Minimal Flavour Violation without R-Parity

DESY THEORY WORKSHOP
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Outline

- Flavor problem and MFV as its solution
- MFV in the lepton sector
- An alternative formulation of MLFV: RPV-MSSM
- Neutrino Masses and phenomenological implications

The Flavour Problem

- The SM is not a complete theory (neutrino masses, dark matter, BAU, ..., gravity)

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}(\text{SM fields}).$$

- Upper bound from the naturalness of the Higgs mass $\Lambda \lesssim 1 \text{ TeV}$

- Lower bounds from FCNC $\Lambda > \begin{cases} 1.3 \times 10^4 \text{ TeV} \times |c_{sd}|^{1/2} \\ 5.1 \times 10^2 \text{ TeV} \times |c_{bd}|^{1/2} \\ 1.1 \times 10^2 \text{ TeV} \times |c_{bs}|^{1/2} \end{cases}$ [Isidori, Nir, Perez (2010)]

- Two (problematic) possibilities:

  (i) $\Lambda \gg 1 \text{ TeV and } c_{ij} = \mathcal{O}(1)$ Hierarchy Problem

  (ii) $\Lambda < 1 \text{ TeV and } c_{ij} \ll 1$ Flavor Problem

Minimal Flavour Violation

- MFV is based on:

[Chivukula, Georgi (1987) -Technicolor]
[Hall, Randall (1990) - SUSY]
[Buras, Gambino, Gorbahn, Jager, Silvestrini (2000) - Pheno]
[D'Ambrosio, Giudice, Isidori, Strumia (2002) - EFT]

(i) a (flavor) symmetry: a subgroup of

$$G^{\mathrm{SM}}_{\mathrm{kin}} = U(3)_q \otimes U(3)_{u^c} \otimes U(3)_{d^c} \otimes U(3)_{e^c} \otimes U(3)_\ell \otimes U(1)_h$$

(ii) a (minimal) set of irreducible symmetry breaking terms

$$\mathcal{L}_Y = y_u \tilde{h} q u^c + y_d h q d^c + y_e h \ell e^c + \mathrm{h.c.}$$

	$\mathrm{SU}(3)_q$	$\mathrm{SU}(3)_{u^c}$	$\mathrm{SU}(3)_{d^c}$	$\mathrm{SU}(3)_\ell$	$\mathrm{SU}(3)_{e^c}$
q	$\square$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
u^c	$\mathbf{1}$	$\square$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
d^c	$\mathbf{1}$	$\mathbf{1}$	$\square$	$\mathbf{1}$	$\mathbf{1}$
ℓ	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\square$	$\mathbf{1}$
e^c	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\square$
y_u	$\overline{\square}$	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
y_d	$\overline{\square}$	$\mathbf{1}$	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$
y_e	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\square}$	$\overline{\square}$

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q	$\square$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
u^c	$\mathbf{1}$	$\square$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
d^c	$\mathbf{1}$	$\mathbf{1}$	$\square$	$\mathbf{1}$	$\mathbf{1}$
ℓ	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\square$	$\mathbf{1}$
e^c	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\square$
y_u	$\overline{\square}$	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
y_d	$\overline{\square}$	$\mathbf{1}$	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$
y_e	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\square}$	$\overline{\square}$

The symmetry is formally restored by promoting the Yukawas to spurion fields

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$$\mathcal{L}_Y = y_u \tilde{h} q u^c + y_d h q d^c + y_e h \ell e^c + \text{h.c.}$$

- The MFV hypothesis consists in the assumptions that:

(i) the full EFT is formally invariant under the flavour symmetry

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}(\text{SM fields}).$$

(ii) the SM Yukawas are the only irreducible sources of flavour breaking

$$c_i^{(d)} = c_i^{(d)}(y_u, y_d, y_e)$$

MFV consequences

(i) flavor violating contributions from combinations of the type* $\left(y_u y_u^\dagger\right)^{ij} \approx \lambda_t^2 (V_{\rm CKM}^{3i})^* V_{\rm CKM}^{3j}$

(ii) predictive hypothesis with correlations among observables

(iii) flavor problem is practically solved (see table)

(iv) there is no flavor violation in the lepton sector

Operator	Bound on Λ	Observables
$H^\dagger \left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} Q_L\right) (eF_{\mu\nu})$	6.1 TeV	$B \to X_s\gamma$, $B \to X_s \ell^+\ell^-$
$\frac{1}{2}(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L)^2$	5.9 TeV	ϵ_K, Δm_{B_d}, Δm_{B_s}
$H_D^\dagger \left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} T^a Q_L\right) (g_s G^a_{\mu\nu})$	3.4 TeV	$B \to X_s\gamma$, $B \to X_s \ell^+\ell^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right) \left(\overline{E}_R \gamma_\mu E_R\right)$	2.7 TeV	$B \to X_s \ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$i\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right) H_U^\dagger D_\mu H_U$	2.3 TeV	$B \to X_s \ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right) \left(\overline{L}_L \gamma_\mu L_L\right)$	1.7 TeV	$B \to X_s \ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right) (eD_\mu F_{\mu\nu})$	1.5 TeV	$B \to X_s \ell^+\ell^-$

[Isidori, Nir, Perez (2010)]
[UTfit coll. (2007)]
[Hurth, Isidori, Kamenik, Mescia (2008)]

* in the basis $y_u = V_{\rm CKM}^\dagger \frac{\hat{m}_u}{v}, \; y_d = \frac{\hat{m}_d}{v}, \; y_e = \frac{\hat{m}_e}{v}$

Minimal Lepton Flavour Violation

- Extension of the MFV notion to the leptons is not straightforward
- Mechanism generating neutrino masses is beyond the SM

[Cirigliano et al. (2005)]
[Davidson et al. (2006)]
[Gavela, et al. (2009)]
[Alonso e al. (2011)]

(i) Minimal field content (Weinberg operator)

$$\mathcal{L}_{break} = y_e h\, \ell e^c + \frac{g_\nu}{2\Lambda_{\rm LN}} (\tilde{h}\,\ell)(\tilde{h}\,\ell) + \text{h.c.}$$

$$\Delta = g_\nu^\dagger g_\nu = \frac{\Lambda_{\rm LN}^2}{v^4}\, \hat{U}\, \hat{m}_\nu^2\, \hat{U}^\dagger$$

	$\mathrm{SU}(3)_\ell$	$\mathrm{SU}(3)_{e^c}$
y_e	$\bar{\Box}$	$\bar{\Box}$
g_ν	$\overline{\Box\Box}$	$\mathbf{1}$

(ii) Extended field content (type-I seesaw)

$$\mathcal{L}_{break} = y_e h\, \ell e^c + y_\nu \tilde{h}\, \ell \nu^c + \tfrac{1}{2} M_\nu \nu^c \nu^c + \text{h.c.}$$

$$\Delta = y_\nu^\dagger y_\nu \xrightarrow[M_\nu \propto \mathbb{1}]{\text{CP-limit}} \frac{M_\nu}{v^2}\, \hat{U}\, \hat{m}_\nu\, \hat{U}^\dagger$$

	$\mathrm{SU}(3)_\ell$	$\mathrm{SU}(3)_{e^c}$	$\mathrm{SU}(3)_\nu$
ν^c	$\mathbf{1}$	$\mathbf{1}$	$\Box$
y_e	$\bar{\Box}$	$\bar{\Box}$	$\mathbf{1}$
y_ν	$\bar{\Box}$	$\mathbf{1}$	$\bar{\Box}$
M_ν	$\mathbf{1}$	$\mathbf{1}$	$\overline{\Box\Box}$

- $BR(\ell_i \to \ell_j\, \gamma) \propto \left|\Delta^{ij}\right|^2$ visible if $\Lambda_{\rm LFV} \ll \Lambda_{\rm LN}$

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(i) Minimal field content (Weinberg operator)

(ii) Extended field content (type-I seesaw)

(iii) Minimal Supersymmetric field content: MSSM without R-parity

MSSM + Type I see-saw in
[Nikolidakis, Smith (2007)]
[Csaki, Grossman, Heidenreich (2011)]

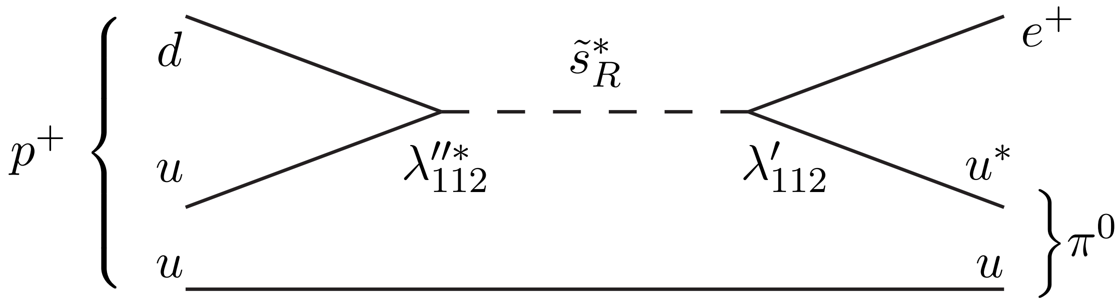
MSSM and R-parity

- Most generic renormalizable superpotential

$$W_{RPC} = y_U^{ij} q_i u_j^c h_u + y_D^{ij} h_d q_i d_j^c + y_E^{ij} h_d \ell_i e_j^c + \mu\, h_u h_d$$

$$W_{RPV} = \mu^i h_u \ell_i + \tfrac{1}{2}\lambda^{ijk} \ell_i \ell_j e_k^c + (\lambda')^{ijk} \ell_i q_j d_k^c + \tfrac{1}{2}(\lambda'')^{ijk} u_i^c d_j^c d_k^c$$

- W_{RPV} violates simultaneously L and B number



$$|\lambda' \cdot \lambda''^*| < 10^{-25} \div 10^{-9} \left(\frac{\tilde{m}}{1\ \mathrm{TeV}}\right)^2$$

[Smirnov, Vissani (1996)]

- Possible solution: M-parity ($M_P = (-)^{3(\mathrm{B-L})}$)

$$M_P(q, u^c, d^c, \ell, e^c) = - \qquad\qquad M_P(h_u, h_d) = +$$

- M-parity equivalent to R-parity ($R_P = (-)^{3(\mathrm{B-L})+2\mathrm{S}}$)

$$R_P(\text{SM fields}) = + \qquad\qquad R_P(\text{SM superpartners}) = -$$

R-parity or not R-parity ?

- The imposition of R-parity strongly influences the MSSM phenomenology

  - B and L accidental global symmetries as in the SM

  - LSP is stable (DM candidate)

  - LSP escapes the detector (missing energy)

- R-parity is not necessary   Huge literature [Barbier et al. (2004)]

  - L breaking generates neutrino masses within the MSSM matter content   [Hall, Suzuki (1984)] [Ross, Valle (1984)]

  - The gravitino is the only DM candidate, NLSP decays before BBN   [Takayama, Yamaguchi (2000)] [Buchmuller, Covi, Hamaguchi, Ibarra, Yanagida (2007)] [Bajc, Enkhbat, Ghosh, Senjanovic, Zhang (2010)] ...

  - Very rich collider phenomenology   [Dreiner, Ross (1991)] ... [Csaki, Grossman, Heidenreich (2011)] [Graham, Kaplan, Rajendran, Saraswat (2012)] [Brust, Katz, Sundrum (2012)] [Evans, Katz (2012)] [Berger, Csaki, Grossman, Heidenreich (2012)]

A closer look to the kinetic term

- Let us restart with the two main ingredients of MFV
  (i) a flavor symmetry
  (ii) a minimal set of irreducible symmetry breaking terms

- $\hat{\ell}_i$ and $\hat{h}_d$ have the same gauge quantum numbers: $\hat{L}_\alpha = (\hat{\ell}_i, \hat{h}_d)$

$$\int d^4\theta\; \hat{\Phi}^\dagger e^{2g\hat{V}} \hat{\Phi} \qquad \hat{\Phi} = \left(\hat{q}_i, \hat{u}^c_i, \hat{d}^c_i, \hat{e}^c_i, \hat{L}_\alpha, \hat{h}_u\right)$$

- SUSY enhances the global symmetry of the kinetic term !

$$G^{\rm MSSM}_{\rm kin} = U(3)_{\hat{q}} \otimes U(3)_{\hat{u}^c} \otimes U(3)_{\hat{d}^c} \otimes U(3)_{\hat{e}^c} \otimes \boxed{U(4)_{\hat{L}}} \otimes U(1)_{\hat{h}_u}$$

- the symmetry is there irrespective of the fact that R-parity is broken or not

A closer look to the kinetic term

- Let us restart with the two main ingredients of MFV
  (i) a flavor symmetry
  (ii) a minimal set of irreducible symmetry breaking terms

- Several sources of flavor breaking in the MSSM $\mathcal{L}_{\mathrm{MSSM}}^{RPV} = \mathcal{L}_{\mathrm{kin}} + \boxed{\mathcal{L}_{\mathrm{W}} + \mathcal{L}_{\mathrm{soft}}}$

- We assume that the irreducible sources of flavor breaking come from superpotential
  - assumption natural in gauge mediation
  - soft terms at low-energy have a MFV structure

Λ_F
- Generation of the flavor structure

M_{mess}
- Mediation of SUSY breaking, universal soft terms generated
- RGE effects

m_{soft}
- Low-energy MSSM

Spurions

- To highlight the enhanced symmetry let us rewrite

$$W = Y_U^{ij} q_i u_j^c h_u + Y_D^{\alpha ij} L_\alpha q_i d_j^c + \tfrac{1}{2} Y_E^{\alpha\beta i} L_\alpha L_\beta e_i^c + \mu^\alpha h_u L_\alpha + \tfrac{1}{2} (\lambda'')^{ijk} u_i^c d_j^c d_k^c$$

$$L \to (\ell, h_d) \qquad Y_D \to (y_d, \lambda') \qquad Y_E \to (y_e, \lambda)$$

	$\mathrm{SU}(3)_q$	$\mathrm{SU}(3)_{u^c}$	$\mathrm{SU}(3)_{d^c}$	$\mathrm{SU}(3)_{e^c}$	$\mathrm{SU}(4)_{\hat{L}}$
$\hat{q}$	$\square$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\hat{u}^c$	$\mathbf{1}$	$\square$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$\hat{d}^c$	$\mathbf{1}$	$\mathbf{1}$	$\square$	$\mathbf{1}$	$\mathbf{1}$
$\hat{e}^c$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\square$	$\mathbf{1}$
$\hat{L}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\square$
Y_u	$\overline{\square}$	$\overline{\square}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
Y_d	$\overline{\square}$	$\mathbf{1}$	$\overline{\square}$	$\mathbf{1}$	$\overline{\square}$
Y_e	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\square}$	$\begin{array}{c}\square\\[-4pt]\square\end{array}$
μ	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\overline{\square}$
λ''	$\mathbf{1}$	$\overline{\square}$	$\square$	$\mathbf{1}$	$\mathbf{1}$

Soft terms

- Up to 3 spurions (in the paper)
- c, d = O(1) coefficients

$$
\begin{aligned}
(\tilde{m}^2_q)^i_j &= \tilde{m}^2 \left(c_q \delta^i_j + d^1_q \; Y_U^{ik} \, (Y_U^*)_{jk} + d^2_q \; Y_D^{\alpha ik} \, (Y_D^*)_{\alpha jk} \right) \\
(\tilde{m}^2_{u^c})^i_j &= \tilde{m}^2 \left(c_{u^c} \delta^i_j + d^1_{u^c} \; Y_U^{ki} \, (Y_U^*)_{kj} + d^2_{u^c} (\lambda'')^{ikl} (\lambda''^*)_{jkl} \right) \\
(\tilde{m}^2_{d^c})^i_j &= \tilde{m}^2 \left(c_{d^c} \delta^i_j + d^2_{d^c} \; Y_D^{\alpha ki} \, (Y_D^*)_{\alpha kj} + d^2_{d^c} (\lambda'')^{kil} (\lambda''^*)_{kjl} \right) \\
(\tilde{m}^2_{e^c})^i_j &= \tilde{m}^2 \left(c_{e^c} \delta^i_j + d^1_{e^c} \; Y_E^{\alpha\beta i} \, (Y_E^*)_{\alpha\beta j} \right) \\
(\tilde{m}^2_L)^\alpha_\beta &= \tilde{m}^2 \left(c_L \delta^\alpha_\beta + d^1_L \; Y_E^{\alpha\gamma k} \, (Y_E^*)_{\beta\gamma k} + d^2_L \; Y_D^{\alpha kl} \, (Y_D^*)_{\beta kl} + d^3_L \, \mu^\alpha \mu^*_\beta / |\mu|^2 \right) \\
B^\alpha &= \tilde{m}^2 \left(c_B \, \mu^\alpha / |\mu| + d^1_B \; Y_D^{\alpha kl} (Y_D^*)_{\beta kl} \, \mu^\beta / |\mu| + d^2_B \; Y_E^{\alpha\beta k} (Y_E^*)_{\gamma\beta k} \, \mu^\gamma / |\mu| \right) \\
A_U^{ij} &= A \left(c_{A_U} Y_U^{ij} + \ldots \right) \\
A_D^{\alpha ij} &= A \left(c_{A_D} Y_D^{\alpha ij} + \ldots \right) \\
A_E^{\alpha\beta i} &= A \left(c_{A_E} Y_E^{\alpha\beta i} + \ldots \right) \\
A_{\lambda''}^{ijk} &= A \left(c_{A_{\lambda''}} + \ldots \right)
\end{aligned}
$$

Soft terms

- In a more familiar language

$$
\begin{aligned}
(\tilde{m}_q^2)^i_j &= \tilde{m}^2 \left(c_q \delta^i_j + d_q^1 (y_U y_U^\dagger)^i_j + d_q^2 \left[(y_D y_D^\dagger)^i_j + (\lambda')^{lik} \lambda'^*_{ljk} \right] \right) \\
(\tilde{m}_{u^c}^2)^i_j &= \tilde{m}^2 \left(c_{u^c} \delta^i_j + d_{u^c}^1 (y_U^\dagger y_U)^i_j + d_{u^c}^2 (\lambda'')^{ikl} (\lambda''^*)_{jkl} \right) \\
(\tilde{m}_{d^c}^2)^i_j &= \tilde{m}^2 \left(c_{d^c} \delta^i_j + d_{d^c}^1 \left[(y_D^\dagger y_D)^i_j + (\lambda')^{lki} \lambda'^*_{lkj} \right] + d_{d^c}^2 (\lambda'')^{kil} (\lambda''^*)_{kjl} \right) \\
(\tilde{m}_{e^c}^2)^i_j &= \tilde{m}^2 \left(c_{e^c} \delta^i_j + d_{e^c}^1 \left[2 (y_E^\dagger y_E)^i_j + \lambda^{lki} \lambda^*_{lkj} \right] \right) \\
(\tilde{m}_\ell^2)^i_j &= \tilde{m}^2 \left(c_L \delta^i_j + d_L^1 \left[(y_E y_E^\dagger)^i_j + \lambda^{ilk} \lambda^*_{jlk} \right] + d_L^2 (\lambda')^{ilk} \lambda'^*_{jlk} + d_L^3 \mu^i \mu^*_j / |\mu|^2 \right) \\
(\tilde{m}_d^2)^i &= \tilde{m}^2 \left(d_L^1 \lambda^{ilk} (y_E^*)_{lk} + d_L^2 (\lambda')^{ilk} (y_D^*)_{lk} + d_L^3 \mu^i \mu^* / |\mu|^2 \right)
\end{aligned}
$$

- Correlation between soft terms and RPV couplings
- Lepton flavor violation in the slepton mass matrices

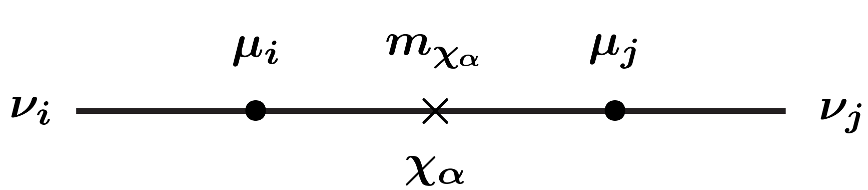
Spurions and physics

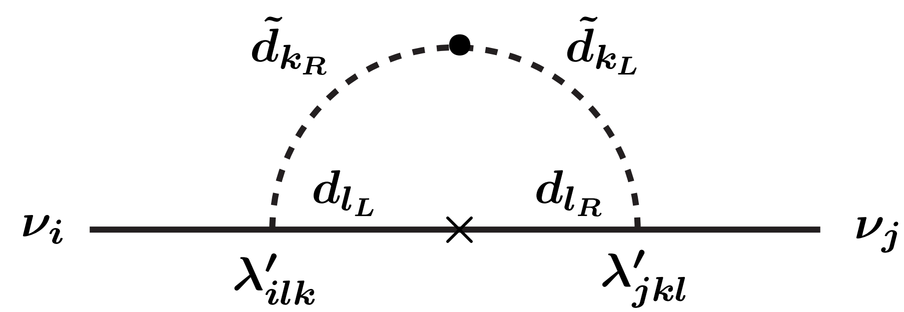
- Minimal flavour breaking:
  only the spurions responsible for fermion masses and mixings are allowed

- According to the assumption of minimal breaking $\lambda'' = 0$

- In the lepton sector many sources for neutrino masses

$$m_\nu \quad \sim \quad \left(\frac{M_Z}{\tilde{m}}\right)^2 \frac{\mu_i \mu_j}{\tilde{m}}\,, \qquad \frac{3\,\lambda'^2}{8\pi^2}\frac{\hat{m}_D^2}{\tilde{m}}\,, \qquad \frac{\lambda^2}{8\pi^2}\frac{\hat{m}_E^2}{\tilde{m}}\,,$$





[Grossman, Rakshit (2004)]

- The connection btw spurions and low-energy observables $\Delta m^2_{\rm atm}$, $\Delta m^2_{\rm sol}$ and $\hat{U}$ requires extra assumptions

A simple model of neutrino masses

- Neutrino mass matrix

$$(m_\nu)^{ij} = \left(\hat{U}\hat{m}_\nu\hat{U}^T\right)^{ij} = m_3\hat{U}^{i3}\hat{U}^{j3} + m_2\hat{U}^{i2}\hat{U}^{j2} + m_1\hat{U}^{i1}\hat{U}^{j1}$$

- A simple ansatz allows to obtain an analytical connection:

  - Normal hierarchy: $m_3 \approx \sqrt{\Delta m^2_{\rm atm}} > m_2 \approx \sqrt{\Delta m^2_{\rm sol}} > m_1 \approx 0$

  - μ^i is responsible for the heaviest neutrino

$$(m_\nu^{(\rm tree)})^{ij} \approx m_3\,\hat{U}^{i3}\hat{U}^{j3} \qquad \frac{\mu^i}{\mu} = 2.4\cdot 10^{-5}\left(\frac{\tilde{m}}{1\ {\rm TeV}}\right)^{1/2}\left(\frac{\tan\beta}{10}\right)\hat{U}^{i3}$$

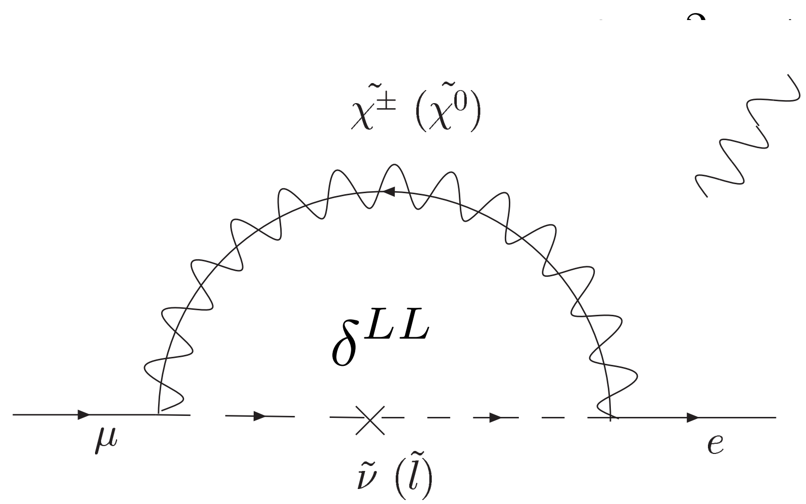
  - $(\lambda')^{i33}$ is responsible for the second neutrino

$$(m_\nu^{(\rm loop)})^{ij} \approx m_2\,\hat{U}^{i2}\hat{U}^{j2} \qquad (\lambda')^{i33} = 3.3\cdot 10^{-5}\left(\frac{\tilde{m}}{1\ {\rm TeV}}\right)^{1/2}\left(\frac{\tan\beta}{10}\right)^{1/2}\hat{U}^{i2}$$

Flavour changing leptonic decays

- μ^i and $(\lambda')^{i33}$ induce LFV soft terms of the type:

$$(\tilde{m}^2_\ell)^{LL}_{ij} = \tilde{m}^2 \left(d_L^2 (\lambda')^{i33} \lambda'^{*}_{j33} + d_L^3 \frac{\mu^i \mu^*_j}{|\mu|^2} \right) \qquad \delta^{LL} \equiv \frac{\tilde{m}^2_\ell}{\tilde{m}^2}$$



Current upper bounds

$BR(\mu \to e\,\gamma)$	2.4×10^{-12}
$BR(\tau \to e\,\gamma)$	1.1×10^{-7}
$BR(\tau \to \mu\,\gamma)$	4.5×10^{-8}

$$\frac{BR(\ell_i \to \ell_j\,\gamma)}{BR(\ell_i \to \ell_j \nu_i \bar{\nu}_j)} \approx \frac{\alpha^3}{G_F^2} \frac{\delta^2_{ij}}{\tilde{m}^4} \tan^2\beta \approx 10^{-27} \left(\frac{\tilde{m}}{1\mathrm{TeV}}\right)^{-4} \left(\frac{\tan\beta}{10}\right)^2 \left(\frac{\lambda'}{10^{-5}}\right)^4$$

- Conclusions: the framework predicts a suppression of LFV

  - an explanation of the smallness of the LFV contributions

  - correlation among observables far away from being tested

A (more) predictive case

- Larger LFV effects are possible if the LN and the LFN are broken independently

[Cirigliano, Grinstein, Isidori, Wise (2005)]

- We consider a subgroup of the original flavor symmetry

$$SU(3)^5 \otimes U(1)_L \otimes U(1)_B$$

- The RPV couplings are split into an abelian and a non-abelian spurion

$$\mu^i = \varepsilon_L \tilde{\mu}^i\,, \qquad \lambda = \varepsilon_L \tilde{\lambda}\,, \qquad \lambda' = \varepsilon_L \tilde{\lambda}'\,, \qquad \lambda'' = \varepsilon_B \tilde{\lambda}''$$

- Performing the MFV expansion and with the same neutrino model as before

$$(\delta^{LL})^i_j = \frac{1}{c_\ell}\left[d^3_\ell \frac{\tilde{\mu}^i \tilde{\mu}^*_j}{|\mu|^2} + d^2_\ell (\tilde{\lambda}')^{i33} \tilde{\lambda}'^*_{j33}\right] \qquad \text{(LN conserving)}$$

$$B_{\ell_i \to \ell_j \gamma} \equiv \frac{BR(\ell_i \to \ell_j\,\gamma)}{BR(\ell_i \to \ell_j \nu_i \overline{\nu}_j)} \approx 10^{-27} \left(\frac{1}{\varepsilon_L}\right)^4 \left(\frac{\tilde{m}}{1\ \mathrm{TeV}}\right)^{-4} \left(\frac{\tan\beta}{10}\right)^2 \left(\frac{\lambda'}{10^{-5}}\right)^4$$

- with $\varepsilon_L \sim 10^{-(3\div 4)}$ can reach the experimental sensitivity

Phenomenological implications

- Remember that:

$$\left(\delta^{LL}\right)^i_j = \frac{1}{c_\ell}\left[d^3_\ell \frac{\tilde{\mu}^i \tilde{\mu}^*_j}{|\mu|^2} + d^2_\ell (\tilde{\lambda}')^{i33} \tilde{\lambda}'^*_{j33}\right]$$

$$\tilde{\mu}^i \propto \hat{U}^{i3}$$

$$(\tilde{\lambda}')^{i33} \propto \hat{U}^{i2}$$

- Specific relations appear

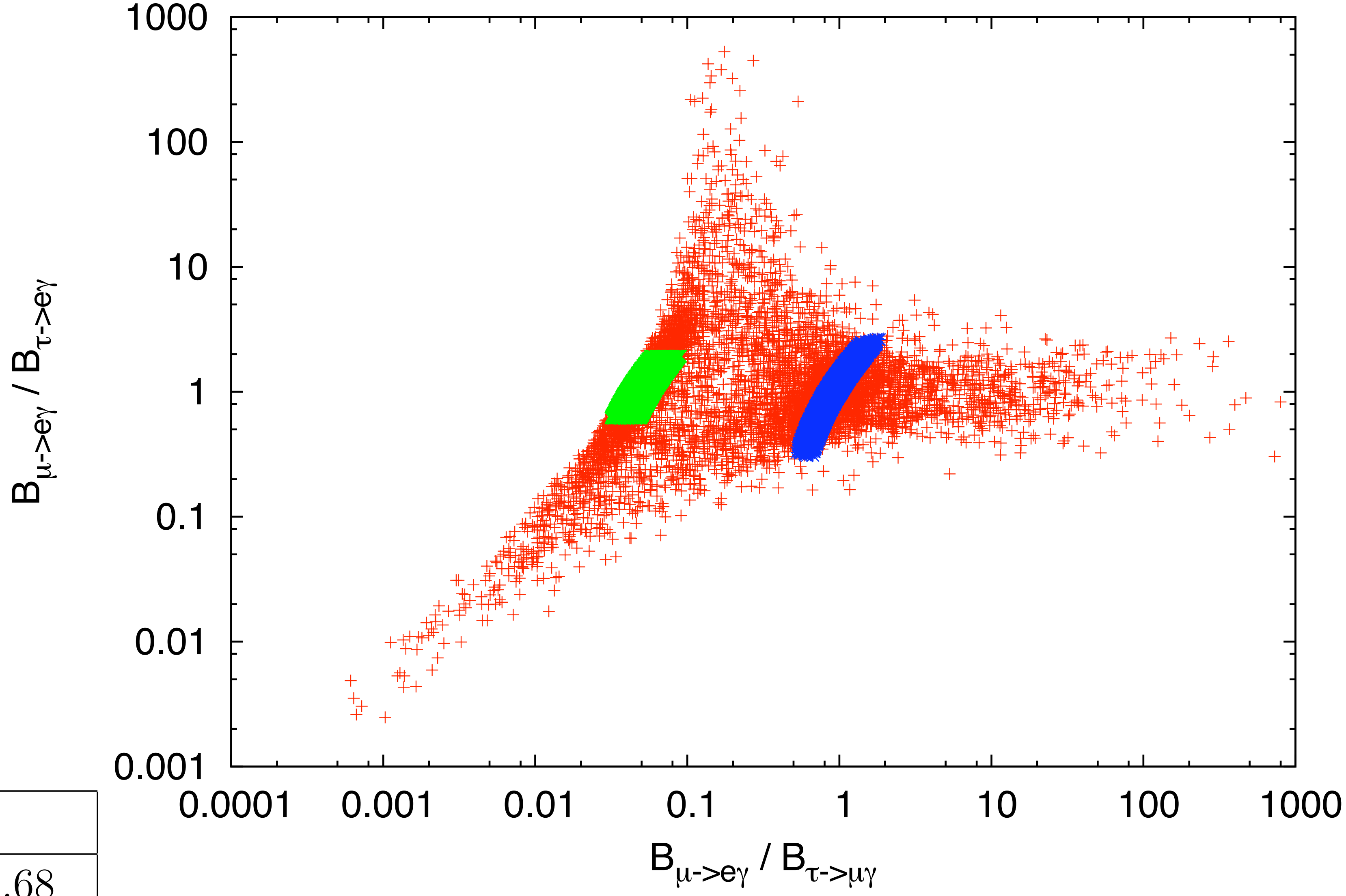
$$\frac{B_{\ell_j \to \ell_i \gamma}}{B_{\ell_k \to \ell_m \gamma}} = \frac{\left|\delta^{LL}_{ij}\right|^2}{\left|\delta^{LL}_{mk}\right|^2} = \frac{|\hat{U}^{i2}(\hat{U}^{j2})^* + c\,\hat{U}^{i3}(\hat{U}^{j3})^*|^2}{|\hat{U}^{m2}(\hat{U}^{k2})^* + c\,\hat{U}^{m3}(\hat{U}^{k3})^*|^2}$$

$$c \approx 1.4 \times 10^{-1} \left(\frac{d^3_\ell}{d^2_\ell}\right)\left(\frac{\tan\beta}{10}\right)^3 \left(\frac{\mu}{1\ \mathrm{TeV}}\right)\left(\frac{\tilde{m}}{1\ \mathrm{TeV}}\right)^{-2}\left(\frac{M_G}{300\ \mathrm{GeV}}\right)$$

Phenomenological implications

$c \in [-100, 100]$

- green: c = 0
- blue: |c| >> 1



Observable	Best fit	2-σ
$\Delta m^2_{\rm atm}[10^{-3}\ {\rm eV}^2]$	2.55	2.38 – 2.68
$\Delta m^2_{\rm sol}[10^{-5}\ {\rm eV}^2]$	7.62	7.27 – 8.01
$\sin^2\theta_{12}$	0.320	0.29 – 0.35
$\sin^2\theta_{23}$	0.613	0.38 – 0.66
$\sin^2\theta_{13}$	0.0246	0.019 – 0.030

[Forero, Tortola, Valle (2012)]

Conclusions

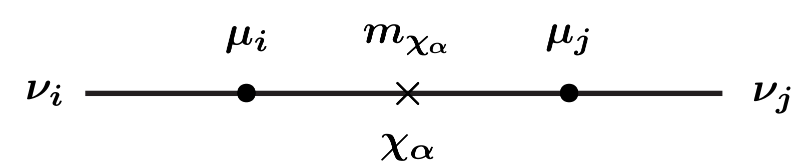
- Extension of the M(L)FV notion to the MSSM without R-parity
- Enhancement of the global symmetry of the kinetic term
- Small effects in lepton flavor changing processes (at least within our simple neutrino mass model)
- In other frameworks like $SU(3)^5 \otimes U(1)_L \otimes U(1)_B$ larger effects are possible

Backup slides

Neutrino masses in the MSSM

(i) Tree level contribution

- with RPV neutrino-neutralinos mixes



$$M_\nu = \begin{array}{c} \\ \\ \end{array}\begin{array}{cc} \nu & \chi^0 \end{array}$$

$$M_\nu = \begin{pmatrix} 0 & m_{RPV} \\ m_{RPV}^T & M_N \end{pmatrix} \begin{array}{c} \nu \\ \chi^0 \end{array}$$

m_{RPV} entries due to $\int d^2\theta\, \mu^i \hat{\ell}_i \hat{h}_u$

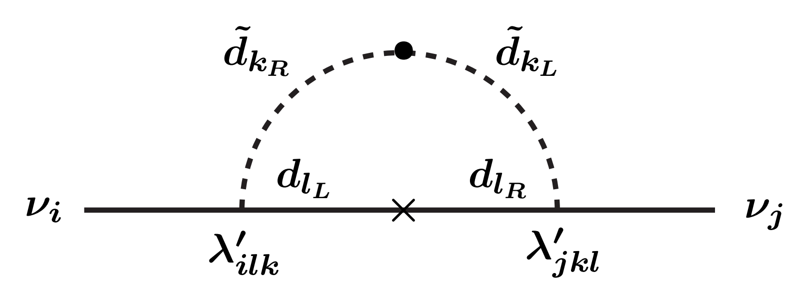
$$(m_\nu^{(\mathrm{tree})})^{ij} \approx -(m_{RPV} M_N^{-1} m_{RPV}^T)^{ij} = m_\nu^{(\mathrm{tree})} \frac{\mu^i \mu^j}{\sum_i |\mu_i^2|}$$

$$m_3^{(\mathrm{tree})} = m_\nu^{(\mathrm{tree})}$$

$$m_2^{(\mathrm{tree})} = m_1^{(\mathrm{tree})} = 0$$

$$m_\nu^{(\mathrm{tree})} = \frac{\left(M_1 \cos^2\theta_W + M_2 \sin^2\theta_W\right) M_Z^2 \cos^2\beta}{\mu\left((M_1\cos^2\theta_W + M_2\sin^2\theta_W) M_Z^2 \sin 2\beta - M_1 M_2\, \mu\right)} \times \sum_i |\mu_i^2|$$

(ii) Loop level contribution



$$(m_\nu^{(\lambda'\lambda')})^{ij} = \frac{3}{16\pi^2} \sum_{k,l,m} \lambda'^{ikl} \lambda'^{jmk}\, \hat{m}_{D_k}\, \frac{(\tilde{m}^{d\,2}_{LR})_{ml}}{m^2_{\tilde{d}_{Rl}} - m^2_{\tilde{d}_{Lm}}} \ln\left(\frac{m^2_{\tilde{d}_{Rl}}}{m^2_{\tilde{d}_{Lm}}}\right)$$

$$\approx \frac{3}{8\pi^2} \frac{\tilde{m}\, c_{A_D} - \mu \tan\beta}{\tilde{m}^2} \frac{1}{c_{d^c} - c_q} \ln\left(\frac{c_{d^c}}{c_q}\right) (\lambda')^{ikl} (\lambda')^{jlk} \hat{m}_{D_k} \hat{m}_{D_l}$$