cot\beta\, m_{\ell i} P_R$

Couplings to quarks: same pattern as Type II 2HDM.
- Constraint from $b \to s\gamma$ same as in Type-II model, $M_{H^+} \gtrsim$ 200–300 GeV [modulo cancellations with other flavor-violating contributions]
- Production rates in $t \to H^+ b$, tH^+ associated production same as in Type-II.

Couplings to leptons: proportional to $\cot\beta$ instead of $\tan\beta$.



For $\tan\beta \gtrsim 3$:
$H^+ \to c\bar{b}$ about 2/3,
$H^+ \to c\bar{s}$ about 1/3

$H^+ \to \tau\nu$ ~0.9 for $\tan\beta \lesssim 3$.

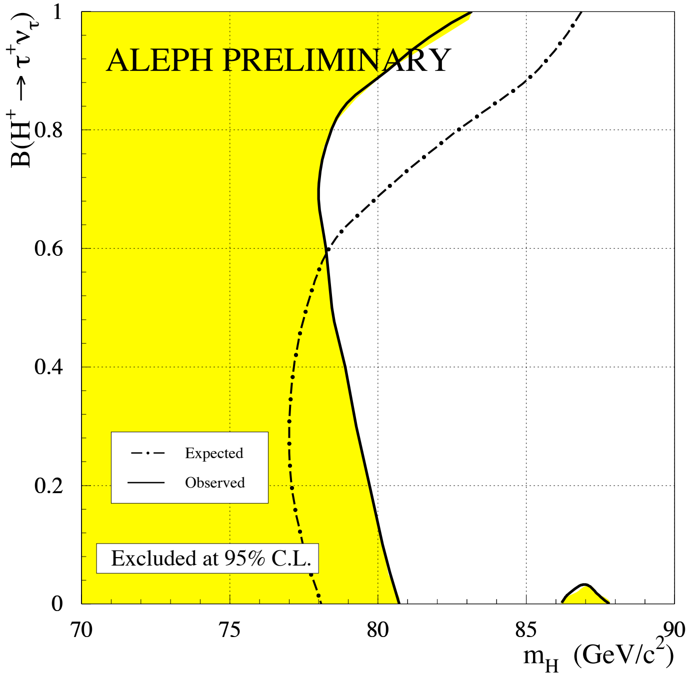
[Plots: Aoki et al, PRD80, 015017(2009)]

Flipped two Higgs doublet model: constraints

Limits from LEP: Can't use LEP combined: DELPHI and L3 actively rejected bs: no good for $H^+ \to c\bar{b}$.
OPAL and ALEPH just selected jets:
assumption is BR$(H^+ \to \tau\nu)$ + BR$(H^+ \to q\bar{q}') = 1$.

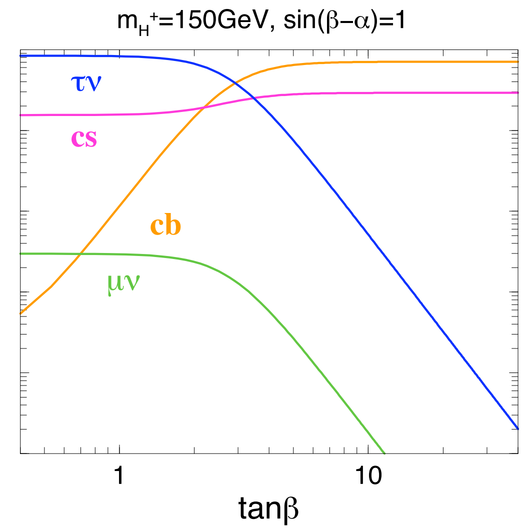
$M_{H+} > 78.0$ GeV overall
83.4 GeV for BR$(H^+ \to \tau\nu) = 1$,
80.7 GeV for BR$(H^+ \to \tau\nu) = 0$

P. Colas [ALEPH], CERN-ALEPH-2001-016

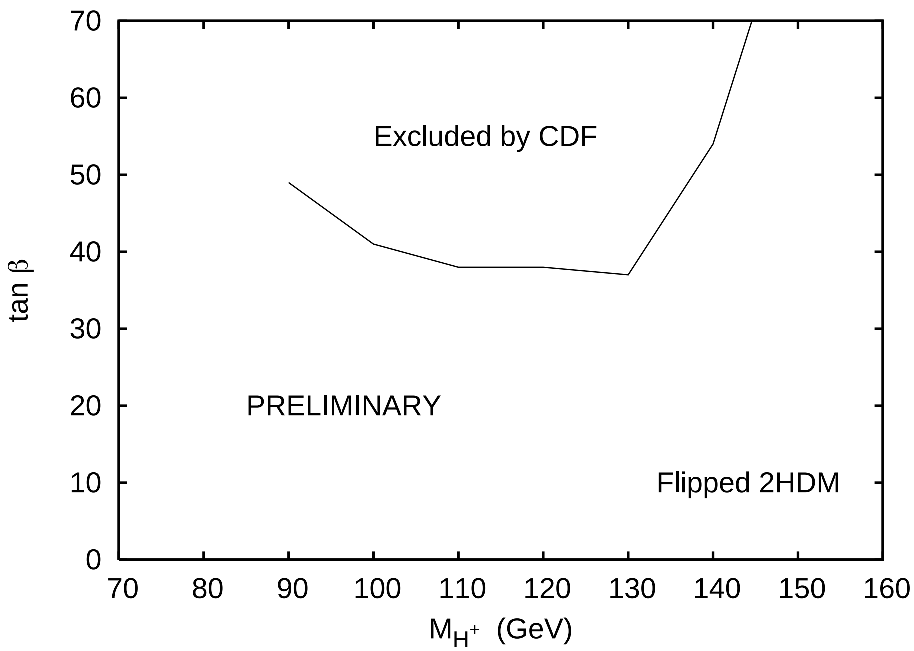


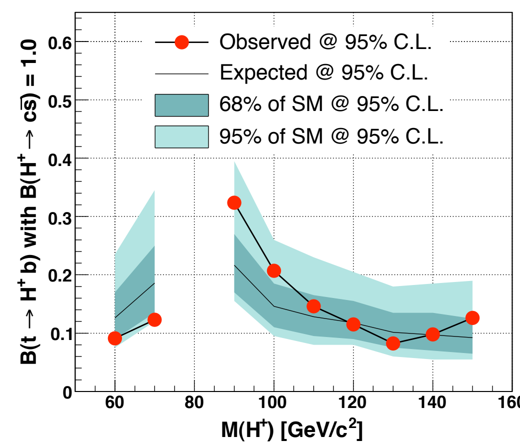
Flipped two Higgs doublet model: constraints

Top quark decay at the Tevatron:
For $\tan\beta \gtrsim 3$, $H^+ \to c\bar{b} + c\bar{s} \simeq 1$. Translate CDF limits on BR($t \to H^+ b$) with BR($H^+ \to c\bar{s}$) = 1. $H^+ \to c\bar{b}$ should have only slightly worse M_{jj} resolution.



Aoki et al (2009)





PRELIMINARY HEL & D. MacLennan, in preparation

CDF (2009)

Flipped two Higgs doublet model: constraints

Top quark decay at the Tevatron:
For $\tan\beta \sim 1$, H^+ branching ratios about the same as in Type **II** model. Use Tevatron limits from DØ directly. (improved extraction in progress)

M_{H^+} (GeV)	$\tan\beta$ lower bound
100	1.4
120	1.1
150	0.5

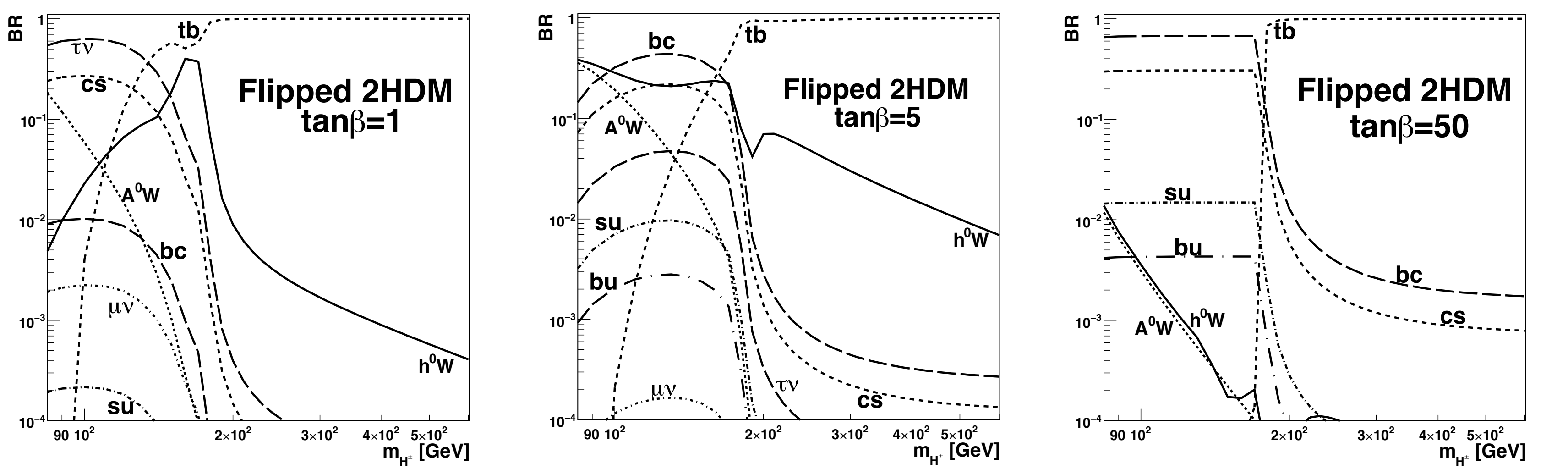
PRELIMINARY HEL & D. MacLennan, in preparation

Flipped two Higgs doublet model: LHC prospects

Production couplings to quarks are identical to Type II 2HDM.

Below tb threshold, decays are to $\tau\nu$ for $\tan\beta < 3$, $cb + cs$ for $\tan\beta > 3$.

Above tb threshold, decays to tb always dominate.



HEL & D. MacLennan, in preparation

Flipped two Higgs doublet model: LHC prospects

Light charged Higgs: BR($t \to H^+ b$) same as Type II model, but $H^+ \to cb$, cs at large $\tan\beta$! LHC studies with $H^+ \to \tau\nu$ not applicable.

Heavy charged Higgs: $H^+ \to tb$ decay dominates; tH^+ associated production cross section same as Type II model. Studies carry over verbatim.

5σ discovery prospects (30 fb^{-1}): [based on ATLAS]

$\tan\beta$	M_{H^+} range accessible (GeV)
30	180–200
45	180–250
60	180–300

Two-doublet model for neutrino masses

S.M. Davidson and H.E.L., arXiv:0906.3335

New field content:

3 right-handed two-component neutrinos ν_{R_i} (EW singlets)

Second scalar doublet Φ_2, same EW charges as SM Higgs

New symmetry: global U(1)

ν_{R_i} and Φ_2 have charge +1; all SM fields uncharged

$M\nu_R\nu_R$ Majorana mass term forbidden by global U(1).

Lepton Yukawa couplings: structure fixed by U(1)

$$\mathcal{L}_{Yuk} = -y^{\ell}_{ij}\bar{e}_{R_i}\Phi_1^\dagger L_{L_j} - y^{\nu}_{ij}\bar{\nu}_{R_i}\tilde{\Phi}_2^\dagger L_{L_j} + \text{h.c.}$$

To generate neutrino masses, break U(1) explicitly:

$$\begin{aligned} V &= m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}] + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 \\ &\quad + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \end{aligned}$$

Φ_2 gets a tiny vev $v_2 \sim$ eV.

Particles and couplings

3 SM neutrinos are Dirac particles; no additional fermionic d.o.f.

4 new scalar degrees of freedom: $H^\pm$, H^0, A^0

Mixing effects: new scalars $\sim \Phi_2 + \mathcal{O}(v_2/v_1)\Phi_1$: completely negligible

Yukawa couplings of physical scalars:

$$\mathcal{L}_{Yuk} = \frac{m_{\nu_i}}{v_2} H^0 \bar{\nu}_i \nu_i - \frac{i m_{\nu_i}}{v_2} A^0 \bar{\nu}_i \gamma_5 \nu_i - \sqrt{2}\frac{m_{\nu_i}}{v_2}[U^*_{\ell i} H^+ \bar{\nu}_i P_L e_\ell + \text{h.c.}]$$

$U_{\ell i}$ is the Maki-Nakagawa-Sakata-Pontecorvo matrix

Constraint from big bang nucleosynthesis:

$$y_i^\nu \equiv \sqrt{2}\frac{m_{\nu_i}}{v_2} \lesssim \frac{1}{30}\left[\frac{M_{H^+}}{100\ \text{GeV}}\right]\left[\frac{1/\sqrt{2}}{|U_{\ell i}|}\right]$$

a little bigger than SM bottom quark Yukawa coupling

or $v_2 \gtrsim 2$ eV (scales with heaviest neutrino mass).

Phenomenology: decays of new scalars

Fermionic modes: $H^+ \to \ell^+\nu$, $A^0/H^0 \to \nu\bar{\nu}$ (via y_i^ν)

Bosonic modes: $A^0/H^0 \to W^+H^-$ or $H^+ \to W^+A^0/H^0$ (gauge int)

depends on masses: $M_A^2 = M_H^2 = M_{H^+}^2 + \lambda_4 v_1^2/2$

Most interesting decays: $H^+ \to \ell^+\nu$.

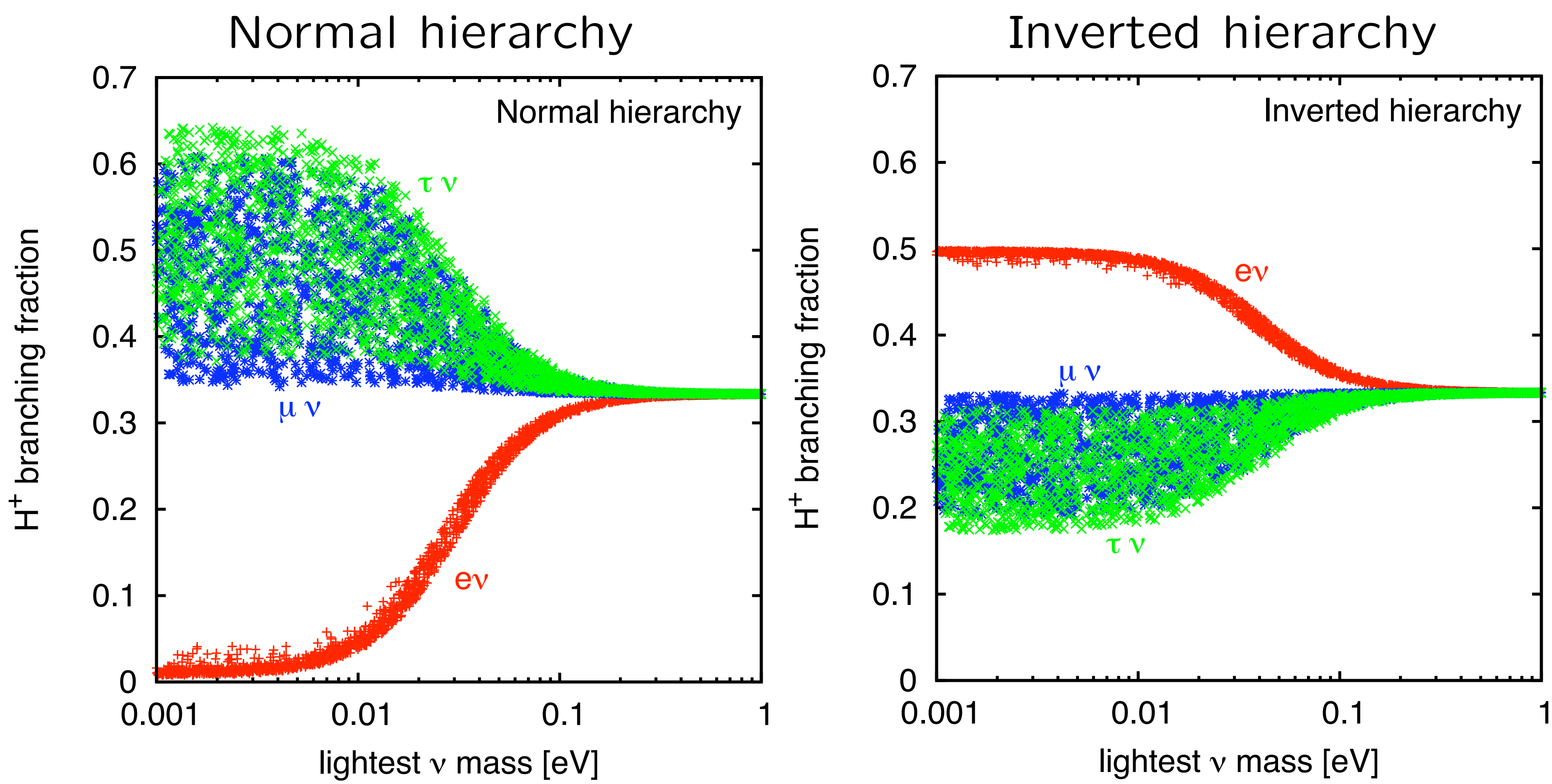
Assume $M_{A,H} > M_{H^+}$: no $H^+ \to W^+H^0/A^0$.

$$\Gamma\left(H^+ \to \ell^+\nu\right) = \frac{M_{H^+}}{8\pi v_2^2} \sum_i m_{\nu_i}^2 |U_{\ell i}|^2$$

Depends on expectation value of m_ν^2 in *flavor* eigenstate ν_ℓ.

$$\mathrm{BR}(H^+ \to \ell^+\nu) = \frac{\sum_i m_{\nu_i}^2 |U_{\ell i}|^2}{\sum_\ell \left[\sum_i m_{\nu_i}^2 |U_{\ell i}|^2\right]}$$

Identical to Φ^+ decay BRs in Type-2 seesaw model.



Behavior controlled by $\theta_{23} \sim 45^\circ$, U_{e3} small.

Normal hierarchy: eigenstate 3 contains half of ν_μ, half of ν_τ, very little ν_e

$\rightarrow$ BR$(\mu\nu) \simeq$ BR$(\tau\nu) \simeq 1/2$, BR$(e\nu) \ll 1$

Inverted hierarchy: eigenstates 1 & 2 contain all of ν_e, half of ν_μ, half of ν_τ

$\rightarrow$ BR$(e\nu) \simeq 1/2$, BR$(\mu\nu) \simeq$ BR$(\tau\nu) \simeq 1/4$

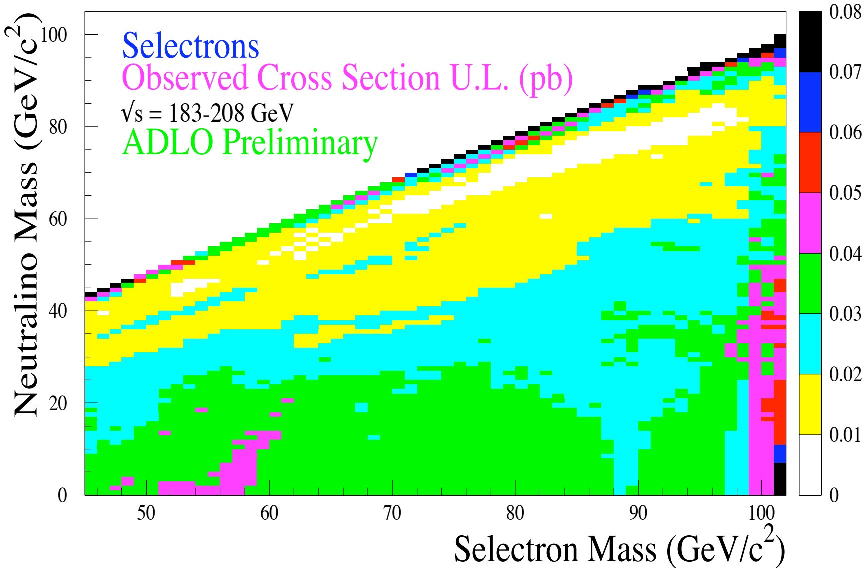
Degenerate spectrum

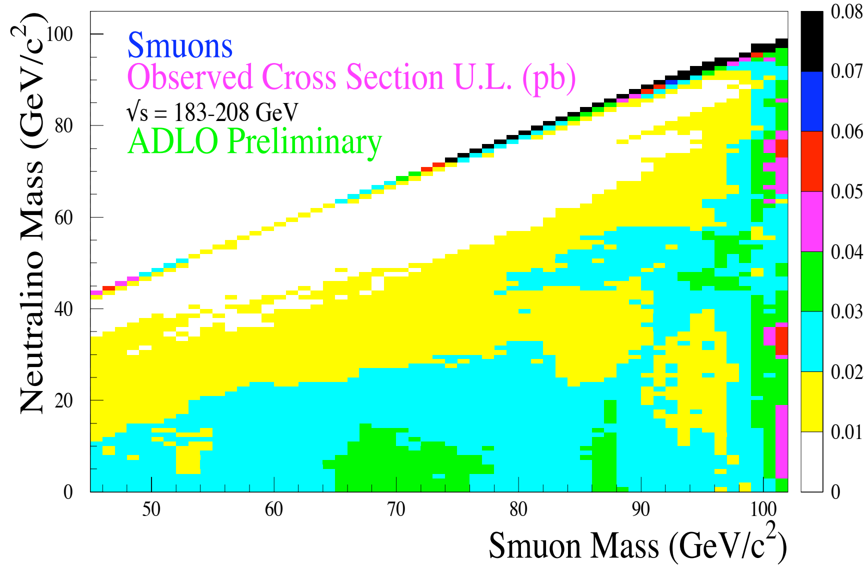
$\rightarrow$ all three BRs $= 1/3$.

Constraints: LEP limit on H^+H^-

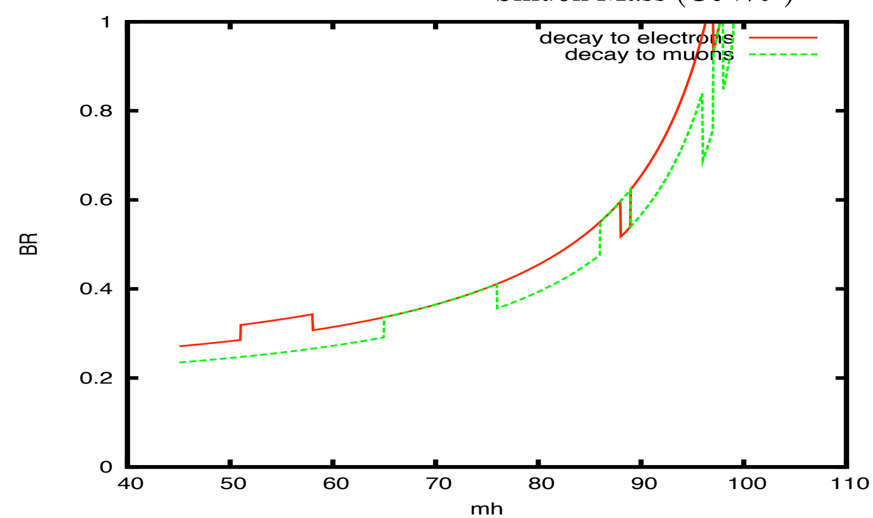
BR($H^+ \to \tau\nu$) too small for usual LEP charged Higgs search.

Look at LEP slepton searches instead with massless "neutralino".

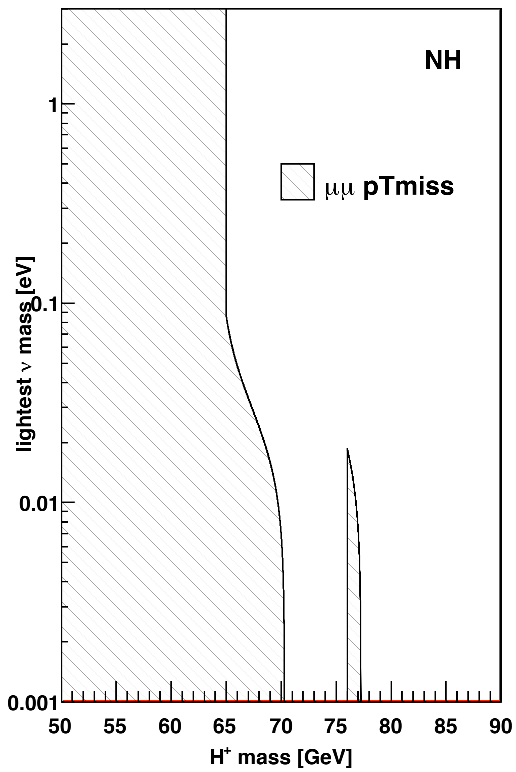


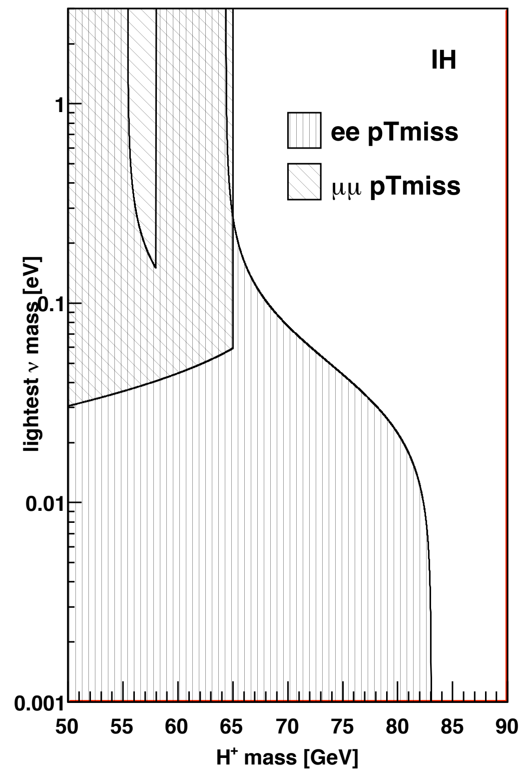


LEPSUSYWG/04-01.1



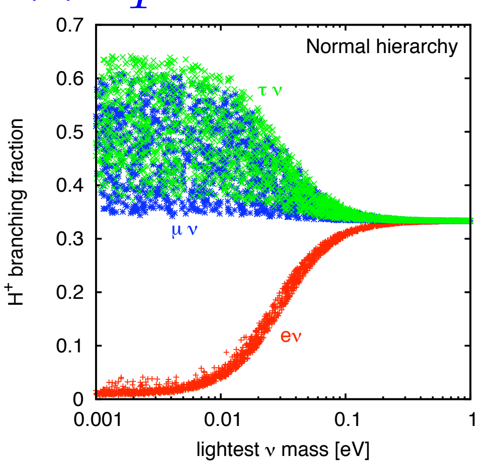
Put in $e^+e^- \to H^+H^-$ xsec, read off upper limit on BRs

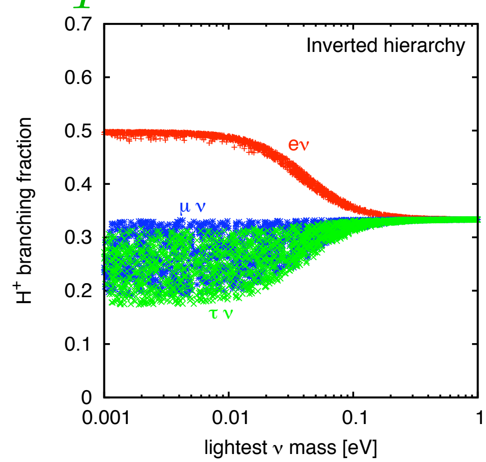




NH: $\mu\mu p_T^{miss}$ channel strongest

IH: eep_T^{miss} channel strongest





Phenomenology: LHC prospects

Rely on pair production: $pp \to H^+H^-$, $H^\pm A^0/H^0$, A^0H^0

- No coups to quarks; $H^+\ell_L^-\nu_R$ coupling $\lesssim 1/30$ (BBN constraint)
- Single production $\sim g^2 v_2$: super tiny

H^+ BR to $\mu\nu$ or $e\nu$ always $\geq 1/3$: $\ell^+\ell^- p_T^{miss}$ signature

Nice feature: H^+H^-Z coupling.

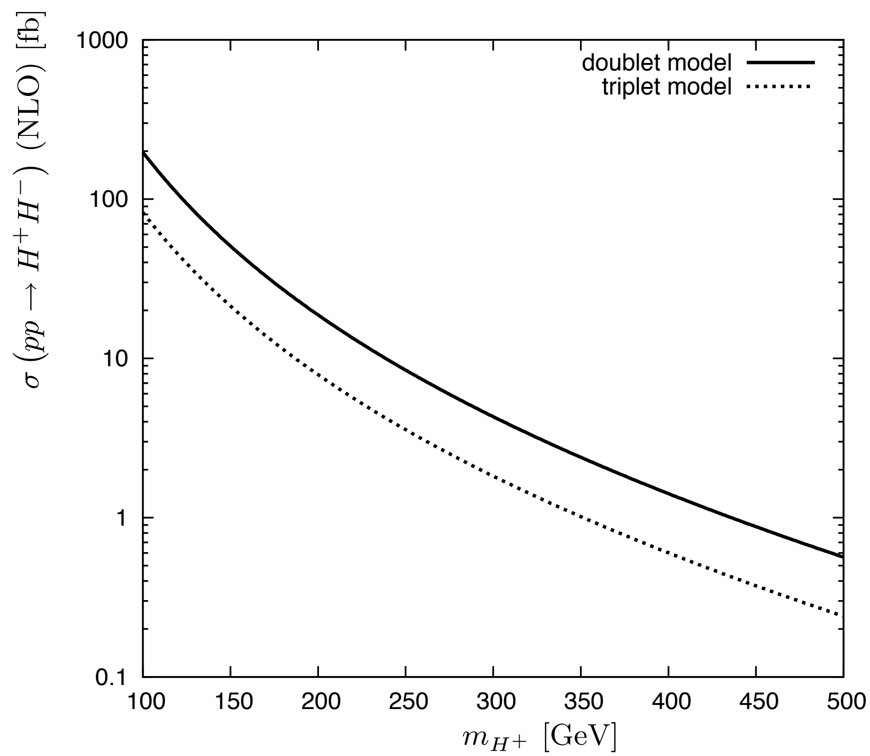
This model: SU(2) doublet:

$$g_{H^+H^-Z} = \frac{e}{s_W c_W}\left(\frac{1}{2} - s_W^2\right)$$

Type-2 seesaw: SU(2) triplet:

$$g_{\Phi^+\Phi^-Z} = \frac{e}{s_W c_W}\left(0 - s_W^2\right)$$

Doublet cross section ~2.5x larger than triplet.



Phenomenology: LHC prospects

S.M. Davidson and H.E.L., work in progress

Signal: $pp \to H^+H^- \to \mu^+\mu^- p_T^{\text{miss}}$, $e^+e^- p_T^{\text{miss}}$, $e^\pm\mu^\mp p_T^{\text{miss}}$

Major backgrounds: W^+W^-, $t\bar{t}$, ZZ, $Z\gamma$

Selection cuts:
Both leptons $p_T > 20$ GeV; $p_T^{\text{miss}} > 30$ GeV
Veto jets with $p_T > 30$ GeV (kills most of $t\bar{t}$ background)
Veto Z pole, 80 GeV $< M_{\ell^+\ell^-} <$ 100 GeV
$H_T' \equiv p_T^{\ell^+} + p_T^{\ell^-} + p_T^{\text{miss}} > 200$ (600) GeV [for $M_{H^+} = 100$ (300) GeV]

Looks promising for discovery of $M_{H+} = 100$ GeV with 30 fb^{-1}
($M_{H+} = 300$ GeV with 300 fb^{-1}) [preliminary]

Conclusions

LHC studies for charged Higgs are well-developed... for the Type II model (and to some extent for Type I).

Other charged Higgs coupling patterns lead to different signal processes – both production and decay.

For some channels, LHC studies can be reinterpreted directly.
- Flipped 2HDM: $H^+ \to t\bar{b}$

For others, new phenomenological & experimental studies needed.
- Neutrino mass model: $H^+H^- \to \ell^+\ell^{(\prime)-}p_T^{\text{miss}}$ promising
- Lepton-specific 2HDM: can we do anything with $H^+H^- \to \tau\tau$?