Large tan β MSSM effects on flavor physics

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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, $d_{e,n}$....)
  - CPV in B_s mixing amplitudes **(Claim of NP by UTfit '08)**
- **Processes predicted with high precision in the SM**
  - EWPO as $\Delta\rho$, $(g-2)_\mu$....
  - LU in $R_M^{e/\mu} = \Gamma(M \to e\nu)/\Gamma(M \to \mu\nu)$ $[M = \pi, K, B]$

General Considerations

G. Isidori – *Flavour Physics now and in the LHC era* LP 2007

Flavour physics in the LHC era

LHC [high p_T]

A *unique* effort toward the high-energy frontier

[to determine the energy scale of NP]

Flavour physics

Improved CKM fits

Rare B decays

CPV in the Bs system

LFV in μ & τ decays

Universality tests in B & K

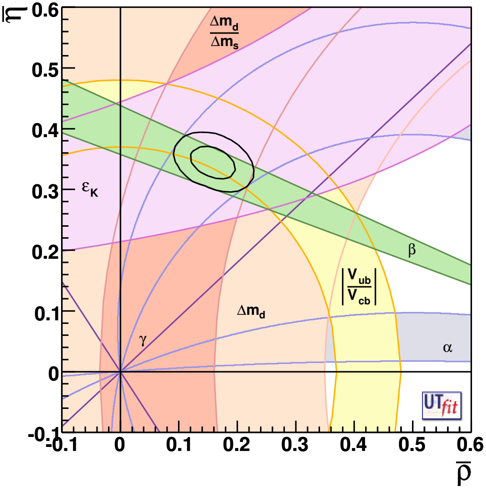
EDMs

Rare K decays

g-2

A *collective* effort toward the high-intensity frontier
[to determine the flavour structure of NP]

SM success



$\bar{\eta}$
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
$\bar{\rho}$
$\frac{\Delta m_d}{\Delta m_s}$
ε_K
β
$\left|\frac{V_{ub}}{V_{cb}}\right|$
Δm_d
γ
α
UTfit

Minimal Flavor Violation (MFV)

Model-independent fits

These general results are quite instructive if interpreted as bounds on the scale of new physics:

$$M(B_d\text{-}\bar{B}_d) \sim \frac{(y_t V_{tb}{}^* V_{td})^2}{16\,\pi^2 M_W{}^2} + c_{NP}\frac{1}{\Lambda^2}$$

← contrbution of the new heavy degrees of freedom

c_{NP}:

- ~ 1 —tree/strong + generic flavour→ $\Lambda \gtrsim 2\times10^4$ TeV [K]
- $\sim 1/(16\,\pi^2)$ —loop + generic flavour→ $\Lambda \gtrsim 2\times10^3$ TeV [K]
- $\sim (y_t V_{ti}{}^* V_{tj})^2$ —tree/strong + MFV→ $\Lambda \gtrsim 5$ TeV [K & B]
- $\sim (y_t V_{ti}{}^* V_{tj})^2/(16\,\pi^2)$ —loop + MFV→ $\Lambda \gtrsim 0.5$ TeV [K & B]

recent analysis: Bona *et al.* '07

If you don't think this is an accident of $\Delta F=2$... ⇒ MFV

MFV @ large tan β

The CKM is the only source of flavor and CP violation also beyond the SM

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

- $\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Gauge} + \mathcal{L}_{\rm Higgs}$= 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.
- $\mathcal{L}_{\rm Yukawa} = \bar{Q}_L \mathbf{Y_D} D_R\phi + \bar{Q}_L \mathbf{Y_U} U_R\phi_c + \bar{L}_L \mathbf{Y_L} E_R\phi + h.c$
  - $\mathbf{Y_U} = \frac{m_U}{<H_U>}$, $\mathbf{Y_{D,L}} = \frac{m_{D,L}}{<H_D>} = \frac{m_{D,L}}{<H_U>}\tan\beta$.
  - For $\tan\beta = O(m_t/m_b) >> 1 \rightarrow \mathbf{Y_t} \sim \mathbf{Y_b} \sim 1$.

SUSY MFV scenario @ large tan β

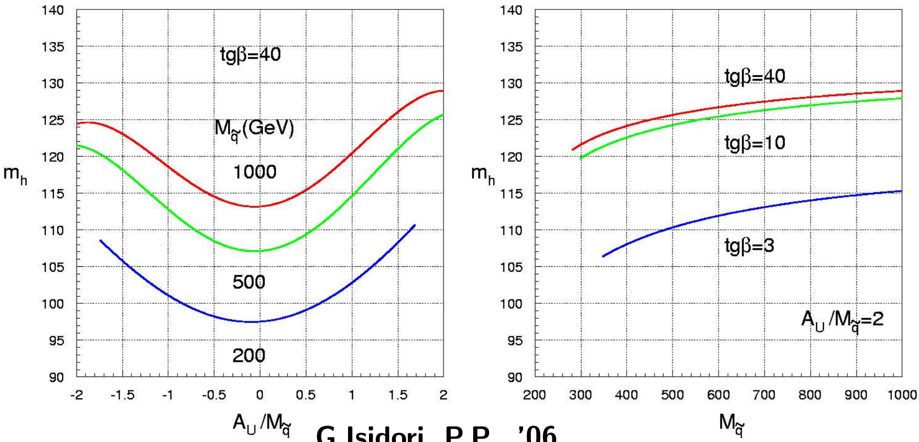
How natural is the MFV SUSY scenario @ large tan β?

- Top-Bottom Yukawa unification in GUT $\Rightarrow$ $\tan\beta = (m_t/m_b)$
- $m_h > 114\mathrm{GeV}$ constraint better satisfied
- $\Delta a_\mu = (g-2)_\mu/2 = (3 \pm 1) \times 10^{-9}$ anomaly naturally explained
- WMAP constraints **"naturally"** satisfied **Ellis et al.**
- Correlations between $\mathcal{B}(B \to \tau\nu)$ and $\mathcal{B}(B \to X_s\gamma)$, ΔM_{B_s}, $\mathcal{B}(B_{s,d} \to \ell^+\ell^-)$, $(g-2)_\mu$ and m_{h^0}

Isidori, P.P., '06

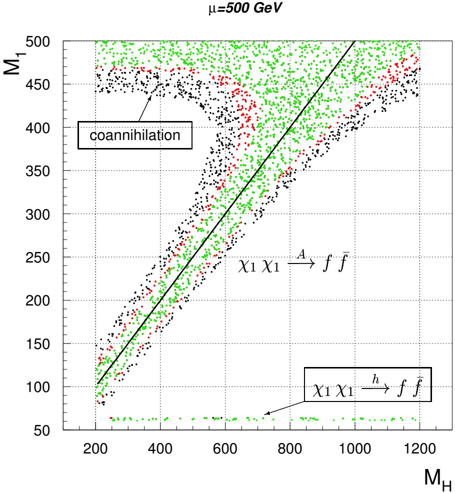
Lightest Higgs boson mass & $(g-2)_\mu$

$$\Delta a_\mu \simeq 3 \times 10^{-9} \left(\frac{400\mathrm{GeV}}{\tilde{m}}\right)^2 \left(\frac{t_\beta}{50}\right) \, sign\, \mu$$



G.Isidori, P.P., '06

WMAP constraints @ large tan β



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

- **Dark Matter constraint satisfied for**

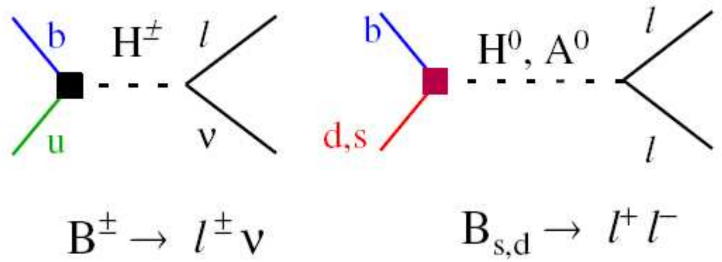
Coannihilation Processes:
$1 \lesssim \frac{M_{\rm NLSP}}{M_{\rm LSP}} \lesssim 1.1$

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

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

B-physics Phenomenology in MFV

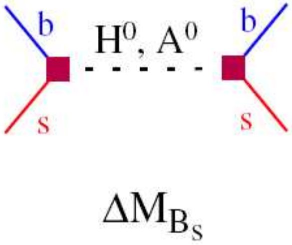
$\tan\beta \sim (30-50)$, $\mathbf{M_H \sim (300-500)GeV}$, $\mathbf{M_{\tilde{q}} \sim (1-2)TeV}$

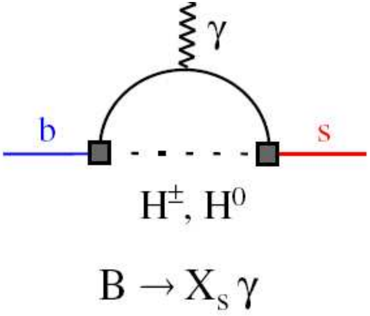


$\sim (10-30)\%$ **suppression** **up to** $10\times$ **enhancement**

B-physics Phenomenology in MFV

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





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

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

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

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

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

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

- $H^\pm$ ($\mathbf{W}^\pm$) 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

B-physics Phenomenology in MFV

- MFV at large $\tan\beta$ predicts a suppression of $\mathcal{B}(B \to \tau\nu)$ compared to the SM predictions

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

- ΔM_{B_s} and $Br(B_s \to \mu^+\mu^-)$ are loop induced and they depend on many NP parameters, in contrast to $B \to \tau\nu$

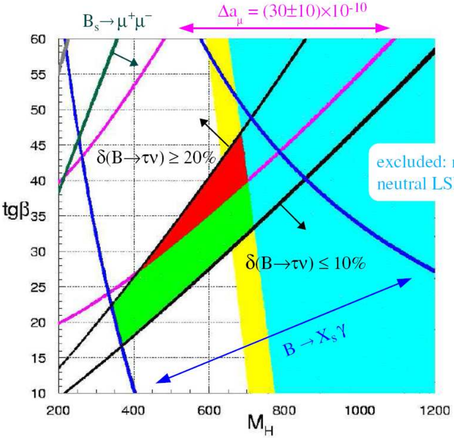
$$Br(B_s \to \mu^+\mu^-) \simeq 6 \times 10^{-8}\left(\frac{400\mathrm{GeV}}{M_H}\right)^4\left(\frac{\mu A_U}{m^2_{\tilde{q}}}\right)^2\left(\frac{t_\beta}{50}\right)^6$$

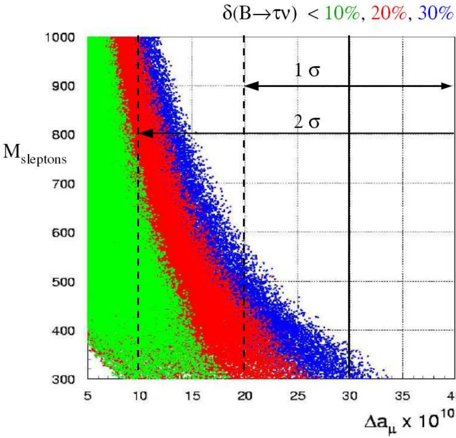
$$\frac{(\Delta M_{B_s})}{(\Delta M_{B_s})^{SM}} \simeq 1 - 3 \times 10^{-2}\left(\frac{\mu A_U}{m^2_{\tilde{q}}}\right)^2\left(\frac{t_\beta}{50}\right)^4\left(\frac{400\mathrm{GeV}}{M_H}\right)^2 .$$

Constraints

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

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





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

$\mu - e$ 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 for R_K by **P326/NA62** (former **NA48**) has been performed 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!!!

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

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

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

- 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

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

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

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

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

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

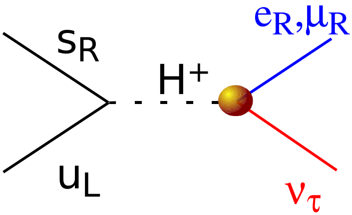
$$R_K^{EXP.} = \frac{\Gamma(K \to e\nu_e) + \Gamma(K \to e\nu_\mu) + \Gamma(K \to e\nu_\tau)}{\Gamma(K \to \mu\nu_\mu) + \Gamma(K \to \mu\nu_e) + \Gamma(K \to \mu\nu_\tau)}$$

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

Masiero, Paradisi, Petronzio, '06

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

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



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

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

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

$$\Downarrow$$

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

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

LU at a (Super)B factories

- $\Delta r_K^{e-\mu} \approx 10^{-2} \Longrightarrow \Delta r_B^{\mu/\tau} \approx \mathcal{O}(1)\,, \Delta r_B^{e/\tau} \leq 2\times 10^2$
- $R_\tau^{\mu/e} = \Gamma(\tau\to\mu\nu\bar\nu)/\Gamma(\tau\to e\nu\bar\nu)$

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

Mursula et al. '83

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

Hou '92, Tanaka '95, Kiers & Soni '97

$$\frac{R_{B\to D}^{\tau/\mu}}{R_{B\to D}^{\tau/\mu}|_{SM}} \simeq 1 - 0.3\left(\frac{t_\beta}{50}\right)^2\left(\frac{200\mathrm{GeV}}{M_{H^\pm}}\right)^2$$

Kamenik & Mescia '08

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

$$Br^{SM}(\mu \to e\gamma) \sim |\delta^{\ell}|^2 \sim \frac{m_\nu^4}{M_W^4} \leq 10^{-50} \qquad m_\nu \sim \mathrm{eV}$$

$$Br^{SUSY}(\mu \to e\gamma) \sim |\delta^{\tilde{\ell}}|^2 \sim \frac{m_\nu^{D\,4}}{\tilde{m}^4} \leq 10^{-11} \qquad m_\nu^D \sim m_{top}$$

$$\Downarrow$$

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

LFV in SUSY

RG induced LFV interactions in SUSY GUTs

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

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

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

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

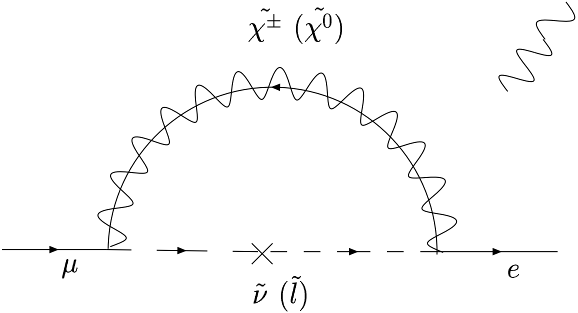
- **SUSY SU(5)+RN** [Moroi, '00] **& SO(10)** [Chang et al., 02]

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

LFV in SUSY

LFV interactions – leptons/sleptons/gauginos

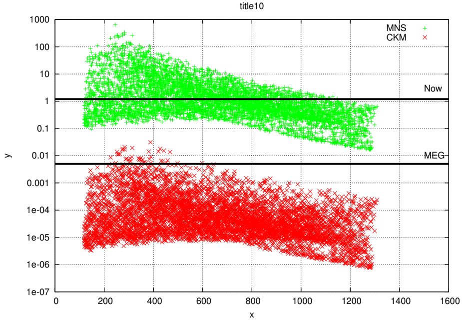
$$\mathcal{L} = \bar{\ell}_i \left(C^R_{ijA} P_R + C^L_{ijA} P_L \right) \tilde{\chi}^-_A \tilde{\nu}_j + \bar{\ell}_i \left(N^R_{ijA} P_R + N^L_{ijA} P_L \right) \tilde{\chi}^0_A \tilde{\ell}_j . \quad (1)$$

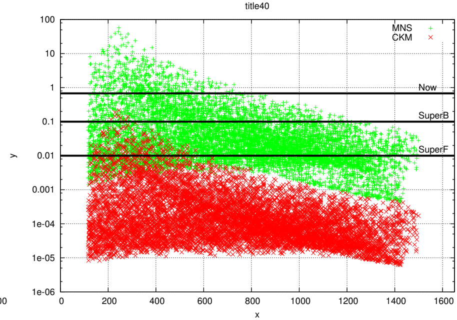


$$\left.\frac{BR(\ell_i \to \ell_j \gamma)}{BR(\ell_i \to \ell_j \nu_i \bar{\nu}_j)}\right|_{\text{Gauge}} \simeq \frac{\alpha_{el}}{20\pi} \left(\frac{m_W^4}{m_{SUSY}^4} \right) \left(\delta^{21}_{LL} \right)^2 t_\beta^2$$

$\mu \to e\gamma$ and $\tau \to \mu\gamma$

Br($\mu \to e\gamma$) Br($\tau \to \mu\gamma$)



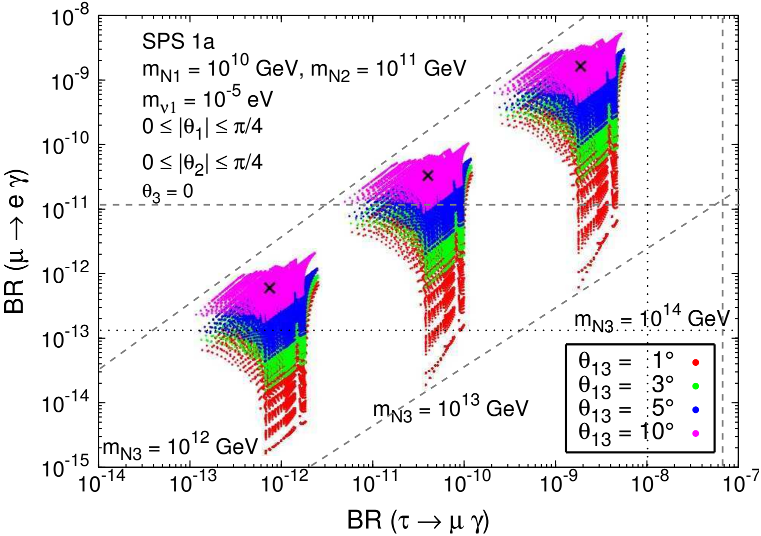


$M_{1/2}$ $M_{1/2}$

$m_0 \leq 1\mathrm{TeV}$, $\tan\beta = 40$

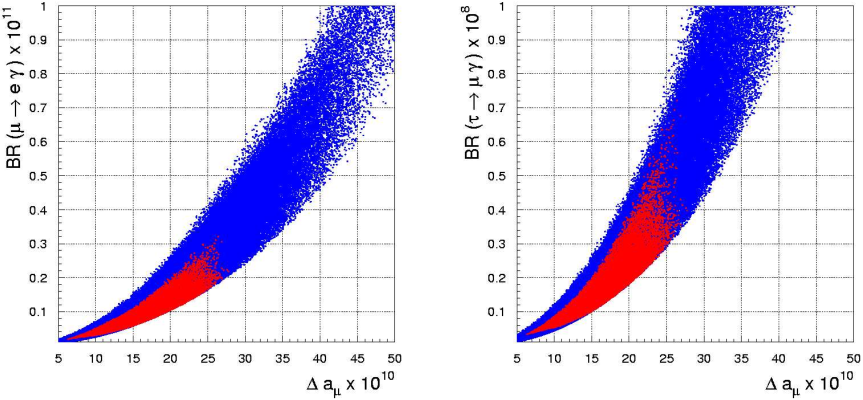
Calibbi, Faccia, Masiero and Vempati, '06

$\mu \to e\gamma$ and $\tau \to \mu\gamma$



Herrero et al., '06

$(g-2)_\mu$ vs $\ell_i \to \ell_j\gamma$



$|\delta^{12}_{LL}| = 10^{-4}$ and $|\delta^{23}_{LL}| = 10^{-2}$, **IMPT, 07**

$$BR(\ell_i \to \ell_j\gamma) \approx \left[\frac{\Delta a_\mu}{20 \times 10^{-10}}\right]^2 \times \begin{cases} 1 \times 10^{-4} \; |\delta^{12}_{LL}|^2 & [\mu \to e] \\ 2 \times 10^{-5} \; |\delta^{23}_{LL}|^2 & [\tau \to \mu] \end{cases}$$

Conclusions

Where to look for New Physics?

- $B^0_{s,d} \to \mu^+\mu^-$ and $B \to \ell\nu$ are still discovery channel and they represent a unique probe for SUSY even in the elegant (but pessimistic) MFV framework
- Visible Lepton Universality breaking effects in $B \to \ell\nu$ and $K \to \ell\nu$ can be generated through LFV effects
- LFV signals in $\ell_i \to \ell_j\gamma$ would be a clear evidence of NP
- $\ell_i \to \ell_j\gamma$ can probe $\Lambda_{NP} > \mathrm{TeV}$, even beyond the LHC reach
- If we explain the $(g-2)_\mu$ anomaly within SUSY, $\ell_i \to \ell_j\gamma$ is expected to be visible in a vast class of LFV models

$$\Downarrow$$

Flavor Physics, Dark Matter and EWPO tests represents a very powerful and complementary tool to the LHC to discover or constraint NP.

Masiero's view