Lepton non-universality at LEP and charged Higgs

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Standard Model

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

Omitted: Majorana mass terms of neutrinos
Standard Model

\[ \mathcal{L}_{\text{SM}} = -\frac{1}{4} F \cdot F + \overline{\psi} i \Phi \psi - \left[ H \overline{\psi}_L Y \psi_R + \text{h.c.} \right] + \frac{g^2 \Theta}{32 \pi^2} F \cdot \tilde{F} + |DH|^2 - V(H) \]

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- tested
- probed
- constrained

Omitted: Majorana mass terms of neutrinos
Standard Model

\[ \mathcal{L}_{\text{SM}} = -\frac{1}{4} F \cdot F + \bar{\psi} i \mathcal{D} \psi - \left[ H \bar{\psi}_L Y \psi_R + \text{h.c.} \right] + \frac{g^2 \theta}{32 \pi^2} F \cdot \tilde{F} + |D H|^2 - V(H) \]

Omitted: Majorana mass terms of neutrinos
Lepton universality in charged current interactions

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

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

- Thoroughly tested in
  \(\mu \rightarrow e\nu\nu, \tau \rightarrow \mu\nu\nu, \tau \rightarrow e\nu\nu, \pi \rightarrow e\nu, \pi \rightarrow \mu\nu, \tau \rightarrow \pi\nu, \ldots\)
  All these consistent with lepton universality.
Test of lepton universality at $\mu \to e \nu \nu$ and $\tau \to \mu \nu \nu$

- Use parameterization

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

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

$$\sim (g_{\tau}/g_{e})_{\tau\mu} = 1.0004 \pm 0.0022$$

Data from Loinaz, Okamura, Rayyan, Takeuchi, Wijewardhana, PRD(2004)
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Perfect agreement with lepton universality
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 \( WW \rightarrow 4f \).

\[
\begin{align*}
(f_1, f_2) &= (e, \bar{\nu}_e), (\mu, \bar{\nu}_\mu), (\tau, \bar{\nu}_\tau), (d, \bar{u}), (s, \bar{c}). \\
(f_4, f_3) & \text{ is a conjugate.}
\end{align*}
\]
Tau mode excess

LEP electroweak working group, hep-ex/0612034

**LEP results**

<table>
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<tr>
<th>Experiment</th>
<th>$B(W \to e\nu_e)$ [%]</th>
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Under assumption of $B(W \to e\nu_e) = B(W \to \mu\nu_\mu)$,

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

**New physics?**
**Tau mode excess**

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7.7% or 2.8 $\sigma$ departure from lepton universality.

New physics?
Previous attempts for explanation

- 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.
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- Mixing of gauge bosons leads to flavor-dependent lightest $W$ boson couplings to leptons.
- Can fit leptonic $W$ branching ratios.
- However, it decreases

$$\frac{\Gamma(\tau \rightarrow \mu \nu \nu)}{\Gamma(\mu \rightarrow e \nu \nu)}$$

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

A model leading to effective interactions

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

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

A different approach is preferable.
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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?

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

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

$\sigma_{HH}$ 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.
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  \[ e^- e^+ W^- \rightarrow f_1 f_2 f_3 f_4 \]

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

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\begin{align*}
& e^- \xrightarrow{\nu_e} W^- f_1 \\
& e^+ \xrightarrow{W^+} W^- f_2 \\
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$$

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  \[
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  \[
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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)

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\[ \tan \beta \equiv \frac{v_2}{v_1} \]

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

\[ \mathcal{L} = \frac{g}{\sqrt{2}m_W} H^+ \left[ V_{ij} m_{u_i} A_u \bar{u}_R i d L_j + V_{ij} m_{d_j} A_d \bar{u}_L i d R_j + m_l A_l \bar{\nu}_L l R \right] + h.c. \]

governs $b \rightarrow s \gamma$, $H^\pm \rightarrow \tau \nu_\tau$, …
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governs $b \rightarrow s\gamma, H^\pm \rightarrow \tau\nu_\tau, \ldots$

$H^+$ 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:

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

- In Models II and III, $A_uA_d = 1$, and therefore

\[
\frac{B(B \to X_s\gamma)}{B_{SM}(B \to X_s\gamma)} \geq 2.9 \quad \text{for} \quad m_{H^\pm} \approx m_W \quad \text{excluded.}
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- In Models I and IV, $A_u = -A_d = \cot \beta$, 

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$\longrightarrow$ excluded.

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

Models I and IV survive if $\tan \beta \gtrsim 4$
Direct constraints on \( m_{H^\pm} \)

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

![Graph showing B(H^± → τντ) vs. tan β]

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 $m_{H^\pm}$

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

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

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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 $qq\nu\nu$ 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.
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- **$S$, $T$, and $U$**: okay unless neutral Higgsses are too heavy.

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  - $t \rightarrow H^+ b$: constraint weakens as $\tan\beta$ grows $\rightarrow$ safe for $\tan\beta \gtrsim 1$.

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\[
\frac{\Gamma(\tau \rightarrow \mu \nu \nu)}{\Gamma(\mu \rightarrow e \nu \nu)} [\mu, \tau, \pi, K \text{ decays}] \text{ safe if } \tan \beta \gtrsim 0.03
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A feature not shared by non-universal charged current interaction models!
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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 $m_{H^\pm} = 81$ GeV, $\sqrt{s} = 200$ GeV $\rightarrow \sigma_{HH} = 0.14$ pb, $\sigma_{WW} = 17$ pb
- For Model I, $B(H^\pm \rightarrow qq) = 0.3$ and $B(H^\pm \rightarrow \tau \nu_\tau) = 0.7$
- $B(W \rightarrow qq) = 6/9$, $B(W \rightarrow \mu \nu_\mu) = 1/9$
- Estimate using $qq\tau\nu$ and $qq\mu\nu$ modes:

  \[
  \frac{B(W \rightarrow \tau \nu_\tau)}{B(W \rightarrow \mu \nu_\mu)} \bigg|_{\text{appar}} = \frac{\sigma_{qq\tau\nu} + \sigma_{qq\tau\nu}}{\sigma_{WW} + \sigma_{HH}} \\
  = 1 + \frac{\sigma_{HH} B(H^\pm \rightarrow \tau \nu_\tau) B(H^\pm \rightarrow qq)}{\sigma_{WW} B(W \rightarrow \mu \nu_\mu) B(W \rightarrow qq)} \approx 1.02
  \]

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

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- Tau mode excess diminished by 4%.
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Lepton non-universality reduced to 1.4 $\sigma$. 

Lepton non-universality at LEP and charged Higgs
Charged Higgs mass dependence of the fit

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

![Graph showing the dependence of \( r \) on \( m_{H^\pm} \).]

- The lighter, the better, but for Model I, LEP constrains \( m_{H^\pm} > 80.7 \) GeV.
Charged Higgs mass dependence of the fit

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

\[ m_{H^\pm} (\text{GeV}) \]

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![Graph showing the fit result](image)

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\[ m_{H^\pm} > 80.7 \text{ GeV}. \]
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.
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for $\sqrt{s} = 500$ GeV, right-handed electron and left-handed positron beam polarizations.

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- 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 $2.8\,\sigma$ of deviation down to $1.4\,\sigma$.
- No conflict with the existing direct or indirect constraints. In particular, $\mu, \tau, \pi, K$ 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 $m_A < 2m_b$.

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

- 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 $B(h \rightarrow AA, b\bar{b}) \approx 90\%, 10\%$, 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, 0806.0847

Dermisek, 0807.2135
More plots

- $W$-pair production cross section

![Graph showing $\sigma_{WW}$ and $100 \times \sigma_{HH}$ vs. $\sqrt{s}$ (GeV)]

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.

![Graph showing constraints on $m_h$ and $m_A$ with $m_H/m_h$ fixed]
Fit in 2HDM

- Modify channel cross sections as

\[
\begin{align*}
\sigma_{sqq}^{\tau\nu} &= \sigma_{WW,s} \cdot 2B(W \to qq)B(W \to \tau\nu_\tau) + \sigma_{HH,s} \cdot 2B(H^\pm \to qq)B(H^\pm \to \tau\nu_\tau) \\
\sigma_{s}^{\tau\nu\tau\nu} &= \sigma_{WW,s} \cdot B^2(W \to \tau\nu_\tau) + \sigma_{HH,s} \cdot B^2(H^\pm \to \tau\nu_\tau) \\
\sigma_{s}^{qqqq} &= \sigma_{WW,s} \cdot B^2(W \to qq) + \sigma_{HH,s} \cdot B^2(H^\pm \to qq)
\end{align*}
\]

- 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 \(B(W \to e\nu_e), B(W \to \mu\nu_\mu), B(W \to \tau\nu_\tau), \sigma_{WW,s}\).