

# Light charged Higgs at LEP and the LHC

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Based on

- JhP, JHEP10(2006)077
- Mader, JhP, Pruna, Stöckinger, Straessner, JHEP09(2012)125

# Standard Model

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

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The diagram illustrates the Standard Model Lagrangian  $\mathcal{L}_{\text{SM}}$  with three terms highlighted for experimental constraints:

- tested** (green):  $-\frac{1}{4}F \cdot F + \bar{\psi} i \not{D} \psi$
- constrained** (blue):  $[H \bar{\psi}_L Y \psi_R + \text{h.c.}] + \frac{g^2 \theta}{32\pi^2} F \cdot \tilde{F}$
- probed** (purple):  $|DH|^2$

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The diagram shows the Standard Model Lagrangian  $\mathcal{L}_{\text{SM}}$  with four terms grouped by colored ovals and labeled with arrows:

- tested** (green oval):  $-\frac{1}{4}F \cdot F + \bar{\psi} i \not{D} \psi$
- constrained** (blue oval):  $[H \bar{\psi}_L Y \psi_R + \text{h.c.}] + \frac{g^2 \theta}{32\pi^2} F \cdot \tilde{F}$
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- to be explored** (red oval):  $V(H)$

# Lepton universality in charged current interactions

- SM predicts lepton universality
- $W$  boson couplings to  $e, \mu, \tau$  are determined by SU(2) gauge invariance

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

- Thoroughly tested in

$$\mu \rightarrow e \nu \nu, \tau \rightarrow \mu \nu \nu, \tau \rightarrow e \nu \nu, \pi \rightarrow e \nu, \pi \rightarrow \mu \nu, \\ \tau \rightarrow \pi \nu, \dots$$

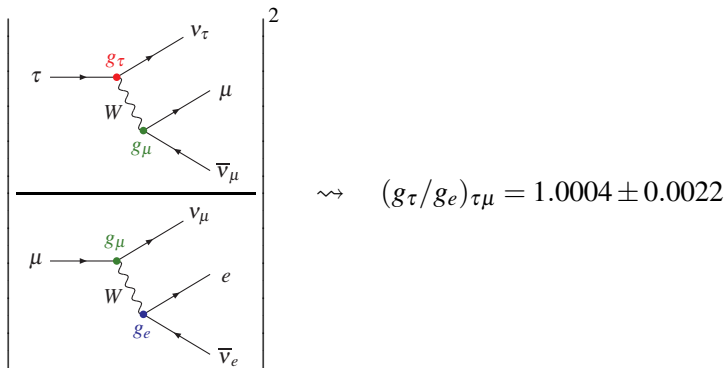
All tests confirm lepton universality

# Test of lepton universality using $\mu \rightarrow e \nu \nu$ and $\tau \rightarrow \mu \nu \nu$

- Parametrize

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



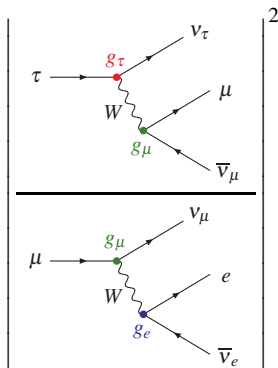
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$$\rightsquigarrow (g_\tau/g_e)\tau_\mu = 1.0004 \pm 0.0022$$

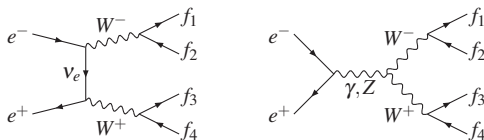
Perfect agreement with  
lepton universality

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

LEP directly measured

$B(W \rightarrow e\nu_e)$ ,  $B(W \rightarrow \mu\nu_\mu)$ ,  $B(W \rightarrow \tau\nu_\tau)$ ,  
from partial cross sections of  $WW \rightarrow 4f$



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

- LEP results

| Experiment | $B(W \rightarrow e \nu_e)$ [%] | $B(W \rightarrow \mu \nu_\mu)$ [%] | $B(W \rightarrow \tau \nu_\tau)$ [%] |
|------------|--------------------------------|------------------------------------|--------------------------------------|
| 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       | $10.40 \pm 0.35$               | $10.61 \pm 0.35$                   | $11.18 \pm 0.48$                     |
| LEP        | $10.65 \pm 0.17$               | $10.59 \pm 0.15$                   | $11.44 \pm 0.22$                     |

- Assume  $B(W \rightarrow e \nu_e) = B(W \rightarrow \mu \nu_\mu)$ , then

$$\frac{B(W \rightarrow \tau \nu_\tau)}{[B(W \rightarrow e \nu_e) + B(W \rightarrow \mu \nu_\mu)]/2} \Big|_{\text{LEP}} = 1.077 \pm 0.026$$

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# 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.
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- **However**, it decreases

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

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

# Dilemma

- A model leading to effective interactions

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

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

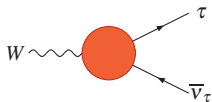
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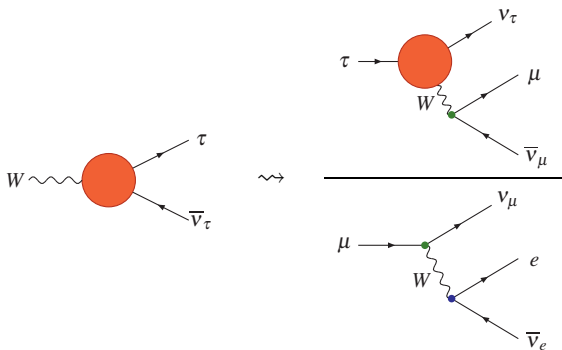
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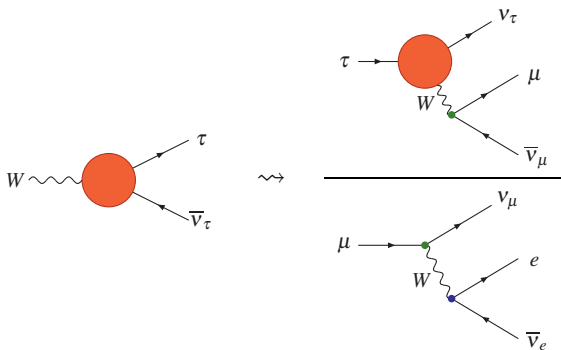
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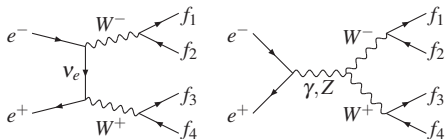


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# Charged Higgs solution

JhP, JHEP(2006)

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



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

- $\sigma_{HH}$  is a decreasing function of  $m_{H^\pm}$   $\rightarrow$   $m_{H^\pm} \approx m_W$  desirable

- Hard to realize in MSSM due to

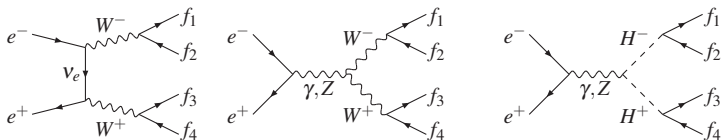
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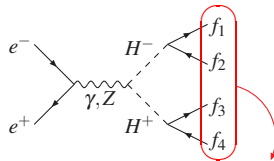
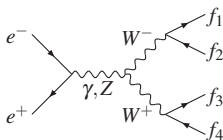
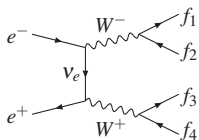
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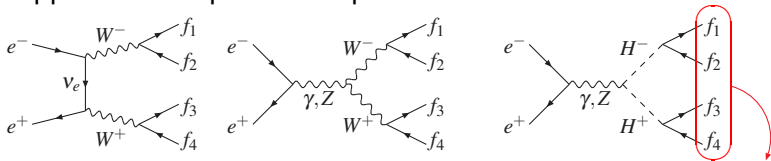
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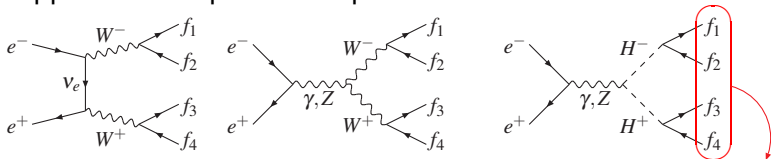
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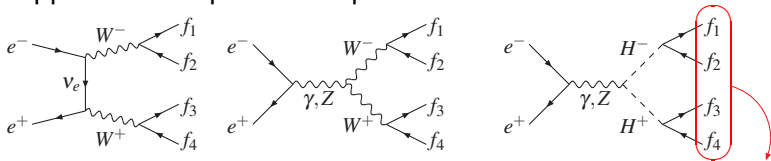
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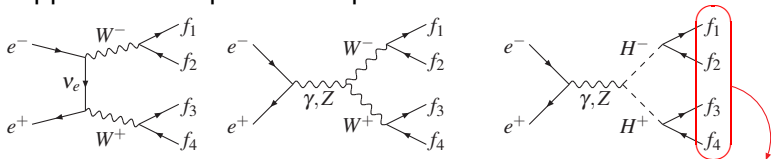
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# Naturally flavour-conserving 2HDMs

- Arrange Yukawas to kill Higgs-mediated tree-level FCNC

Glashow, Weinberg, PRD(1977)

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

| Models                                   | I                                                       | II                                                     | III                                                    | IV                                                      |
|------------------------------------------|---------------------------------------------------------|--------------------------------------------------------|--------------------------------------------------------|---------------------------------------------------------|
|                                          | VEV $A_f$                                               | VEV $A_f$                                              | VEV $A_f$                                              | VEV $A_f$                                               |
| $\begin{pmatrix} u \\ d \end{pmatrix}$   | $\Phi_2 \quad \cot \beta$<br>$\Phi_2 \quad -\cot \beta$ | $\Phi_2 \quad \cot \beta$<br>$\Phi_1 \quad \tan \beta$ | $\Phi_2 \quad \cot \beta$<br>$\Phi_1 \quad \tan \beta$ | $\Phi_2 \quad \cot \beta$<br>$\Phi_2 \quad -\cot \beta$ |
| $\begin{pmatrix} \nu \\ l \end{pmatrix}$ | $\Phi_2 \quad -\cot \beta$                              | $\Phi_1 \quad \tan \beta$                              | $\Phi_2 \quad -\cot \beta$                             | $\Phi_1 \quad \tan \beta$                               |

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

- $H^\pm$ -fermion-fermion interactions

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

govern  $b \rightarrow s\gamma$ ,  $t \rightarrow H^+ b$ ,  $H^\pm \rightarrow \tau \nu_\tau$ , ...

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govern  $b \rightarrow s\gamma$ ,  $t \rightarrow H^+ b$ ,  $H^\pm \rightarrow \tau \nu_\tau$ , ...

$H^+$ -fermion couplings in **Model I** are **suppressed by  $\cot \beta$**

## $b \rightarrow s\gamma$ constraint

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

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

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

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

→ **excluded.**

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

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

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

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

→ **excluded**.

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

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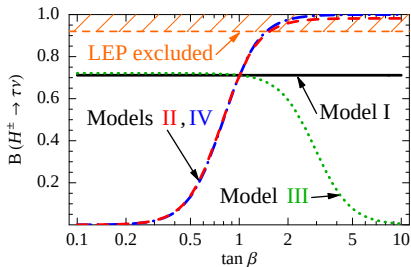
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Models **I** and **IV** survive if  $\tan \beta \gtrsim 4$

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

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



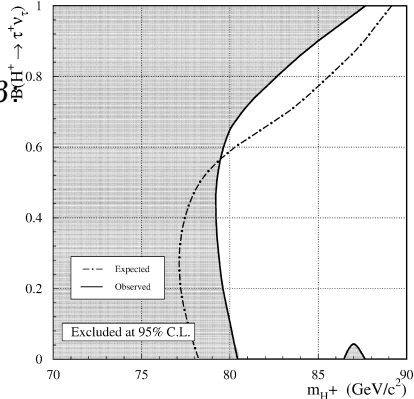
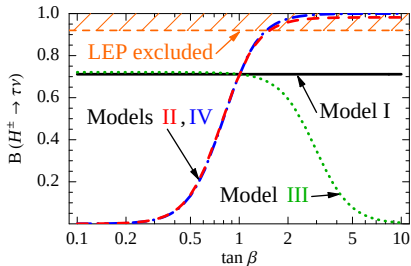
Hatched region is excluded for  $m_{H^\pm} = 86$  GeV.

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ALEPH, PLB(2002)

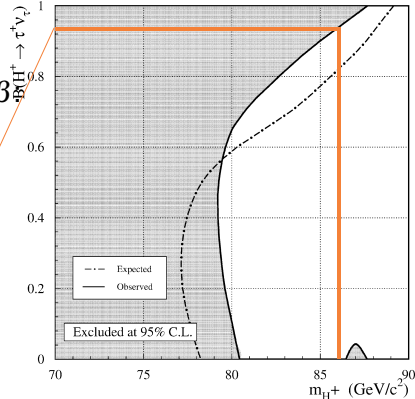
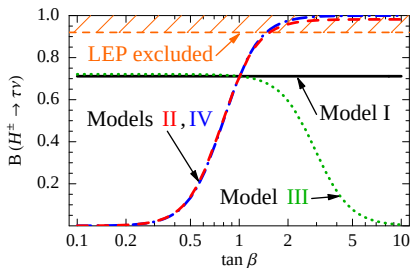
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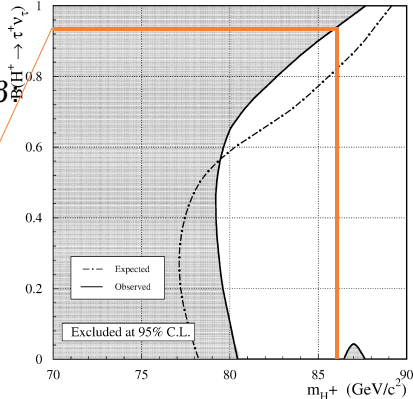
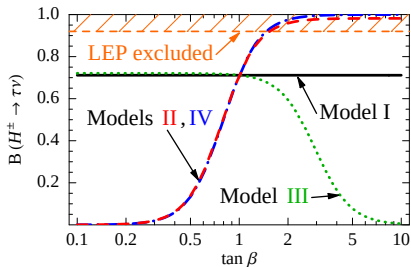
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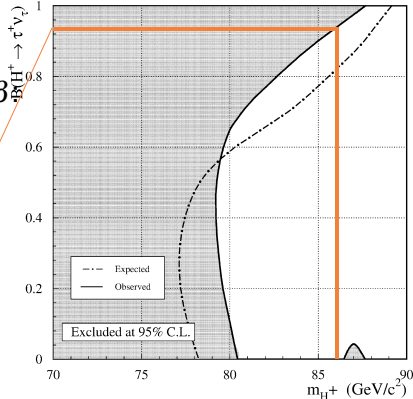
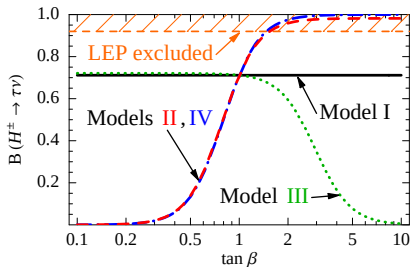
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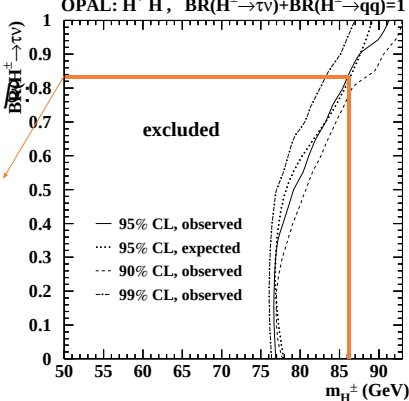
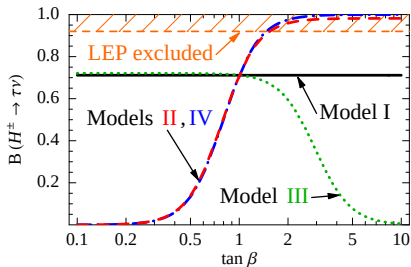
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OPAL, 0812.0267

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## Other constraints

- From LEP

- ▶  **$W$ -pair production cross section:**  $\sigma_{HH} < 1\% \cdot \sigma_{WW} < \text{error of } \sigma_{WW}$
- ▶ **Angular distribution of  $W$ -pair:**  
measured from  $qqe\nu$  and  $qq\mu\nu$  final states  $\rightarrow$  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 the LHC

- ▶  **$t \rightarrow H^+ b$ :** constraint weakens as  $\tan\beta$  grows  $\rightarrow$  safe for  $\tan\beta \gtrsim 5$ .

- **FCNC and  $CP$  violation:**  $B_s - \overline{B}_s$ ,  $B^0 - \overline{B}^0$ ,  $K^0 - \overline{K}^0$ ,  $\varepsilon'/\varepsilon_K$ ,  $B^- \rightarrow \tau \overline{\nu}$ , ...

**$H^\pm$  decouples from fermions for high  $\tan\beta$**   $\rightarrow$  Safe for  $\tan\beta \gtrsim 4$ .

- For the same reason,

$\Gamma(\tau \rightarrow \mu \nu \nu)/\Gamma(\mu \rightarrow e \nu \nu)$  [ $\mu$ ,  $\tau$ ,  $\pi$ ,  $K$  decays] **safe** if  $\tan\beta \gtrsim 0.03$

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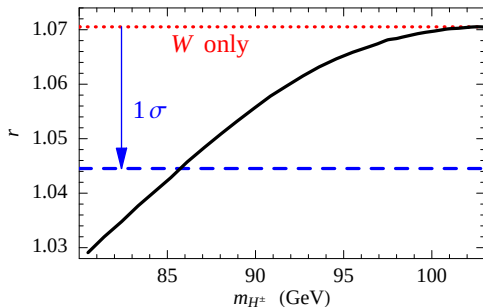
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**A feature not shared by non-universal charged current interaction models!**

Thanks to  $\cot\beta$  suppression of  $H^+$ -fermion couplings

# Charged Higgs mass dependence of the fit

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



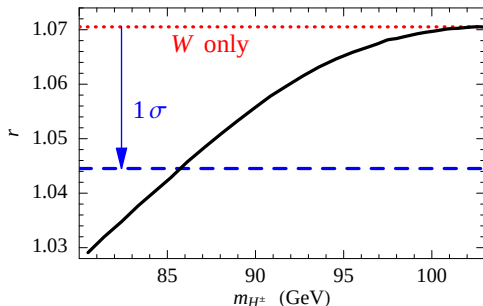
- The lighter, the better, but for Model I, LEP constrains

$$m_{H^\pm} > 82 \text{ GeV}$$

OPAL, EPJC(2012)

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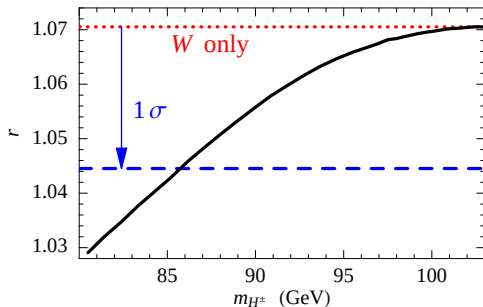
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OPAL, EPJC(2012)

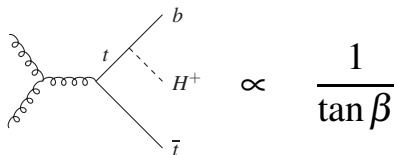
# Test at ILC

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

| $e^-/e^+$ polarization | $\sigma_{HH}$ [pb] | $\sigma_{WW}$ [pb] | $\sigma_{HH}/\sigma_{WW}$ [%] |
|------------------------|--------------------|--------------------|-------------------------------|
| 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

# Standard light $H^\pm$ search at hadron colliders

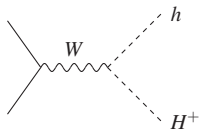

$$\propto \frac{1}{\tan \beta}$$

- Escapes from Tevatron search if  $\tan \beta \gtrsim 1$
- Can be relevant at the LHC for low  $\tan \beta$

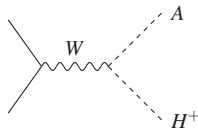
ATLAS, CMS, JHEP(2012)

# Alternative channels for $H^\pm$ search

Djouadi, Kilian, Muhlleitner, Zerwas, EPJC(1999)



$$\propto \cos(\beta - \alpha)$$



$$\propto 1$$

- May survive even at high  $\tan\beta$
- $\sigma(pp \rightarrow H^\pm, h|A) \sim 100 \text{ fb}$

## $CP$ -violating neutral Higgs mixing

$$\begin{bmatrix} H_1 \\ H_2 \\ H_3 \end{bmatrix} = \begin{bmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{bmatrix} \begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{bmatrix}$$

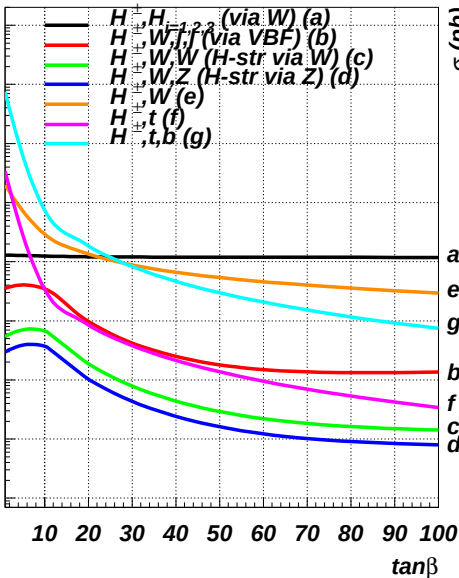
$$\Phi_1 = \begin{bmatrix} i \sin \beta H^+ \\ \frac{1}{\sqrt{2}}(v_1 + \eta_1 - i \sin \beta \eta_3) \end{bmatrix}$$

$$\Phi_2 = \begin{bmatrix} -i \cos \beta H^+ \\ \frac{1}{\sqrt{2}}(v_2 + \eta_2 + i \cos \beta \eta_3) \end{bmatrix}$$

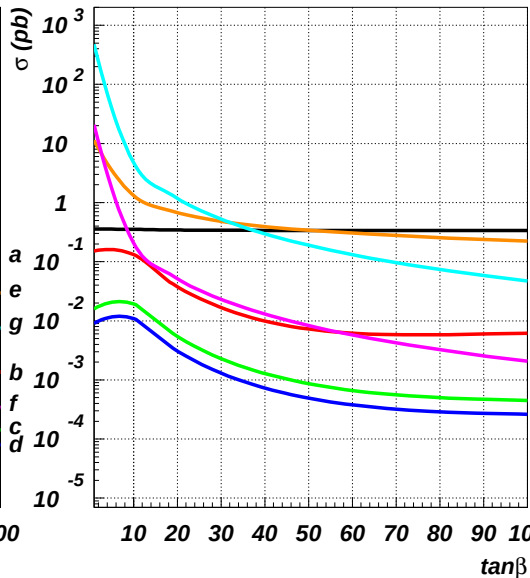
$$s_i = \sin \alpha_i, \quad c_i = \cos \alpha_i$$

# $H^\pm$ production at the LHC

$\sqrt{s} = 7$  TeV

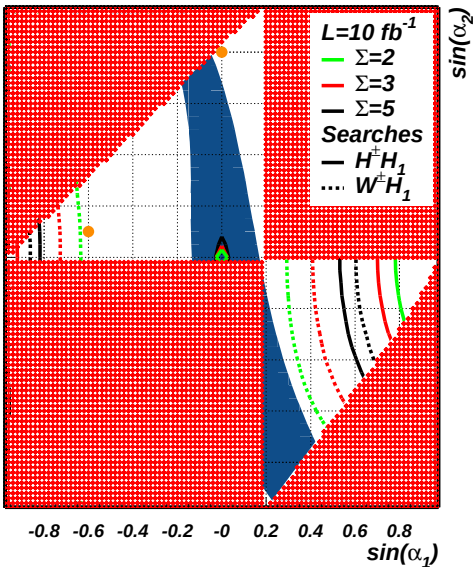


$\sqrt{s} = 14$  TeV

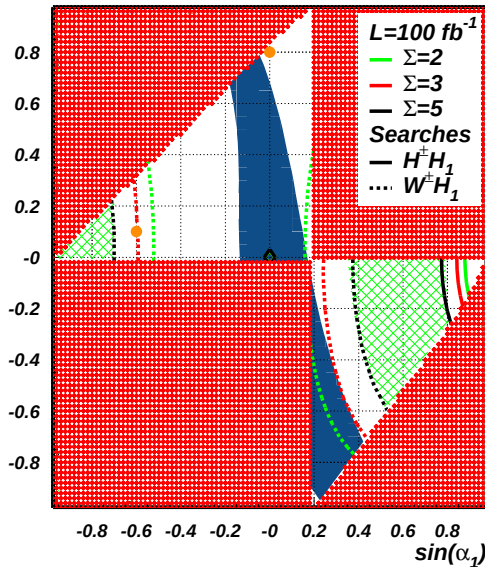


$$ud \rightarrow W \rightarrow H^\pm H_1 \rightarrow \tau \nu b \bar{b}$$

$\sqrt{s}=7$  TeV



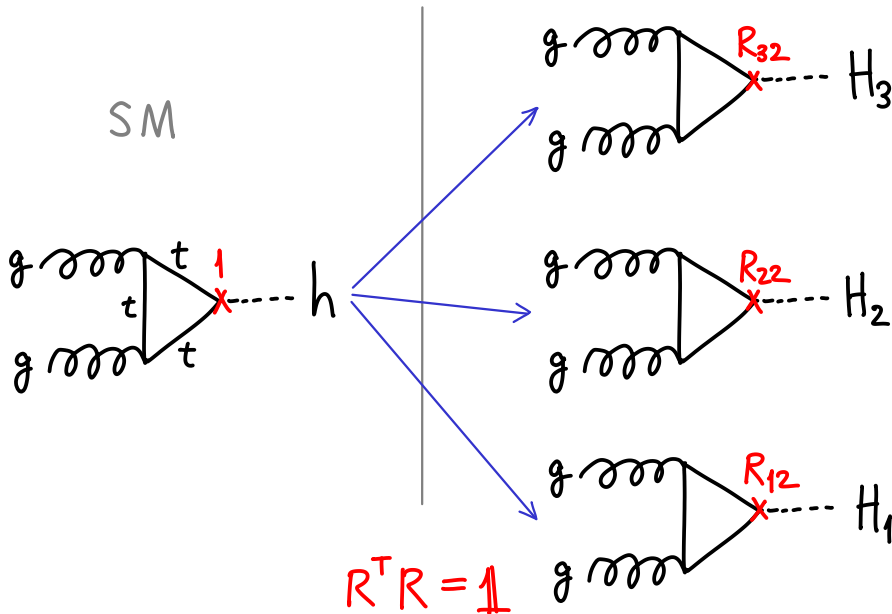
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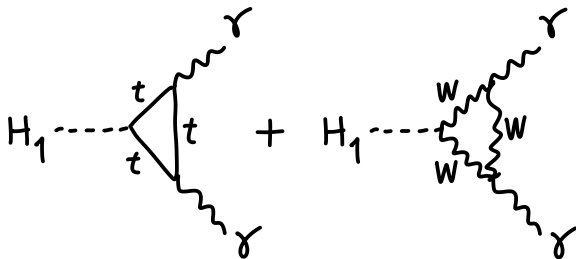
# Suppressed lightest Higgs production

2HDMI

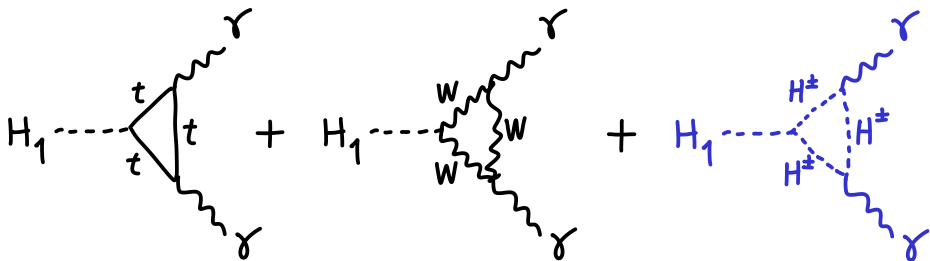
SM



$H^\pm$ -loop enhances  $H_1 \rightarrow \gamma\gamma$

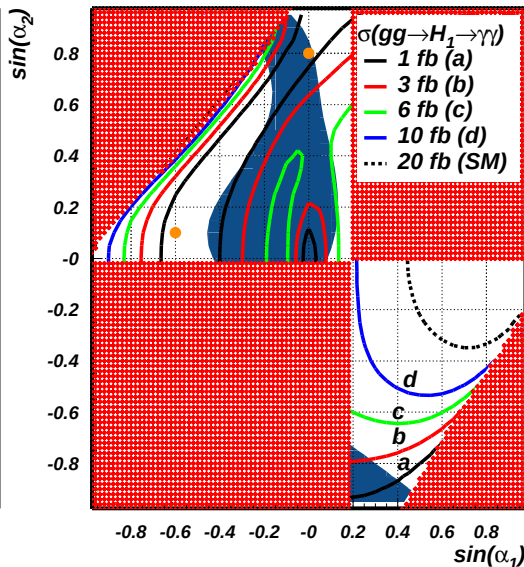
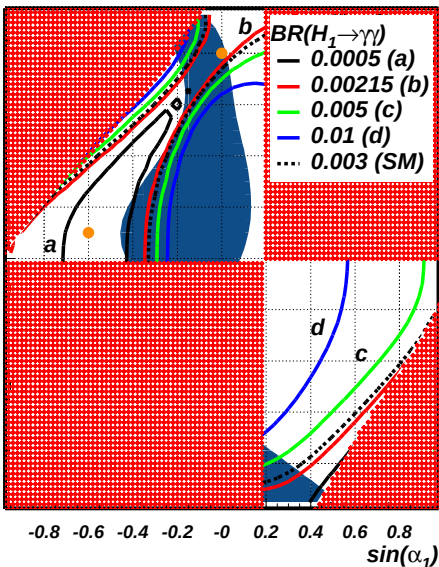


$H^\pm$ -loop enhances  $H_1 \rightarrow \gamma\gamma$



$$gg \rightarrow H_1 \rightarrow \gamma\gamma$$

$$\sqrt{s} = 7 \text{ TeV}$$



# Summary

- Type-I 2HDM could resolve lepton non-universality in  $W$ -pair production at LEP
- $H^\pm$  almost degenerate with  $W$  reduces  $2.8 \sigma$  of deviation down to  $1.4 \sigma$
- LHC has excellent potential to discover  $H^+$  in this scenario
- Light  $H^\pm$  loop can enhance  $H_1 \rightarrow \gamma\gamma$

# A supersymmetric solution

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

Dermisek, 0806.0847

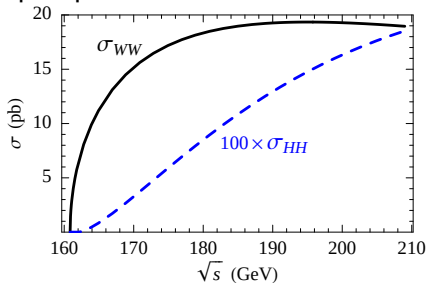
$$m_{H^\pm} = \sqrt{m_W^2 + m_A^2} \approx m_W$$

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

Dermisek, 0807.2135

# More plots

- W-pair production cross section

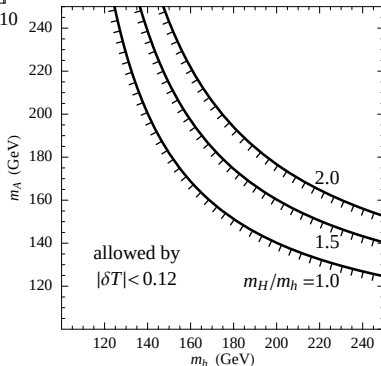


Error of  $\sigma_{WW}$  is  
between 0.21 pb and  
0.7 pb.

- $S$ ,  $T$ ,  $U$  constraints

Constraints on  $m_h$  and  $m_A$   
from  $\delta T$ , 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

$$\sigma_s^{qq\tau\nu} = \sigma_{WW,s} \cdot 2B(W \rightarrow qq)B(W \rightarrow \tau\nu_\tau) + \sigma_{HH,s} \cdot 2B(H^\pm \rightarrow qq)B(H^\pm \rightarrow \tau\nu_\tau)$$

$$\sigma_s^{\tau\nu\tau\nu} = \sigma_{WW,s} \cdot B^2(W \rightarrow \tau\nu_\tau) + \sigma_{HH,s} \cdot B^2(H^\pm \rightarrow \tau\nu_\tau)$$

$$\sigma_s^{qqqq} = \sigma_{WW,s} \cdot B^2(W \rightarrow qq) + \sigma_{HH,s} \cdot B^2(H^\pm \rightarrow qq)$$

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