Flavour Physics in SUSY at large $\tan\beta$

P. Paradisi

Università di Valencia and IFIC

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The Standard Model

Virtues and flaws of the SM

- **Virtues**
  - Great phenomenological success (**LEP**)
  - FCNC and CP violation through the CKM
  - Renormalizability (Gauge theory)
- **Flaws**
  - Flavor Problem
  - Unification of forces
  - Gauge hierarchy $\Rightarrow \Lambda_{NP} \lesssim TeV$
  - Neutrino Masses and mixings angles
  - Dark Matter

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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.

$$\mathcal{L}_{\rm eff.} = \mathcal{L}_{\rm Gauge}(A_i, \Psi_i) + \mathcal{L}_{\rm Higgs}(A_i, \Psi_i, \phi_i) + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^d(A_i, \Psi_i, \phi_i)$$

- $\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Gauge} + \mathcal{L}_{\rm Higgs} =$ all possible operators with $d \leq 4$ (renormalizable) compatible with the Gauge symmetry.
- $\sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^d$ =most general parameterization of the new (heavy) d.o.f as long as we perform low-energy experiments.

NP search strategies

Where to look for New Physics?

- **Processes forbidden or much suppressed 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 $R_M^{e/\mu} = \Gamma(M \to e\nu)/\Gamma(M \to \mu\nu)$ $(M = \pi, K)$

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MFV hypothesis

- Rare processes like $K \to \pi\nu\bar{\nu}$ and $B^0_{s,d} \to \mu^+\mu^-$ offer a unique possibility in probing the underlying flavour mixing mechanism. In fact,
    - No SM tree-level contributions (FCNC decays)
    - One-loop SM contributions CKM-suppressed
    - Dominance of short distance (e.w.) effects → SM uncertainties at % (for $K \to \pi\nu\bar{\nu}$)

$$A(q_i \to q_j)_{\rm FCNC} \sim c_{\rm SM}\frac{y_t^2 V_{ti}^* V_{tj}}{16\pi^2 M_W^2} + c_{\rm NP}\frac{\delta_{ij}}{16\pi^2 \Lambda_{NP}{}^2}$$

- If $\Lambda_{NP} \leq \mathrm{TeV}$, $\delta_{ij} \sim V_{ti}^* V_{tj}$ is a natural way to explain the great agreement of SM EXP. results in Flavor Physics
- **MFV** hypotesis: the Yukawa couplings of the SM are the the only source of FV also beyond the SM

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LFV frameworks

- **Neutrino Oscillation** $\Rightarrow m_{\nu_i} \neq m_{\nu_j} \Rightarrow$ **LFV**
- **see-saw**: $m_\nu = \frac{(m_\nu^D)^2}{M_R} \sim eV$, $M_R \sim 10^{14-16} \Rightarrow m_\nu^D \sim m_{top}$
- LFV transitions like $\mu \to e\gamma$ @ 1 loop with exchange of
  - W and ν in the SM framework (GIM)

$$Br(\mu \to e\gamma) \sim \frac{m_\nu^4}{M_W^4} \leq 10^{-50} \qquad m_\nu \sim \mathrm{eV}$$

  - $\tilde{W}$ and $\tilde{\nu}$ in the MSSM framework (SUPER-GIM)

$$Br(\mu \to e\gamma) \sim \frac{m_\nu^{D\,4}}{\tilde{m}^4} \leq 10^{-11} \qquad m_\nu^D \sim m_{top}$$

$$\Downarrow$$

- LFV signals are undetectable (detectable) in the SM (MSSM)

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LFV in SUSY

RG induced LFV interactions in SUSY see-saw

- SUSY see-saw superpotential (MSSM + RN)

$$W = h^e L e^c H_1 + h^\nu L \nu^c H_2 + M_R \nu^c \nu^c + \mu H_1 H_2,$$

$$\mathcal{M}_\nu = -h^\nu M_R^{-1} h^{\nu\ T} v_2^2,$$

$$M_{\tilde{\ell}}^2 = \begin{pmatrix} m_L^2(1+\delta_{LL}^{ij}) & (A-\mu t_\beta)m_\ell + m_L m_R \delta_{LR}^{ij} \\ (A-\mu t_\beta)m_\ell + m_L m_R \delta_{LR}^{ij}{}^\dagger & m_R^2(1+\delta_{RR}^{ij}) \end{pmatrix}$$

- If $h^e = h^e_{ij}\delta_{ij}$ and $M_R = M_{R\,ij}\delta_{ij} \Rightarrow h^\nu \neq h^\nu_{ij}\delta_{ij}$ in general.

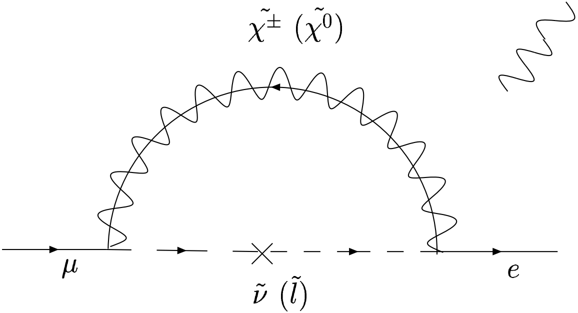
$$\delta_{LL}^{ij} \approx -\frac{3}{8\pi^2}(h^\nu h^{\nu\dagger})_{ij} \ln\frac{M_X}{M_R},$$

[Borzumati & Masiero, '86]

LFV in SUSY

LFV interactions – leptons/sleptons/gauginos

$$\mathcal{L} = \bar{\ell}_i \left(C^R_{ijA} P_R + C^L_{ijA} P_L \right) \tilde{\chi}^-_A \tilde{\nu}_j + \bar{\ell}_i \left(N^R_{ijA} P_R + N^L_{ijA} P_L \right) \tilde{\chi}^0_A \tilde{\ell}_j . \quad (1)$$



$$\left.\frac{BR(\ell_i \to \ell_j \gamma)}{BR(\ell_i \to \ell_j \nu_i \bar{\nu}_j)}\right|_{\rm Gauge} \simeq \frac{\alpha_{el}}{20\pi} \left(\frac{m_W^4}{m_{SUSY}^4} \right) \left(\delta^{21}_{LL} \right)^2 t^2_\beta \qquad \delta_{LL} \sim h^\nu h^{\nu\dagger}$$

LFV in SUSY

RG induced LFV interactions in SUSY GUTs

- **SUSY SU(5)** [Barbieri & Hall, '95]

$$(\delta^{\tilde{q}}_{LL})_{ij} \sim h^u h^{u\dagger}{}_{ij} \sim h_t^2 V^{ik}_{CKM} V^{kj*}_{CKM} \rightarrow (\delta^{\tilde{\ell}}_{RR})_{ij} \simeq (\delta^{\tilde{q}}_{LL})_{ij}$$

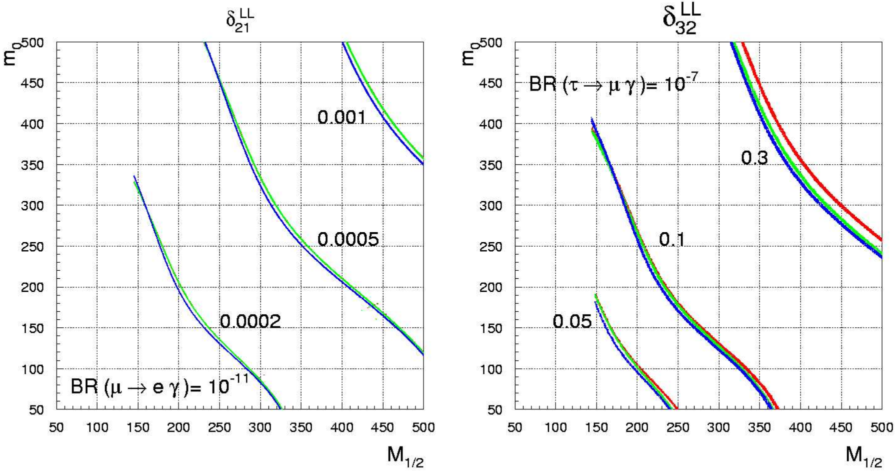
item **SUSY SU(5)+RN** [Yanagida et al., '95]

$$(\delta^{\tilde{\ell}}_{LL})_{ij} \sim (h^\nu h^{\nu\dagger})_{ij} \qquad \& \qquad (\delta^{\tilde{\ell}}_{RR})_{ij} \sim (h^u h^{u\dagger})_{ij}$$

- **SUSY SU(5)+RN** [Moroi, '00] **&** **SO(10)** [Chang et al., 02]

$$\sin\theta_{\mu\tau} \sim \frac{\sqrt{2}}{2} \Rightarrow (\delta^{\tilde{\ell}}_{LL})_{23} \sim 1 \Rightarrow (\delta^{\tilde{q}}_{RR})_{23} \sim 1$$

LFV MIs bounds



P. P, JHEP 0510 (2005) 006.

Higgs Mediated LFV

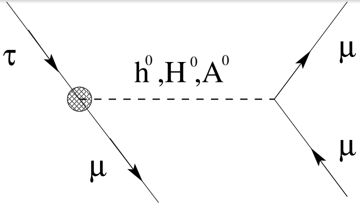
- LFV Yukawa Int. (if $\delta_{ij} = \tilde{m}^2_{ij}/\tilde{m}^2 \neq 0$) [Babu & Kolda, '02]:

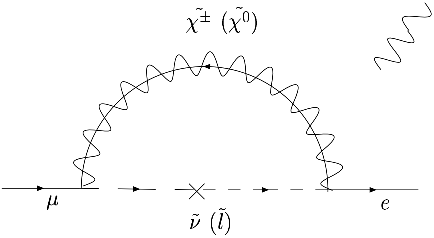
$$
\begin{aligned}
-\mathcal{L} &\simeq (2G_F^2)^{\frac{1}{4}} \frac{m_\tau}{c_\beta^2} \left(\Delta_L^{3j} \overline{\tau}_R l_L^j + \Delta_R^{3j} \overline{\tau}_L l_R^j \right) \left(c_{\beta-\alpha} h^0 - s_{\beta-\alpha} H^0 - i A^0 \right) \\
&+ (8G_F^2)^{\frac{1}{4}} \frac{m_\tau}{c_\beta^2} \left(\Delta_L^{3j} \overline{\tau}_R \nu_L^j + \Delta_R^{3j} \nu_L^\tau \overline{l}_R^j \right) H^\pm + h.c.
\end{aligned}
$$

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

- **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, $\delta_{3j} \sim \mathcal{O}(1)$, ($m_{SUSY} > 1\text{TeV}$)

Higgs vs Gauge LFV





$$\frac{BR(\tau\to 3\mu)}{BR(\tau\to\mu\nu\bar{\nu})} \simeq \left(\frac{\alpha_2}{48\pi}\right)^2 \left(\frac{m_\tau m_\mu}{M_H^2}\right)^2 \delta_{32}^2 t_\beta^6 \qquad \frac{BR(\tau\to\mu\gamma)}{BR(\tau\to\mu\nu\bar{\nu})} \simeq \frac{\alpha_{el}}{20\pi}\frac{m_w^4}{\tilde{m}^4}\delta_{32}^2 t_\beta^2$$

If $t_\beta \sim 50$ and $M_H \ll \tilde{m}$, i.e. $M_H \sim m_w$ and $\tilde{m} \sim TeV$

$$\Downarrow$$

$$\frac{BR(\tau\to 3\mu)}{BR(\tau\to\mu\gamma)} \not\propto \alpha_{el}$$

Correlations

- **Higgs mediated $\tau - \mu(e)$ transitions**

$$\frac{Br(\tau \to l_j\gamma)}{Br(\tau \to l_j\eta)} \geq 1\,, \frac{Br(\tau \to l_j\mu\mu)}{Br(\tau \to l_j\gamma)} \geq \frac{3+5\delta_{j\mu}}{36}$$

$$\frac{Br(\mu N \to eN)}{Br(\mu \to e\gamma)} \sim 10^{-1}$$

- **Gaugino mediated transitions**

$$\frac{BR(\tau \to l_j l_k l_k)}{BR(\tau \to l_j\gamma)} \simeq \alpha_{el}\,, \quad \frac{Br(\mu N \to eN)}{Br(\mu \to e\gamma)} \simeq \alpha_{el}.$$

$$\frac{Br(\tau \to \mu\mu\mu)}{Br(\tau \to \mu\eta)} \simeq \tan^2\beta \gg 1$$

P. P, '05; '06.

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

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

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

$\mu - e$ 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.:

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

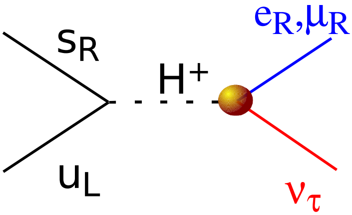
- we get at the 2σ level:

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

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

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

$$R_K = (1+\Delta r_K^{e-\mu}) = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \simeq \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)}$$



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

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

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

$$\Downarrow$$

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

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

Masiero, P.P, Petronzio, Phys. Rev. D 74, 011701 (2006)

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

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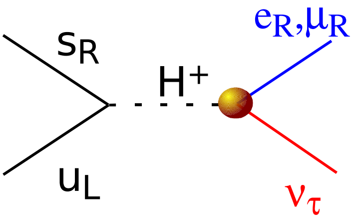

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LFV channels in $B \to \ell\nu$

- 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

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

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

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

Isidori, P.P, Phys. Lett. B 639 (2006) 499.

SUSY MFV scenario @ large tan β

How natural is the MFV SUSY scenario @ large tan β?

- Top-Bottom Yukawa unification in GUT (minimal $SO(10)$) $\Rightarrow$ $\tan\beta = (m_t/m_b)$
- 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}

[Isidori, P.P., '06]

- WMAP constraints are **"naturally"** satisfied for $\tan\beta = (m_t/m_b)$

[Lunghi, Porod & Vives, '06]

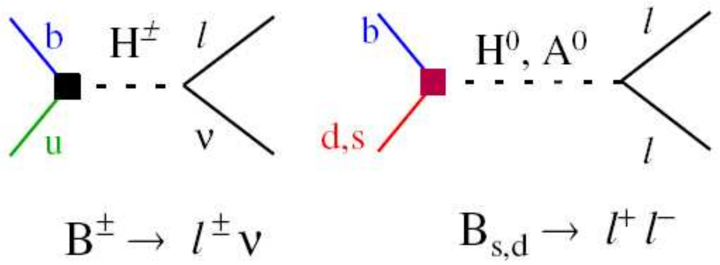
[Isidori, Mescia, P.P., Temes, '07]

Constraints/Reference-Ranges

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

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 $\tan\beta$

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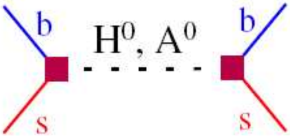

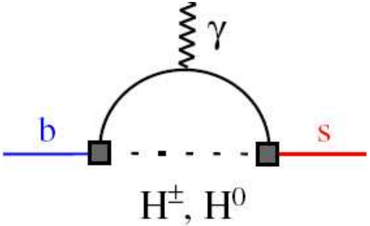

ΔM_{B_s} $\quad\quad$ $B \to X_s \gamma$

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

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

$$Br(B_s \to \mu^+\mu^-) \simeq \frac{6\times 10^{-8}}{\left(\frac{2}{3}+\frac{1}{3}\frac{t_\beta}{50}\right)^4}\left(\frac{400\mathrm{GeV}}{M_H}\right)^4\left(\frac{\mu A_U}{m_{\tilde q}^2}\right)^2\left(\frac{t_\beta}{50}\right)^6$$

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

$$r_B \simeq \left(1 - 0.3\frac{(t_\beta/50)^2}{\left(\frac{2}{3}+\frac{1}{3}\frac{t_\beta}{50}\right)}\left(\frac{400\mathrm{GeV}}{m_{H^\pm}}\right)^2\right)^2$$

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

Phenomenology of MFV at large tan β

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

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

$$Br(B_s \to \mu^+\mu^-) \simeq \frac{6 \times 10^{-8}}{\left(\frac{2}{3} + \frac{1}{3}\frac{t_\beta}{50}\right)^4} \left(\frac{400\mathrm{GeV}}{M_H}\right)^4 \left(\frac{\mu A_U}{m_{\tilde{q}}^2}\right)^2 \left(\frac{t_\beta}{50}\right)^6$$

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

$$r_B \simeq \left(1 - 0.3\frac{(t_\beta/50)^2}{\left(\frac{2}{3} + \frac{1}{3}\frac{t_\beta}{50}\right)} \left(\frac{400\mathrm{GeV}}{m_{H^\pm}}\right)^2\right)^2$$

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

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

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

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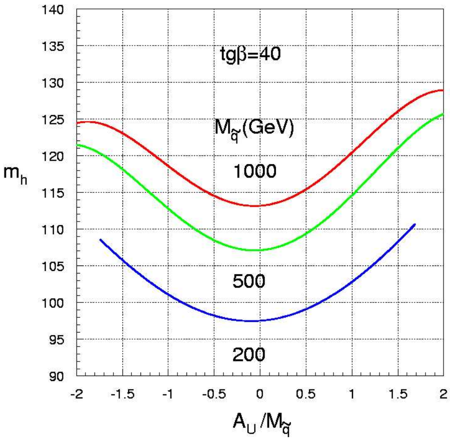
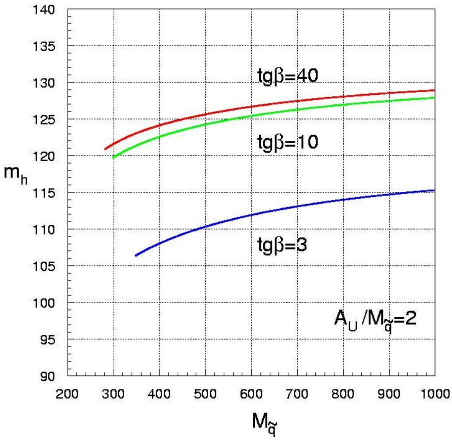
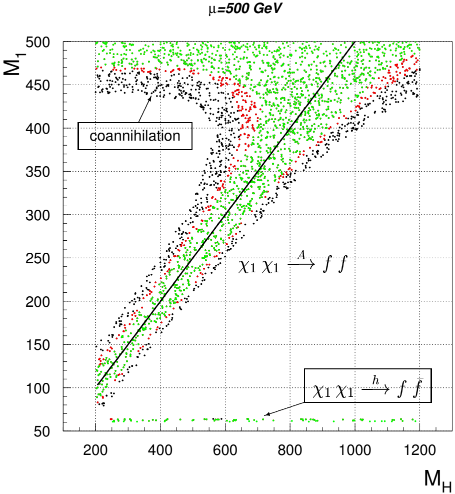
Lightest Higgs boson mass





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

WMAP constraints @ large tan β



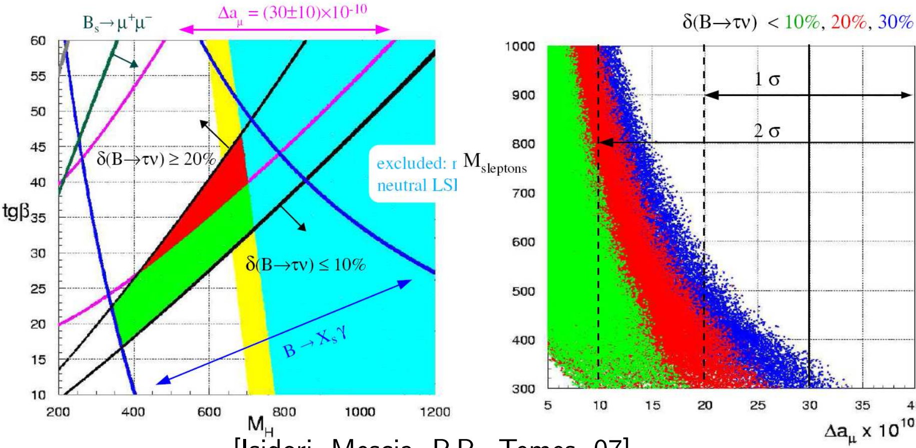
- **Dark Matter constraint satisfied for**

- **Coannihilation Processes**: $1 \lesssim \frac{M_{\rm NLSP}}{M_{\rm LSP}} \lesssim 1.1$

- **Resonant Processes**: $M_A \simeq 2M_{\rm LSP}$

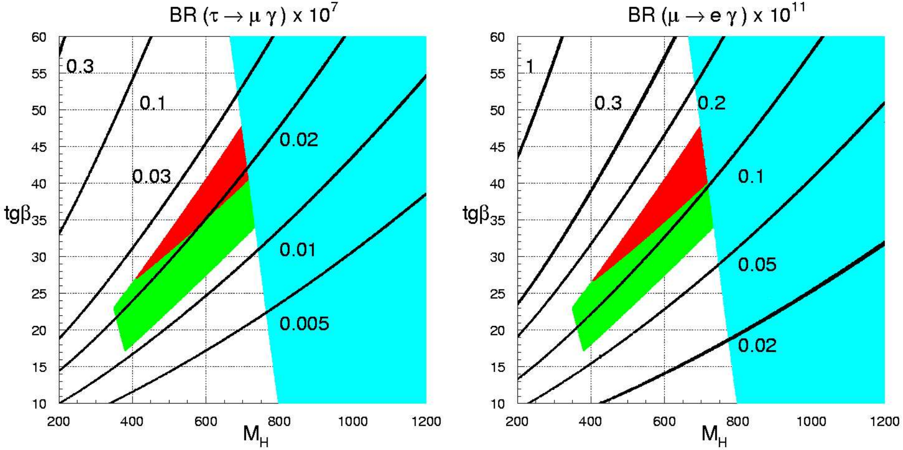
[Isidori, Mescia, P.P., Temes, '07]

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



[Isidori, Mescia, P.P., Temes, 07]

LFV under B-physics and WMAP



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

Conclusions

Where to look for New Physics?

- LFV can probe $\Lambda_{NP} > \mathrm{TeV}$, even beyond the LHC reach
- A combined analysis of B physics observables ($B^0_{s,d} \to \mu^+\mu^-$, $B \to \ell\nu$...) offers a unique chance to probe SUSY even in the elegant (but quite pessimistic) MFV framework
- Dark Matter constraints are fulfilled in a natural way within SUSY @ large t_β
- LU breaking @ % in $R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$ is generated by the LFV
- All the above effects are strongly reduced (or completely disappear!) at moderate to low t_β

Flavor Physics strongly loves SUSY @ LARGE $\tan\beta$!

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