Lepton non-universality at LEP and charged Higgs

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Based on JHEP10(2006)077 [hep-ph/0607280].

Lepton universality in charged current interactions

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

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

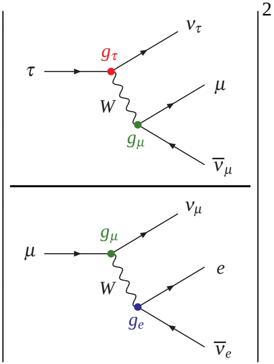
- Thoroughly tested in
  $\mu \to e\nu\nu$, $\tau \to \mu\nu\nu$, $\tau \to e\nu\nu$, $\pi \to e\nu$, $\pi \to \mu\nu$, $\tau \to \pi\nu$, ...
  All these consistent with lepton universality.

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

- Use parameterization

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

- 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)

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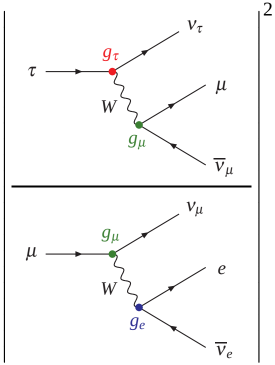

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Perfect agreement with lepton universality

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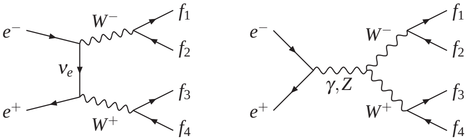
Measurement of $B(W \to l\nu)$ at LEP

- 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/0511027

- 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?

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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.
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- 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.

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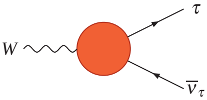

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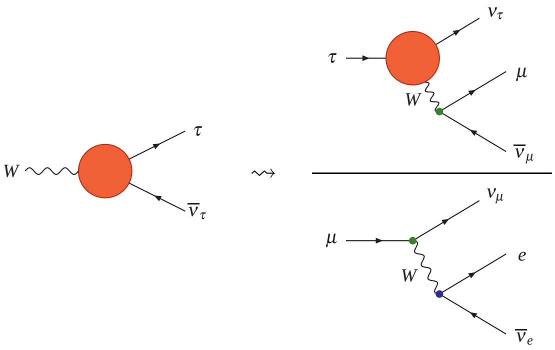

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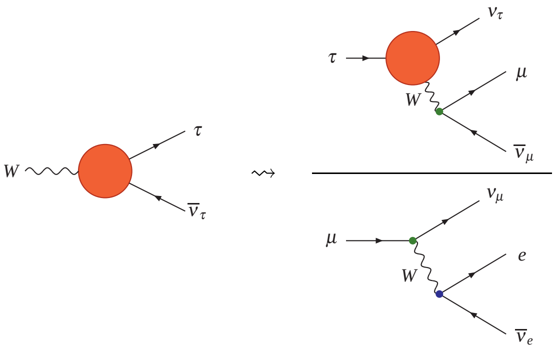

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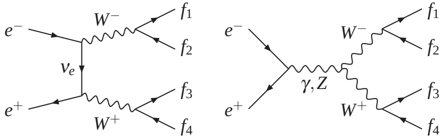
Outline

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

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.
- σ_{HH} is a decreasing function of $m_{H^\pm}$ $\rightarrow$ $m_{H^\pm} \approx m_W$ desirable.
  See the plot on Page 16.
- Hard to realize in MSSM due to
  $m^2_{H^\pm} = m^2_W + m^2_A$ and $m_A > 93$ GeV.
- Consider a 2HDM.

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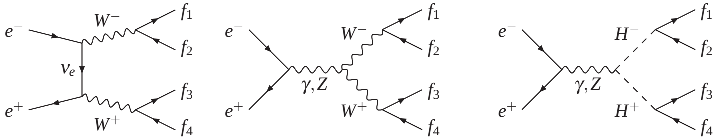

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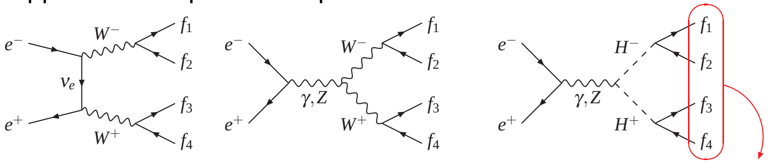

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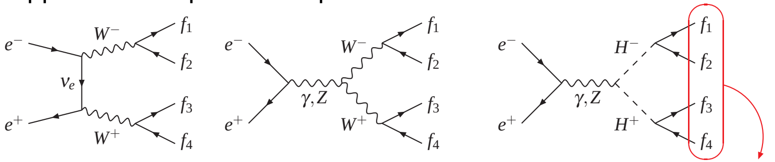

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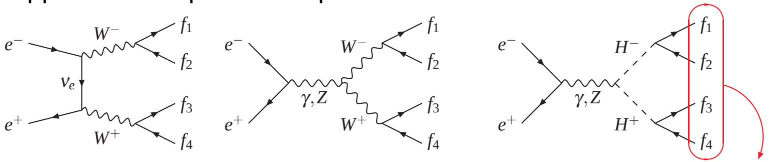

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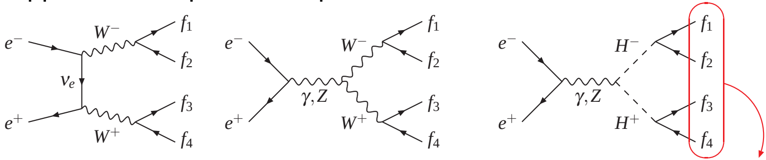

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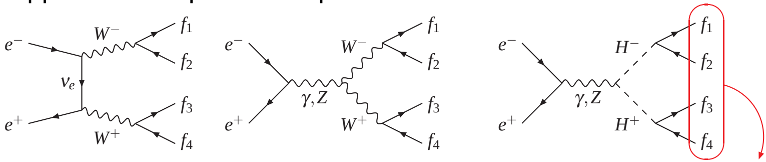

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2HDM's free of tree-level FCNC

- 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	$-\cot\beta$
$\begin{pmatrix} \nu \\ l \end{pmatrix}$	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

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

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

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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:

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

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

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

$\longrightarrow$ **excluded**.

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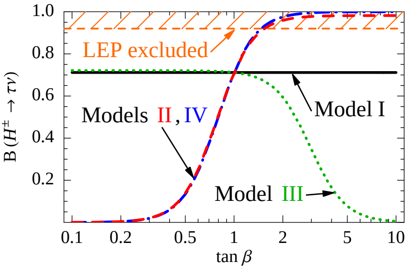
Models **I** and **IV** survive if $\boxed{\tan\beta \gtrsim 4}$

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

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



Hatched region is excluded for $m_{H^\pm} = 86$ GeV [plot on Page 16].

- 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.

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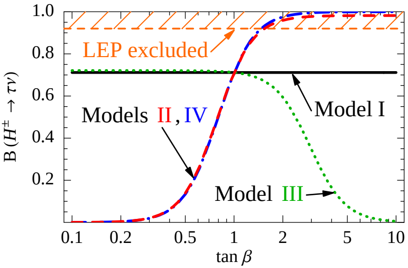

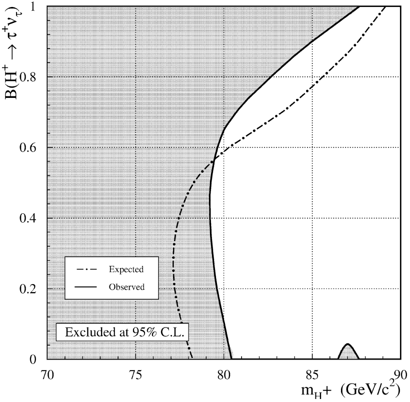

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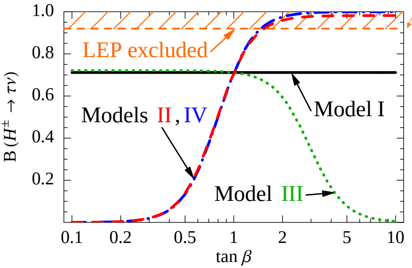

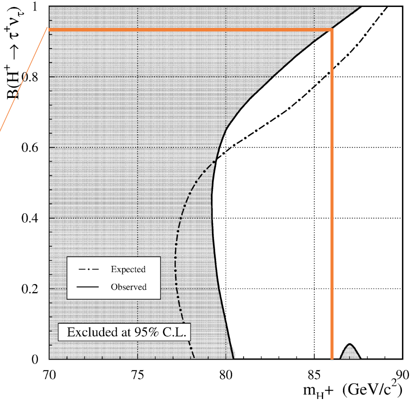

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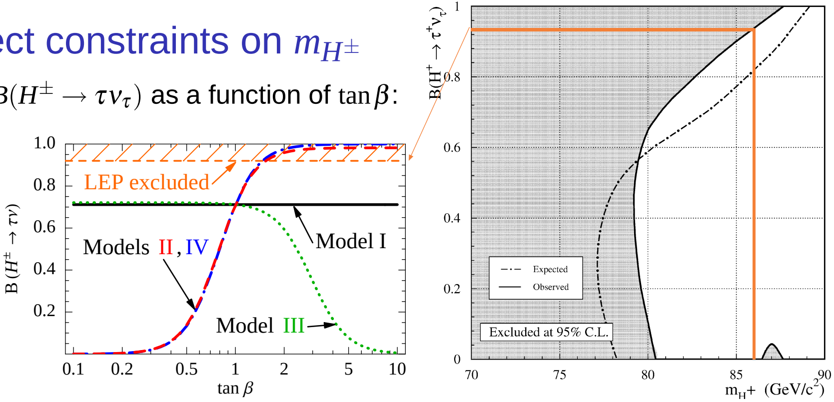

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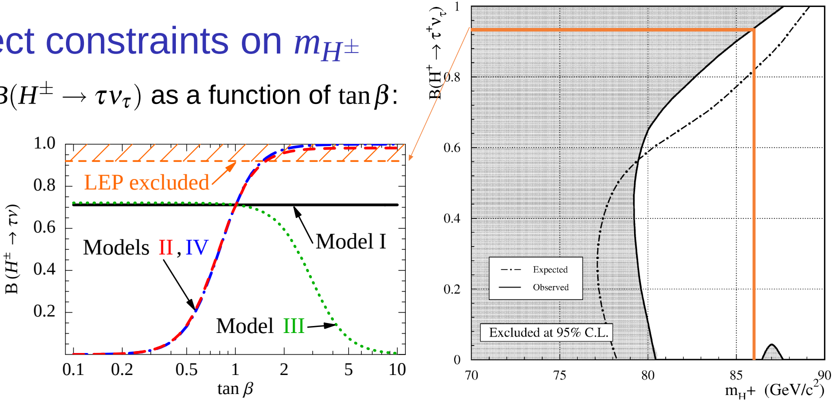

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- From LEP
  - W-pair production cross section: $\sigma_{HH} < 1\% \cdot \sigma_{WW} <$ error of σ_{WW}
  - Angular distribution of W-pair:
    measured from $qqe\nu$ and $qq\mu\nu$ final states $\longrightarrow$ irrelevant.
  - Anomalous triple-gauge-boson 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 $\tan\beta \gtrsim 1$.
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  $\Gamma(\tau \to \mu\nu\nu)/\Gamma(\mu \to e\nu\nu)$ [μ, τ, π, K decays] **safe** if $\tan\beta \gtrsim 0.03$

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

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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 $\longrightarrow \sigma_{HH} = 0.14$ pb, $\sigma_{WW} = 17$ pb
- For Model I, $B(H^\pm \to qq) = 0.3$ and $B(H^\pm \to \tau\nu_\tau) = 0.7$
- $B(W \to qq) = 6/9, \quad B(W \to \mu\nu_\mu) = 1/9$
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Lepton non-universality reduced to 1.4 σ

Charged Higgs mass dependence of the fit

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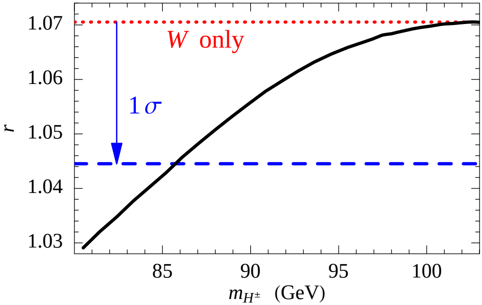

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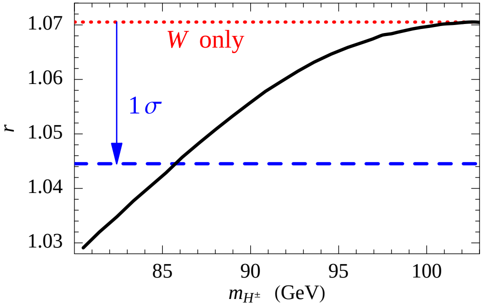

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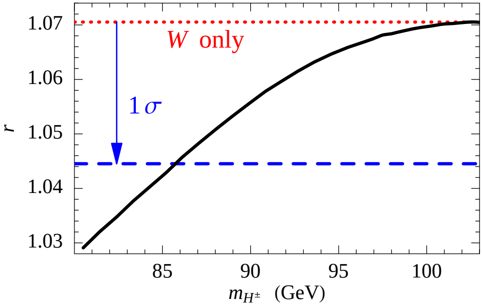

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Test at ILC

- 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? Not sure.

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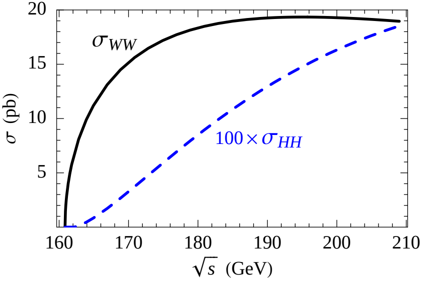
Summary

- 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.

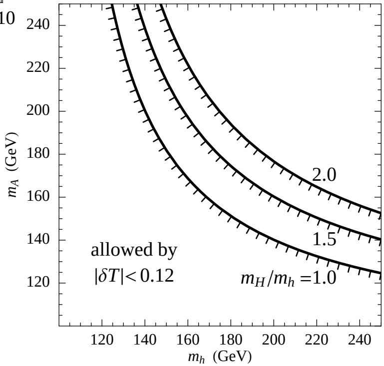
More plots

- 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

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

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