Minimal Flavour Violation for Leptons

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Introduction

- The SM does not explain : *Dark Matter*, *Baryon Asymmetry*, *Neutrino Masses* and $\Delta T/T$ in the CMB
- Hierarchy problem $\Rightarrow$ New Physics at the TeV scale

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  $\Rightarrow$ we can deduce the existence of a principle of MFV which gives us a predictive framework in which we can work
- Straightforward definition in the quark sector, not so clear in the lepton sector

Outline

The Standard Model

$$\mathscr{L}_{kinetic} = i(\bar{Q}^i \not{D} Q_i + \bar{u}^i_R \not{D} u_{Ri} + \bar{d}^i_R \not{D} d_{Ri} + \bar{L}^i \not{D} L_i + \bar{e}^i_R \not{D} e_{Ri})$$

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$$\mathscr{L}_{yukawa} = \bar{Q}^{i\alpha} (Y_u)^j_i u_{Rj} \tilde{\phi}_\alpha + \bar{Q}^{i\alpha} (Y_d)^j_i d_{Rj} \phi_\alpha + \bar{L}^{i\alpha} (Y_e)^j_i e_{Rj} \phi_\alpha + \text{h.c.}$$

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- The Yukawa couplings break the global flavour symmetry :

$$U(3)^5 \to U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$

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In the quark sector :

- Two "symmetry breaking" operators in the Q space : $Y_u Y_u^\dagger$ and $Y_d Y_d^\dagger$

  $\Rightarrow$ *FV processes* and *CP violation* (mediated by the CKM matrix and confirmed by experiments)

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In the lepton sector :

- Only one "symmetry breaking" operator per vector space : $Y_e Y_e^\dagger$ in the L space and $Y_e^\dagger Y_e$ in the e_R space

  $\Rightarrow$ *No neutrino oscillations* and *no FV processes*

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Flavour violating processes $\Rightarrow$ constraints on New Physics

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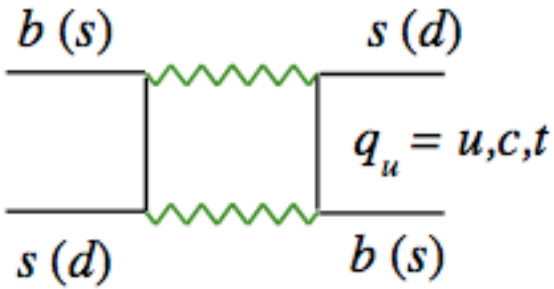

$$M(B_d - \bar{B}_d) \sim c_{SM} \frac{y_y V_{tb}^* V_{td}}{16\pi^2 M_W^2} + c_{new} \frac{1}{\Lambda^2}$$

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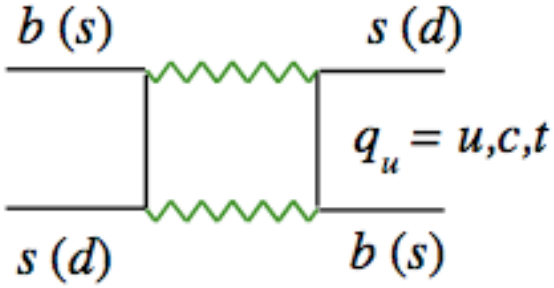

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- If $c_{new} \sim c_{SM} \sim 1$:

$\Rightarrow \Lambda_{NP} > 10^4 \text{TeV}$ for $O^6 \sim (\bar{s}d)^2$, for $K^0 - \bar{K}^0$ mixing

$\Rightarrow \Lambda_{NP} > 10^3 \text{TeV}$ for $O^6 \sim (\bar{b}d)^2$, for $B^0 - \bar{B}^0$ mixing

Minimal Flavour Violation

Two possible deductions :

- The new d.o.f. involving flavour appear at very high energy $\Rightarrow$ hierarchy problem unsolved
- Principle in the flavour sector $\Rightarrow$ Minimal Flavour Violation

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The Yukawa couplings are the only source of quark flavour symmetry breaking

$\Rightarrow$ Flavour change and CP-violation in the quark sector are proportional to the CKM matrix and to the Yukawa couplings

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- Predictive framework that encompasses many models

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The lepton sector

Lepton sector differs sensibly :

- Not so well tested :
  - Neutrinos are weakly interacting
  - Two different mass scales : charged lepton masses and neutrino mass scale ($m_{atm} << m_{\tau}$)

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- Not so well tested :
  - Neutrinos are weakly interacting
  - Two different mass scales : charged lepton masses and neutrino mass scale ($m_{atm} << m_{\tau}$)
- New physics exists in this sector :
  - Neutrino oscillations have been observed
  - Are consistent with small mass differences

$\Rightarrow$ Standard Model lepton sector must be extended

Lepton flavour processes

Oscillations tell us that :

- A new operator exists : $[m_\nu]$ neutrino mass matrix
- There is neutrino mixing (U_{MNS} matrix) $\Leftrightarrow$ $[m_\nu]$ and Y_e are not simultaneously diagonalized in the L space

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Strongest upper bound :

$$\mathrm{BR}(\mu \to e\gamma) < 1.2 \times 10^{-11}$$

Physics at TeV scale again strongly constrained $\Rightarrow$ MFV for Leptons ?

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At present, observations do not tell us :

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Dirac neutrinos :

- We add the Yukawa coupling Y_ν, so right-handed neutrinos ν_R
  $\Rightarrow$ extended flavour symmetry group :

$$\mathscr{G}_{flavour} = U(3)^5 \times U(3)_{\nu_R}$$

- Two basis choosing operators, Y_ν and Y_e, in the L space :

$$U(3)^3_Q \rightarrow U(1)_B \qquad U(3)^3_L \rightarrow U(1)_L$$

- Flavour violating processes are controlled by the U_{MNS} mixing matrix

Same flavour structure of quarks $\Rightarrow$ same definition of MFV

Lepton flavour group

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Majorana neutrinos (case 1) :

- Enlarged flavour symmetry :

  $\Rightarrow$ Lagrangian gauge term has a global $U(3)^6$ symmetry

- New particles unobserved should be heavy or weakly coupled

- Usual example : See-saw model

$$\mathscr{L} = \mathscr{L}_{SM} + \bar{L}^{i\alpha}(Y_\nu)^j_i \nu_{Rj}\tilde{\phi}_\alpha + \tfrac{1}{2}\bar{\nu^c}_{Ri} M_{ij} \nu_{Rj} + \text{h.c.}$$

Flavour violating processes not necessarily controlled by the U_{MNS} mixing matrix

Lepton flavour group

At present, observations do not tell us :

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Majorana neutrinos (case 2) :

- Standard Model flavour symmetry :

  $\Rightarrow$ New flavoured particles live in the 5-dimensional space of the Standard Model

- Neutrino mass matrix is a non-renormalizable operator :

$$(L_j H_u)\mathbf{K}^{jk}(L_k H_u)$$

- Example : m_ν coming from loops in models with R-parity violation

Flavour violating processes not necessarily controlled by the U_{MNS} mixing matrix

Minimal Flavour Violation for Leptons

Different possible definitions of MFV for Leptons

1. Y_e and m_ν are the basis choosing operators in the L space [2]

   $\Rightarrow$ Flavour Violation driven by the U_{MNS} matrix

   - Minimal scenario, so very predictive

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2. MFV as a restriction on *renormalizable* couplings [3] :

New renormalizable interactions can choose only one more basis in the L space

   $\Rightarrow$ FV processes are not necessarily controlled by the U_{MNS} mixing matrix

   - Extensive definition which includes many models

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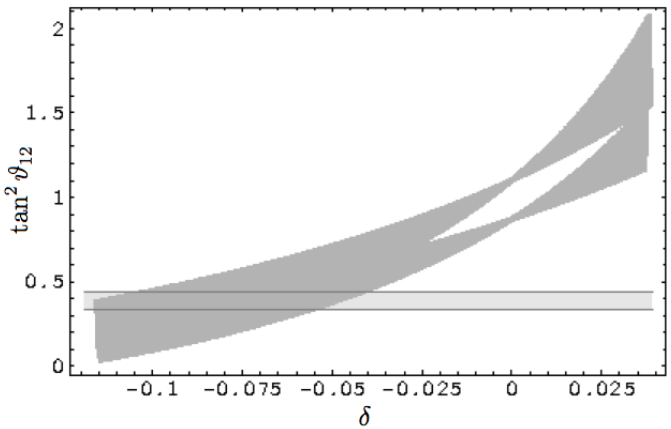
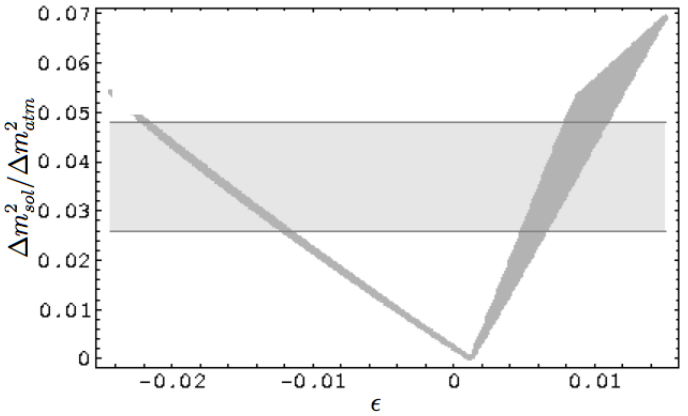
Example : Neutrino masses generated by the λ couplings

- We consider supersymmetry with R-parity violation :

$$\mathscr{W}_{\not R_p} = \lambda LLE^c + \lambda' LQD^c + \lambda'' U^c D^c D^c$$

- MFV constraints :
  - One more basis allowed in the L space
  - No more bases for Q, u_R, d_R, e_R spaces
- The inverse hierarchy is obtained
- λ couplings in the L space are not diagonal in the neutrino mass basis
  $\Rightarrow$ Flavour violation, also at tree level
  - Estimate on $\mu \longrightarrow e\gamma$ decay branching ratio $\sim 10^{-13}$





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  - Different neutrino mass generating mechanisms are allowed
  - Upper bounds on FV processes in the lepton sector

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$\Rightarrow$ Not obvious how to define MFV for Leptons

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- A definition of MFV for Leptons recently proposed implied FV processes controlled by the U_{MNS} matrix
- We have explored the possibility of defining a MFV for Leptons such that FV processes are not necessarily determined by the U_{MNS} matrix