Flavor Physics in the LHC era

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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.

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]

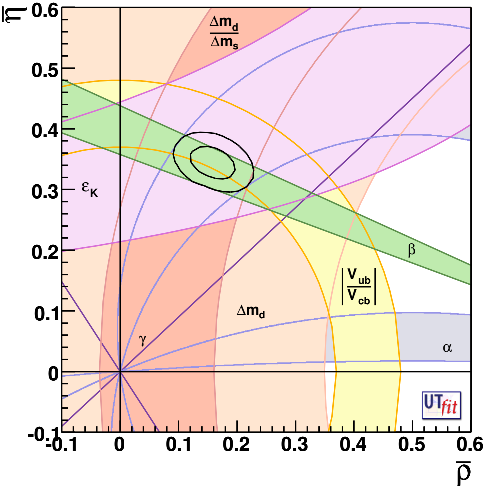
NP search strategies

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 $R_M^{e/\mu} = \Gamma(M \to e\nu)/\Gamma(M \to \mu\nu)$ $(M = \pi, K)$

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 ΔF=2... ⇒ MFV

Flavor Physics and LHC discoveries

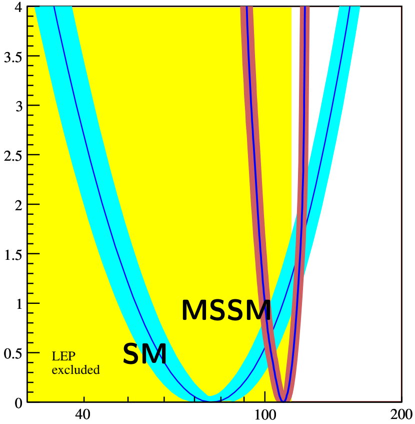
- m_{h} in the CMSSM from a fit inclusing **EWPO** (crucial impact of $(g-2)_{\mu}$), **F**lavour **P**hysics **O**bservables (crucial impact of $b \to s\gamma$) and the Cold **Dark Matter**.

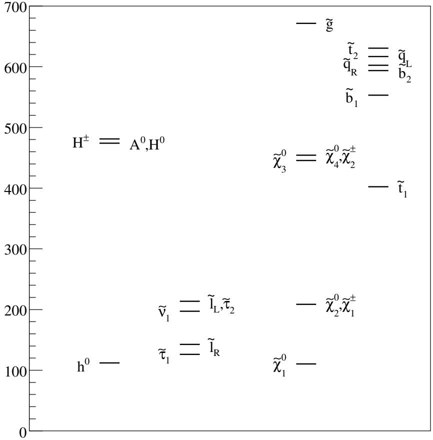
$$m_{\mathrm{h}}^{\mathrm{CMSSM}} = 110^{+8}_{-10}\ (\mathrm{exp.}) \pm 3\ (\mathrm{theo.})\ \mathrm{GeV}/c^2$$
$$m_{\mathrm{h}}^{\mathrm{SM}} = 76^{+33}_{-24}\ \mathrm{GeV}/c^2$$

- **Exended Higgs sector**: SUSY or a simple 2HDM? $m_{H^+} > 295\mathrm{GeV}$ @95%C.L. within a 2HDM (from $b \to s\gamma$ constraints), $m_{H^+} \gtrsim 130\mathrm{GeV}$ in SUSY.
- $t \to H^+ b$ still allowed in SUSY
- $B_s \to \mu^+\mu^-$ unobservable (observable) in 2HDM (SUSY) after the $b \to s\gamma$ constraints.

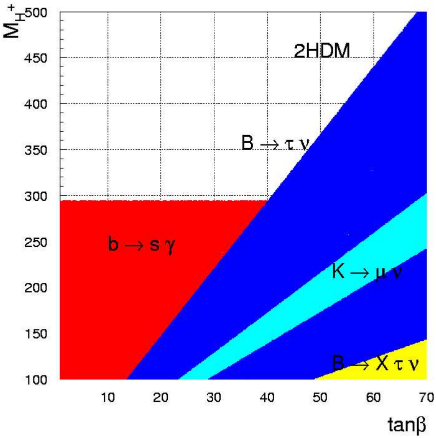
Lightest Higgs boson

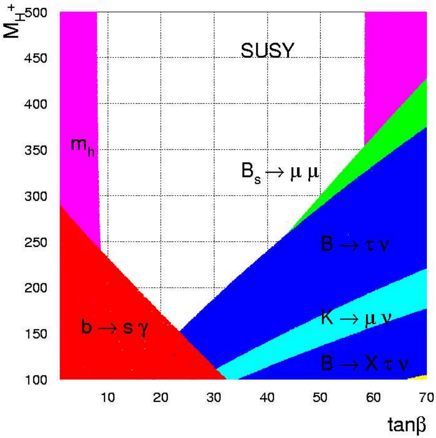
O. Buchmueller et al. '07





Hevy Higgs bosons

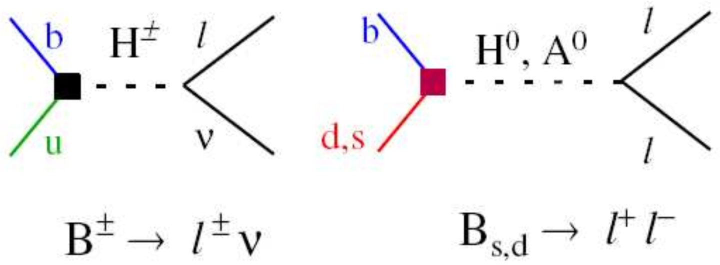




$$m_{SUSY} = -2A_{\tilde{t}} = 1\mathrm{TeV}$$

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**

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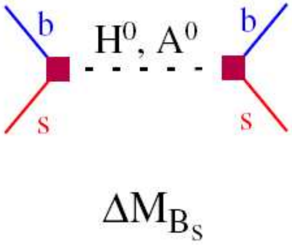
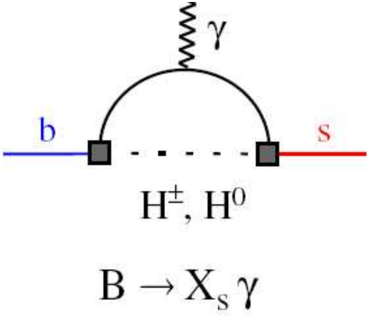




$\sim (0-10)\%$ **suppression**

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

B-physics Phenomenology in MFV

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

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

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

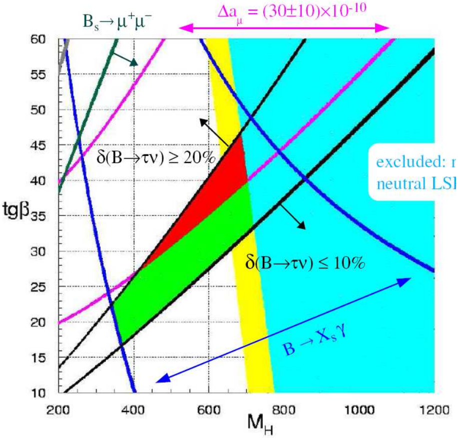
$$\frac{Br(B\to\ell\nu)}{Br(B\to\ell\nu)^{SM}} \simeq \left(1 - 0.3\left(\frac{t_\beta}{50}\right)^2\left(\frac{400\mathrm{GeV}}{m_{H^\pm}}\right)^2\right)^2$$

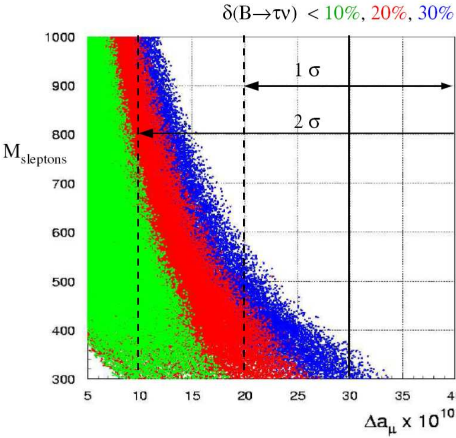
$\frac{Br(B\to\tau\nu)}{(\Delta M_{B_d})} \sim (V_{ub}/V_{td})^2/\hat{B}_d$ much better then $|V_{ub}|^2 f_B^2$!

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**

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)

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

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

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

$$\Downarrow$$

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

LFV frameworks

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LFV in SUSY

RG induced LFV interactions in SUSY GUTs

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

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

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

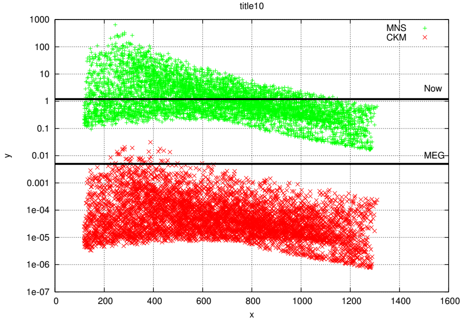
$$(\delta^{\tilde{\ell}}_{LL})_{ij} \sim (h^\nu h^{\nu\dagger})_{ij} \qquad \& \qquad (\delta^{\tilde{\ell}}_{RR})_{ij} \sim (h^u h^{u\dagger})_{ij}$$

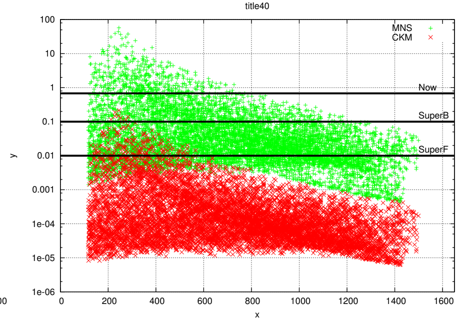
- **SUSY SU(5)+RN** [Moroi, '00] **& SO(10)** [Chang et al., 02]

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

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

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



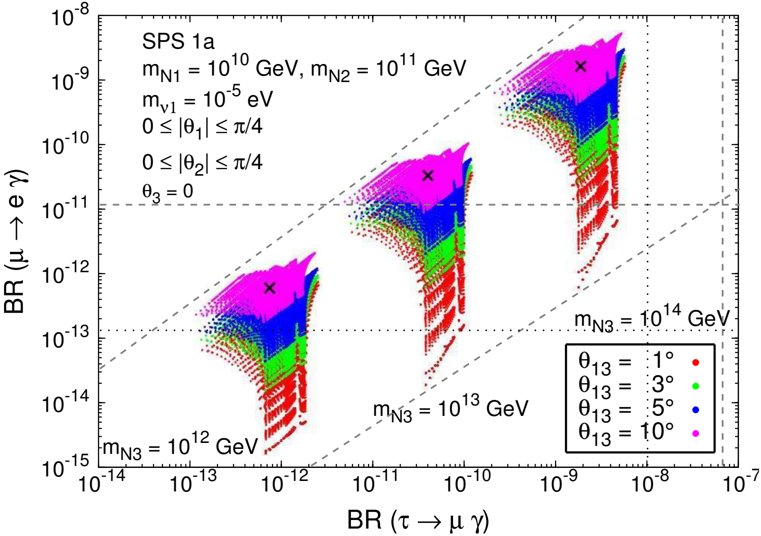


$M_{1/2}$ $M_{1/2}$

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

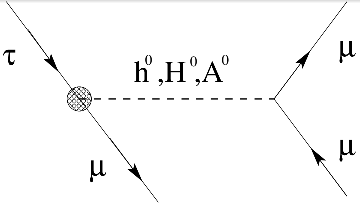
Calibbi, Faccia, Masiero and Vempati, '06

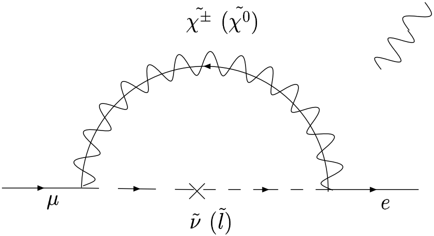
$\mu \to e\gamma$ and $\tau \to \mu\gamma$



Herrero et al., '06

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





$$\frac{BR(\tau\to3\mu)}{BR(\tau\to\mu\nu\bar{\nu})} \simeq \left(\frac{\alpha_2}{48\pi}\right)^2 \left(\frac{m_\tau m_\mu}{M_H^2}\right)^2 \delta_{32}^2 t_\beta^6 \qquad \frac{BR(\tau \to \mu\gamma)}{BR(\tau \to \mu\nu\bar{\nu})} \simeq \frac{\alpha_{el}}{20\pi} \frac{m_w^4}{\tilde{m}^4} \delta_{32}^2 t_\beta^2$$

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

$$\Downarrow$$

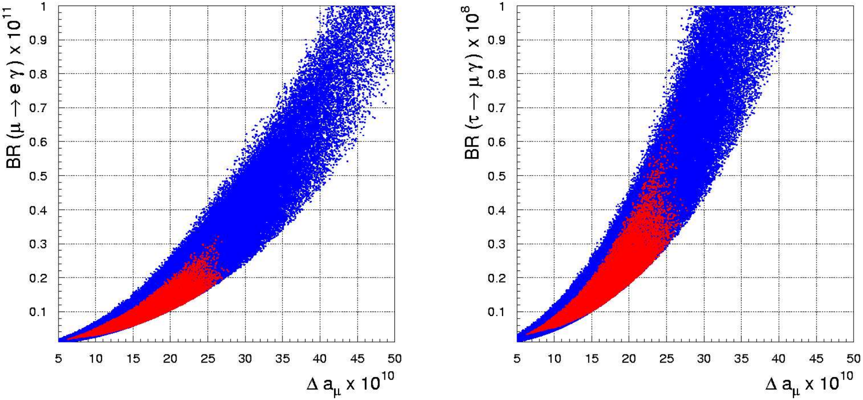
$$\frac{BR(\tau\to3\mu)}{BR(\tau\to\mu\gamma)} \not\propto \alpha_{el}$$

Correlations among LFV processes

ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)}$	$0.4 \dots 2.5$	$\sim 6 \cdot 10^{-3}$	$\sim 6 \cdot 10^{-3}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau \to e\gamma)}$	$0.4 \dots 2.3$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau \to \mu\gamma)}$	$0.4 \dots 2.3$	$\sim 2 \cdot 10^{-3}$	$0.06 \dots 0.1$
$\frac{Br(\tau^- \to e^- \mu^+ \mu^-)}{Br(\tau \to e\gamma)}$	$0.3 \dots 1.6$	$\sim 2 \cdot 10^{-3}$	$0.02 \dots 0.04$
$\frac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau \to \mu\gamma)}$	$0.3 \dots 1.6$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau^- \to e^- \mu^+ \mu^-)}$	$1.3 \dots 1.7$	~ 5	$0.3 \dots 0.5$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau^- \to \mu^- e^+ e^-)}$	$1.2 \dots 1.6$	~ 0.2	$5 \dots 10$
$\frac{R(\mu \mathrm{Ti} \to e \mathrm{Ti})}{Br(\mu \to e\gamma)}$	$10^{-2} \dots 10^{2}$	$\sim 5 \cdot 10^{-3}$	$0.08 \dots 0.15$

Buras et al., '07 **Paradisi, '05,'06**

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



$|\delta_{LL}^{12}| = 10^{-4}$ and $|\delta_{LL}^{23}| = 10^{-2}$,

IMPT, 07

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

Conclusions

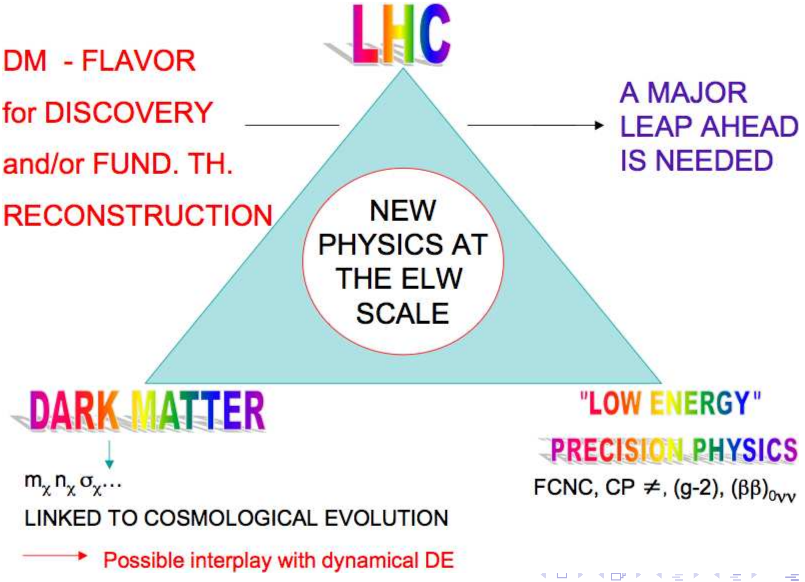
Where to look for New Physics?

- 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
- $B^0_{s,d} \to \mu^+\mu^-$ 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

$\Downarrow$

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

Masiero's view



Back-up

BACK-UP

Lepton Universality @ the B-factories

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

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

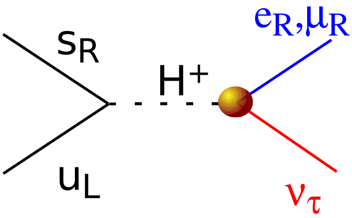
  - No visible effects in $\Gamma(\tau \to M\nu)/\Gamma(M \to \mu\nu)$, $M = K, \pi$
- B **Physics**
  - Semileptonic B decays, i.e. $B \to X\ell\nu$

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

  - Leptonic B decays, i.e. $B \to \ell\nu$

LU in $K \to \ell\nu$

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



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

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

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

$$\Downarrow$$

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

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

Masiero, P.P, Petronzio '06

LU 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

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

Isidori, P.P. '06

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, $\delta_{3j} \sim \mathcal{O}(1)$, ($m_{SUSY} \geq 1\mathrm{TeV}$)
- 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}

Isidori, P.P., '06