Probing New Physics through Lepton Universality

P. Paradisi

Rome University "Tor Vergata"

INFN sez. Rome II

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Plan

Where to look for New Physics?

- **Processes forbidden or much suppressed in the SM**
  - FCNC processes ($\mu \to e\gamma$, $\tau \to \mu\gamma$,...) or
  - CPV effects (electron edm, d_n,...)
- **Processes predicted with high precision in the SM**

Marriage of LFV and LU in $R_M^{e/\mu}$

[A.Masiero, P.P, R.Peronzio '05]

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$\mu - e$ universality in $M \to l\nu$

- $\mu - e$ universality in $R_K = \Gamma(K \to e\nu_e)/\Gamma(K \to \mu\nu_\mu)$

$$R_K^{exp.} = (2.416 \pm 0.043_{stat.} \pm 0.024_{syst.}) \cdot 10^{-5} \quad \text{NA48/2 '05}$$

$$R_K^{exp.} = (2.44 \pm 0.11) \cdot 10^{-5} \quad PDG$$

$$R_K^{SM} = (2.472 \pm 0.001) \cdot 10^{-5} \quad SM$$

- $\mu - e$ universality in $R_\pi = \Gamma(\pi \to e\nu_e)/\Gamma(\pi \to \mu\nu_\mu)$

$$R_\pi^{exp.} = (1.230 \pm 0.004) \cdot 10^{-4} \quad \text{PDG}$$

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$\mu - e$ universality in $M \to l\nu$

- Denoting by $\Delta r_{NP}^{e-\mu}$ the deviation from $\mu - e$ universality in $R_{K,\pi}$ due to new physics, i.e.:

$$R_{K,\pi} = R_{K,\pi}^{SM}\left(1 + \Delta r_{K,\pi\, NP}^{e-\mu}\right),$$

- we get at the 2σ level:

$$-0.063 \leq \Delta r_{K\, NP}^{e-\mu} \leq 0.017 \quad \text{NA48/2}$$

$$-0.0107 \leq \Delta r_{\pi\, NP}^{e-\mu} \leq 0.0022 \quad \text{PDG}$$

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$\mu - e$ universality in $M \to l\nu$

- In the SM $M \to l\nu$ is induced by a tree level $W^\pm$ exchange
- In a 2HDM (including SUSY) also $H^\pm$ provides tree level effects to $M \to l\nu$
- Four-Fermi interaction for $M \to \ell\nu$ induced by $W^\pm$, $H^\pm$

$$\frac{4G_F}{\sqrt{2}} V_{ud} \left[(\bar{u}\gamma_\mu P_L d)(\bar{\ell}\gamma^\mu P_L \nu_\ell) - \tan^2\beta \left(\frac{m_d m_\ell}{m^2_{H^\pm}} \right) (\bar{u} P_R d)(\bar{\ell} P_L \nu_\ell) \right]$$

- PCAC's

$$< 0|\bar{u}\gamma_\mu\gamma_5 d|M^- >= i f_M p^\mu_M$$

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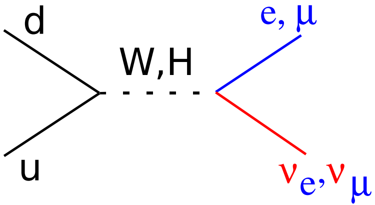

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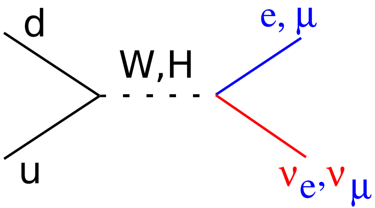

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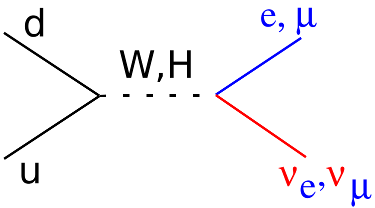

$\mu - e$ universality in $M \to l\nu$

- $H^{\pm}$ ($\mathbf{W}^{\pm}$) amplitude is proportional to m_ℓ because of the Yukawa coupling (**helicity suppression**)

$$\mathcal{M}_{M\to\ell\nu} = \frac{G_F}{\sqrt{2}} V_{ud} f_M \left[m_\ell - m_\ell \ \tan^2\beta \left(\frac{m_d}{m_d + m_u} \right) \frac{m_M^2}{m_{H^\pm}^2} \right] \bar{\ell}(1-\gamma_5)\nu.$$

- Including $H^{\pm}$ and $W^{\pm}$ effects, the decay rates for $M \to \ell\nu$ is

$$\Gamma(M\to\ell\nu) = \frac{G_F^2}{8\pi} |V_{ud}|^2 f_M^2 m_M m_\ell^2 \left(1 - \frac{m_\ell^2}{m_M^2}\right) \times r_M$$

$$r_M = \left[1 - \tan^2\beta \left(\frac{m_d}{m_u + m_d} \right) \frac{m_M^2}{m_{H^\pm}^2} \right]^2 .$$

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Tree level $H^{\pm}$ effects (r_M) are lepton flavour blind

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- $e - \mu$ non universal effects in R_M arise from the one loop $\ell^{\mp} W^{\pm} \nu_\ell$ vertex corrections through the exchange of
  - $H^0(A^0) - H^{\pm} - \ell^{\mp}$ (with $\ell = e, \mu$) leading to (for $m_H \geq 300\text{GeV}$ and $\tan\beta \leq 50$)

$$\Delta r^{e-\mu}_{SUSY} \sim \frac{\alpha_2}{4\pi}\left(\frac{m_\mu^2 - m_e^2}{m_H^2}\right)\tan^2\beta \leq 10^{-6}$$

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well below the $\Delta r^{e-\mu}_{\pi\, NP} \leq 0.0022$ and $\Delta r^{e-\mu}_{K\, NP} \leq 0.017$ exp. bounds

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$$R_K^{EXP.} = \frac{\Gamma(K \to e\nu_e) + \Gamma(K \to e\nu_\mu) + \Gamma(K \to e\nu_\tau)}{\Gamma(K \to \mu\nu_\mu) + \Gamma(K \to \mu\nu_e) + \Gamma(K \to \mu\nu_\tau)}$$

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Higgs Mediated LFV

- LFV Yukawa Interactions (if $\delta_{ij} = \tilde{m}^2_{ij}/\tilde{m}^2 \neq 0$):

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\begin{aligned}
-\mathcal{L} \;\; &\simeq \;\; (2G_F^2)^{\frac{1}{4}} \frac{m_\tau}{c_\beta^2} \left(\Delta_L^{3j} \overline{\tau}_R l_L^j + \Delta_R^{3j} \overline{\tau}_L l_R^j \right) \left(c_{\beta-\alpha} h^0 - s_{\beta-\alpha} H^0 - iA^0 \right) \\
&+ \;\; (8G_F^2)^{\frac{1}{4}} \frac{m_\tau}{c_\beta^2} \left(\Delta_L^{3j} \overline{\tau}_R \nu_L^j + \Delta_R^{3j} \nu_L^\tau \overline{l}_R^j \right) H^\pm + h.c.
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- **Higgs** (gaugino) mediated LFV effects decouple as $m_H \to \infty$ ($m_{SUSY} \to \infty$),
- Key ingredients in the Higgs mediated LFV:
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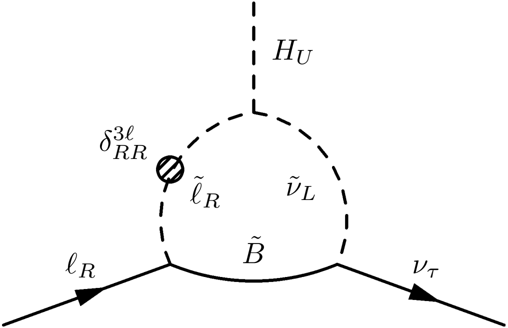
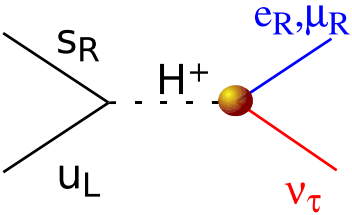


$\mu - e$ universality in $M \to l\nu$

$$R_K^{LFV} = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \simeq \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)} \; , \quad i = e, \mu, \tau$$



$$eH^\pm \nu_\tau \to \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta_R^{31} \tan^2\beta$$

$$\Delta_R^{31} \sim \frac{\alpha_2}{4\pi} \delta_{RR}^{31}$$

$$\Delta_R^{31} \sim 5 \cdot 10^{-4} \quad t_\beta = 40 \quad M_{H^\pm} = 500\text{GeV}$$

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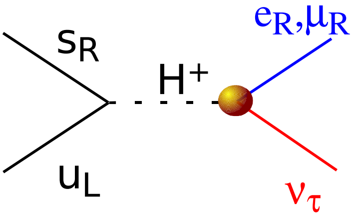

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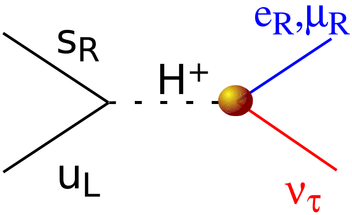

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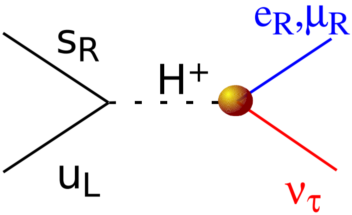

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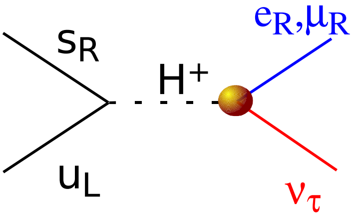

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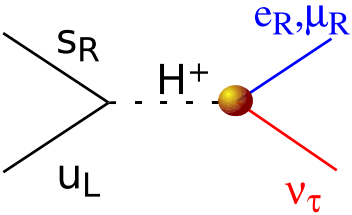

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Which is the sign of $\Delta r_{NP}^{e-\mu}$?

- LFV effects to LFC channels in R_M

$$\ell H^{\pm} \nu_\ell \to \frac{g_2}{\sqrt{2}} \frac{m_\ell}{M_W} \tan\beta \left(1 + \frac{m_\tau}{m_\ell} \Delta_{RL}^{\ell\ell} \tan\beta\right) \qquad (\ell = e, \mu)$$

$$\Delta_{RL}^{\ell\ell} \sim \frac{\alpha_1}{4\pi} \delta_{RR}^{\ell 3} \delta_{LL}^{3\ell} f_{loop} \leq 10^{-4}$$

- Deviations from $\mu - e$ universality in K_{l2} and π_{l2}

$$\frac{R_{K,\pi}^{LFV}}{R_{K,\pi}^{SM}} \simeq \left[\left(1 - \frac{m_\tau}{m_e} \frac{m_{K,\pi}^2}{M_{H^\pm}^2} \Delta_{RL}^{11} \tan^3\beta \right)^2 + \frac{m_\tau^2}{m_e^2} \frac{m_{K,\pi}^4}{M_{H^\pm}^4} |\Delta_R^{31}|^2 \tan^6\beta \right]$$

$$R_K^{LFV} \simeq R_K^{SM}(1 - 0.032)\,, \qquad R_\pi^{LFV} \simeq R_\pi^{SM}(1 - 0.0021)$$

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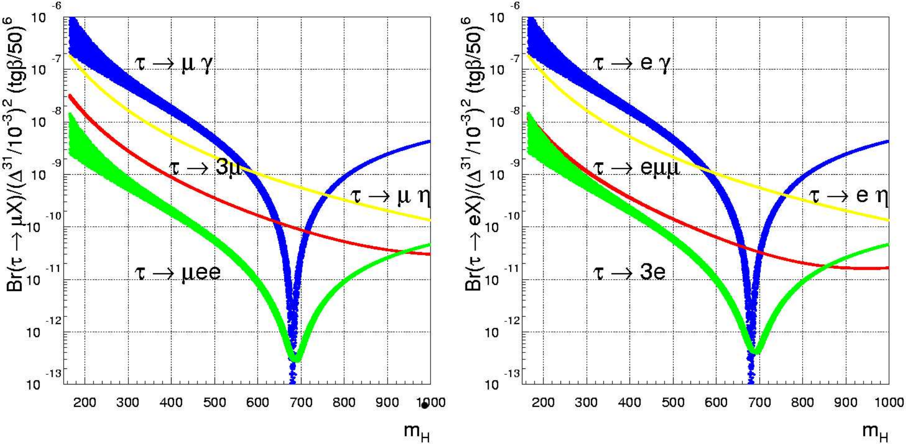

P. P, hep-ph/0508054

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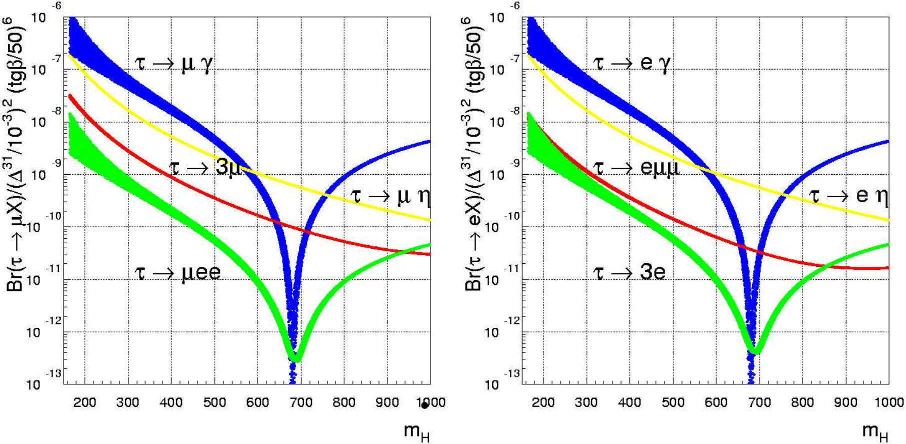

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$B \to \ell\nu$ as a probe of New Physics

Decay	SM Prediction	Belle	BABAR
$B \to e\nu_e$	$(9.8 \pm 4.1) \times 10^{-12}$	$\leq 1.5 \times 10^{-5}$	$\leq 5.4 \times 10^{-6}$
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$f_B = 0.216 \pm 0.022\mathrm{GeV}$ $\qquad |V_{ub}| = (4.39 \pm 0.33) \times 10^{-3}$

$$\mathcal{B}(B^- \to \tau^- \bar\nu)^{\rm exp} = (1.06^{+0.34}_{-0.28}(\text{stat})^{+0.18}_{-0.16}(\text{syst}))\times 10^{-4} \quad (BELLE\,'06)$$

$$R^{\rm exp}_{B\tau\nu} = \frac{\mathcal{B}^{\rm exp}(B_u \to \tau\nu)}{\mathcal{B}^{\rm SM}(B_u \to \tau\nu)} = 0.67^{+0.30}_{-0.27} = 0.67^{+0.24}_{-0.21}{}_{\rm exp} \pm 0.14_{|f_B|} \pm 0.10_{|V_{ub}|}$$

$$\Gamma(B \to \ell\nu) = \frac{G_F^2}{8\pi}|V_{ub}|^2 f_B^2 m_B m_\ell^2 \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 \times r_B$$

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LFV channels in $B \to \ell\nu$

- Including LFV channels in $B \to \ell\nu$, with $\ell = e, \mu$

$$R_{LFV}^{\ell/\tau} \simeq R_{SM}^{\ell/\tau}\left[1 + r_H^{-1}\left(\frac{m_B^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{m_\ell^2}\right)|\Delta_R^{3\ell}|^2 \tan^6\beta\right]$$

- Imposing the $\tau \to \ell_j X$ $(X = \gamma, \eta, \ell_j\ell_j(\ell_k\ell_k))$ constraints

$$R_{LFV}^{\mu/\tau} \leq 1.5 R_{SM}^{\mu/\tau}\,, \qquad R_{LFV}^{e/\tau} \leq 2 \cdot 10^4 \cdot R_{SM}^{e/\tau}$$

[G.Isidori, P.P., hep-ph/0605012]

- Imposing the $\mu - e$ universality constraints in R_K

$$\frac{R_{LFV}^{e/\tau}}{R_{SM}^{e/\tau}} \simeq \left[1 + r_H^{-1}\frac{m_B^4}{m_K^4}\Delta r_{K\,Susy}^{e-\mu}\right] \leq 4 \cdot 10^2$$

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$$R_{LFV}^{\ell/\tau} \simeq R_{SM}^{\ell/\tau}\left[1 + r_H^{-1}\left(\frac{m_B^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{m_\ell^2}\right)|\Delta_R^{3\ell}|^2 \tan^6\beta\right]$$

- Imposing the $\tau \to \ell_j X$ $(X = \gamma, \eta, \ell_j\ell_j(\ell_k\ell_k))$ constraints

$$R_{LFV}^{\mu/\tau} \leq 1.5 R_{SM}^{\mu/\tau}\ , \qquad R_{LFV}^{e/\tau} \leq 2 \cdot 10^4 \cdot R_{SM}^{e/\tau}$$

[G.Isidori, P.P., hep-ph/0605012]

- Imposing the $\mu - e$ universality constraints in R_K

$$\frac{R_{LFV}^{e/\tau}}{R_{SM}^{e/\tau}} \simeq \left[1 + r_H^{-1}\frac{m_B^4}{m_K^4}\Delta r_{K\ Susy}^{e-\mu}\right] \leq 4 \cdot 10^2$$

Lepton Universality in τ decays

- Tree level $H^{\pm}$ effects to $R_\tau = \mathcal{B}(\tau \to \mu\nu\bar{\nu})/\mathcal{B}(\mu \to e\nu\bar{\nu})$

$$R_\tau/R_\tau|_{SM} \simeq 1 - 2\frac{m_\mu^2 \tan^2\beta}{M_{H^\pm}^2} \simeq 1 - 6\times 10^{-4}\left(\frac{\tan\beta}{50}\right)^2\left(\frac{300\mathrm{GeV}}{M_{H^\pm}}\right)^2$$

- Tree level $H^{\pm}$ effects to $R_\tau = \mathcal{B}(\tau \to K(\pi)\nu)/\mathcal{B}(K(\pi) \to \mu\nu)$ cancel

- Tree level $H^{\pm}$ effects to $\mathcal{B}(B \to X\tau\nu)$

$$\frac{\mathcal{B}(B \to X\tau\nu)}{\mathcal{B}(B \to X\tau\nu)|_{SM}} \simeq 1 - 2\frac{m_\tau^2 \tan^2\beta}{M_{H^\pm}^2} \simeq 1 - 0.2\left(\frac{\tan\beta}{50}\right)^2\left(\frac{300\mathrm{GeV}}{M_{H^\pm}}\right)^2$$

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The large $\tan\beta$ scenario

Key ingredients for the LU breaking:

- $M_{\ell 2}$ ($M = \pi, K, B$) physics:
  - Large $\tan\beta$, $M_H < 1 TeV$
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[G.Isidori, P.P., hep-ph/0605012]

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- MFV at large $\tan\beta$ predicts a suppression of $B \to \tau\nu$ and ΔM_s with respect to the SM

$$R^{\exp}_{B\tau\nu} = \frac{\mathcal{B}^{\exp}(B_u \to \tau\nu)}{\mathcal{B}^{SM}(B_u \to \tau\nu)} = 0.67^{+0.30}_{-0.27} \qquad \textit{Belle '06}$$

$$R^{\exp}_{\Delta M_s} = \frac{(\Delta M_{B_s})^{\exp}}{(\Delta M_{B_s})^{SM}} = 0.80 \pm 0.12 \qquad \textit{CDF '06}$$

$$0.76 < R_{BX_s\gamma} = \frac{\mathcal{B}(B \to X_s\gamma)^{SUSY}}{\mathcal{B}(B \to X_s\gamma)^{SM}} < 1.15 \qquad [90\%\ \mathrm{C.L.}]\ .$$

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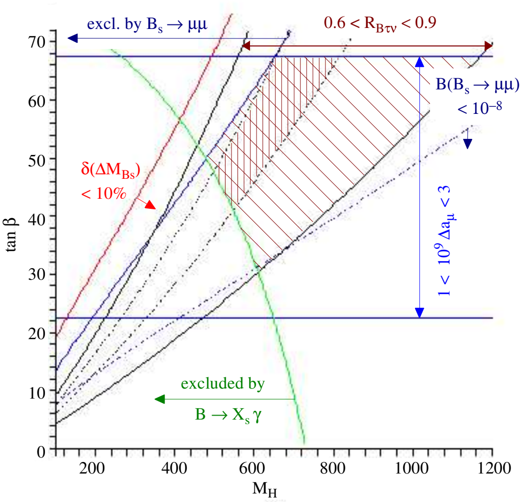
Phenomenology of MFV at large tan β



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Conclusion

- Susy effects can induce violations of lepton universality which can reach the % level in $R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$ and the 0.1% level in R_π
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