Lepton non-universality at LEP and charged Higgs

Jae-hyeon Park

TU Dresden

Institutsseminar
TU Dresden, 13.10.2011

Standard Model

$$\mathscr{L}_{\text{SM}} = -\frac{1}{4} F \cdot F + \overline{\psi} i \not{D} \psi - [H \overline{\psi}_L Y \psi_R + \text{h.c.}] + \frac{g^2 \theta}{32\pi^2} F \cdot \widetilde{F} + |DH|^2 - V(H)$$

Omitted: Majorana mass terms of neutrinos

Standard Model

$$\mathscr{L}_{\text{SM}} = \underbrace{-\frac{1}{4}F\cdot F + \overline{\psi} i \not{D} \psi}_{\text{tested}} - [H\,\overline{\psi}_L Y\,\psi_R + \text{h.c.}] + \frac{g^2\theta}{32\pi^2} F\cdot\widetilde{F} + |DH|^2 - V(H)$$

Omitted: Majorana mass terms of neutrinos

Standard Model

$$\mathscr{L}_{\mathrm{SM}} = \boxed{-\frac{1}{4}F\cdot F + \overline{\psi} i \not{D}\psi} - \boxed{[H\,\overline{\psi}_L Y\,\psi_R + \mathrm{h.c.}]} + \frac{g^2\theta}{32\pi^2}F\cdot\widetilde{F} + \boxed{|DH|^2} - V(H)$$

tested

probed

Omitted: Majorana mass terms of neutrinos

Standard Model

$$\mathscr{L}_{\mathrm{SM}} = \underbrace{-\frac{1}{4}F\cdot F+\overline{\psi}i\not{D}\psi}_{\text{tested}} - \underbrace{\underbrace{[H\,\overline{\psi}_L Y\,\psi_R+\mathrm{h.c.}]}_{\text{probed}}+\frac{g^2\theta}{32\pi^2}F\cdot\widetilde{F}}_{\text{constrained}}+\underbrace{|DH|^2}_{\text{probed}}-V(H)$$

Omitted: Majorana mass terms of neutrinos

Standard Model

$$\mathscr{L}_{\mathrm{SM}} = \underbrace{-\frac{1}{4}F\cdot F + \overline{\psi} i \not{D} \psi}_{\text{tested}} - \underbrace{\underbrace{[H\,\overline{\psi}_L Y\,\psi_R + \mathrm{h.c.}]}_{\text{probed}} + \frac{g^2\theta}{32\pi^2}F\cdot\widetilde{F}}_{\text{constrained}} + \underbrace{|DH|^2}_{\text{probed}} - \underbrace{V(H)}_{\text{to be explored}}$$

Omitted: Majorana mass terms of neutrinos

Lepton universality in charged current interactions

- SM predicts lepton universality.
- W boson couplings to e, μ, τ are determined by SU(2) gauge invariance.

$$\mathscr{L}_{\mathrm{CC}} = \frac{g}{\sqrt{2}} \sum_{l=e,\mu,\tau} W_\mu^\dagger \, \overline{\nu}_l \, \gamma^\mu \left(\frac{1-\gamma_5}{2} \right) l + \mathrm{h.c.}$$

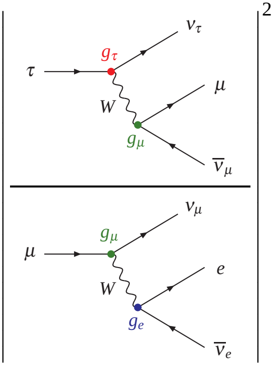
- Thoroughly tested in
  $\mu \to e\nu\nu$, $\tau \to \mu\nu\nu$, $\tau \to e\nu\nu$, $\pi \to e\nu$, $\pi \to \mu\nu$, $\tau \to \pi\nu$, ...
  All these consistent with lepton universality.

Test of lepton universality at $\mu \to e\nu\nu$ and $\tau \to \mu\nu\nu$

- Use parameterization

$$\mathscr{L}_{\mathrm{CC}} = \sum_{l=e,\mu,\tau} \frac{g_l}{\sqrt{2}} W_\mu^\dagger \, \overline{\nu}_l \gamma^\mu \left(\frac{1-\gamma_5}{2} \right) l + \mathrm{h.c.}$$

- Take ratio $\Gamma(\tau \to \mu\nu\nu)/\Gamma(\mu \to e\nu\nu)$:



$$\rightsquigarrow \quad (g_\tau/g_e)_{\tau\mu} = 1.0004 \pm 0.0022$$

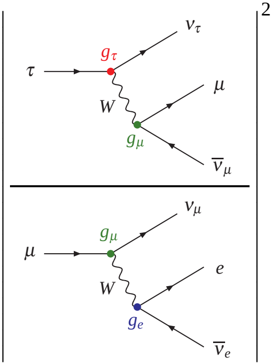
Data from Loinaz, Okamura, Rayyan, Takeuchi, Wijewardhana, PRD(2004)

Test of lepton universality at $\mu \to e\nu\nu$ and $\tau \to \mu\nu\nu$

- Use parameterization

$$\mathscr{L}_{\mathrm{CC}} = \sum_{l=e,\mu,\tau} \frac{g_l}{\sqrt{2}} W^\dagger_\mu \overline{\nu}_l \gamma^\mu \left(\frac{1-\gamma_5}{2}\right) l + \mathrm{h.c.}$$

- Take ratio $\Gamma(\tau \to \mu\nu\nu)/\Gamma(\mu \to e\nu\nu)$:



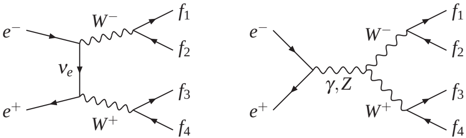
$$\rightsquigarrow \quad (g_\tau/g_e)_{\tau\mu} = 1.0004 \pm 0.0022$$

Perfect agreement with lepton universality

Data from Loinaz, Okamura, Rayyan, Takeuchi, Wijewardhana, PRD(2004)

Measurement of $B(W \to l\nu)$ at LEP

- LEP directly measured $B(W \to e\nu_e)$, $B(W \to \mu\nu_\mu)$, $B(W \to \tau\nu_\tau)$, from partial cross sections of $WW \to 4f$.



$(f_1, f_2) = (e, \overline{\nu}_e), (\mu, \overline{\nu}_\mu), (\tau, \overline{\nu}_\tau), (d, \overline{u}), (s, \overline{c})$.
(f_4, f_3) is a conjugate.

Tau mode excess

LEP electroweak working group, hep-ex/0612034

- LEP results

Experiment	$B(W \to e\nu_e)$ [%]	$B(W \to \mu\nu_\mu)$ [%]	$B(W \to \tau\nu_\tau)$ [%]
ALEPH	$10.78 \pm 0.29^*$	$10.87 \pm 0.26^*$	$11.25 \pm 0.38^*$
DELPHI	$10.55 \pm 0.34^*$	$10.65 \pm 0.27^*$	$11.46 \pm 0.43^*$
L3	$10.78 \pm 0.32^*$	$10.03 \pm 0.31^*$	$11.89 \pm 0.45^*$
OPAL	10.40 ± 0.35	10.61 ± 0.35	11.18 ± 0.48
LEP	10.65 ± 0.17	10.59 ± 0.15	11.44 ± 0.22

- Under assumption of $B(W \to e\nu_e) = B(W \to \mu\nu_\mu)$,

$$\left.\frac{B(W \to \tau\nu_\tau)}{[B(W \to e\nu_e) + B(W \to \mu\nu_\mu)]/2}\right|_{\mathrm{LEP}} = 1.077 \pm 0.026$$

- New physics?

Tau mode excess

LEP electroweak working group, hep-ex/0612034

- LEP results

Experiment	$B(W \to e\nu_e)$ [%]	$B(W \to \mu\nu_\mu)$ [%]	$B(W \to \tau\nu_\tau)$ [%]
ALEPH	$10.78 \pm 0.29^*$	$10.87 \pm 0.26^*$	$11.25 \pm 0.38^*$
DELPHI	$10.55 \pm 0.34^*$	$10.65 \pm 0.27^*$	$11.46 \pm 0.43^*$
L3	$10.78 \pm 0.32^*$	$10.03 \pm 0.31^*$	$11.89 \pm 0.45^*$
OPAL	10.40 ± 0.35	10.61 ± 0.35	11.18 ± 0.48
LEP	10.65 ± 0.17	10.59 ± 0.15	11.44 ± 0.22

- Under assumption of $B(W \to e\nu_e) = B(W \to \mu\nu_\mu)$,

$$\left.\frac{B(W \to \tau\nu_\tau)}{[B(W \to e\nu_e) + B(W \to \mu\nu_\mu)]/2}\right|_{\mathrm{LEP}} = 1.077 \pm 0.026$$

- New physics?

Tau mode excess

LEP electroweak working group, hep-ex/0612034

- LEP results

Experiment	$B(W \to e\nu_e)$ [%]	$B(W \to \mu\nu_\mu)$ [%]	$B(W \to \tau\nu_\tau)$ [%]
ALEPH	$10.78 \pm 0.29^*$	$10.87 \pm 0.26^*$	$11.25 \pm 0.38^*$
DELPHI	$10.55 \pm 0.34^*$	$10.65 \pm 0.27^*$	$11.46 \pm 0.43^*$
L3	$10.78 \pm 0.32^*$	$10.03 \pm 0.31^*$	$11.89 \pm 0.45^*$
OPAL	10.40 ± 0.35	10.61 ± 0.35	11.18 ± 0.48
LEP	10.65 ± 0.17	10.59 ± 0.15	11.44 ± 0.22

- Under assumption of $B(W \to e\nu_e) = B(W \to \mu\nu_\mu)$,

$$\left.\frac{B(W \to \tau\nu_\tau)}{[B(W \to e\nu_e) + B(W \to \mu\nu_\mu)]/2}\right|_{\mathrm{LEP}} = 1.077 \pm 0.026$$

7.7% or 2.8 σ departure from lepton universality.

- New physics?

Previous attempts for explanation

X.-Y. Li, E. Ma, hep-ph/0507017

- Gauge model of generation non-universality.
- Two SU(2) gauge groups:
  one for 1st and 2nd family fermions, the other for 3rd.
- Mixing of gauge bosons leads to flavor-dependent lightest W boson couplings to leptons.
- Can fit leptonic W branching ratios.

Previous attempts for explanation

X.-Y. Li, E. Ma, hep-ph/0507017

- Gauge model of generation non-universality.
- Two SU(2) gauge groups:
  one for 1st and 2nd family fermions, the other for 3rd.
- Mixing of gauge bosons leads to flavor-dependent lightest W boson couplings to leptons.
- Can fit leptonic W branching ratios.
- **However**, it decreases

$$\Gamma(\tau \to \mu \nu \nu)/\Gamma(\mu \to e \nu \nu)$$

by **7%** $\approx$ **15** σ $\longrightarrow$ **ruled out.**

Dilemma

- A model leading to effective interactions

$$\mathscr{L}_{\mathrm{CC}} = \sum_{l=e,\mu,\tau} \frac{g_l}{\sqrt{2}} W_\mu^\dagger \overline{\nu}_l \gamma^\mu \left(\frac{1-\gamma_5}{2} \right) l + \mathrm{h.c.},$$

  with $g_\tau \neq g_{e,\mu}$, generically conflicts with lepton universality tests from μ, τ decays.

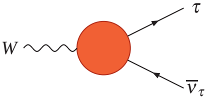
- A different approach is preferable.

Dilemma

- A model leading to effective interactions

$$\mathscr{L}_{\mathrm{CC}} = \sum_{l=e,\mu,\tau} \frac{g_l}{\sqrt{2}} W^\dagger_\mu \overline{\nu}_l \gamma^\mu \left(\frac{1-\gamma_5}{2} \right) l + \mathrm{h.c.},$$

  with $g_\tau \neq g_{e,\mu}$, generically conflicts with lepton universality tests from μ, τ decays.



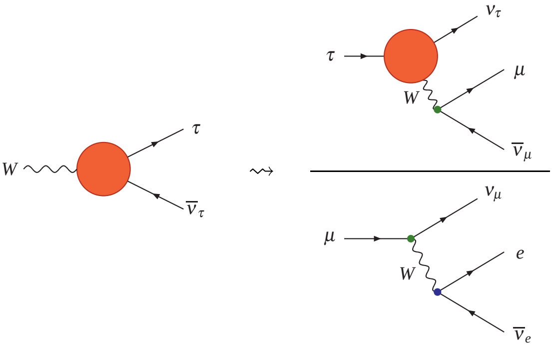
- A different approach is preferable.

Dilemma

- A model leading to effective interactions

$$\mathscr{L}_{\rm CC} = \sum_{l=e,\mu,\tau} \frac{g_l}{\sqrt{2}} W_\mu^\dagger \overline{\nu}_l \gamma^\mu \left(\frac{1-\gamma_5}{2}\right) l + \text{h.c.},$$

  with $g_\tau \neq g_{e,\mu}$, generically conflicts with lepton universality tests from μ, τ decays.



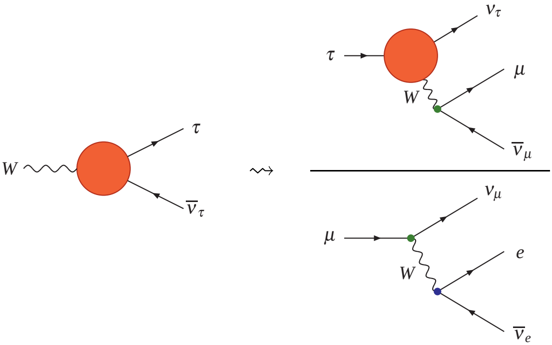
- A different approach is preferable.

Dilemma

- A model leading to effective interactions

$$\mathscr{L}_{\mathrm{CC}} = \sum_{l=e,\mu,\tau} \frac{g_l}{\sqrt{2}} W_\mu^\dagger \, \overline{\nu}_l \, \gamma^\mu \left(\frac{1-\gamma_5}{2} \right) l + \mathrm{h.c.},$$

with $g_\tau \neq g_{e,\mu}$, generically conflicts with lepton universality tests from μ, τ decays.



- A different approach is preferable.

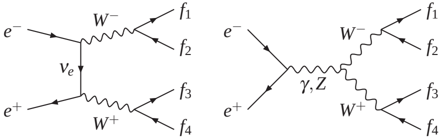
Outline

1. Introduction
2. Charged Higgs solution
3. Constraints from data
4. Effects on $B(W \to l\nu)$
5. Test at future experiments
6. Other related works

Can charged Higgs be a solution?

JhP, JHEP(2006)

- Suppose H^+H^- pairs were produced at LEP.

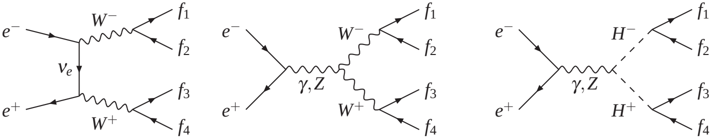


- $B(W \to l\nu)$ is measured by counting final state fermions.
- σ_{HH} is a decreasing function of $m_{H^\pm}$ → $\boxed{m_{H^\pm} \approx m_W \text{ desirable.}}$
  See the plot on Page 17.
- Hard (but not impossible) to realize in MSSM due to
  $m_{H^\pm}^2 = m_W^2 + m_A^2$ and $m_A > 93$ GeV.
- Here consider a 2HDM.

Can charged Higgs be a solution?

JhP, JHEP(2006)

- Suppose H^+H^- pairs were produced at LEP.

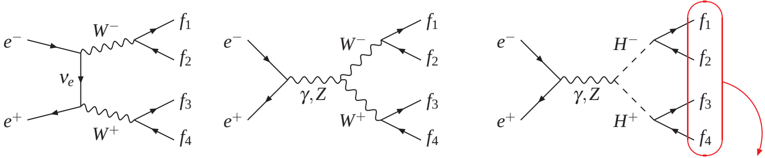


- $B(W \to l\nu)$ is measured by counting final state fermions.
- σ_{HH} is a decreasing function of $m_{H^\pm}$ → $\boxed{m_{H^\pm} \approx m_W \text{ desirable.}}$
  See the plot on Page 17.
- Hard (but not impossible) to realize in MSSM due to
  $m^2_{H^\pm} = m^2_W + m^2_A$ and $m_A > 93$ GeV.
- Here consider a 2HDM.

Can charged Higgs be a solution?

JhP, JHEP(2006)

- Suppose H^+H^- pairs were produced at LEP.



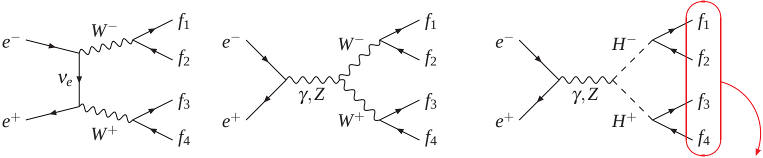
Mostly, $(f_1, f_2) = (\tau, \overline{\nu}_\tau), (s, \overline{c})$.

- $B(W \to l\nu)$ is measured by counting final state fermions.
- σ_{HH} is a decreasing function of $m_{H^\pm}$ → $m_{H^\pm} \approx m_W$ desirable.
  See the plot on Page 17.
- Hard (but not impossible) to realize in MSSM due to
  $m_{H^\pm}^2 = m_W^2 + m_A^2$ and $m_A > 93$ GeV.
- Here consider a 2HDM.

Can charged Higgs be a solution?

JhP, JHEP(2006)

- Suppose H^+H^- pairs were produced at LEP.



Mostly, $(f_1, f_2) = (\tau, \overline{\nu}_\tau), (s, \overline{c})$.

- $B(W \to l\nu)$ is measured by counting final state fermions.

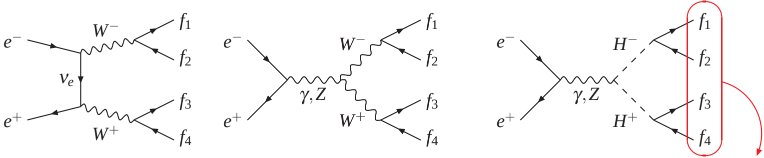
Charged Higgs contamination may appear as excessive $B(W \to \tau\nu_\tau)$

- σ_{HH} is a decreasing function of $m_{H^\pm}$ → $m_{H^\pm} \approx m_W$ desirable.
  See the plot on Page 17.
- Hard (but not impossible) to realize in MSSM due to
  $m^2_{H^\pm} = m^2_W + m^2_A$ and $m_A > 93$ GeV.
- Here consider a 2HDM.

Can charged Higgs be a solution?

JhP, JHEP(2006)

- Suppose H^+H^- pairs were produced at LEP.



Mostly, $(f_1, f_2) = (\tau, \overline{\nu}_\tau), (s, \overline{c})$.

- $B(W \to l\nu)$ is measured by counting final state fermions.

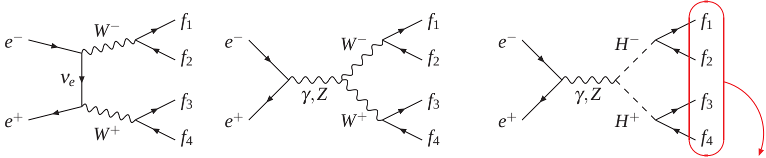
Charged Higgs contamination may appear as excessive $B(W \to \tau\nu_\tau)$

- σ_{HH} is a decreasing function of $m_{H^\pm}$ → $\boxed{m_{H^\pm} \approx m_W \text{ desirable.}}$
  See the plot on Page 17.
- Hard (but not impossible) to realize in MSSM due to
  $m^2_{H^\pm} = m^2_W + m^2_A$ and $m_A > 93$ GeV.
- Here consider a 2HDM.

Can charged Higgs be a solution?

JhP, JHEP(2006)

- Suppose H^+H^- pairs were produced at LEP.



Mostly, $(f_1, f_2) = (\tau, \overline{\nu}_\tau), (s, \overline{c})$.

- $B(W \to l\nu)$ is measured by counting final state fermions.

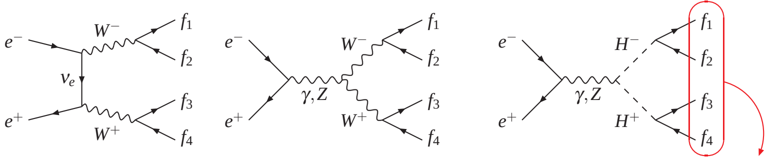
Charged Higgs contamination may appear as excessive $B(W \to \tau\nu_\tau)$

- σ_{HH} is a decreasing function of $m_{H^\pm}$ → $\boxed{m_{H^\pm} \approx m_W \text{ desirable.}}$
  See the plot on Page 17.
- Hard (but not impossible) to realize in MSSM due to
  $m_{H^\pm}^2 = m_W^2 + m_A^2$ and $m_A > 93$ GeV.
- Here consider a 2HDM.

Can charged Higgs be a solution?

JhP, JHEP(2006)

- Suppose H^+H^- pairs were produced at LEP.



Mostly, $(f_1, f_2) = (\tau, \overline{\nu}_\tau), (s, \overline{c})$.

- $B(W \to l\nu)$ is measured by counting final state fermions.

Charged Higgs contamination may appear as excessive $B(W \to \tau\nu_\tau)$

- σ_{HH} is a decreasing function of $m_{H^\pm}$ → $\boxed{m_{H^\pm} \approx m_W \text{ desirable.}}$
  See the plot on Page 17.
- Hard (but not impossible) to realize in MSSM due to
  $m^2_{H^\pm} = m^2_W + m^2_A$ and $m_A > 93$ GeV.
- Here consider a 2HDM.

2HDM's free of tree-level FCNC

- Make assumptions on Higgs Yukawa couplings for suppressing tree-level FCNC.
- Four example models

Model labels borrowed from Barger, Hewett, Phillips, PRD(1990)

Models	I		II		III		IV	
	VEV	A_f	VEV	A_f	VEV	A_f	VEV	A_f
u	H_2	$\cot\beta$	H_2	$\cot\beta$	H_2	$\cot\beta$	H_2	$\cot\beta$
d	H_2	$-\cot\beta$	H_1	$\tan\beta$	H_1	$\tan\beta$	H_2	$-\cot\beta$
ν								
l	H_2	$-\cot\beta$	H_1	$\tan\beta$	H_2	$-\cot\beta$	H_1	$\tan\beta$

$$\tan\beta \equiv v_2/v_1$$

- $H^{\pm}$-fermion-fermion interaction Lagrangian

$$\mathscr{L} = \frac{g}{\sqrt{2}m_W} H^{+}[V_{ij}m_{u_i}A_u\,\overline{u}_{Ri}d_{Lj} + V_{ij}m_{d_j}A_d\,\overline{u}_{Li}d_{Rj} + m_l A_l\,\overline{\nu}_L l_R] + \text{h.c.}$$

governs $b \to s\gamma$, $H^{\pm} \to \tau\nu_{\tau}$, $\ldots$

2HDM's free of tree-level FCNC

- Make assumptions on Higgs Yukawa couplings for suppressing tree-level FCNC.
- Four example models

Model labels borrowed from Barger, Hewett, Phillips, PRD(1990)

Models	I		II		III		IV	
	VEV	A_f	VEV	A_f	VEV	A_f	VEV	A_f
$\begin{pmatrix} u \\ d \end{pmatrix}$	H_2 H_2	$\cot\beta$ $-\cot\beta$	H_2 H_1	$\cot\beta$ $\tan\beta$	H_2 H_1	$\cot\beta$ $\tan\beta$	H_2 H_2	$\cot\beta$ $-\cot\beta$
$\begin{pmatrix} \nu \\ l \end{pmatrix}$	H_2	$-\cot\beta$	H_1	$\tan\beta$	H_2	$-\cot\beta$	H_1	$\tan\beta$

$$\tan\beta \equiv v_2/v_1$$

- $H^{\pm}$-fermion-fermion interaction Lagrangian

$$\mathscr{L} = \frac{g}{\sqrt{2}m_W} H^+ [V_{ij} m_{u_i} A_u \bar{u}_{Ri} d_{Lj} + V_{ij} m_{d_j} A_d \bar{u}_{Li} d_{Rj} + m_l A_l \overline{\nu}_L l_R] + \mathrm{h.c.}$$

governs $b \to s\gamma$, $H^{\pm} \to \tau\nu_{\tau}$, $\ldots$

H^+ in Model I becomes fermiophobic for high $\tan\beta$

$b \to s\gamma$ constraint

- One of the most stringent constraints on $m_{H^\pm}$.
- Branching ratio in 2HDM:

$$\frac{B(B \to X_s\gamma)}{B_{\text{SM}}(B \to X_s\gamma)} = \left| \frac{C_{7\gamma}^{\text{SM}}(m_b) + C_{7\gamma}^{H^\pm}(m_b)}{C_{7\gamma}^{\text{SM}}(m_b)} \right|^2 = \left| 1 + 0.71 A_u A_d + 0.15 A_u^2 \right|^2$$

- In Models **II** and **III**, $A_u A_d = 1$, and therefore

$$\frac{B(B \to X_s\gamma)}{B_{\text{SM}}(B \to X_s\gamma)} \geq 2.9 \quad \text{for} \quad m_{H^\pm} \approx m_W$$

$\longrightarrow$ **excluded**.

- In Models **I** and **IV**, $A_u = -A_d = \cot\beta$,

$b \to s\gamma$ constraint

- One of the most stringent constraints on $m_{H^\pm}$.
- Branching ratio in 2HDM:

$$\frac{B(B \to X_s\gamma)}{B_{\text{SM}}(B \to X_s\gamma)} = \left| \frac{C_{7\gamma}^{\text{SM}}(m_b) + C_{7\gamma}^{H^\pm}(m_b)}{C_{7\gamma}^{\text{SM}}(m_b)} \right|^2 = \left| 1 + 0.71 A_u A_d + 0.15 A_u^2 \right|^2$$

- In Models **II** and **III**, $A_u A_d = 1$, and therefore

$$\frac{B(B \to X_s\gamma)}{B_{\text{SM}}(B \to X_s\gamma)} \geq 2.9 \quad \text{for} \quad m_{H^\pm} \approx m_W$$

$\longrightarrow$ **excluded**.

- In Models **I** and **IV**, $A_u = -A_d = \cot\beta$,

$b \to s\gamma$ constraint

- One of the most stringent constraints on $m_{H^\pm}$.
- Branching ratio in 2HDM:

$$\frac{B(B \to X_s\gamma)}{B_{\text{SM}}(B \to X_s\gamma)} = \left| \frac{C_{7\gamma}^{\text{SM}}(m_b) + C_{7\gamma}^{H^\pm}(m_b)}{C_{7\gamma}^{\text{SM}}(m_b)} \right|^2 = \left| 1 + 0.71 A_u A_d + 0.15 A_u^2 \right|^2$$

- In Models **II** and **III**, $A_u A_d = 1$, and therefore

$$\frac{B(B \to X_s\gamma)}{B_{\text{SM}}(B \to X_s\gamma)} \geq 2.9 \quad \text{for} \quad m_{H^\pm} \approx m_W$$

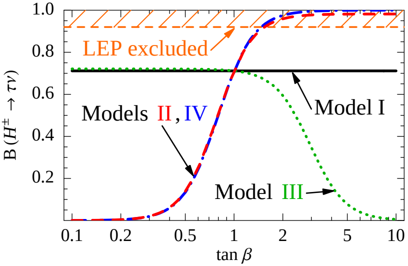
$\longrightarrow$ **excluded**.

- In Models **I** and **IV**, $A_u = -A_d = \cot\beta$,

Models **I** and **IV** survive if $\boxed{\tan\beta \gtrsim 4}$

Direct constraints on $m_{H^\pm}$

- $B(H^\pm \to \tau\nu_\tau)$ as a function of $\tan\beta$:



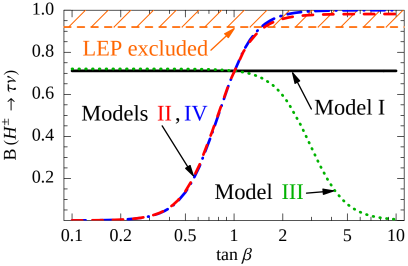
Hatched region is excluded for $m_{H^\pm} = 86\,\mathrm{GeV}$ [plot on Page 17].

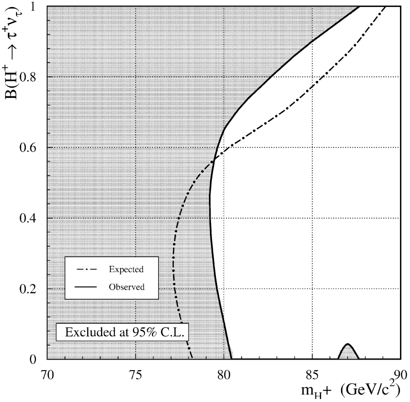
- Model IV leads to $B(H^\pm \to \tau\nu_\tau) \gtrsim 0.99$ for $\tan\beta \gtrsim 4$.

- $b \to s\gamma$ and direct search largely determine one viable model.
- Consider only **Model I** from here on.

Direct constraints on $m_{H^\pm}$

- $B(H^\pm \to \tau\nu_\tau)$ as a function of $\tan\beta$:





ALEPH, PLB(2002)

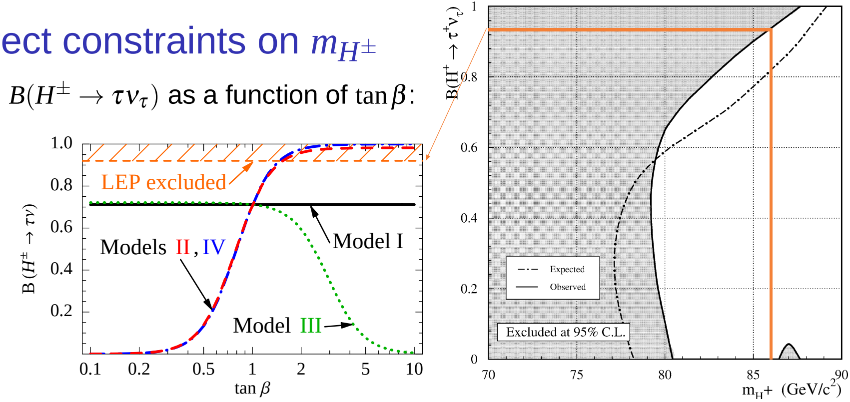
Hatched region is excluded for $m_{H^\pm} = 86$ GeV [plot on Page 17].

- Model IV leads to $B(H^\pm \to \tau\nu_\tau) \gtrsim 0.99$ for $\tan\beta \gtrsim 4$.

- $b \to s\gamma$ and direct search largely determine one viable model.
- Consider only **Model I** from here on.

Direct constraints on $m_{H^\pm}$

- $B(H^\pm \to \tau\nu_\tau)$ as a function of $\tan\beta$:



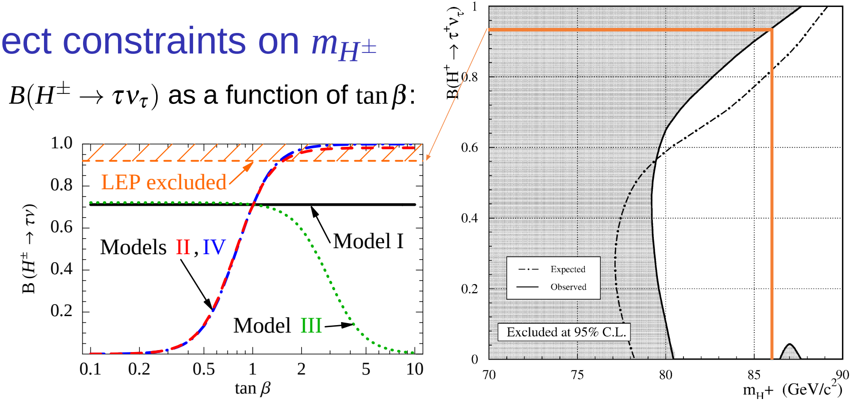
ALEPH, PLB(2002)

Hatched region is excluded for $m_{H^\pm} = 86$ GeV [plot on Page 17].

- Model IV leads to $B(H^\pm \to \tau\nu_\tau) \gtrsim 0.99$ for $\tan\beta \gtrsim 4$.
- $b \to s\gamma$ and direct search largely determine one viable model.
- Consider only **Model I** from here on.

Direct constraints on $m_{H^\pm}$

- $B(H^\pm \to \tau\nu_\tau)$ as a function of $\tan\beta$:



ALEPH, PLB(2002)

Hatched region is excluded for $m_{H^\pm} = 86\ \mathrm{GeV}$ [plot on Page 17].

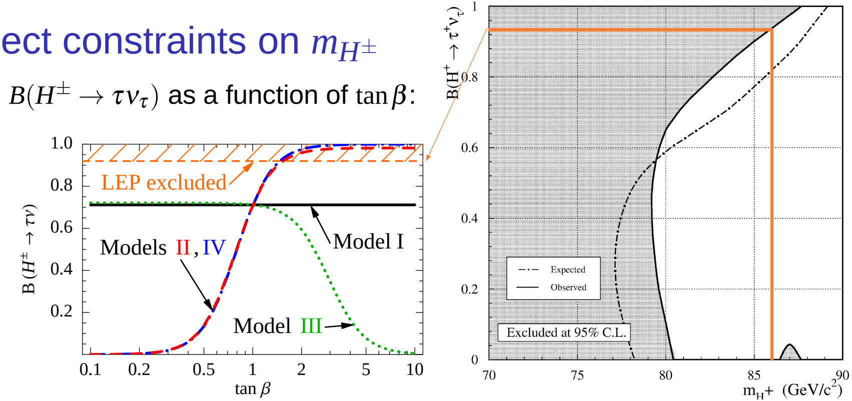
- Model IV leads to $B(H^\pm \to \tau\nu_\tau) \gtrsim 0.99$ for $\tan\beta \gtrsim 4$.

Model I is favored for $m_{H^\pm} \approx m_W$

- $b \to s\gamma$ and direct search largely determine one viable model.
- Consider only **Model I** from here on.

Direct constraints on $m_{H^\pm}$

- $B(H^\pm \to \tau\nu_\tau)$ as a function of $\tan\beta$:



ALEPH, PLB(2002)

Hatched region is excluded for $m_{H^\pm} = 86$ GeV [plot on Page 17].

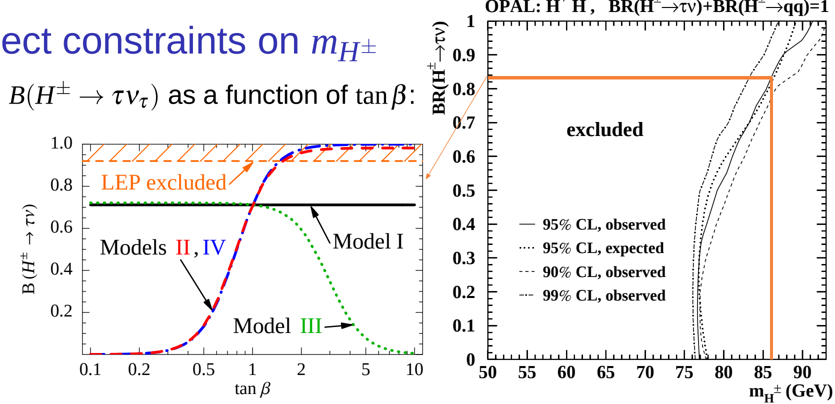
- Model IV leads to $B(H^\pm \to \tau\nu_\tau) \gtrsim 0.99$ for $\tan\beta \gtrsim 4$.

Model I is favored for $m_{H^\pm} \approx m_W$

- $b \to s\gamma$ and direct search largely determine one viable model.
- Consider only **Model I** from here on.

Direct constraints on $m_{H^\pm}$

- $B(H^\pm \to \tau\nu_\tau)$ as a function of $\tan\beta$:



OPAL, 0812.0267

Hatched region is excluded for $m_{H^\pm} = 86$ GeV [plot on Page 17].

- Model IV leads to $B(H^\pm \to \tau\nu_\tau) \gtrsim 0.99$ for $\tan\beta \gtrsim 4$.

Model I is favored for $m_{H^\pm} \approx m_W$

- $b \to s\gamma$ and direct search largely determine one viable model.
- Consider only **Model I** from here on.

Other constraints

- From LEP
  - W-pair production cross section: $\sigma_{HH} < 1\% \cdot \sigma_{WW} <$ error of σ_{WW}
  - Angular distribution of W-pair:
    measured from $qqe\nu$ and $qq\mu\nu$ final states $\longrightarrow$ irrelevant.
  - Anomalous triple-gauge-boson couplings measurement:
    charged Higgs effect is smaller than or comparable to an error.
  - W mass and width: shifts are smaller than errors.
- S, T, and U: okay unless neutral Higgses are too heavy.
- From CDF
  - $t \to H^+ b$: constraint weakens as $\tan\beta$ grows $\longrightarrow$ safe for $\tan\beta \gtrsim 1$.
- FCNC and CP violation: B_s–$\overline{B_s}$, B^0–$\overline{B^0}$, K^0–$\overline{K^0}$, $\varepsilon'/\varepsilon_K$, $B^- \to \tau\overline{\nu}$, ...

  $H^{\pm}$ decouples from fermions for high $\tan\beta$ $\longrightarrow$ Safe for $\tan\beta \gtrsim 4$.

Other constraints

- From LEP
  - W-pair production cross section: $\sigma_{HH} < 1\% \cdot \sigma_{WW} <$ error of σ_{WW}
  - Angular distribution of W-pair:
    measured from $qqe\nu$ and $qq\mu\nu$ final states $\longrightarrow$ irrelevant.
  - Anomalous triple-gauge-boson couplings measurement:
    charged Higgs effect is smaller than or comparable to an error.
  - W mass and width: shifts are smaller than errors.
- S, T, and U: okay unless neutral Higgses are too heavy.
- From CDF
  - $t \to H^+ b$: constraint weakens as $\tan\beta$ grows $\longrightarrow$ safe for $\tan\beta \gtrsim 1$.
- FCNC and CP violation: B_s–$\overline{B_s}$, B^0–$\overline{B^0}$, K^0–$\overline{K^0}$, $\varepsilon'/\varepsilon_K$, $B^- \to \tau\overline{\nu}$, ...
  $\boxed{H^\pm \text{ decouples from fermions for high } \tan\beta} \longrightarrow$ Safe for $\tan\beta \gtrsim 4$.

Other constraints

- From LEP
  - W-pair production cross section: $\sigma_{HH} < 1\% \cdot \sigma_{WW} <$ error of σ_{WW}
  - Angular distribution of W-pair:
    measured from $qqe\nu$ and $qq\mu\nu$ final states $\longrightarrow$ irrelevant.
  - Anomalous triple-gauge-boson couplings measurement:
    charged Higgs effect is smaller than or comparable to an error.
  - W mass and width: shifts are smaller than errors.
- S, T, and U: okay unless neutral Higgses are too heavy.
- From CDF
  - $t \to H^+ b$: constraint weakens as $\tan\beta$ grows $\longrightarrow$ safe for $\tan\beta \gtrsim 1$.
- FCNC and CP violation: B_s–$\overline{B_s}$, B^0–$\overline{B^0}$, K^0–$\overline{K^0}$, $\varepsilon'/\varepsilon_K$, $B^- \to \tau\overline{\nu}$, . . .
  $\boxed{H^\pm \text{ decouples from fermions for high } \tan\beta} \longrightarrow$ Safe for $\tan\beta \gtrsim 4$.
- For the same reason,

$\Gamma(\tau \to \mu\nu\nu)/\Gamma(\mu \to e\nu\nu)$ [μ, τ, π, K decays] **safe** if $\tan\beta \gtrsim 0.03$

A feature not shared by non-universal charged current interaction models!

Other constraints

- From LEP
  - W-pair production cross section: $\sigma_{HH} < 1\% \cdot \sigma_{WW} <$ error of σ_{WW}
  - Angular distribution of W-pair: measured from $qqe\nu$ and $qq\mu\nu$ final states $\longrightarrow$ irrelevant.
  - Anomalous triple-gauge-boson couplings measurement: charged Higgs effect is smaller than or comparable to an error.
  - W mass and width: shifts are smaller than errors.
- S, T, and U: okay unless neutral Higgses are too heavy.
- From CDF
  - $t \to H^+ b$: constraint weakens as $\tan\beta$ grows $\longrightarrow$ safe for $\tan\beta \gtrsim 1$.
- FCNC and CP violation: B_s–$\overline{B_s}$, B^0–$\overline{B^0}$, K^0–$\overline{K^0}$, $\varepsilon'/\varepsilon_K$, $B^- \to \tau\overline{\nu}$, ...

  $\boxed{H^{\pm} \text{ decouples from fermions for high } \tan\beta}$ $\longrightarrow$ Safe for $\tan\beta \gtrsim 4$.
- For the same reason,

  $\Gamma(\tau \to \mu\nu\nu)/\Gamma(\mu \to e\nu\nu)$ [μ, τ, π, K decays] **safe** if $\tan\beta \gtrsim 0.03$

  A feature not shared by non-universal charged current interaction models!

Okay thanks to H^+'s fermiophobia for high $\tan\beta$

How effective is charged Higgs contribution?

- Take $m_{H^\pm} = 81\ \mathrm{GeV}, \sqrt{s} = 200\ \mathrm{GeV} \longrightarrow \sigma_{HH} = 0.14\ \mathrm{pb}, \sigma_{WW} = 17\ \mathrm{pb}$
- For Model I, $B(H^\pm \to qq) = 0.3$ and $B(H^\pm \to \tau\nu_\tau) = 0.7$
- $B(W \to qq) = 6/9, \quad B(W \to \mu\nu_\mu) = 1/9$
- Estimate using $qq\tau\nu$ and $qq\mu\nu$ modes:

$$\left.\frac{B(W \to \tau\nu_\tau)}{B(W \to \mu\nu_\mu)}\right|_{\mathrm{appar}} = \frac{\sigma_{WW}^{qq\tau\nu} + \sigma_{HH}^{qq\tau\nu}}{\sigma_{WW}^{qq\mu\nu}}$$

$$= 1 + \frac{\sigma_{HH}}{\sigma_{WW}} \frac{B(H^\pm \to \tau\nu_\tau)}{B(W \to \mu\nu_\mu)} \frac{B(H^\pm \to qq)}{B(W \to qq)} \approx 1.02$$

- Estimate using $\tau\nu\tau\nu$ and $\mu\nu\mu\nu$:

$$\left.\frac{B(W \to \tau\nu_\tau)}{B(W \to \mu\nu_\mu)}\right|_{\mathrm{appar}} = \sqrt{1 + \frac{\sigma_{HH}}{\sigma_{WW}} \left(\frac{B(H^\pm \to \tau\nu_\tau)}{B(W \to \mu\nu_\mu)}\right)^2} \approx 1.15$$

- Can accommodate a few % of tau mode excess.

How effective is charged Higgs contribution?

- Take $m_{H^\pm} = 81\text{ GeV}, \sqrt{s} = 200\text{ GeV} \longrightarrow \sigma_{HH} = 0.14\text{ pb}, \sigma_{WW} = 17\text{ pb}$
- For Model I, $B(H^\pm \to qq) = 0.3$ and $B(H^\pm \to \tau\nu_\tau) = 0.7$
- $B(W \to qq) = 6/9, \quad B(W \to \mu\nu_\mu) = 1/9$
- Estimate using $qq\tau\nu$ and $qq\mu\nu$ modes:

$$\left.\frac{B(W \to \tau\nu_\tau)}{B(W \to \mu\nu_\mu)}\right|_{\text{appar}} = \frac{\sigma_{WW}^{qq\tau\nu} + \sigma_{HH}^{qq\tau\nu}}{\sigma_{WW}^{qq\mu\nu}}$$

$$= 1 + \frac{\sigma_{HH}}{\sigma_{WW}} \frac{B(H^\pm \to \tau\nu_\tau)}{B(W \to \mu\nu_\mu)} \frac{B(H^\pm \to qq)}{B(W \to qq)} \approx 1.02$$

- Estimate using $\tau\nu\tau\nu$ and $\mu\nu\mu\nu$:

$$\left.\frac{B(W \to \tau\nu_\tau)}{B(W \to \mu\nu_\mu)}\right|_{\text{appar}} = \sqrt{1 + \frac{\sigma_{HH}}{\sigma_{WW}} \left(\frac{B(H^\pm \to \tau\nu_\tau)}{B(W \to \mu\nu_\mu)}\right)^2} \approx 1.15$$

- Can accommodate a few % of tau mode excess.

Maximum likelihood fit

- Use data available in DELPHI, EPJC (2004).
- Likelihood fit with only W gives

$$\left.\frac{B(W\to\tau\nu_\tau)}{[B(W\to e\nu_e)+B(W\to\mu\nu_\mu)]/2}\right|_{W\text{ only}}=1.071.$$

- Likelihood fit in 2HDM I gives

$$\left.\frac{B(W\to\tau\nu_\tau)}{[B(W\to e\nu_e)+B(W\to\mu\nu_\mu)]/2}\right|_{\text{2HDM fit}}=1.031$$

  for $m_{H^\pm}=81\ \text{GeV}$.
- **Tau mode excess diminished by $\boxed{\textbf{4\%.}}$**
- Can expect an improvement of the ratio

$$\left.\frac{B(W\to\tau\nu_\tau)}{[B(W\to e\nu_e)+B(W\to\mu\nu_\mu)]/2}\right|_{\mathrm{LEP,2HDM}}\simeq1.037\pm0.026.$$

Maximum likelihood fit

- Use data available in DELPHI, EPJC (2004).
- Likelihood fit with only W gives

$$\left.\frac{B(W \to \tau\nu_\tau)}{[B(W \to e\nu_e) + B(W \to \mu\nu_\mu)]/2}\right|_{W\text{ only}} = 1.071.$$

- Likelihood fit in 2HDM I gives

$$\left.\frac{B(W \to \tau\nu_\tau)}{[B(W \to e\nu_e) + B(W \to \mu\nu_\mu)]/2}\right|_{\text{2HDM fit}} = 1.031$$

  for $m_{H^\pm} = 81\ \mathrm{GeV}$.
- **Tau mode excess diminished by $\boxed{\textbf{4\%.}}$**
- Can expect an improvement of the ratio

$$\left.\frac{B(W \to \tau\nu_\tau)}{[B(W \to e\nu_e) + B(W \to \mu\nu_\mu)]/2}\right|_{\mathrm{LEP,2HDM}} \simeq 1.037 \pm 0.026.$$

Maximum likelihood fit

- Use data available in DELPHI, EPJC (2004).
- Likelihood fit with only W gives

$$\left.\frac{B(W\to\tau\nu_\tau)}{[B(W\to e\nu_e)+B(W\to\mu\nu_\mu)]/2}\right|_{W\text{ only}} = 1.071.$$

- Likelihood fit in 2HDM I gives

$$\left.\frac{B(W\to\tau\nu_\tau)}{[B(W\to e\nu_e)+B(W\to\mu\nu_\mu)]/2}\right|_{\text{2HDM fit}} = 1.031$$

  for $m_{H^\pm} = 81\ \mathrm{GeV}$.
- **Tau mode excess diminished by $\boxed{\text{4\%.}}$**
- Can expect an improvement of the ratio

$$\left.\frac{B(W\to\tau\nu_\tau)}{[B(W\to e\nu_e)+B(W\to\mu\nu_\mu)]/2}\right|_{\mathrm{LEP,2HDM}} \simeq 1.037\pm0.026.$$

Maximum likelihood fit

- Use data available in DELPHI, EPJC (2004).
- Likelihood fit with only W gives

$$\left.\frac{B(W \to \tau\nu_\tau)}{[B(W \to e\nu_e) + B(W \to \mu\nu_\mu)]/2}\right|_{W \text{ only}} = 1.071.$$

- Likelihood fit in 2HDM I gives

$$\left.\frac{B(W \to \tau\nu_\tau)}{[B(W \to e\nu_e) + B(W \to \mu\nu_\mu)]/2}\right|_{\text{2HDM fit}} = 1.031$$

  for $m_{H^\pm} = 81$ GeV.
- **Tau mode excess diminished by $\boxed{\textbf{4\%.}}$**
- Can expect an improvement of the ratio

$$\left.\frac{B(W \to \tau\nu_\tau)}{[B(W \to e\nu_e) + B(W \to \mu\nu_\mu)]/2}\right|_{\mathrm{LEP,2HDM}} \simeq 1.037 \pm 0.026.$$

Maximum likelihood fit

- Use data available in DELPHI, EPJC (2004).
- Likelihood fit with only W gives

$$\left.\frac{B(W\to\tau\nu_\tau)}{[B(W\to e\nu_e)+B(W\to\mu\nu_\mu)]/2}\right|_{W\text{ only}} = 1.071.$$

- Likelihood fit in 2HDM I gives

$$\left.\frac{B(W\to\tau\nu_\tau)}{[B(W\to e\nu_e)+B(W\to\mu\nu_\mu)]/2}\right|_{\text{2HDM fit}} = 1.031$$

  for $m_{H^\pm} = 81\ \mathrm{GeV}$.
- **Tau mode excess diminished by $\boxed{\textbf{4\%.}}$**
- Can expect an improvement of the ratio

$$\left.\frac{B(W\to\tau\nu_\tau)}{[B(W\to e\nu_e)+B(W\to\mu\nu_\mu)]/2}\right|_{\mathrm{LEP,2HDM}} \simeq 1.037\pm0.026.$$

Maximum likelihood fit

- Use data available in DELPHI, EPJC (2004).
- Likelihood fit with only W gives

$$\left.\frac{B(W\to\tau\nu_\tau)}{[B(W\to e\nu_e)+B(W\to\mu\nu_\mu)]/2}\right|_{W\text{ only}}=1.071.$$

- Likelihood fit in 2HDM I gives

$$\left.\frac{B(W\to\tau\nu_\tau)}{[B(W\to e\nu_e)+B(W\to\mu\nu_\mu)]/2}\right|_{\text{2HDM fit}}=1.031$$

  for $m_{H^\pm}=81\ \mathrm{GeV}$.

- **Tau mode excess diminished by $\boxed{\textbf{4\%.}}$**
- Can expect an improvement of the ratio

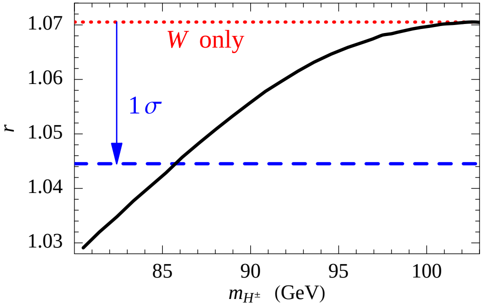
$$\left.\frac{B(W\to\tau\nu_\tau)}{[B(W\to e\nu_e)+B(W\to\mu\nu_\mu)]/2}\right|_{\mathrm{LEP,2HDM}}\simeq 1.037\pm0.026.$$

Lepton non-universality reduced to $\boxed{\textbf{1.4}\ \sigma}$

Charged Higgs mass dependence of the fit

- Likelihood fit result of $r \equiv \left. \frac{B(W \to \tau\nu_\tau)}{[B(W \to e\nu_e)+B(W \to \mu\nu_\mu)]/2} \right|_{\text{2HDM fit}}$

  as a function of $m_{H^\pm}$:



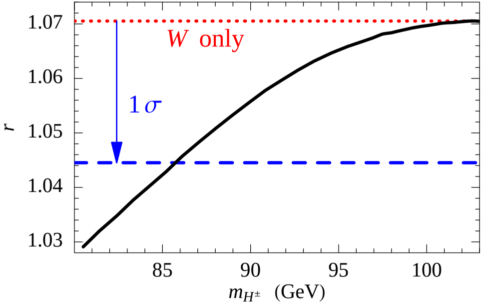
- The lighter, the better, but for Model I, LEP constrains

$$m_{H^\pm} > 80.7 \text{ GeV}.$$

Charged Higgs mass dependence of the fit

- Likelihood fit result of $r \equiv \left.\frac{B(W\to\tau\nu_\tau)}{[B(W\to e\nu_e)+B(W\to\mu\nu_\mu)]/2}\right|_{\text{2HDM fit}}$

  as a function of $m_{H^\pm}$:



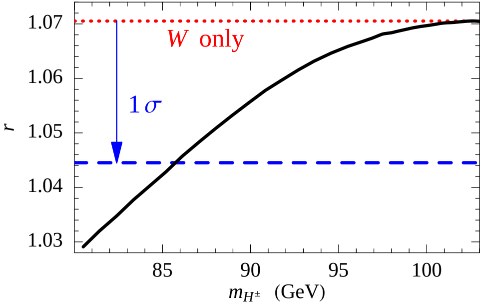
1-σ mitigation needs $\boxed{m_{H^\pm} \lesssim 86\ \text{GeV}}$

- The lighter, the better, but for Model I, LEP constrains

$$m_{H^\pm} > 80.7\ \text{GeV}.$$

Charged Higgs mass dependence of the fit

- Likelihood fit result of $r \equiv \left.\frac{B(W \to \tau\nu_\tau)}{[B(W \to e\nu_e)+B(W \to \mu\nu_\mu)]/2}\right|_{\text{2HDM fit}}$ as a function of $m_{H^\pm}$:



1-σ mitigation needs $\boxed{m_{H^\pm} \lesssim 86\ \text{GeV}}$

- The lighter, the better, but for Model I, LEP constrains

$$m_{H^\pm} > 80.7\ \text{GeV}.$$

Test at ILC

- What to look for: charged Higgs with $m_{H^\pm} \approx m_W$ that couples very weakly to fermions.
- Test of scenario is charged Higgs search.
- Doable at ILC.
- Beam polarization helps a lot.

e^-/e^+ polarization	σ_{HH} [pb]	σ_{WW} [pb]	σ_{HH}/σ_{WW} [%]
0%/ 0%	0.10	7.13	1.4
80%/ 0%	0.05	1.47	3.3
90%/ 0%	0.04	0.76	5.4
80%/60%	0.06	0.65	8.7
90%/60%	0.06	0.37	15.0

for $\sqrt{s} = 500$ GeV, right-handed electron and left-handed positron beam polarizations.

- At LHC?

Test at ILC

- What to look for: charged Higgs with $m_{H^\pm} \approx m_W$ that couples very weakly to fermions.
- Test of scenario is charged Higgs search.
- Doable at ILC.
- Beam polarization helps a lot.

e^-/e^+ polarization	σ_{HH} [pb]	σ_{WW} [pb]	σ_{HH}/σ_{WW} [%]
0%/ 0%	0.10	7.13	1.4
80%/ 0%	0.05	1.47	3.3
90%/ 0%	0.04	0.76	5.4
80%/60%	0.06	0.65	8.7
90%/60%	0.06	0.37	15.0

for $\sqrt{s} = 500\ \mathrm{GeV}$, right-handed electron and left-handed positron beam polarizations.

- At LHC?

Test at ILC

- What to look for: charged Higgs with $m_{H^\pm} \approx m_W$ that couples very weakly to fermions.
- Test of scenario is charged Higgs search.
- Doable at ILC.
- Beam polarization helps a lot.

e^-/e^+ polarization	σ_{HH} [pb]	σ_{WW} [pb]	σ_{HH}/σ_{WW} [%]
0%/ 0%	0.10	7.13	1.4
80%/ 0%	0.05	1.47	3.3
90%/ 0%	0.04	0.76	5.4
80%/60%	0.06	0.65	8.7
90%/60%	0.06	0.37	15.0

for $\sqrt{s} = 500\ \mathrm{GeV}$, right-handed electron and left-handed positron beam polarizations.

- At LHC?

Test at ILC

- What to look for: charged Higgs with $m_{H^\pm} \approx m_W$ that couples very weakly to fermions.
- Test of scenario is charged Higgs search.
- Doable at ILC.
- Beam polarization helps a lot.

e^-/e^+ polarization	σ_{HH} [pb]	σ_{WW} [pb]	σ_{HH}/σ_{WW} [%]
0%/ 0%	0.10	7.13	1.4
80%/ 0%	0.05	1.47	3.3
90%/ 0%	0.04	0.76	5.4
80%/60%	0.06	0.65	8.7
90%/60%	0.06	0.37	15.0

for $\sqrt{s} = 500\ \mathrm{GeV}$, right-handed electron and left-handed positron beam polarizations.

- At LHC? **What do you think?**

Summary

- A resolution is proposed of the possible lepton non-universality observed at the W-pair production experiments at LEP.
- $H^{\pm}$ **almost degenerate with** W, within 2HDM, **could reduce 2.8 σ of deviation down to 1.4 σ.**
- No conflict with the existing direct or indirect constraints. In particular, μ, τ, π, K **decays are safe.**
- Charged Higgs direct search at LEP in combination with $b \to s\gamma$ singles out one viable type of 2HDM out of the four that are free of tree-level FCNC interactions.
- No $\tan\beta$ dependence in prediction.
- Testable at ILC.

A supersymmetric solution

- Light CP-odd Higgs scenario where $m_A < 2m_b$.

Dermisek, 0806.0847

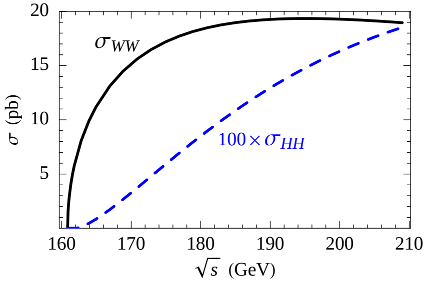
$$m_{H^\pm} = \sqrt{m_W^2 + m_A^2} \approx m_W$$

- Circumvent LEP bound, $m_A > 93$ GeV, by suppressing $\sigma(e^+e^- \to hA) \propto \cos^2(\beta - \alpha)$.
- Escape from detection of higgstrahlung, $e^+e^- \to hZ$, using $B(h \to AA, b\bar{b}) \simeq 90\%, 10\%$, plus $A \to \tau^+\tau^-, c\bar{c}$, and/or adding a singlet to MSSM.
- As for $b \to s\gamma$, cancel charged Higgs loop with chargino-stop loop.
- Account for apparent excess of $B(W \to \tau\nu_\tau)$ at LEP using $H^\pm \to \tau\nu_\tau$.

Dermisek, 0807.2135

More plots

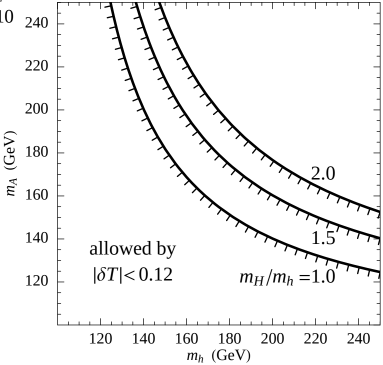
- W-pair production cross section



Error of σ_{WW} is between 0.21 pb and 0.7 pb.

- S, T, U constraints

Constraints on m_h and m_A from δT, with m_H/m_h fixed at 1.0, 1.5, and 2.0, respectively.
S and U constraints are weaker.



Fit in 2HDM

- Modify channel cross sections as

$$\begin{aligned}
\sigma_s^{qq\tau\nu} &= \sigma_{WW,s} \cdot 2B(W \to qq)B(W \to \tau\nu_\tau) + \sigma_{HH,s} \cdot 2B(H^\pm \to qq)B(H^\pm \to \tau\nu_\tau) \\
\sigma_s^{\tau\nu\tau\nu} &= \sigma_{WW,s} \cdot B^2(W \to \tau\nu_\tau) + \sigma_{HH,s} \cdot B^2(H^\pm \to \tau\nu_\tau) \\
\sigma_s^{qqqq} &= \sigma_{WW,s} \cdot B^2(W \to qq) + \sigma_{HH,s} \cdot B^2(H^\pm \to qq)
\end{aligned}$$

- Use $B(H^\pm \to qq) = 0.3$ and $B(H^\pm \to \tau\nu_\tau) = 0.7$ for Model I, and calculated $\sigma_{HH,s}$.
- Fit variables are $B(W \to e\nu_e), B(W \to \mu\nu_\mu), B(W \to \tau\nu_\tau), \sigma_{WW,s}$.