FLAVOUR AND CP VIOLATION IN THE LEPTON SECTOR AND NEW PHYSICS

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- quark versus lepton sector
- $\not{CP}$ in oscillations
- lepton flavour violating processes
- electric dipole moments of charged leptons
- conclusions

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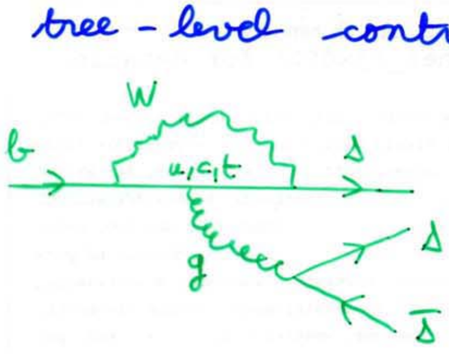
Quark sector versus lepton sector

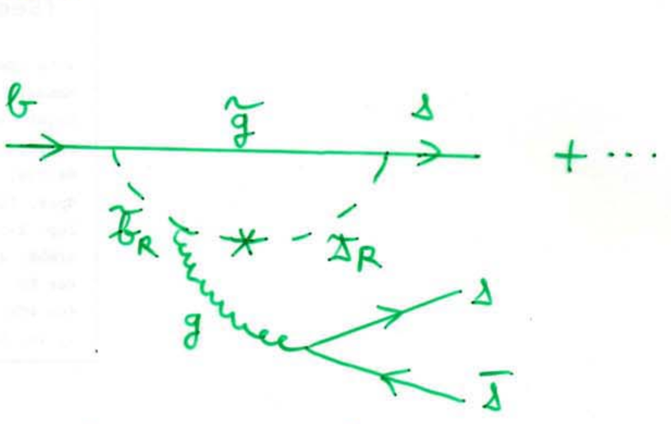
quark sector

- in the SM, the CKM matrix is the only source for flavour and CP violation
- a number of observables allow to constrain the CKM parameters and to check the consistency of the CKM picture (unitary triangle)
- if there is new physics beyond the SM, expect new sources of flavour and CP violation [eg Susy: new phases, FV in squark sector] that may lead to deviations from SM predictions

example: observed discrepancy between $S_{J/\psi K_S}$ and $S_{\phi K_S}$ could be due to Susy loop contributions to $B \to \phi K_S$, while $B \to J/\psi K_S$ is dominated by the SM tree-level contribution



$b \to s\bar{s}s$ (SM)

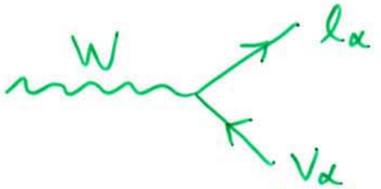


$b \to s\bar{s}s$ (Susy)

lepton sector

- in the absence of ν masses, L_e, L_μ, L_τ would be separately conserved, and there would be no FV in the lepton sector (LFV) (and the only source of $\cancel{CP}$ would be the CKM phase)

- $m_\nu \neq 0$ (and $m_{\nu i} \neq m_{\nu j}$) $\Rightarrow$ lepton mixing



$[\alpha = e, \mu, \tau]$

$$\underbrace{\nu_\alpha}_{\text{flavour eigenstate}} \equiv \sum_i \overset{\uparrow}{U_{\alpha i}} \underbrace{\nu_i}_{\text{mass eigenstate with mass } m_i} \qquad [i = 1,2,3]$$

lepton mixing matrix

[MNS(P) = Maki - Nakagawa - Sakata - (Pontecorvo)]

- $U_{MNSP} \neq \mathbb{1}$ $\Rightarrow$ neutrino oscillations

  $\theta_{12} \leftrightarrow$ solar neutrinos
  $\theta_{23} \leftrightarrow$ atmospheric neutrinos
  $\theta_{13} \leftrightarrow$ reactor $\bar{\nu}_e$'s

- $\cancel{CP}$ phase δ $\Rightarrow$ $\cancel{CP}$ in oscillations

$$P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq P(\nu_\alpha \to \nu_\beta)$$

can be tested with neutrino superbeams or with a neutrino factory

[if ν's are Majorana, U contains 2 additional phases ϕ_2, ϕ_3 which do not enter oscillation probabilities $\Rightarrow$ not discussed here]

- $U_{MNSP} \neq \mathbb{1}$ ⇒ expect LFV processes and $\cancel{CP}$ in the lepton sector

e.g.

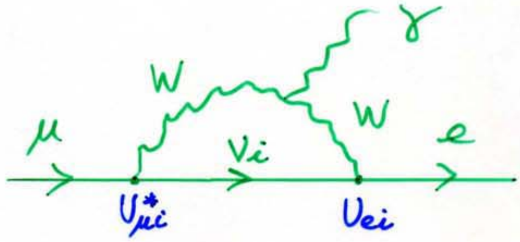
$$\text{LFV} \begin{cases} \mu \to e\gamma \;,\; \tau \to \mu\gamma \;,\; \mu \to eee \\ K_L^0 \to \mu e \;,\; K^+ \to \pi^+ \mu^- e^+ \\ \cdots \end{cases}$$

$$\cancel{CP} \; \left(d_e , d_\mu , d_\tau \neq 0 \right.$$

however if U_{MNSP} is the only source for LFV and $\cancel{CP}$ (like in the SM + Dirac ν or in the SM + seesaw) , the corresponding observables are negligibly small and unaccessible to experiment

≠ quark sector

e.g. $\mu \to e\gamma$



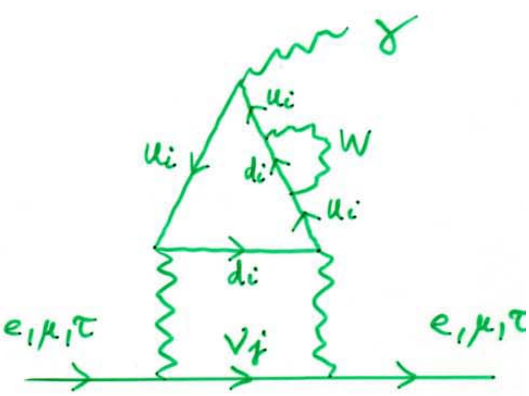
$$BR(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{M_W^2} \right|^2$$

suppressed by $\left(\frac{m_{\nu_i}}{M_W}\right)^4$ ⇒ $BR \leq 10^{-48}$ for $m_\nu \leq 1\text{eV}$!

[current limit : 1.2×10^{-11}]

- charged lepton electric dipole moments (EDM):

in the absence of δ_{MNSP},
induced by δ_{CKM} at
the 3-loop level



$\Rightarrow d_e|_{CKM} \lesssim 10^{-38}$ e.cm !

[present limit :
$d_e \leq 1.6 \times 10^{-27}$ e.cm]

if $\delta_{MNSP} \neq 0$, again d_i arise at the multiloop level and are unobservably small

→ the observation of any FV or $\not{CP}$ process in the lepton sector would be a direct signature of new physics

(new physics could also play a subleading rôle in neutrino oscillations)

observable	SM + ν_R prediction	present limit	expected improv.
$BR(\mu \to e\gamma)$	$\leq 10^{-48}$	1.2×10^{-11} [MEGA]	10^{-14} [PSI] 10^{-15} [ν FACT]
$BR(\tau \to \mu\gamma)$	$\leq 10^{-48}$	1.1×10^{-6} [CLEO] 5×10^{-7} [Belle]	10^{-8} [B factories]
$BR(\tau \to e\gamma)$	$\leq 10^{-48}$	2.7×10^{-6}	10^{-8} [B factories]
$BR(\mu \to eee)$	$\leq 10^{-50}$	1.0×10^{-12} [SINDRUM]	10^{-16} [ν FACT]
$BR(\tau \to \mu\mu\mu)$	$\leq 10^{-51}$	8.7×10^{-7} [Belle]	
d_e (e.cm)	$\leq 10^{-38}$	1.6×10^{-27}	10^{-29} 10^{-32} (nucl-ex/0109014)
d_μ (e.cm)	$\leq 10^{-35}$	$(3.7 \pm 3.4) \times 10^{-19}$	10^{-24} [BNL] 5×10^{-26} [νFACT]
d_τ (e.cm)	$\leq 10^{-34}$	3.1×10^{-16} [L3]	

other processes of interest: $K_L^0 \to \mu e$, $K^+ \to \pi^+ \mu^- e^+$ ...
and CP asymmetries in LFV decays of τ, μ

$\not{CP}$ in neutrino oscillations

standard parametrization of U_{MNSP}
[possible Majorana phases not included]

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

only source of information on U : <u>oscillations</u>

<u>global fit</u> (M.C. Gonzalez-Garcia et al., hep-ph (0212147)

$$\left.\begin{array}{ll} 5\times10^{-5}\,eV^2 \le \Delta m^2_{21} \le 2\times10^{-4}\,eV^2 & 0.28 \le \tan^2\theta_{12} \le 0.91 \\ 1.4\times10^{-3}\,eV^2 \le \Delta m^2_{32} \le 6.0\times10^{-3}\,eV^2 & 0.4 \le \tan^2\theta_{23} \le 3.0 \\ & |U_{e3}|^2 = \sin^2\theta_{13} \le 0.06 \end{array}\right\} 3\sigma$$

or $$\boxed{\underbrace{28^\circ \le \theta_{12} \le 44^\circ \qquad 32^\circ \le \theta_{23} \le 60^\circ}_{} \qquad \theta_{13} \le 14^\circ}$$

2 large angles [b.f. $\theta_{12} = 30^\circ$, $\theta_{23} = 45^\circ$]

→ <u>very different from quark sector</u>

oscillation formula:

$$P(\nu_\alpha \to \nu_\beta \,; L) = \sum_{i,j} \underbrace{U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}}_{\text{amplitude}} \; e^{-i \underbrace{\frac{\Delta m^2_{ij}}{2E}}_{\text{frequency}} L}$$

$$\Delta m^2_{ij} \equiv m^2_{\nu_i} - m^2_{\nu_j} \qquad\qquad E \gg m_{\nu_i}, m_{\nu_j}$$

separating the CP-even from the CP-odd terms:

$$\boxed{\begin{aligned} P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = {} & \delta_{\alpha\beta} - 4 \sum_{i<j} \mathrm{Re}\left[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) \\ & \pm 2J \left[\sin\left(\frac{\Delta m^2_{21} L}{2E}\right) + \sin\left(\frac{\Delta m^2_{32} L}{2E}\right) - \sin\left(\frac{\Delta m^2_{31} L}{2E}\right) \right] \end{aligned}}$$

$$\begin{cases} - \text{ for } \nu_\alpha \to \nu_\beta & \text{and } (\alpha,\beta,\gamma) \text{ even perm. of } (e,\mu,\tau) \\ + \text{ for } \bar\nu_\alpha \to \bar\nu_\beta & \text{and } (\alpha,\beta,\gamma) \text{ even perm. of } (e,\mu,\tau) \end{cases}$$

$$|J| \equiv \left| \mathrm{Im}\left[U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}\right] \right| \qquad \text{Jarlskog invariant}$$

$$\boxed{P(\nu_\alpha \to \nu_\beta) - P(\bar\nu_\alpha \to \bar\nu_\beta) \underset{\substack{\uparrow \\ \Delta m^2_{21} \ll |\Delta m^2_{31}|}}{\simeq} \pm 8J \left(\frac{\Delta m^2_{21} L}{2E}\right) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)}$$

$$J = \frac{1}{8} c_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin\delta$$

→ $\cancel{CP}$ effects proportional to J, and can be observed only when subdominant oscillations develop

→ conditions for observing $\cancel{CP}$

$$\begin{cases} \cdot \; \Delta m^2_{21}, \theta_{12} \text{ large} \rightarrow \text{LMA} \qquad \underline{\text{OK}} \\ \cdot \; \theta_{13} \text{ and } \delta \text{ not too small} \\ \cdot \; \text{(very) long baseline} \end{cases}$$

"golden channel": $\nu_e \to \nu_\mu$ at a ν factory

- at second order in θ_{13} and $\frac{\Delta m^2_{21} L}{2E}$:

$$P_{\nu_e\to\nu_\mu(\bar\nu_e\to\bar\nu_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

$$+ \frac{1}{2} c_{13} \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \cos\delta \left(\frac{\Delta m^2_{21} L}{4E}\right) \sin\left(\frac{\Delta m^2_{31} L}{2E}\right)$$

$$-(+)\, c_{13} \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \sin\delta \left(\frac{\Delta m^2_{21} L}{4E}\right) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$\boxed{\begin{gathered} P(\nu_e\to\nu_\mu) - P(\bar\nu_e\to\bar\nu_\mu) \simeq -8J \left(\frac{\Delta m^2_{21} L}{2E}\right) \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \\ J = \frac{1}{8} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin\delta \end{gathered}}$$

in the limit $\sin^2 2\theta_{13} > \frac{\Delta m^2_{21} L}{4E}$

$$A^{CP}_{e\mu} \equiv \frac{P(\nu_e\to\nu_\mu) - P(\bar\nu_e\to\bar\nu_\mu)}{P(\nu_e\to\nu_\mu) + P(\bar\nu_e\to\bar\nu_\mu)} \simeq -\frac{\sin 2\theta_{12} \left(\frac{\Delta m^2_{21} L}{2E}\right) \sin\delta}{\sin 2\theta_{13}}$$

→ need a long baseline

- typically $L \sim 3000$ km / 7000 km for a ν factory
  [matter effects must be taken into account - induce an asymmetry $P(\nu_e\to\nu_\mu) \neq P(\bar\nu_e\to\bar\nu_\mu)$]
- other option : ν superbeams (JHF, NuMI, SPL)
  $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ with a lower $\langle E_\nu \rangle$ and a shorter baseline ($L \simeq 130, 300, 730$ km) possibly in combination with a bêta beam ($\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\mu$)

$$\frac{N(\bar{\nu}_e \to \bar{\nu}_\mu)}{N(\nu_e \to \nu_\mu)}$$

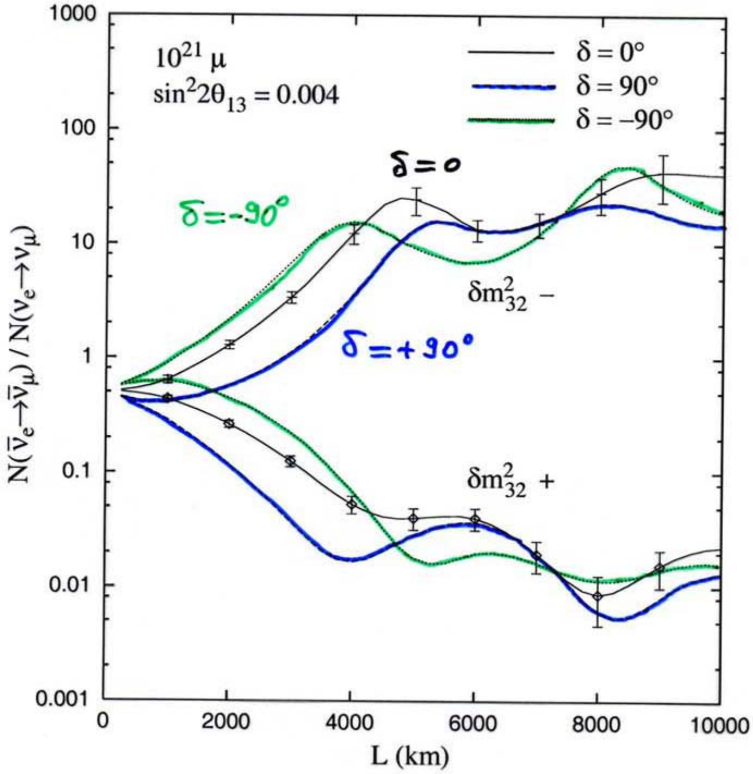
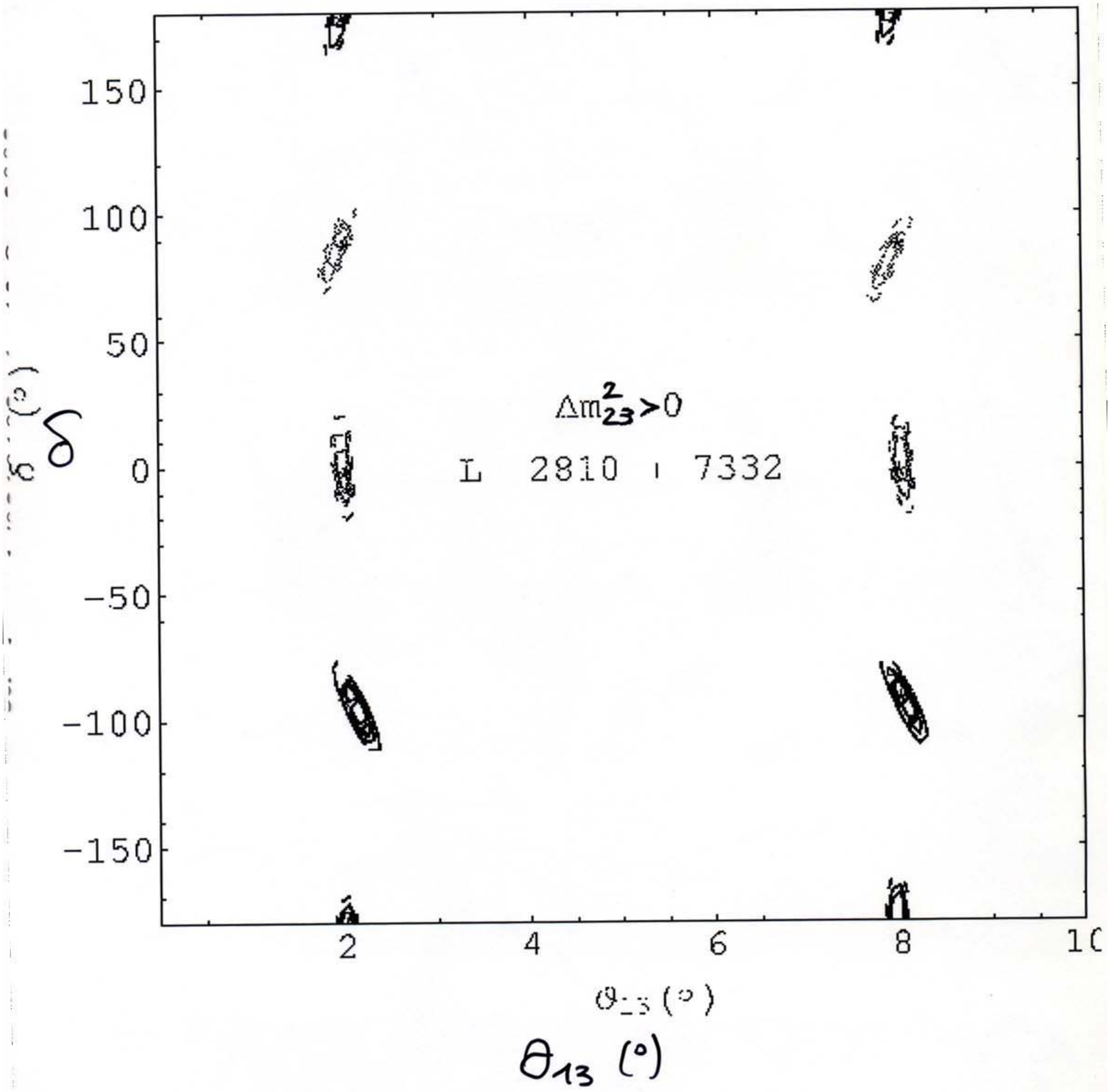


Fig. 46: *Ratio of the oscillation probabilities of neutrinos and antineutrinos as a function of the baseline. The different lines correspond to values of the CP-violating phase δ of* 0°, 90° *and* −90°. *After about 1000 km, matter effects dominate over CP violation, whose effects even go to zero at a particular baseline around 7500 km [165].*

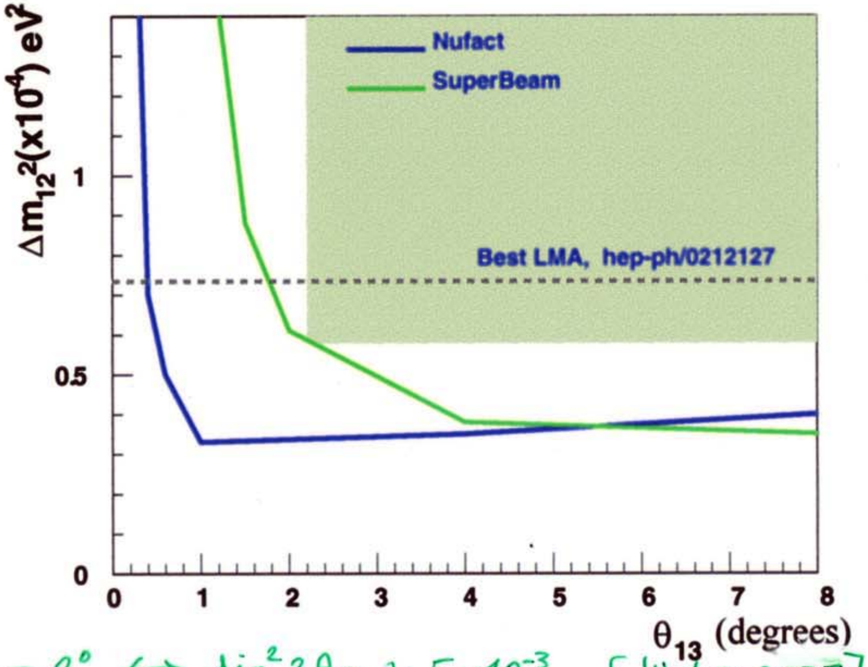
CERN Yellow Report on ν Factories



A comparison of CP sensitivities of Nufact vs. SuperBeam

CP sensitivity, defined as the capacity to separate at 99%CL max CP ($\delta = \pi/2$) from no CP ($\delta = 0$).

Nufact and SPL-SuperBeam sensitivities computed with the same conditions.



$\theta_{13} = 2° \leftrightarrow \sin^2 2\theta_{13} \gtrsim 5\times10^{-3}$ $[|U_{e3}| \approx 0.035]$

$\theta_{13} = 0.4° \Leftrightarrow \sin^2 2\theta_{13} \gtrsim 2\times10^{-4}$ $[|U_{e3}| \approx 0.007]$

The limiting factors for the SuperBeam at small θ_{13} values are:

- The low flux of $\overline{\nu}$ and their small cross section. This limits the overall statistic.
- The beam related backgrounds that increase the statistical errors, hiding the CP signal.

As an example for θ_{13}=3°, $\delta m_{12}^2 = 0.7 \cdot 10^{-4}\, eV^2, \sin^2 2\theta_{12} = 0.8$:

	ν_μ beam 2 years	$\overline{\nu}_\mu$ beam 8 years
μCC (no osc)	36698	23320
Oscillated events (total)	45	133
Oscillated events (cp-odd)	-84	53
Intrinsic beam background	140	101
Detector backgrounds	36	49

M. Mezzetto, "Future Neutrino Oscillations ", Moriond, March 17, 2003. .

Lepton flavour violating processes

LFV processes are unobservable in the SM with a ν_R, and more generally if U_{MNSP} is the only source of flavour violation at low energy

on the other hand most extensions of the SM provide new sources of flavour violation (and of $\not{CP}$), which may be related to the mechanism responsible for ν masses or not

<u>examples</u>:

- models of radiative generation of ν masses
- supersymmetric extensions of the SM
- supersymmetric seesaw models
- Susy GUTs

models of radiative generation of ν masses

FV interactions of neutrinos generate ν masses and mixings, and induce LFV processes

example: Zee model

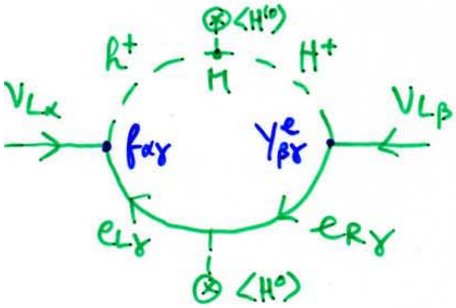
add new couplings between charged leptons and ν's

$$\underbrace{f_{\alpha\beta}}_{\text{LFV couplings } (f_{\alpha\beta}=-f_{\beta\alpha})} \left[\nu_{L\alpha}^T C e_{L\beta} - e_{L\alpha}^T C \nu_{L\beta} \right] \overset{}{h^+} + h.c.$$

↑ charged Higgs $SU(2)_L$ singlet

and a second Higgs doublet H'

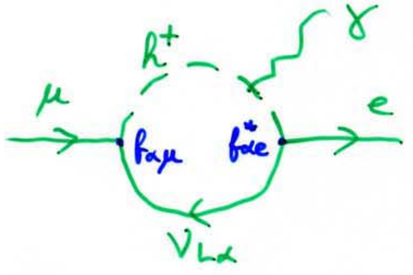
$$V \ni \quad M\, h^+ H H' + h.c. \qquad \not{L}$$



$$\Rightarrow \quad m_\nu \propto \begin{pmatrix} 0 & \alpha & \beta \\ \alpha & 0 & \gamma \\ \beta & \gamma & 0 \end{pmatrix}$$

$$\alpha = f_{e\mu}\left(\frac{m_\mu}{m_\tau}\right)^2, \quad \beta = f_{e\tau}, \quad \gamma = f_{\mu\tau}$$

the $f_{\alpha\beta}$ also induce LFV processes:



$$\Rightarrow BR(\mu \to e\gamma) = \frac{\alpha}{48\pi^2}\left(\frac{f_{e\tau} f_{\mu\tau}}{M^2 G_F}\right)^2$$

$BR \sim 10^{-15}$ for $f_{\alpha\beta} \sim 10^{-3}$ and $M \sim 100\,\text{GeV}$

other example: Susy with $\not{R}_p$

Susy: new source of LFV in the sfermion sector

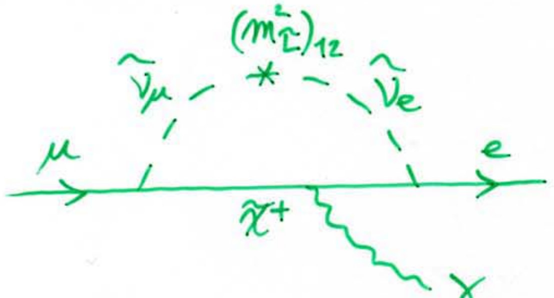
$$\underbrace{\tilde{L}_\alpha = \begin{pmatrix}\tilde{\nu}_{L\alpha}\\ \tilde{e}_{L\alpha}\end{pmatrix}, \tilde{e}_{R\alpha}}_{\text{sleptons } (s=0)} \quad \xleftrightarrow[\text{susy}]{} \quad \underbrace{L_\alpha = \begin{pmatrix}\nu_{L\alpha}\\ e_{L\alpha}\end{pmatrix}, e_{R\alpha}}_{\text{leptons } (s=\frac{1}{2})}$$

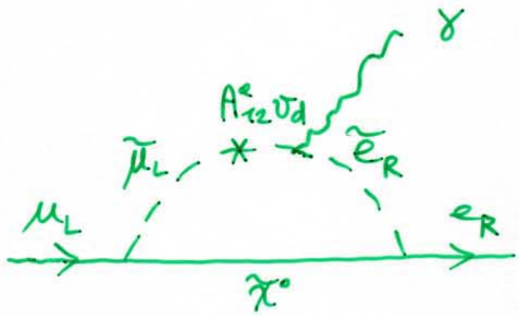
Susy ⇒ slepton masses ≠ lepton masses

$$\underbrace{(m^2_{\tilde{L}})_{\alpha\beta}, (m^2_{\tilde{e}})_{\alpha\beta}, A^e_{\alpha\beta}}_{\substack{\text{soft susy masses}\\ \text{not diagonal in general}}} \qquad M_e = \text{Diag}(m_e, m_\mu, m_\tau)$$

→ potentially large LFV processes

example: $\mu \to e\gamma$





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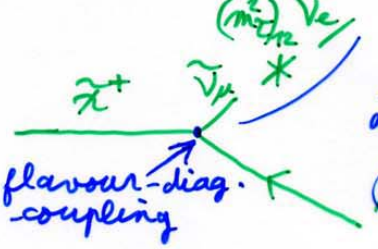
mass insertion approximation



off-diagonal slepton propagator, expanded around the diagonal

μ charged lepton mass eigenstate

⇒ BR($\mu \to e\gamma$) depends on:

- superpartner masses (sleptons, $\tilde{\chi}^+$, $\tilde{\chi}^0$)
- $\tan\beta \equiv \frac{\langle H_u^0 \rangle}{\langle H_d^0 \rangle}$ [BR $\propto \tan^2\beta$ for large $\tan\beta$]
- LFV mass insertions $(m^2_{\tilde{L}})_{12}$, $(m^2_{\tilde{e}})_{12}$, A^e_{12}
  [BR $\propto \delta^2$]

- already the present experimental limits set strong constraints on the LFV soft masses:

$$\left.\begin{array}{l} \delta^{LL}_{12} \equiv \frac{(m^2_{\tilde{L}})_{12}}{m_L^2} \lesssim 10^{-4} - 10^{-3} \\ \delta^{RR}_{12} \equiv \frac{(m^2_{\tilde{e}})_{12}}{m_R^2} \lesssim 10^{-4} - 1 \end{array}\right\} \tan\beta = 10$$

$$\delta^{LR}_{12} \equiv \frac{A^e_{12} v_d}{m_L m_R} \lesssim 10^{-6} - 10^{-5}$$

where $m_L \, (m_R)$ = average $\tilde{\ell} \, (\tilde{e}_R)$ mass

[the smallness of the bound on δ^{LR}_{12} reflects the fact that $A^e v_d \sim M_{susy} M^e \ll M^2_{susy} \sim m^2_{\tilde{L}}, m^2_{\tilde{e}}$]

- similarly, for $\tau \to \mu\gamma$, one obtains

$$\left.\begin{array}{l} \delta^{LL}_{23} \equiv \frac{(m^2_{\tilde{L}})_{23}}{m_L^2} \lesssim 0.1 - 3 \\ \delta^{RR}_{23} \equiv \frac{(m^2_{\tilde{e}})_{23}}{m_R^2} \lesssim 0.3 - 300 \end{array}\right\} \tan\beta = 10$$

$$\delta^{LR}_{23} \equiv \frac{A^e_{23} v_d}{m_L m_R} \lesssim 0.03 - 0.3$$

- constraints on δ_{13}'s from $BR(\tau \to e\gamma)$ are similar to constraints on δ_{23}'s

Susy can lead to observable LFV decays of charged leptons, but these processes are controlled by Susy rather than the mechanism responsible for ν masses

Masina, Savoy

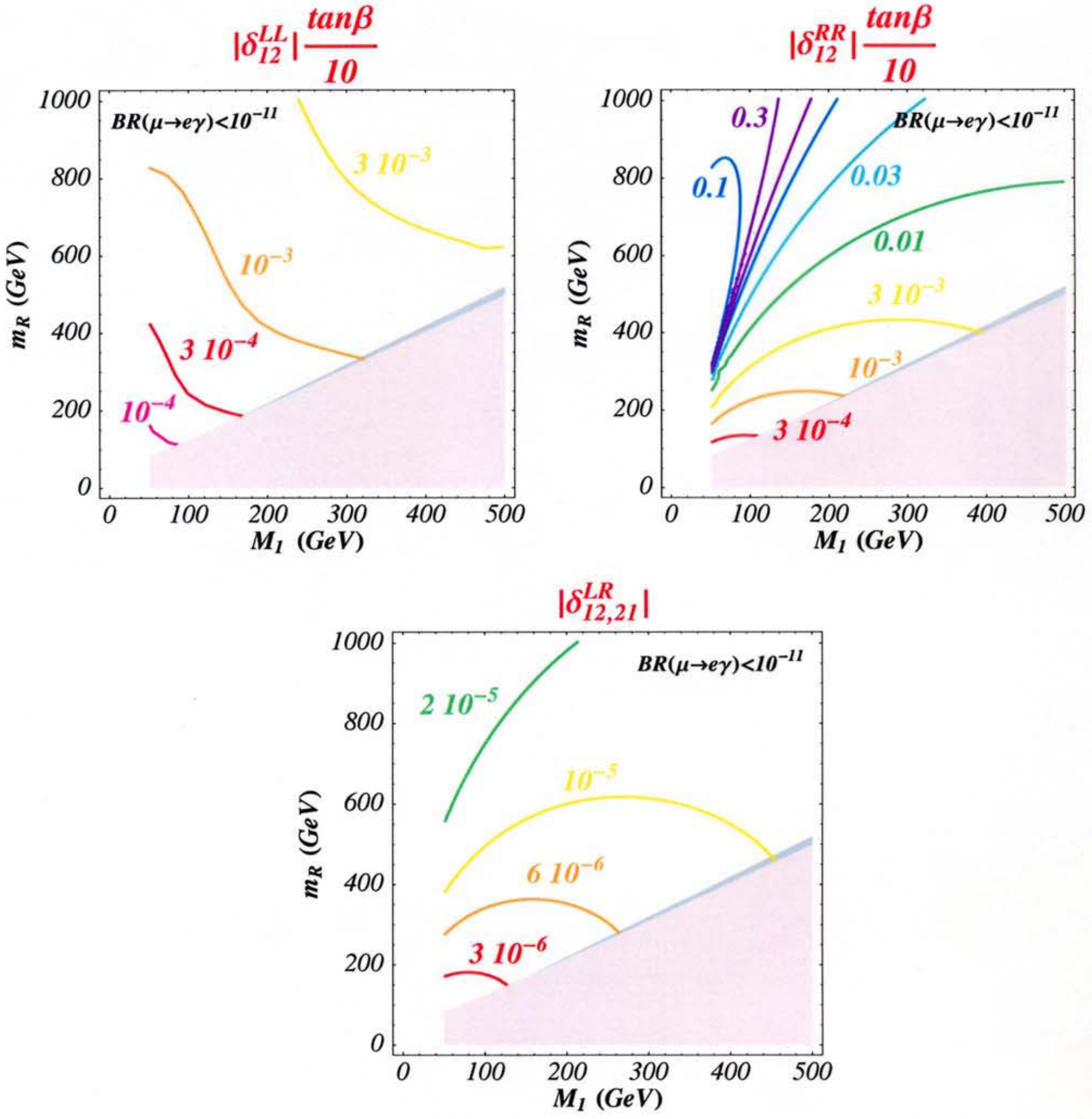


Figure 2: Upper limits on δ_{12}'s in mSUGRA.

singularity and yields a good approximation in the chargino dominance sector [2].

If one relaxes even more the mSUGRA constraints, it becomes legitimate to ask if one can escape the LFV limits on δ^{LL}'s or, conversely, how model independent are, *e.g.* , the more stringent limits on δ_{12}^{LL} . The only possibility is to play with violations of gaugino mass universality. For instance, by

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[2] The $SU(2)$ contribution can be identified with the chargino one, since the latter is always much bigger than the corresponding neutralino contribution.

Masina, Savoy

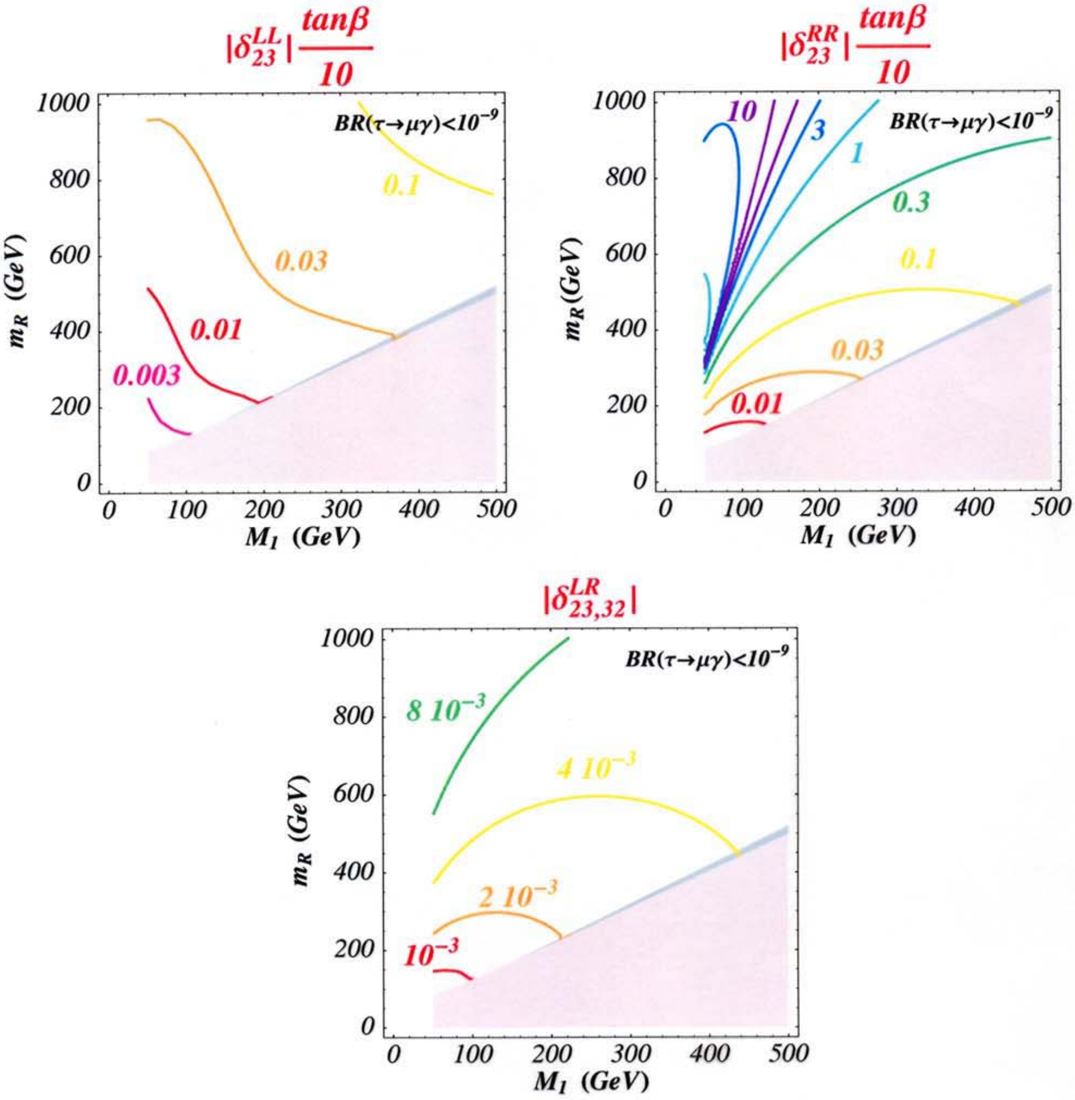


Figure 3: Upper limits on δ_{23}'s in mSUGRA.

reducing $|\mu|$ (i.e., the gluino mass, in current models) the $\tilde{B}-\tilde{H}^0$ and $\tilde{W}-\tilde{H}$ contributions increase as $|\mu|^{-2}$, while the $\tilde{B}$ contribution is $|\mu|$ independent. Therefore one needs opposite phases for M_2 and M_1, in which case the δ^{LL}'s would remain unconstrained inside a relatively narrow sector of the (m_R, M_1) semi-plane.

In figs. 2 and 3 we show the global bounds on $\delta^{LL}_{12}\tan\beta/10$ and $\delta^{LL}_{23}\tan\beta/10$ that follow from $BR(\mu\to e\gamma)<10^{-11}$ and $BR(\tau\to\mu\gamma)<10^{-9}$ respectively. The former corresponds to the present bound (see Table 1). Since the branching ratio is quadratic in the δ's, the planned improvement by however, if susy is flavour-blind and ν masses are generated by the seesaw mechanism, LFV rates are controlled by the seesaw parameters

seesaw ($N_f=1$) $\quad m_D \bar{N}_R \nu_L + \frac{1}{2} M_R N_R^T C N_R + h.c.$

$$m_D \ll M_R \quad \Rightarrow \quad m_\nu \simeq \frac{m_D^2}{M_R} \ll m_D$$

for $m_D \sim m_t$, $m_\nu \sim \sqrt{\Delta m^2_{atm}} \Rightarrow M_R \sim 5 \times 10^{14}$ GeV

$N_f = 3$ $\quad \underbrace{Y_{k\alpha}}_{\text{Dirac matrix}} \bar{N}_{Rk} L_\alpha H_u + \frac{1}{2} \underbrace{(M_R)_{kl}}_{\text{Majorana matrix}} N_{Rk}^T C N_{Rl} + h.c.$

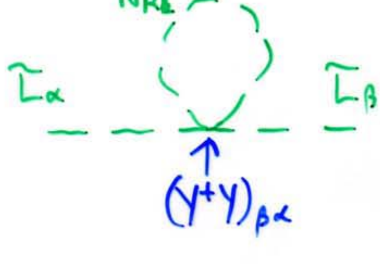
$$\Rightarrow \quad \mathcal{M}_\nu = Y^T M_R^{-1} Y$$

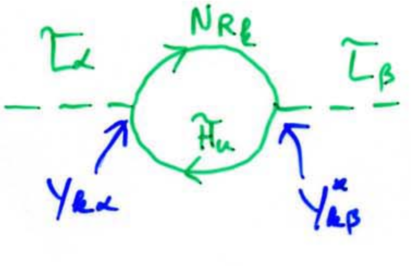
work in basis $M_e = \begin{pmatrix} m_e & & \\ & m_\mu & \\ & & m_\tau \end{pmatrix}$, $M_R = \begin{pmatrix} M_1 & & \\ & M_2 & \\ & & M_3 \end{pmatrix}$

- even if at some high scale $M_U > M_R$ the soft susy masses are universal,

$$(m^2_{\tilde{L}})_{\alpha\beta} = (m^2_{\tilde{e}})_{\alpha\beta} = m_0^2 \mathbb{1} \qquad A^e_{\alpha\beta} = A_0 Y^e_{\alpha\beta} \delta_{\alpha\beta}$$

the LFV Dirac couplings $Y_{k\alpha}$ induce flavour off-diagonal entries through loops
(Borzumati, Masiero)





→ below M_R:

$$\begin{cases} (m^2_{\tilde{L}})_{\alpha\beta} \simeq - \frac{3m_0^2 + A_0^2}{8\pi^2} C_{\alpha\beta} \\ (m^2_{\tilde{e}})_{\alpha\beta} \simeq 0 \\ A^e_{\alpha\beta} \simeq - \frac{3}{8\pi} A_0 Y^e_\alpha C_{\alpha\beta} \end{cases}$$

$\boxed{C_{\alpha\beta} \equiv \sum_k Y^*_{k\alpha} Y_{k\beta} \ln \frac{M_U}{M_k}}$ encapsulates all dependence on the seesaw parameters

$$BR(\mu \to e\gamma) \quad \propto \quad |C_{12}|^2$$
$$BR(\tau \to \mu\gamma) \quad \propto \quad |C_{23}|^2$$

- in a large class of seesaw models:

$$|C_{23}| \sim |Y_{33}|^2 \ln \frac{M_U}{M_3}$$

⇒ if $Y_{33} \sim 1$ [as happens in SO(10) GUTs], $BR(\tau \to \mu\gamma) \gtrsim 10^{-9}$ over a large portion of the MSSM parameter space

- values of $|C_{12}|$ are more model-dependent

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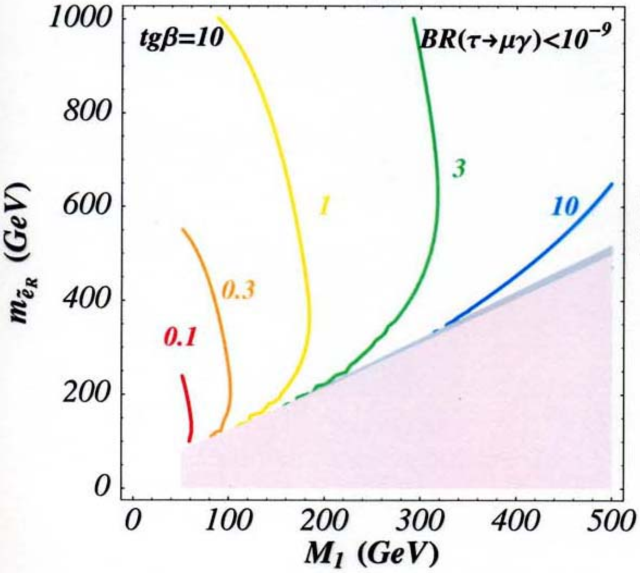
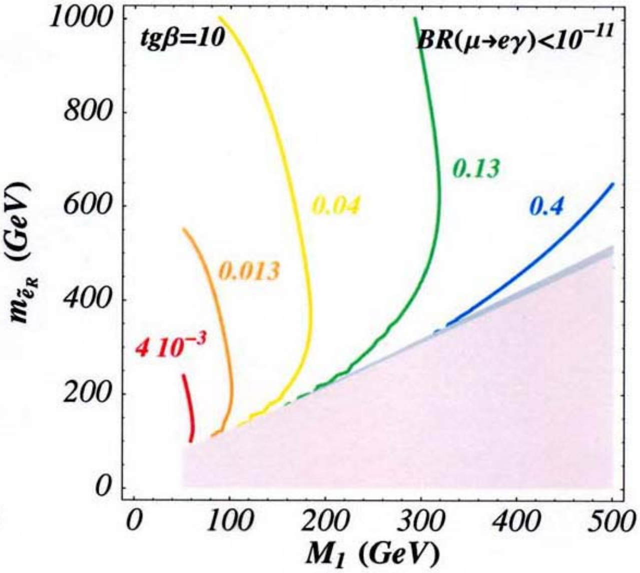


C_{32}



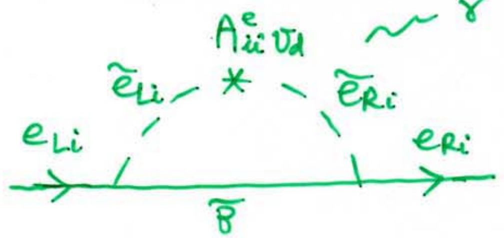
C_{21}

EDMs of charged leptons

- while charged lepton EDMs arise only at multiloop level in the SM, they are generated at one loop in Susy models (new $\not{CP}$ phases in soft terms)

- 2 types of contributions :

1) flavour conserving from phases in flavour diagonal parameters (μ, A_i)



$$A^e_{ii} v_d = (\underset{\nearrow\ \phi_{A_i}}{A_i} - \underset{\nwarrow\ \phi_\mu}{\mu^*} \tan\beta)\, m_{e_i}$$

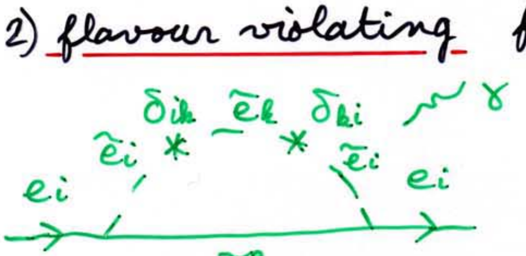
$$d_i \propto m_{e_i} \Rightarrow \frac{d_i}{d_j} \simeq \frac{m_{e_i}}{m_{e_j}}$$

(unless strong hierarchy among A_i's)

thus $d_e \leq 1.6 \times 10^{-27}$ e.cm (exp. limit)

implies $d_\mu \lesssim \frac{m_\mu}{m_e} d_e|_{exp.} = \underbrace{3.3 \times 10^{-25} \text{ e.cm}}_{\text{below the sensitivity of the planned BNL experiment}}$

2) flavour violating from phases in δ_{ij}'s



$$\mathrm{Im}(\delta^{LL}_{ik} \delta^{RR}_{ki}),\ \mathrm{Im}(\delta^{LL}_{ik} \delta^{LR}_{ki}),$$
$$\mathrm{Im}(\delta^{LR}_{ik} \delta^{RR}_{ki}),\ \mathrm{Im}(\delta^{LR}_{ik} \delta^{LR}_{ki})$$

scaling relation $\frac{d_i}{d_j} \simeq \frac{m_{e_i}}{m_{e_j}}$ no longer satisfied

$\Rightarrow d_\mu \gg \frac{m_\mu}{m_e} d_e|_{exp.}$ possible

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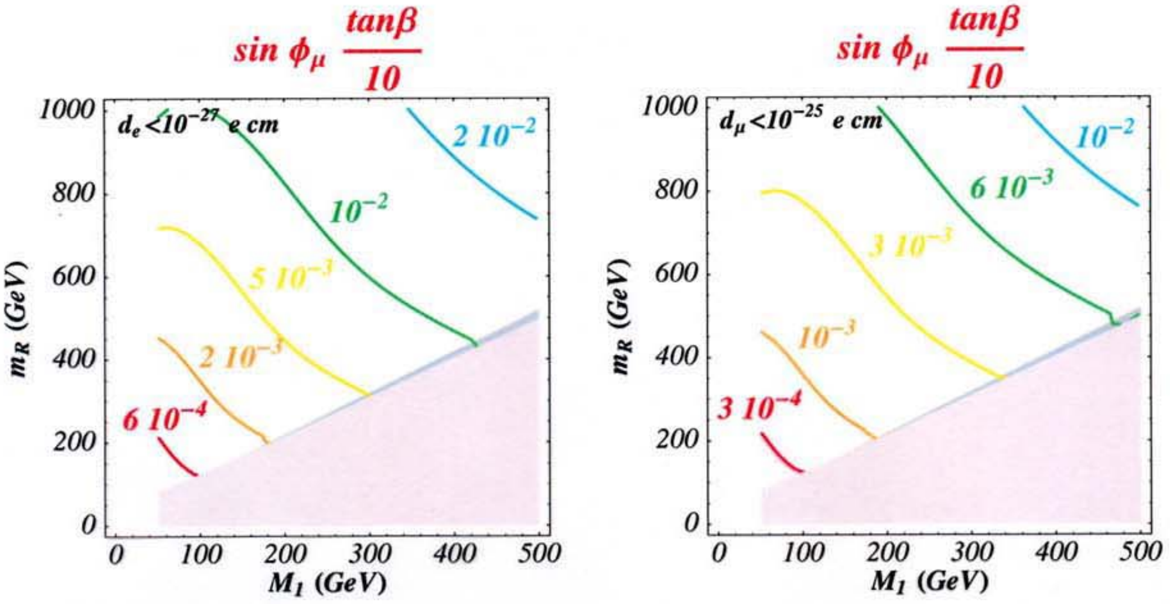

Figure 7: Upper limit on $\sin\phi_\mu \tan\beta/10$ in mSUGRA. Vanishing A-term is assumed.

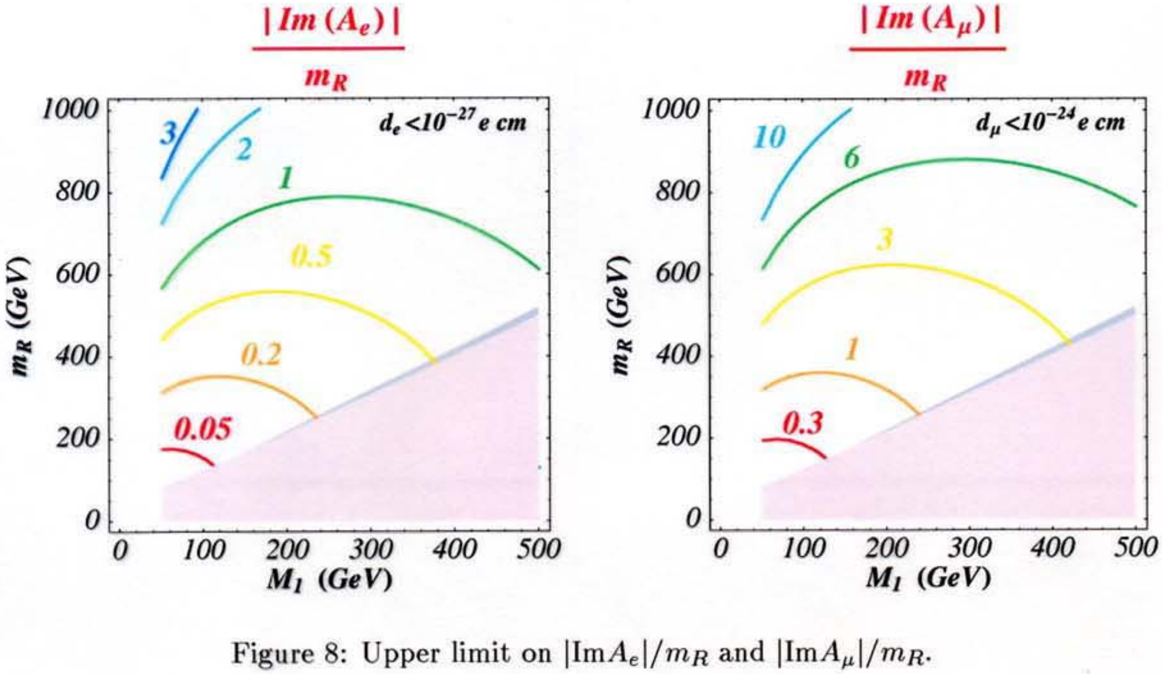

Figure 8: Upper limit on $|\mathrm{Im}A_e|/m_R$ and $|\mathrm{Im}A_\mu|/m_R$.

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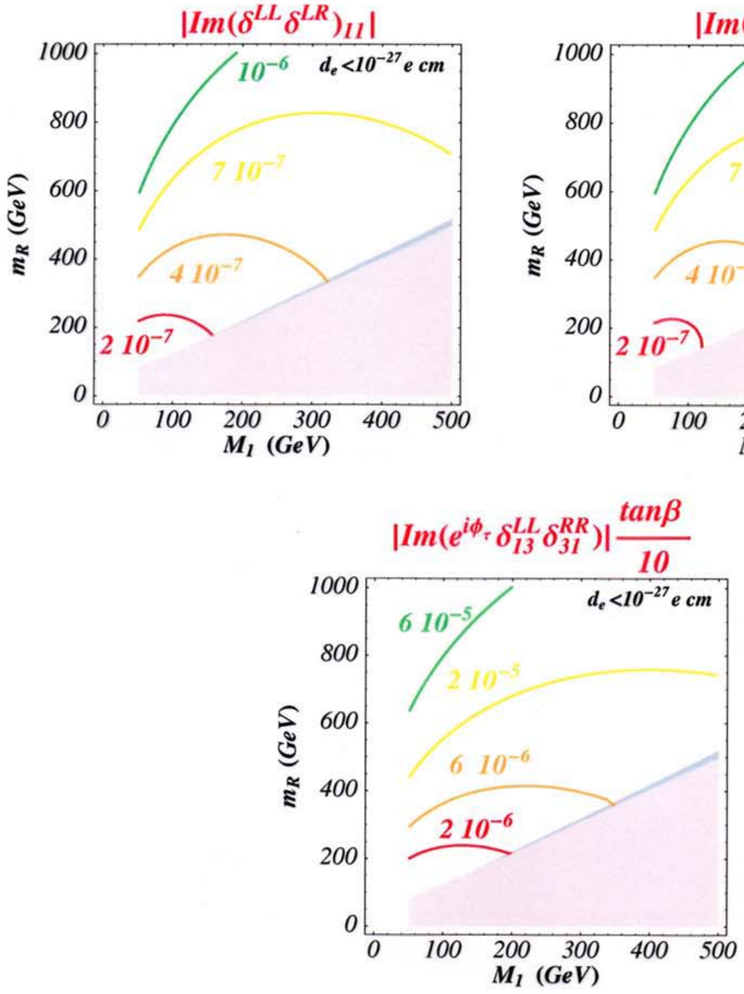

Figure 10: Upper bounds on the imaginary part of products of δ's with the present limit on d_e; ϕ_τ is defined in the text.

extract the lepton mass dependence. Notice that the limits on $Im(e^{i\phi_\tau}\delta^{LL}_{i3}\delta^{RR}_{3i})$ and $Im(e^{-i\phi_\tau}\delta^{LR}_{i3}\delta^{LR}_{3i})$ are inversely proportional to $\mu\tan\beta$.

All these results are easily understood from the approximations in the Appendix, which are also useful for a quick evaluation of alternative models.

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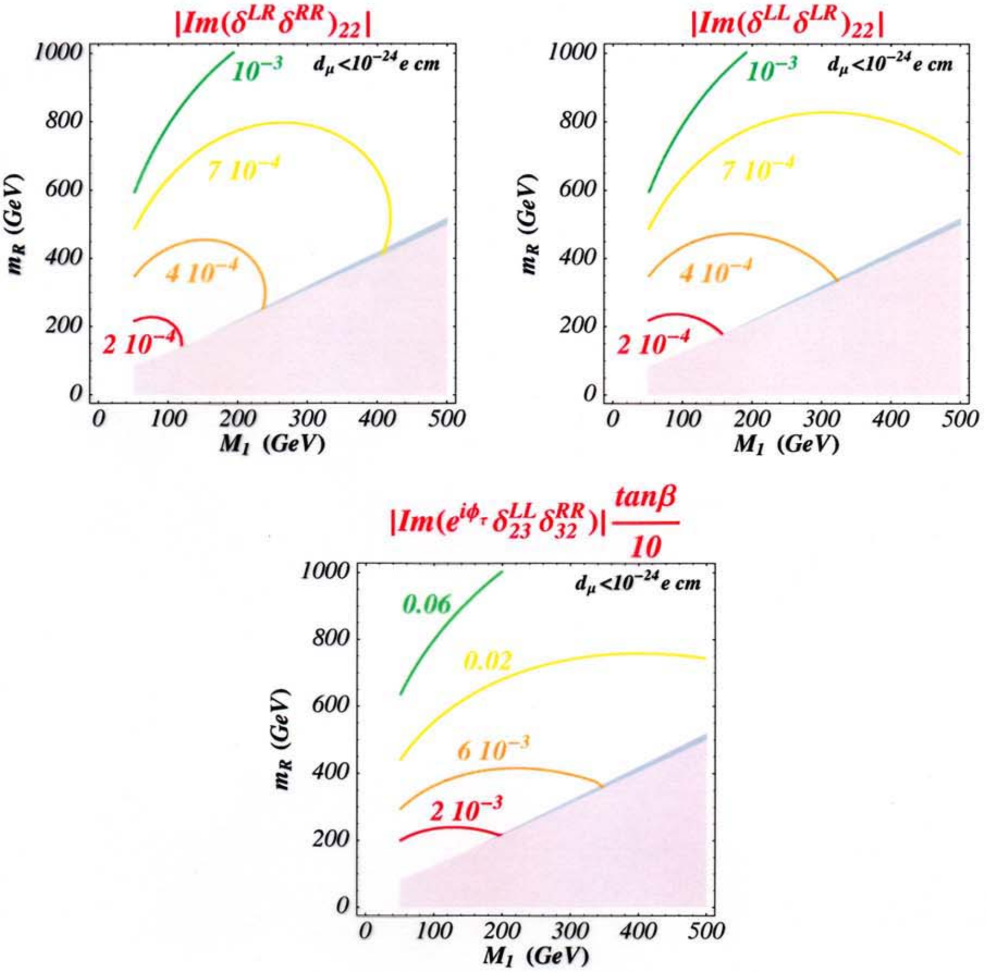

Figure 11: Upper bounds on the imaginary part of products of δ's for a limit of 10^{-24}e cm on d_μ; ϕ_τ is defined in the text.

5 Limits on FV contributions to EDM from LFV decays

Of course, all these tests of the lepton flavour structure of the soft parameters of supersymmetric extensions of the SM are quite complementary. For instance, as we now turn to discuss, the conjunction of experimental bounds on LFV transitions and on MDM and EDM would help in disentangling the FC and FV contributions in (18) and in learning whether CP violation is more present in one or the other kind of soft masses.

As a case study, we concentrate here on d_μ and evaluate the maximal FV contribution by using the limits on $|\delta^{LL}|$, $|\delta^{RR}|$, $|\delta^{LR}|$, matrix elements obtained from $\tau \to \mu\gamma$ (those from $\mu \to e\gamma$ are much in Susy seesaw models with flavour-blind Susy

the Dirac couplings $Y_{k\alpha}$ can induce complex flavour off-diagonal slepton masses

eg $\mathrm{Im}\left(\delta^{LL} M_e \delta^{RR}\right)_{ii} \propto \ln\frac{M_3}{M_2}\,\mathrm{Im}\left[Y_{2i}^* Y_{2j} \frac{m_{e_j}^2}{m_\tau^2} Y_{3j}^* Y_{3i}\right]$

Conclusions

- if U_{MNSP} is the only source of flavour and CP violation in the lepton sector, then no other LFV ($\not{CP}$) process than oscillations should be observable

- LFV processes and EDMs of charged leptons are therefore a unique probe of new physics: the observation of e.g. $\mu \to e\gamma$ ($\tau \to \mu\gamma$) or the measurement of a nonzero d_μ would definitely testify for physics beyond the SM

- a significant improvement of the experimental upper limits on $BR(\mu \to e\gamma)$ and $BR(\tau \to \mu\gamma)$ would already provide strong constraints on Susy and on Susy seesaw models