Lepton Universality Breaking as a probe of New Physics

P. Paradisi

University of Valencia and IFIC

SUSY 2007
Karlsruhe, Germany 27 July 2007

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 $R_M^{e/\mu}$

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 $R_M^{e/\mu}$

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 $R_M^{e/\mu}$

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 $R_M^{e/\mu}$

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

- NA48/2

$$R_K^{exp.} = (2.416 \pm 0.043_{stat.} \pm 0.024_{syst.}) \cdot 10^{-5} \qquad \text{'03 DATA}$$

$$R_K^{exp.} = (2.455 \pm 0.045_{stat.} \pm 0.041_{syst.}) \cdot 10^{-5} \qquad \text{'04 DATA}$$

A dedicated run (of 4 month) for R_K by **P326/NA62** (former **NA48**) is started at the **CERN**. Goal: the error @ 0.3%**!**

Fantechi @ EPS '07

- KLOE

$$R_K^{exp.} = (2.55 \pm 0.05_{stat.} \pm 0.05_{syst.}) \cdot 10^{-5}$$

The complete analysis of data will push the error @ 1%

Spadaro @ EPS '07

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

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

- NA48/2

  $$R_K^{exp.} = (2.416 \pm 0.043_{stat.} \pm 0.024_{syst.}) \cdot 10^{-5} \qquad '03\ DATA$$

  $$R_K^{exp.} = (2.455 \pm 0.045_{stat.} \pm 0.041_{syst.}) \cdot 10^{-5} \qquad '04\ DATA$$

  A dedicated run (of 4 month) for R_K by **P326/NA62** (former **NA48**) is started at the **CERN**. Goal: the error @ 0.3%**!**

  Fantechi @ EPS '07

- KLOE

  $$R_K^{exp.} = (2.55 \pm 0.05_{stat.} \pm 0.05_{syst.}) \cdot 10^{-5}$$

  The complete analysis of data will push the error @ 1%

  Spadaro @ EPS '07

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

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

- NA48/2

  $R_K^{exp.} = (2.416 \pm 0.043_{stat.} \pm 0.024_{syst.}) \cdot 10^{-5}$ *'03 DATA*

  $R_K^{exp.} = (2.455 \pm 0.045_{stat.} \pm 0.041_{syst.}) \cdot 10^{-5}$ *'04 DATA*

  A dedicated run (of 4 month) for R_K by **P326/NA62** (former **NA48**) is started at the **CERN**. Goal: the error @ 0.3%**!**

  Fantechi @ EPS '07

- KLOE

  $$R_K^{exp.} = (2.55 \pm 0.05_{stat.} \pm 0.05_{syst.}) \cdot 10^{-5}$$

  The complete analysis of data will push the error @ 1%

  Spadaro @ EPS '07

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

SM prediction for $R_{K,\pi}$

- $R_K^{SM} = (2.472 \pm 0.001) \cdot 10^{-5}$ SM
- $R_\pi^{SM} = (1.2354 \pm 0.0002) \cdot 10^{-4}$ SM

Marciano Sirlin '93, Finkemeyer '96

- $R_K^{SM} = (2.477 \pm 0.001) \cdot 10^{-5}$ SM
- $R_\pi^{SM} = (1.2352 \pm 0.0001) \cdot 10^{-4}$ SM

Cirigliano Rossell '07

The total errors in $R_{K,\pi}$ are dominated by the EXP. ERRORS!!!

SM prediction for $R_{K,\pi}$

- $R_K^{SM} = (2.472 \pm 0.001) \cdot 10^{-5}$ SM
- $R_\pi^{SM} = (1.2354 \pm 0.0002) \cdot 10^{-4}$ SM

Marciano Sirlin '93, Finkemeyer '96

- $R_K^{SM} = (2.477 \pm 0.001) \cdot 10^{-5}$ SM
- $R_\pi^{SM} = (1.2352 \pm 0.0001) \cdot 10^{-4}$ SM

Cirigliano Rossell '07

The total errors in $R_{K,\pi}$ are dominated by the EXP. ERRORS!!!

SM prediction for $R_{K,\pi}$

- $R_K^{SM} = (2.472 \pm 0.001) \cdot 10^{-5}$ SM
- $R_\pi^{SM} = (1.2354 \pm 0.0002) \cdot 10^{-4}$ SM

Marciano Sirlin '93, Finkemeyer '96

- $R_K^{SM} = (2.477 \pm 0.001) \cdot 10^{-5}$ SM
- $R_\pi^{SM} = (1.2352 \pm 0.0001) \cdot 10^{-4}$ SM

Cirigliano Rossell '07

The total errors in $R_{K,\pi}$ are dominated by the EXP. ERRORS!!!

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

- Any deviation from the SM expectation for $R_{K,\pi}$ due to NP can be written as

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

- Violations of **LU** in **CCI** can be classified as
  - i) **Corrections** to $(V-A)\times(V-A)$ interaction through $W\ell\nu_\ell$ vertex correction induced by a loop of NP particles

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

  - ii) **New Lorentz Structures**, i.e. **scalar CCI** with

$$H\ell\nu \sim m_\ell \tan\beta$$

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

- Any deviation from the SM expectation for $R_{K,\pi}$ due to NP can be written as

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

- Violations of **LU** in **CCI** can be classified as
  - i) **Corrections** to $(V-A)\times(V-A)$ interaction through $W\ell\nu_\ell$ vertex correction induced by a loop of NP particles

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

  - ii) **New Lorentz Structures**, i.e. **scalar CCI** with

$$H\ell\nu \sim m_\ell \tan\beta$$

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

- Four-Fermi interaction for $M \to \ell\nu$ induced by $W^\pm$, $H^\pm$

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

- PCAC's
  - $< 0|\bar{u}\gamma_\mu\gamma_5 d|M >= i f_M p_M^\mu$ $< 0|\bar{u}\gamma_5 d|M >= -i f_M \frac{m_M^2}{m_d+m_u}$

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

$$\frac{\Gamma^{H^\pm + W^\pm}(M \to \ell\nu)}{\Gamma^{W^\pm}(M \to \ell\nu)} = r_M = \left[1 - t_\beta^2 \left(\frac{m_d}{m_u + m_d}\right)\frac{m_M^2}{m^2_{H^\pm}}\right]^2 .$$

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

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

- Four-Fermi interaction for $M \to \ell\nu$ induced by $W^\pm$, $H^\pm$

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

- PCAC's
  - $< 0|\overline{u}\gamma_\mu\gamma_5 d|M >= if_M p_M^\mu$ $\qquad < 0|\overline{u}\gamma_5 d|M >= -if_M \frac{m_M^2}{m_d+m_u}$

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

$$\frac{\Gamma^{H^\pm+W^\pm}(M\to\ell\nu)}{\Gamma^{W^\pm}(M\to\ell\nu)} = r_M = \left[1 - t_\beta^2\ \left(\frac{m_d}{m_u+m_d}\right)\frac{m_M^2}{m_{H^\pm}^2}\right]^2 .$$

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

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

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

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

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

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

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

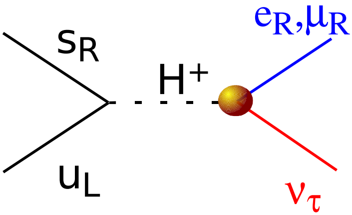
$$R_K^{EXP.} = \frac{\Gamma(K \to e\nu_e) + \Gamma(K \to e\nu_\mu) + \Gamma(K \to e\nu_\tau)}{\Gamma(K \to \mu\nu_\mu) + \Gamma(K \to \mu\nu_e) + \Gamma(K \to \mu\nu_\tau)}$$

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

Masiero, Paradisi, Petronzio, '06

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

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



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

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

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

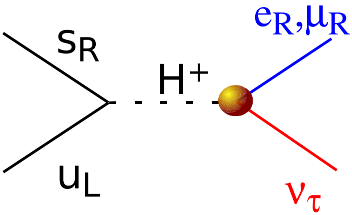
$$\Downarrow$$

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

$$\Delta r_{K\,SUSY}^{e-\mu} \approx 10^{-2} \quad \Longrightarrow \quad Br^{th.(exp.)}(\tau \to eX) \leq 10^{-10(-7)}$$

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

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



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

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

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

$$\Downarrow$$

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

$$\Delta r^{e-\mu}_{K\,SUSY} \approx 10^{-2} \quad \Longrightarrow \quad Br^{th.(exp.)}(\tau \to eX) \leq 10^{-10(-7)}$$

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

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

LU in τ and B decays

LU breaking induced by the tree level $H^\pm$ exchange

- $R_\tau^{\mu/e} = \Gamma(\tau \to \mu\nu\bar{\nu})/\Gamma(\tau \to e\nu\bar{\nu})$

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

- $R_B^{\tau/\ell} = \Gamma(B \to X\tau\nu)/\Gamma(B \to X\ell\nu)$

$$R_B^{\tau/\ell} \simeq 1 - 0.4\left(\frac{t_\beta}{50}\right)^2\left(\frac{200\mathrm{GeV}}{M_{H^\pm}}\right)^2$$

The large $\tan\beta$ scenario

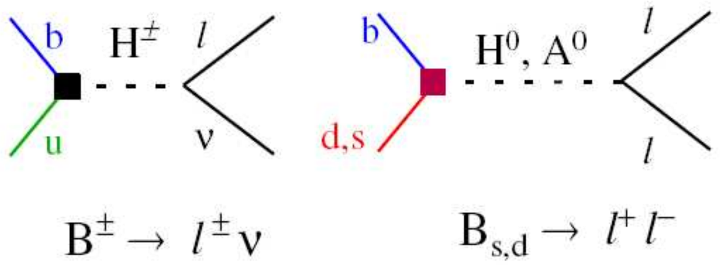
Key ingredients for the LU breaking:

- $M_{\ell 2}$ $(M = \pi,\ K,\ B)$ physics:
  - Large $\tan\beta$, $M_H < 1\,TeV$
  - Large LFV slepton minxings, $\delta_{3j} \in (O.1\,,1)$, $(\mathrm{m}_{SUSY} \geq 1\mathrm{TeV})$
- 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 $\tan\beta$

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

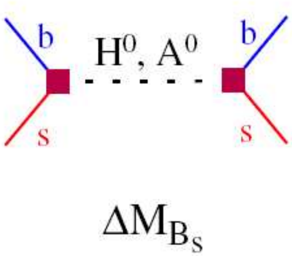


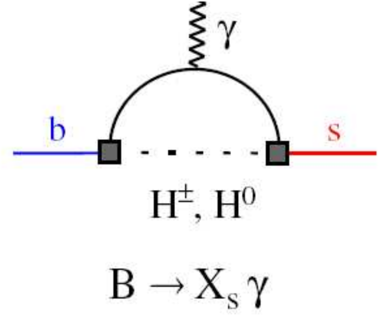
$\sim (10-30)\%$ **suppression**

up to $10\times$ **enhancement**

Phenomenology of MFV at large tan β

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

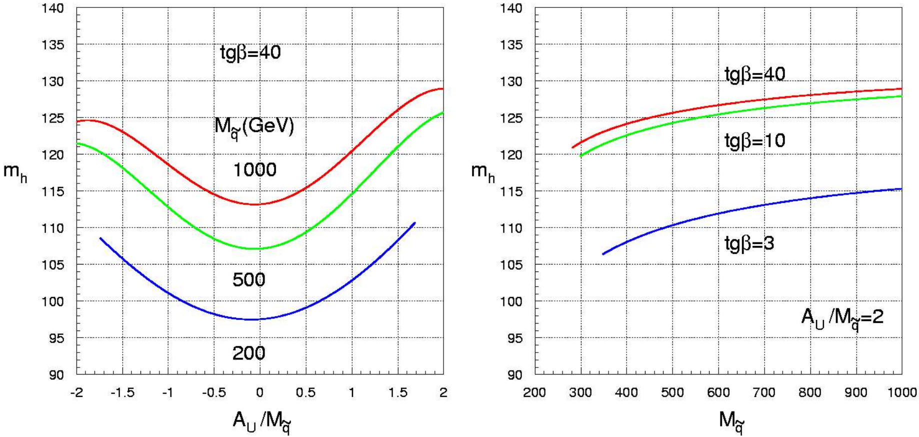




$\sim (0-10)\%$ **suppression**

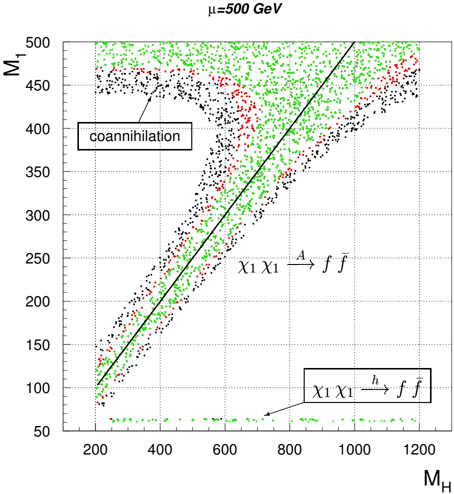
up $\sim (0-20)\%$ **enhancement**

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**: $1 \lesssim \frac{M_{\rm NLSP}}{M_{\rm LSP}} \lesssim 1.1$
- **Resonant Processes**: $M_A \simeq 2 M_{\rm LSP}$

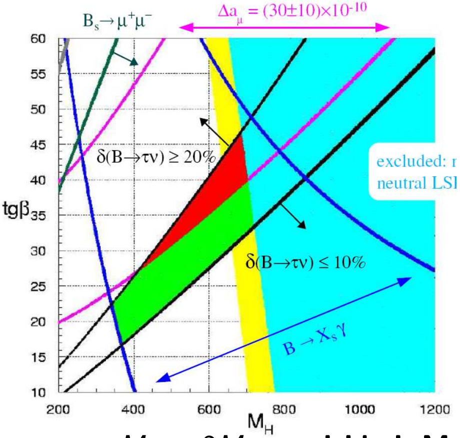
Isidori, Mescia, P.P., Temes, '07

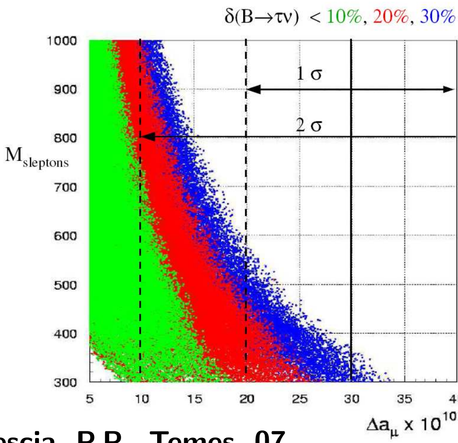
Constraints/Reference-Ranges

Constraints/Reference-Ranges under WMAP constraints

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

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 .