Theoretical Review on Lepton Universality and LFV

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General Considerations

Flavor Physics in the LHC era

- **High energy experiments** are the key tool to determine the **energy scale** Λ by direct production of NP particles.

- **Low energy experiments** are a fundamental ingredient to determine the **symmetry properties** of the new d.o.f. via their virtual effects in precision observables.

NP search strategies

Where to look for New Physics?

- Processes very **suppressed** or even **forbidden** in the SM
  - FCNC processes ($\mu \to e\gamma$, $\tau \to \mu\gamma$, $B^0_{s,d} \to \mu^+\mu^-$, $K \to \pi\nu\bar{\nu}$)
  - CPV effects (electron/neutron EDMs, $d_{e,n}$,...)
- Processes predicted with **high precision** in the SM
  - EWPO as $\Delta\rho$, $(g-2)_\mu$,...
  - LU in $R_M^{e/\mu} = \Gamma(M \to e\nu)/\Gamma(M \to \mu\nu)$ $(M = \pi, K)$

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

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$K \to \pi\nu\bar{\nu}$ and NP

- FCNC processes as $K \to \pi\nu\bar{\nu}$ offers a unique possibility in probing the underlying flavour mixing mechanism of **NP**
  - No SM tree-level contributions (FCNC decays)
  - One-loop SM contributions CKM-suppressed ($V_{ts}^{*}V_{td} \sim \lambda^{5}$)
  - Dominance of short distance (e.w.) effects $\to$ SM uncertainties at %
  - Great sensitivity to NP effects of many theories as SUSY, LHT, Z' models.....

$$A(s \to d)_{\mathrm{FCNC}} \sim c_{\mathrm{SM}} \frac{y_t^2 V_{ts}^{*} V_{td}}{16\pi^2 M_W^2} + c_{\mathrm{NP}} \frac{\delta_{21}}{16\pi^2 \Lambda_{NP}{}^2}$$

- Large departures from the SM only if $\delta_{21} \not\propto V_{ts}^{*}V_{td}$ (beyond MFV)

see talks of Haisch, Smith and Tarantino

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

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

$$R_\pi^{SM} = (1.2354 \pm 0.0002) \cdot 10^{-4} \quad \text{SM}$$

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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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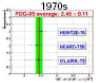
Ne

Experiments

$\pi \to e\nu$	$K \to e\nu / K \to \mu\nu$
$R_{e/\mu}^{\exp\pi}$ ($\pm 0.4\%$)	$R_{e/\mu}^{\exp K}$ ($\pm 2\%$)
$1.2265(34)(44) x 10^{-4}$ TRIUMF (1992)	$2.45(11) x 10^{-5}$
$1.2346(35)(36) x 10^{-4}$ PSI (1993)	$2.416(43)(24) x 10^{-5}$ CERN(2006)
$R_{e/\mu}^{th} - R_{e/\mu}^{\exp} = 43(37) x 10^{-8}$	$R_{e/\mu}^{th} - R_{e/\mu}^{\exp} = 56(46) x 10^{-8}$



Two new $\pi \to e\nu$ experiments.
Goals: $\pm(5)x10^{-8}$ (0.05%)

KLOE: Stay tuned $\to$ (1-2%?);
New $K \to e\nu$ experiment at CERN.
Goal: $\pm(10)x10^{-8}$ (0.3%)

Bryman at this conference

$\mu - e$ 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
  - $< 0|\bar{u}\gamma_\mu\gamma_5 d|M^- >= i f_M p^\mu_M$
  - $< 0|\bar{u}\gamma_5 d|M^- >= -i f_M \frac{m^2_M}{m_d+m_u}$

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

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

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

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

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

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

$$\Downarrow$$

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

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

- $e - \mu$ 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 $m_H \geq 300\mathrm{GeV}$ and $t_\beta \leq 50$)

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

  - $\tilde{\chi}^{\pm} - \tilde{\chi}^0 - \tilde{\ell}^{\mp}_{e,\mu}$ leading to (with $\delta\tilde{m}/\tilde{m} \leq 0.1$)

$$\Delta r^{e-\mu}_{SUSY} \sim \frac{\alpha_2}{4\pi} \left(\frac{\tilde{m}_\mu^2 - \tilde{m}_e^2}{\tilde{m}_\mu^2 + \tilde{m}_e^2} \right) \frac{m_W^2}{M_{SUSY}^2} \leq 10^{-4}$$

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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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WHAT ARE WE MISSING ?..........

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

..........EXPERIMENTALLY THE NEUTRINO FLAVOUR IS UNDETERMINED !!

Masiero, Paradisi, Petronzio, '06

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Higgs Mediated LFV

- LFV Yukawa Int. (if $\delta_{ij} = \tilde{m}^2_{ij}/\tilde{m}^2 \neq 0$) **Babu & Kolda, '02**:

$$-\mathcal{L} \simeq (2G_F^2)^{\frac{1}{4}} \frac{m_\tau}{c_\beta^2} \left(\Delta_L^{3j} \overline{\tau}_R l_L^j + \Delta_R^{3j} \overline{\tau}_L l_R^j \right) \left(c_{\beta-\alpha} h^0 - s_{\beta-\alpha} H^0 - i A^0 \right)$$

$$+ (8G_F^2)^{\frac{1}{4}} \frac{m_\tau}{c_\beta^2} \left(\Delta_L^{3j} \overline{\tau}_R \nu_L^j + \Delta_R^{3j} \nu_L^\tau \overline{l}_R^j \right) H^\pm + h.c.$$

$$\Delta_{3j} \sim \frac{\alpha_2}{4\pi} \delta_{3j}$$

- **Higgs** (gaugino) mediated LFV effects decouple as $m_H \to \infty$ ($m_{SUSY} \to \infty$),

- Key ingredients in the Higgs mediated LFV:
  - large $\tan\beta \sim 50$
  - large slepton mixings, $\delta_{3j} \sim \mathcal{O}(1)$, ($m_{SUSY} > 1\mathrm{TeV}$)

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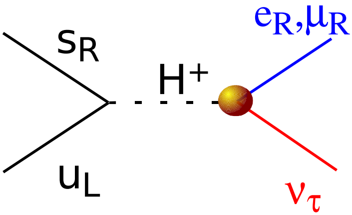
$$R_K^{LFV} = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \simeq \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)}\ , \quad i = e, \mu, \tau$$



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

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

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

$$\Downarrow$$

$$\Delta r^{e-\mu}_{K\,SUSY} \simeq \left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right)|\Delta_R^{31}|^2 \tan^6\beta \approx 10^{-2}$$

$$\Delta r^{e-\mu}_{\pi\,SUSY} \simeq \left(\frac{m_d}{m_u+m_d}\right)^2 \left(\frac{m_\pi^4}{m_k^4}\right) \Delta r^{e-\mu}_{K\,SUSY} \leq 10^{-4}$$

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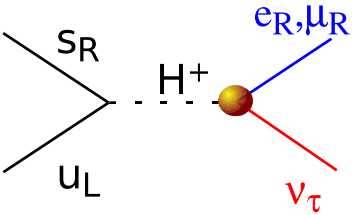

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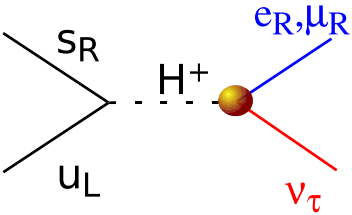

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$\mu - e$ universality in $M \to l\nu$

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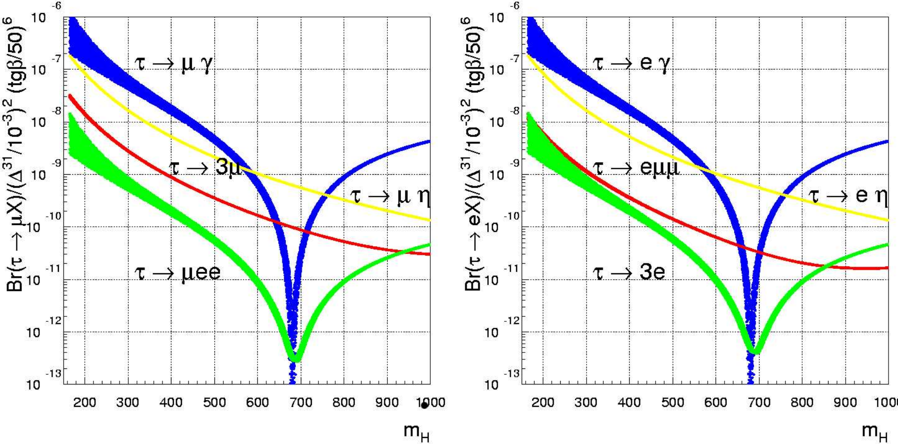
$$R_K^{LFV} \simeq R_K^{SM}(1-0.032)\,, \qquad R_{\pi}^{LFV} \simeq R_{\pi}^{SM}(1-0.0021)$$

Phenomenology: $\tau \to l_j X$ $(X = \gamma, \eta, l_j l_j (l_k l_k))$



P. P, hep-ph/0508054

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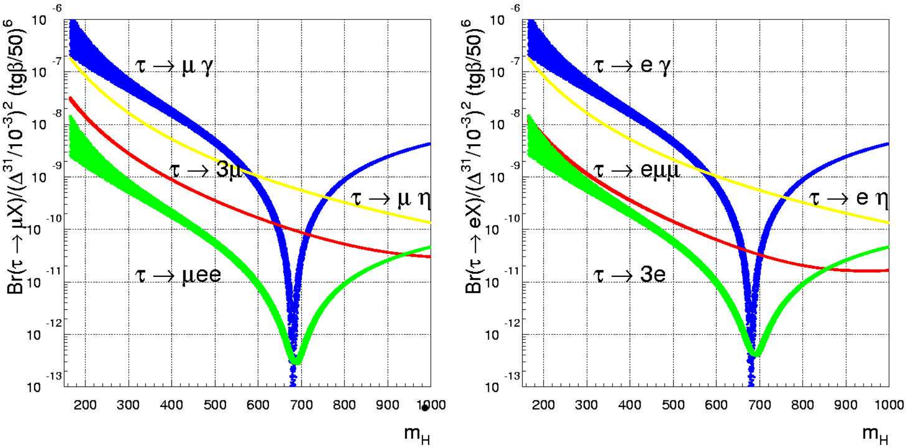

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LFV channels in $B \to \ell\nu$

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

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

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

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

[G.Isidori, P.P., '06]

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

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

Lepton Universality in τ decays

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

$$R_\tau / R_\tau|_{SM} \simeq 1 - 2\frac{m_\mu^2 t_\beta^2}{M_{H^\pm}^2} \simeq 1 - 10^{-3}\left(\frac{t_\beta}{50}\right)^2 \left(\frac{200\mathrm{GeV}}{M_{H^\pm}}\right)^2$$

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

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

$$\frac{\mathcal{B}(B \to X\tau\nu)}{\mathcal{B}(B \to X\tau\nu)|_{SM}} \simeq 1 - 2\frac{m_\tau^2 t_\beta^2}{M_{H^\pm}^2} \simeq 1 - 0.4\left(\frac{t_\beta}{50}\right)^2 \left(\frac{200\mathrm{GeV}}{M_{H^\pm}}\right)^2$$

The large $\tan\beta$ scenario

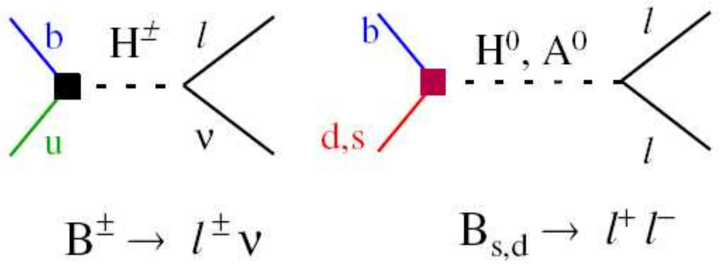
Key ingredients for the LU breaking:

- $M_{\ell 2}$ $(M = \pi,\ K,\ B)$ physics:
  - Large $\tan\beta$, $M_H < 1\,TeV$
  - Large LFV slepton minxings, $\delta_{3j} \sim \mathcal{O}(1)$, ($\mathrm{m}_{SUSY} \geq 1\mathrm{TeV}$)
- τ physics:
  - Large $\tan\beta$, $M_H < 1\,TeV$
  - No LFV effects
- How natural is the large $\tan\beta$ scenario?
  - Top-Bottom Yukawa unification in GUT ($SO(10)$) $\Rightarrow$ $\tan\beta = (m_t/m_b)$
  - Correlations between $(B \to \tau\nu)$ and $(B \to X_s\gamma)$, ΔM_{B_s}, $(B_{s,d} \to \ell^+\ell^-)$, $(g-2)_\mu$ and m_{h^0}

[G.Isidori, P.P., '06]

Phenomenology of MFV at large $\tan\beta$

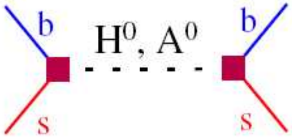
$\tan\beta \sim (30-50)$, $\mathbf{M_H \sim (300-500)GeV}$, $\mathbf{M_{\tilde{q}} \sim (1-2)TeV}$

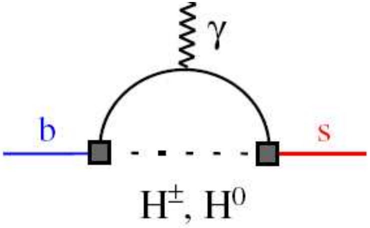


$\sim (10-30)\%$ **suppression** up to $10\times$ **enhancement**

Phenomenology of MFV at large tan β

$t_\beta \sim (30-50)$, $\mathbf{M_H \sim (300-500)GeV}$, $\mathbf{M_{\tilde{q}} \sim (1-2)TeV}$





ΔM_{B_s} $\sim (0-10)\%$ **suppression**

$B \to X_s \gamma$ **up** $\sim (0-20)\%$ **enhancement**

Phenomenology of MFV at large $\tan\beta$

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

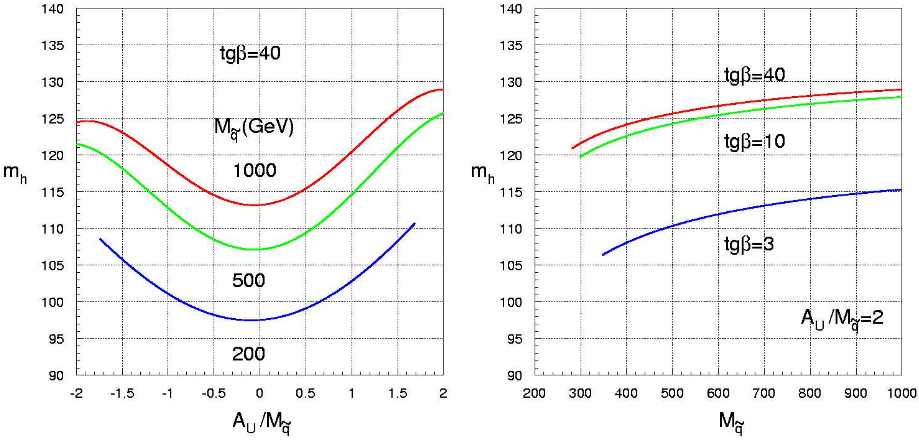
$$\frac{(\Delta M_{B_s})}{(\Delta M_{B_s})^{SM}} \simeq 1 - 3 \times 10^{-2} \left(\frac{\mu A_U}{m_{\tilde{q}}^2}\right)^2 \left(\frac{t_\beta}{50}\right)^4 \left(\frac{400\text{GeV}}{M_H}\right)^2 .$$

$$Br(B_s \to \mu^+\mu^-) \simeq 6 \times 10^{-8} \left(\frac{400\text{GeV}}{M_H}\right)^4 \left(\frac{\mu A_U}{m_{\tilde{q}}^2}\right)^2 \left(\frac{t_\beta}{50}\right)^6$$

$$\frac{Br(B \to \ell\nu)}{Br(B \to \ell\nu)^{SM}} \simeq \left(1 - 0.3 \left(\frac{t_\beta}{50}\right)^2 \left(\frac{400\text{GeV}}{m_{H^\pm}}\right)^2\right)^2$$

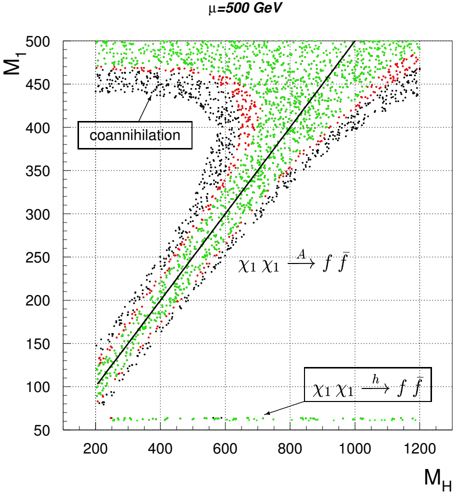
$\frac{Br(B \to \tau\nu)}{(\Delta M_{B_d})} \sim (V_{ub}/V_{td})^2/\hat{B}_d$ much better then $|V_{ub}|^2 f_B^2$!

Lightest Higgs boson mass



G.Isidori, P.P., '06

WMAP constraints @ large tan β



$t_\beta = 20\,(green), 30\,(red), 50\,(black)$

- **Dark Matter constraint satisfied for**
- **Coannihilation Processes**: $1 \lesssim \frac{M_{\mathrm{NLSP}}}{M_{\mathrm{LSP}}} \lesssim 1.1$
- **Resonant Processes**: $M_A \simeq 2M_{\mathrm{LSP}}$

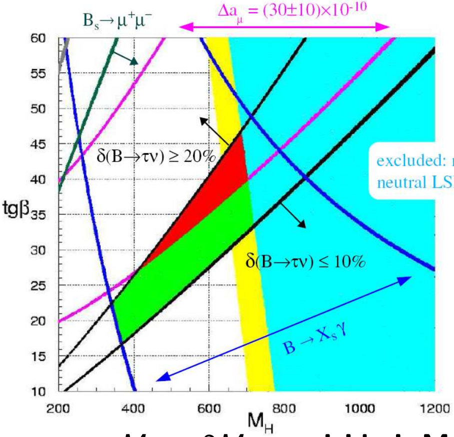
Isidori, Mescia, P.P., Temes, '07

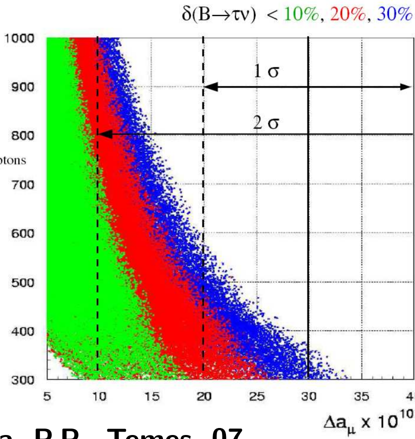
Constraints/Reference-Ranges

Constraints/Reference-Ranges under WMAP constraints

- $\mathbf{B} \to \mathbf{X_s}\gamma$: $[1.01 < \mathbf{R_{Bs\gamma}} < 1.24]$
- $\mathbf{a}_\mu$: $[2 < 10^{-9}(\mathbf{a}_\mu^{\rm exp} - \mathbf{a}_\mu^{\rm SM}) < 4]$
- $\mathbf{B} \to \mu^+\mu^-$: $[\mathcal{B}^{\rm exp} < 8.0 \times 10^{-8}]$
- ΔM_{B_s} : $[\mathbf{\Delta M_{B_s}} = 17.35 \pm 0.25 \ {\rm ps}^{-1}]$
- $B \to \tau\nu$: $[0.8 < \mathbf{R_{B\tau\nu}} < 0.9]$

B-physics, $(g-2)_\mu$ under WMAP constraints





$M_H \sim 2M_1$ **Isidori, Mescia, P.P., Temes, 07**

Conclusion

Where to look for New Physics?

- LU breaking @ % in $R_K^{e/\mu} = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$ can be generated by the LFV
- LU breaking @ 0.1% in $R_\pi^{e/\mu} = \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$ can be generated by the LFV
- LFV SUSY effects can greatly enhance also $R_B^{\ell/\tau}$, $\ell = e, \mu$.
- The relevant SUSY parameter space for large **LU** breaking effects is allowed by the constraints of rare LFV decays, **B**-physics observables and **D**ark **M**atter

$$\Downarrow$$

Charged meson decays offer a great chance to probe LFV in New Physics .