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Minimal Flavor Violation, Seesaw, and R-parity

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Based on: E. Nikolidakis, C.S., arXiv:0710.3129

- Outline

A - Motivations for the MFV hypothesis

B - MFV: spurions and expansions

C - Phenomenological consequences

D - Conclusion and perspectives

Motivations for MFV

- MSSM flavor-related puzzles

Flavor-symmetry: three generations of quarks and leptons with identical gauge interactions → Invariance under:

Chivukula,Georgi '87

$$G_f = U(3)^5 = \underbrace{SU(3)_Q \times SU(3)_U \times SU(3)_D}_{G_q} \times \underbrace{SU(3)_L \times SU(3)_E}_{G_\ell} \times G_1$$

$$Q \overset{G_f}{\to} g_Q Q,\quad U \overset{G_f}{\to} U g_U^\dagger,\quad D \overset{G_f}{\to} D g_D^\dagger,\quad L \overset{G_f}{\to} g_L L,\quad E \overset{G_f}{\to} E g_E^\dagger$$

1. Superpotential Yukawa couplings: sets flavored-fermion masses and mixings:

$$\mathcal{W}_{RPC} = U^I \mathbf{Y}_u^{IJ} (Q^J H_u) - D^I \mathbf{Y}_d^{IJ} (Q^J H_d) - E^I \mathbf{Y}_\ell^{IJ} (L^J H_d) + \mu (H_u H_d)$$

2. Seesaw and neutrino masses: In the MSSM, no ν_R and ν_L massless.

Seesaw from heavy right-handed neutrinos: $\mathcal{W}_N = N^I \mathbf{M}^{IJ} N^J + N^I \mathbf{Y}_\nu^{IJ} (L^J H_u)$

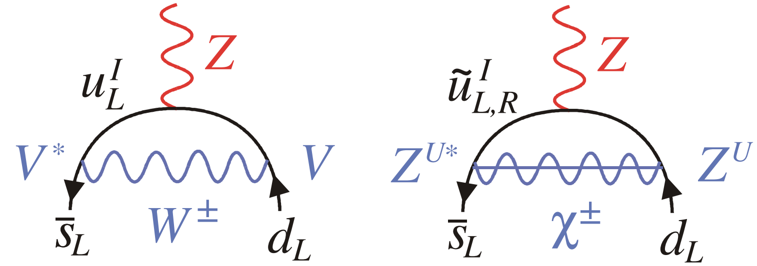
$$\to (\mathbf{Y}_\nu^T \mathbf{M}^{-1} \mathbf{Y}_\nu)^{IJ} (L^I H_u)(L^J H_u) \to v_u^2 \nu_L^I (\mathbf{Y}_\nu^T \mathbf{M}^{-1} \mathbf{Y}_\nu)^{IJ} \nu_L^J$$

Minkowski '77, Gell-Mann,Ramond,Slansky '79, Yanagida '79, Glashow '79,...

3. Squark misalignment and FCNC due to soft SUSY-breaking terms:

$$\mathcal{L}_{soft}^{RPC} \ni -\tilde{Q}^{\dagger}\mathbf{m}_{Q}^{2}\tilde{Q} - \tilde{U}\mathbf{m}_{U}^{2}\tilde{U}^{\dagger} - \tilde{D}\mathbf{m}_{D}^{2}\tilde{D}^{\dagger} - \tilde{U}\mathbf{A}_{u}(\tilde{Q}H_{u}) + \tilde{D}\mathbf{A}_{d}(\tilde{Q}H_{d}) + \ldots$$

Constraints: $\Delta M_{Bs,Bd}, b \to s\gamma, B \to \psi K,$
$B_{s,d} \to \ell^{+}\ell^{-}, B \to X\ell^{+}\ell^{-}, \varepsilon_{K}, K \to \pi\nu\bar{\nu}, \ldots$

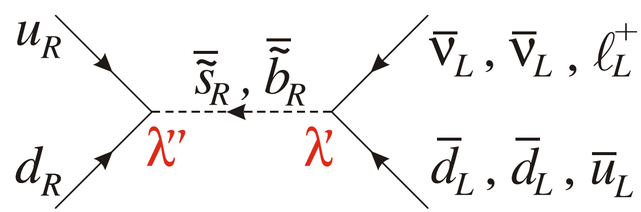


MFV to enforce sufficient alignment.

Hall,Randall '90, D'Ambrosio,Giudice,Isidori,Strumia '02

4. R-parity and proton decay: $\tau_{p^+} > 10^{30}\ years \Rightarrow |\lambda'\lambda''| \leq 10^{-27}$?

$$\mathcal{W}_{RPV} = \lambda^{IJK}(L^I L^J)E^K + \lambda'^{IJK}(L^I Q^J)D^K + \lambda''^{IJK}U^I D^J D^K + \mu'^I(L^I H_d)$$



Forbidden by R-parity → sparticle pair production, LSP and dark matter,...

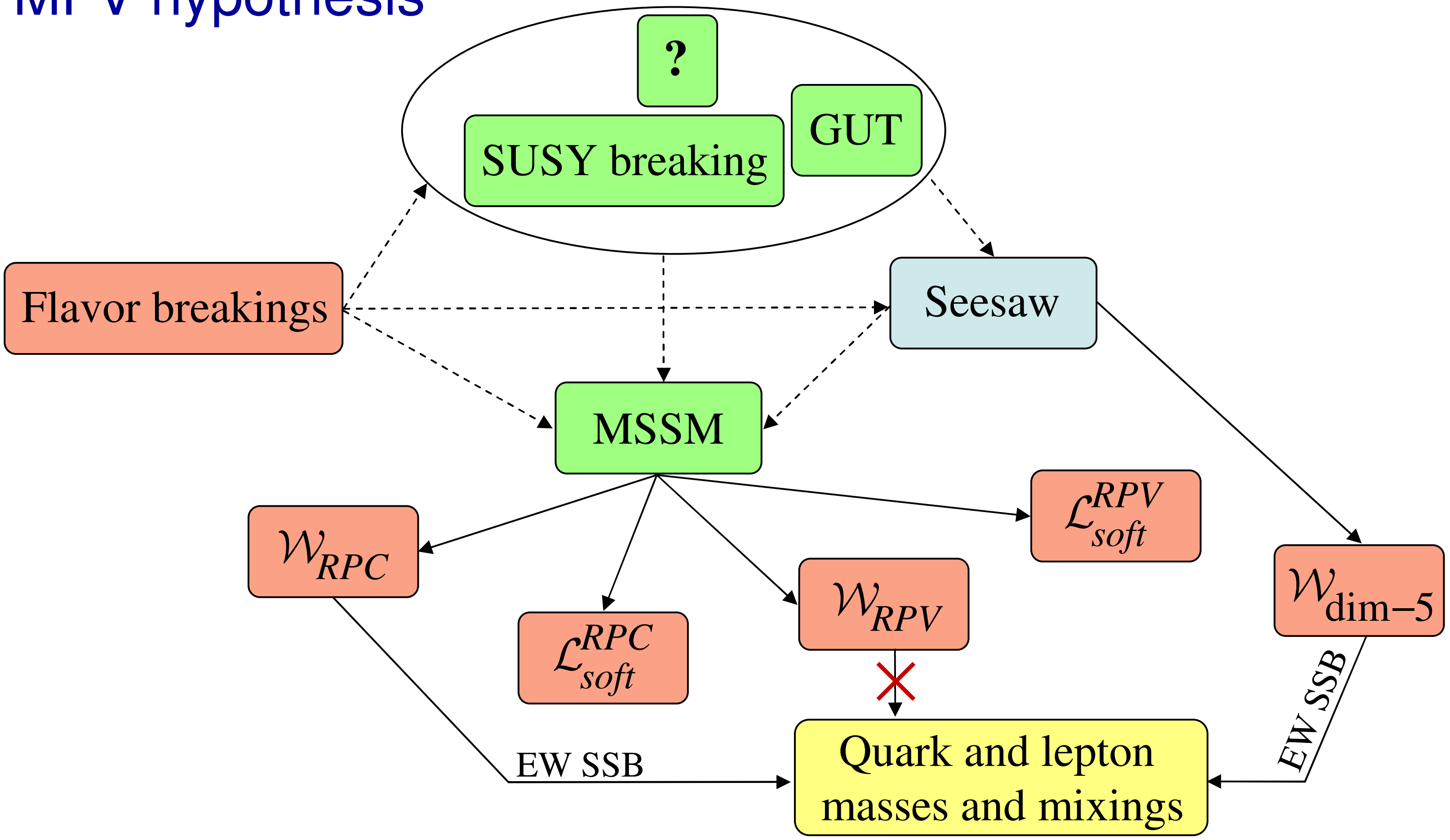
Farrar,Fayet '78

But RPV couplings are flavor-breaking:

If MFV is enforced, what are their "natural" size?

Can MFV replace R-parity as the origin of proton stability?

- MFV hypothesis



Assume: - Simple (though unknown) origin for the flavor symmetry breaking.
- Percolates down to the lowest level → Relations between flavor-breakings.

Bottom-up approach: start from the experimentally known flavor-structures.
Symmetry principle: elementary sources of flavor-breaking treated as spurions.

MFV spurions and expansions

• Construction of the MFV expansions

Spurions and invariance: Out of a *minimal set of spurions*, i.e. breakings in definite directions in flavor-space, parametrize all the *MSSM flavor-breaking couplings as formally invariant under* G_f, up to some *flavor* $U(1)$'s which are a priori broken.

Hall,Randall '90, D'Ambrosio,Giudice,Isidori,Strumia '02, Cirigliano,Grinstein,Isidori,Wise '05

1. Which spurions to choose? Minimal set able to induce known masses & mixings:

$SU(3)_{Q,U,D} \otimes SU(3)_{L,E}$	Aligned with:	Background value:
$(\bar{3},3,1) \otimes (1,1)$	$\rightarrow \mathrm{Y}_u$	$= \frac{1}{v_u} \mathrm{m}_u \cdot V_{CKM}$
$(\bar{3},1,3) \otimes (1,1)$	$\rightarrow \mathrm{Y}_d$	$= \frac{1}{v_u} \mathrm{m}_d \tan\beta$
$(1,1,1) \otimes (\bar{3},3)$	$\rightarrow \mathrm{Y}_\ell$	$= \frac{1}{v_u} \mathrm{m}_\ell \tan\beta$
$(1,1,1) \otimes (\bar{6},1)$	$\rightarrow \Upsilon_\nu \equiv v_u \mathrm{Y}_\nu^T \mathrm{M}^{-1} \mathrm{Y}_\nu$	$= \frac{1}{v_u} U_{PMNS}^* \cdot \mathrm{m}_\nu \cdot U_{PMNS}^\dagger$
$(1,1,1) \otimes (8,1)$	$\rightarrow \mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu$	$= \frac{1}{v_u} M_R \Upsilon_\nu$ (CP-limit)

Up to $O(1)$ redefinitions, spurions and Yukawa couplings are aligned.

Chosen such that the $\mathcal{W}$ terms $U\mathrm{Y}_u Q,\ D\mathrm{Y}_d Q,\ E\mathrm{Y}_\ell L,\ L^T \Upsilon_\nu L$ are invariant.

For simplicity, $\mathrm{M} \equiv M_R \mathbf{1}$ with the seesaw scale $M_R \sim 10^{12-14}\,\mathrm{GeV}$.

2. Invariants: contract spurions and fields using the invariant tensors δ^{IJ}, ε^{IJK}

$$Q^{\dagger I}(\mathrm{m}_Q^2)^{IJ}Q^J \;\Rightarrow\; \mathrm{m}_Q^2 \xrightarrow{G_f} g_Q \mathrm{m}_Q^2 g_Q^\dagger \;\Rightarrow\; \mathrm{m}_Q^2 = m_0^2(a_0 1 + a_1 \mathrm{Y}_u^\dagger \mathrm{Y}_u + a_2 \mathrm{Y}_d^\dagger \mathrm{Y}_d + \ldots)$$

→ The CKM matrix still tunes flavor-mixing in the quark sector.

Sometimes large (but always *finite*!) number of possible terms.

(*Cayley-Hamilton matrix identities* + *Third generation dominance for* u,d,ℓ)

$$\mathrm{m}_Q^2 = m_0^2[\mathrm{R}_q]_{h.c.}, \quad \mathrm{R}_q = 1,\ \mathrm{Y}_u^\dagger\mathrm{Y}_u,\ \mathrm{Y}_d^\dagger\mathrm{Y}_d,\ \mathrm{Y}_u^\dagger\mathrm{Y}_u\mathrm{Y}_d^\dagger\mathrm{Y}_d,\ \mathrm{Y}_d^\dagger\mathrm{Y}_d\mathrm{Y}_u^\dagger\mathrm{Y}_u \sim \mathbf{8}_Q$$

Similar for leptons, with nine terms for $\mathrm{R}_\ell \sim \mathbf{8}_L$

→ Useful for LFV effects. *Borzumati,Masiero '86*

3. At least one ε*-tensor for RPV terms* → invariance only under $G_q \times G_\ell = SU(3)^5$

$$\lambda''^{IJK} = \varepsilon^{LJK}(\mathrm{Y}_u\mathrm{Y}_d^\dagger)^{IL} \qquad \Rightarrow \lambda''^{IJK}U^I D^J D^K \to \det(g_D^\dagger)\lambda''^{IJK}U^I D^J D^K$$

$$\lambda''^{IJK} = \varepsilon^{IMN}(\mathrm{Y}_d\mathrm{Y}_u^\dagger)^{JM}(\mathrm{Y}_d\mathrm{Y}_u^\dagger)^{KN} \qquad \Rightarrow \lambda''^{IJK}U^I D^J D^K \to \det(g_U^\dagger)\lambda''^{IJK}U^I D^J D^K$$

$$\lambda''^{IJK} = \varepsilon^{LMN}\mathrm{Y}_u^{IL}\mathrm{Y}_d^{JM}\mathrm{Y}_d^{KN} \qquad \Rightarrow \lambda''^{IJK}U^I D^J D^K \to \det(g_Q^\dagger)\lambda''^{IJK}U^I D^J D^K$$

Flavor-directions in which baryon and lepton-numbers are violated are free.
In other words: some $U(1)$'s can still be enforced (but not the five of them).

RPV structures ($\mathcal{W}_{RPV} = \mu' L H_d + \lambda LLE + \lambda' LQD + \lambda'' UDD$)		Scaling	Breaking
$\mu_1'^I$	$\mu \bar{\Upsilon}_\nu^I, \quad \bar{\Upsilon}_\nu^I \equiv \varepsilon^{QMJ} (\mathrm{R}_\ell \Upsilon_\nu^\dagger \mathrm{R}_\ell^T)^{QM} \mathrm{R}_\ell^{JI}$	$\tan^2\beta$	$U(1)_L$
λ_1^{IJK}	$\bar{\Upsilon}_\nu^I (\mathrm{Y}_\ell \mathrm{R}_\ell)^{KJ}$	$\tan^3\beta$	$U(1)_L$
λ_2^{IJK}	$\varepsilon^{LMN} \mathrm{R}_\ell^{LI} (\mathrm{Y}_\ell \mathrm{R}_\ell \Upsilon_\nu^\dagger \mathrm{R}_\ell^T)^{KM} \mathrm{R}_\ell^{NJ}$	$\tan\beta$	$U(1)_L$
λ_3^{IJK}	$\bar{\Upsilon}_\nu^I \varepsilon^{LMN} \varepsilon^{ABC} \mathrm{R}_e^{KA} (\mathrm{R}_\ell \mathrm{Y}_\ell^\dagger)^{LB} (\mathrm{R}_\ell \mathrm{Y}_\ell^\dagger)^{MC} \mathrm{R}_\ell^{NJ}, \ldots$	$\tan^4\beta$	$U(1)_{L,E}$
$\lambda_1'^{IJK}$	$\bar{\Upsilon}_\nu^I (\mathrm{Y}_d \mathrm{R}_q)^{KJ}$	$\tan^3\beta$	$U(1)_L$
$\lambda_2'^{IJK}$	$\bar{\Upsilon}_\nu^I \varepsilon^{LMN} \varepsilon^{ABC} \mathrm{R}_d^{KA} (\mathrm{R}_q \mathrm{Y}_d^\dagger)^{LB} (\mathrm{R}_q \mathrm{Y}_d^\dagger)^{MC} \mathrm{R}_q^{NJ}$	$\tan^4\beta$	$U(1)_{L,D,Q}$
$\lambda_1''^{IJK}$	$\varepsilon^{LMN} (\mathrm{Y}_u \mathrm{R}_q \mathrm{Y}_d^\dagger)^{IL} \mathrm{R}_d^{JM} \mathrm{R}_d^{KN}$	$\tan\beta$	$U(1)_D$
$\lambda_2''^{IJK}$	$\varepsilon^{LMN} \mathrm{R}_u^{IL} (\mathrm{Y}_d \mathrm{R}_q \mathrm{Y}_u^\dagger)^{JM} (\mathrm{Y}_d \mathrm{R}_q \mathrm{Y}_u^\dagger)^{KN}$	$\tan^2\beta$	$U(1)_U$
$\lambda_3''^{IJK}$	$\varepsilon^{LMN} (\mathrm{Y}_u \mathrm{R}_q)^{IL} (\mathrm{Y}_d \mathrm{R}_q)^{JM} (\mathrm{Y}_d \mathrm{R}_q)^{KN}$	$\tan^2\beta$	$U(1)_Q$
$\lambda_4''^{IJK}$	$\varepsilon^{LMN} \varepsilon^{ABC} \varepsilon^{DEF} (\mathrm{R}_q \mathrm{Y}_d^\dagger)^{LD} (\mathrm{R}_q \mathrm{Y}_u^\dagger)^{MA} (\mathrm{R}_q \mathrm{Y}_u^\dagger)^{NB} \mathrm{R}_u^{IC} \mathrm{R}_d^{JE} \mathrm{R}_d^{KF}$	$\tan\beta$	$U(1)_{Q,U,D}$

Only the minimal set of spurions is needed!

Spurion $\Upsilon_\nu \sim (\bar{6}, 1)_{G_\ell}$ needed for $\Delta L = 1$ couplings → suppressed by neutrino masses.

→ $\Delta L = 1$ forbidden when $m_\nu = 0$.

RPV structures ($\mathcal{W}_{RPV} = \mu' LH_d + \lambda LLE + \lambda' LQD + \lambda'' UDD$)		Scaling	Breaking
$\mu_1'^I$	$\mu \overline{\Upsilon}_\nu^I, \quad \overline{\Upsilon}_\nu^I \equiv \varepsilon^{QMJ} (\mathrm{R}_\ell \Upsilon_\nu^\dagger \mathrm{R}_\ell^T)^{QM} \mathrm{R}_\ell^{JI}$	$\tan^2\beta$	$U(1)_L$
λ_1^{IJK}	$\overline{\Upsilon}_\nu^I (\mathrm{Y}_\ell \mathrm{R}_\ell)^{KJ}$	$\tan^3\beta$	$U(1)_L$
λ_2^{IJK}	$\varepsilon^{LMN} \mathrm{R}_\ell^{LI} (\mathrm{Y}_\ell \mathrm{R}_\ell \Upsilon_\nu^\dagger \mathrm{R}_\ell^T)^{KM} \mathrm{R}_\ell^{NJ}$	$\tan\beta$	$U(1)_L$
λ_3^{IJK}	$\overline{\Upsilon}_\nu^I \varepsilon^{LMN} \varepsilon^{ABC} \mathrm{R}_e^{KA} (\mathrm{R}_\ell \mathrm{Y}_\ell^\dagger)^{LB} (\mathrm{R}_\ell \mathrm{Y}_\ell^\dagger)^{MC} \mathrm{R}_\ell^{NJ}, \ldots$	$\tan^4\beta$	$U(1)_{L,E}$
$\lambda_1'^{IJK}$	$\overline{\Upsilon}_\nu^I (\mathrm{Y}_d \mathrm{R}_q)^{KJ}$	$\tan^3\beta$	$U(1)_L$
$\lambda_2'^{IJK}$	$\overline{\Upsilon}_\nu^I \varepsilon^{LMN} \varepsilon^{ABC} \mathrm{R}_d^{KA} (\mathrm{R}_q \mathrm{Y}_d^\dagger)^{LB} (\mathrm{R}_q \mathrm{Y}_d^\dagger)^{MC} \mathrm{R}_q^{NJ}$	$\tan^4\beta$	$U(1)_{L,D,Q}$
$\lambda_1''^{IJK}$	$\varepsilon^{LMN} (\mathrm{Y}_u \mathrm{R}_q \mathrm{Y}_d^\dagger)^{IL} \mathrm{R}_d^{JM} \mathrm{R}_d^{KN}$	$\tan\beta$	$U(1)_D$
$\lambda_2''^{IJK}$	$\varepsilon^{LMN} \mathrm{R}_u^{IL} (\mathrm{Y}_d \mathrm{R}_q \mathrm{Y}_u^\dagger)^{JM} (\mathrm{Y}_d \mathrm{R}_q \mathrm{Y}_u^\dagger)^{KN}$	$\tan^2\beta$	$U(1)_U$
$\lambda_3''^{IJK}$	$\varepsilon^{LMN} (\mathrm{Y}_u \mathrm{R}_q)^{IL} (\mathrm{Y}_d \mathrm{R}_q)^{JM} (\mathrm{Y}_d \mathrm{R}_q)^{KN}$	$\tan^2\beta$	$U(1)_Q$
$\lambda_4''^{IJK}$	$\varepsilon^{LMN} \varepsilon^{ABC} \varepsilon^{DEF} (\mathrm{R}_q \mathrm{Y}_d^\dagger)^{LD} (\mathrm{R}_q \mathrm{Y}_u^\dagger)^{MA} (\mathrm{R}_q \mathrm{Y}_u^\dagger)^{NB} \mathrm{R}_u^{IC} \mathrm{R}_d^{JE} \mathrm{R}_d^{KF}$	$\tan\beta$	$U(1)_{Q,U,D}$

- All $\Delta L = 1$ couplings further suppressed by lepton-mass factors (Υ_ν symmetric).

$$\varepsilon^{QMI} (\Upsilon_\nu^\dagger)^{QM} \equiv 0 \quad \Rightarrow \quad \overline{\Upsilon}_\nu^I = \varepsilon^{QMI} (\mathrm{Y}_\ell^\dagger \mathrm{Y}_\ell \Upsilon_\nu^\dagger)^{QM} + \ldots$$

- All couplings scale at least linearly with $\tan\beta$.

RPV structures ($\mathcal{W}_{RPV} = \mu' L H_d + \lambda LLE + \lambda' LQD + \lambda'' UDD$)		Scaling	Breaking
$\mu_1'^I$	$\mu \bar{\Upsilon}_\nu^I, \quad \bar{\Upsilon}_\nu^I \equiv \varepsilon^{QMJ} (\mathrm{R}_\ell \Upsilon_\nu^\dagger \mathrm{R}_\ell^T)^{QM} \mathrm{R}_\ell^{JI}$	$\tan^2\beta$	$U(1)_L$
λ_1^{IJK}	$\bar{\Upsilon}_\nu^I (\mathrm{Y}_\ell \mathrm{R}_\ell)^{KJ}$	$\tan^3\beta$	$U(1)_L$
λ_2^{IJK}	$\varepsilon^{LMN} \mathrm{R}_\ell^{LI} (\mathrm{Y}_\ell \mathrm{R}_\ell \Upsilon_\nu^\dagger \mathrm{R}_\ell^T)^{KM} \mathrm{R}_\ell^{NJ}$	$\tan\beta$	$U(1)_L$
λ_3^{IJK}	$\bar{\Upsilon}_\nu^I \varepsilon^{LMN} \varepsilon^{ABC} \mathrm{R}_e^{KA} (\mathrm{R}_\ell \mathrm{Y}_\ell^\dagger)^{LB} (\mathrm{R}_\ell \mathrm{Y}_\ell^\dagger)^{MC} \mathrm{R}_\ell^{NJ}, \ldots$	$\tan^4\beta$	$U(1)_{L,E}$
$\lambda_1'^{IJK}$	$\bar{\Upsilon}_\nu^I (\mathrm{Y}_d \mathrm{R}_q)^{KJ}$	$\tan^3\beta$	$U(1)_L$
$\lambda_2'^{IJK}$	$\bar{\Upsilon}_\nu^I \varepsilon^{LMN} \varepsilon^{ABC} \mathrm{R}_d^{KA} (\mathrm{R}_q \mathrm{Y}_d^\dagger)^{LB} (\mathrm{R}_q \mathrm{Y}_d^\dagger)^{MC} \mathrm{R}_q^{NJ}$	$\tan^4\beta$	$U(1)_{L,D,Q}$
$\lambda_1''^{IJK}$	$\varepsilon^{LMN} (\mathrm{Y}_u \mathrm{R}_q \mathrm{Y}_d^\dagger)^{IL} \mathrm{R}_d^{JM} \mathrm{R}_d^{KN}$	$\tan\beta$	$U(1)_D$
$\lambda_2''^{IJK}$	$\varepsilon^{LMN} \mathrm{R}_u^{IL} (\mathrm{Y}_d \mathrm{R}_q \mathrm{Y}_u^\dagger)^{JM} (\mathrm{Y}_d \mathrm{R}_q \mathrm{Y}_u^\dagger)^{KN}$	$\tan^2\beta$	$U(1)_U$
$\lambda_3''^{IJK}$	$\varepsilon^{LMN} (\mathrm{Y}_u \mathrm{R}_q)^{IL} (\mathrm{Y}_d \mathrm{R}_q)^{JM} (\mathrm{Y}_d \mathrm{R}_q)^{KN}$	$\tan^2\beta$	$U(1)_Q$
$\lambda_4''^{IJK}$	$\varepsilon^{LMN} \varepsilon^{ABC} \varepsilon^{DEF} (\mathrm{R}_q \mathrm{Y}_d^\dagger)^{LD} (\mathrm{R}_q \mathrm{Y}_u^\dagger)^{MA} (\mathrm{R}_q \mathrm{Y}_u^\dagger)^{NB} \mathrm{R}_u^{IC} \mathrm{R}_d^{JE} \mathrm{R}_d^{KF}$	$\tan\beta$	$U(1)_{Q,U,D}$

- If some $U(1)$'s are imposed, some terms get suppressed by $\det(\mathrm{Y}_{u,d,\ell})$ factors.
- Similar expansions for RPV soft-breaking terms (up to their normalization).
- Basis-independence (near-alignment): $\langle \tilde{\nu}^I \rangle \sim v_d \bar{\Upsilon}_\nu^I$ and $\delta m_\nu \sim O(m_\nu^2)$.

Phenomenological consequences

- Bounds on RPV couplings

Antisymmetry and suppression: Besides the proportionality to *neutrino masses*, the antisymmetric ε-tensors imply that all RPV couplings are proportional to *light-fermion masses*, hence significantly suppressed.

1. All bounds from $\Delta L = 1$, $\Delta B = 0$ processes easily passed: $\mu', \lambda, \lambda' < O(10^{-12})$.

2. Bounds from $\Delta B = 1$ nucleon decays: $p, n \to \pi\nu, \pi\ell, K\nu, K\ell, \ldots$

Leading-order: *constraining bounds* on various combinations $|(\mu', \lambda, \lambda') \times \lambda''|$.

Loop-level: automatic, for example $|\lambda'_{IJK}\lambda''_{I'J'K'}| < O(10^{-9} - 10^{-11})$.

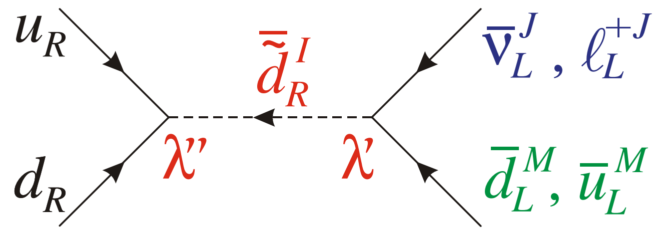
3. Direct bounds on λ'' from neutron oscillations:

Leading-order (very approximative): $|\lambda''_{11I}| < (10^{-8} - 10^{-7})(\tilde{m}/100\,\text{GeV})^{5/2}$.

Loop-level (not very constraining): $|\lambda''_{312}| < [10^{-3}, 10^{-2}]$ for $\tilde{m}_q \sim [100, 200]\,\text{GeV}$.

For a review of the bounds, see e.g. Barbier et al. '05

4. Example:



$$\Rightarrow \left|\lambda'_{JMI}\lambda''^{*}_{11I}\right| < 10^{-27}(m[\tilde{d}_R^I]/100\,GeV)^2$$

Suppose the leading operators are:

$$\lambda'^{IJK} = \varepsilon^{LMI}(\mathrm{Y}_\ell^\dagger \mathrm{Y}_\ell \Upsilon_\nu^\dagger)^{LM}(\mathrm{Y}_d \mathrm{Y}_u^\dagger \mathrm{Y}_u)^{KJ}$$

$$\lambda''^{IJK} = a_1\varepsilon^{LJK}(\mathrm{Y}_u \mathrm{Y}_d^\dagger)^{IL} + a_2\varepsilon^{LMN}\mathrm{Y}_u^{IL}\mathrm{Y}_d^{JM}\mathrm{Y}_d^{KN}$$

The MFV prediction is then (for $m_\nu = 0, \theta_{13} \approx 0, \theta_{atm} \approx 45^\circ$):

$$\left|\lambda'_{JMI}\lambda''^{*}_{11I}\right| \approx \frac{\Delta m_{31}^\nu}{v_u}\frac{\lambda^3 m_\tau^2 m_b m_t^2 m_u}{v_d^3 v_u^3}\left(a_1\frac{9m_s}{v_d} + a_2\frac{m_d m_b}{v_d^2}\right) \approx a_1 10^{-27}\tan^4\beta + a_2 10^{-31}\tan^5\beta$$

- m_ν : Δm_{31}^ν grows with smaller m_ν → light neutrinos slightly disfavored.
- M_R : Softens the hierarchy $\left|\lambda'_{1MI}\lambda''^{*}_{11I}\right| >> \left|\lambda'_{2MI}\lambda''^{*}_{11I}\right| >> \left|\lambda'_{3MI}\lambda''^{*}_{11I}\right|$,
  Sets an upper bound on m_ν such that $\mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu < 1$.

} Small LFV effect?

- Small to moderate $\tan\beta$ preferred → Suppressed Higgs FCNC?

- $U(1)$'s: $SU(3)^5 \times U(1)_D : \left|\lambda'_{JMI}\lambda''^{*}_{11I}\right| \approx (\det(\mathrm{Y}_d)a_1 10^{-27}\tan^4\beta) + a_2 10^{-31}\tan^5\beta$

  $SU(3)^5 \times U(1)_L : \left|\lambda'_{JMI}\lambda''^{*}_{11I}\right| \approx \det(\mathrm{Y}_\ell)(a_1 10^{-27}\tan^4\beta + a_2 10^{-31}\tan^5\beta)$

• Consequences

1. MFV can naturally account for the very long proton lifetime.

Conservative: - MFV coefficients of $O(1)$, while $O(\lambda)$ or $O(g^2/4\pi)$ also natural,
- No GIM-like interferences, no cancellations among mechanisms.

For experiments: proton decay could be very close to current bounds.

2. Apart for proton decay, lepton-number effectively conserved ($\mu', \lambda, \lambda' < O(10^{-12})$).

3. MFV predictions for the baryonic couplings $\lambda''^{IJK} U^I D^J D^K$*:*

Structure	λ''_1	λ''_2	λ''_3	$\lambda''_{4,5}$
Broken $U(1)$	$U(1)_D$	$U(1)_U$	$U(1)_Q$	$U(1)_{U,D,Q}$
$\tan\beta = 5$	$\begin{pmatrix} 8 & 8 & 8 \\ 4 & 6 & 5 \\ 1 & 6 & 4 \end{pmatrix}$	$\begin{pmatrix} 11 & 6 & 7 \\ 12 & 9 & 9 \\ 13 & 12 & 13 \end{pmatrix}$	$\begin{pmatrix} 13 & 8 & 10 \\ 10 & 6 & 7 \\ 6 & 5 & 6 \end{pmatrix}$	$\begin{pmatrix} 5 & 5 & 5 \\ 7 & 9 & 7 \\ 7 & 12 & 10 \end{pmatrix}$
$\tan\beta = 50$	$\begin{pmatrix} 7 & 7 & 7 \\ 3 & 5 & 4 \\ 0 & 5 & 3 \end{pmatrix}$	$\begin{pmatrix} 9 & 4 & 5 \\ 10 & 7 & 7 \\ 11 & 10 & 11 \end{pmatrix}$	$\begin{pmatrix} 11 & 6 & 8 \\ 8 & 4 & 5 \\ 4 & 3 & 4 \end{pmatrix}$	$\begin{pmatrix} 4 & 4 & 4 \\ 6 & 8 & 6 \\ 6 & 11 & 9 \end{pmatrix}$

Notation:
$x \equiv O(10^{-x})$
$X^{IJ} \equiv \lambda''^{I(JK)}$,
$(JK) = 12, 23, 31$

4. $\Delta B = 1$ effects at low-energy: squarks as di-quark currents

Largest for the stop exchange, when $\tan\beta$ not large so that $U(1)_D$ can be broken.

$$\left|\lambda''_{312}\lambda''^{*}_{331}\right| \sim 10^{-4} - 10^{-5}, \; \left|\lambda''_{312}\lambda''^{*}_{323}\right| \sim 10^{-5} - 10^{-6}$$

But, typically small w.r.t. SM contributions, and challenging hadronic uncertainties.

5. $\Delta B = 1$ effects at colliders: RPV implies drastic changes for the phenomenology

Accessibility of the signals strongly depends on $\left|\lambda''_{312}\right| \sim 10^{-1} - 10^{-5}$

- *LSP decays*, maybe in the detector, and needs not be colorless and neutral.
- *Single stop* resonant production $pp \to \tilde{t}$, single gluino production $\tilde{t} \to t\tilde{g}$.
- *Top production* from down squark decay $(\tilde{d}, \tilde{s}, \tilde{b}) \to t + (d, s, b)$.
- …

Conclusion and perspectives

The MFV hypothesis under the $U(3)^5$ MSSM flavor-group simultaneously:

- accounts for FCNC suppression (squark-quark alignment)
- suppresses the proton decay width down to acceptable levels.

The *very long proton lifetime* is then seen a direct consequence of:

- Hierarchy in the fermion masses and CKM matrix,
- Smallness of the neutrino masses.

MSSM R-parity looses its main appeal (already undermined by dim-5 ops.)
But, may have to be replaced by some flavor U(1)'s.

Some consequences:

- Indirect constraints on m_ν, $\tan\beta$, and the seesaw scale (for *FCNC* and *LFV*),
- *Proton decay* presumably close to its current experimental bounds,
- *Colliders*: MFV can tell us where to expect significant SUSY signals.
  In particular: single stop production or top production.

Possible extensions and improvements

1. More precise analysis of the bounds, including GIM-like cancellations,

- Correlation with the squark mass-spectrum?
- What can be said about the leptonic CP-phases?
- What happens if MFV is imposed at some high-energy scale?

2. Signatures in flavor physics?

3. Signatures at LHC?

} Have already received some attention, but could be re-evaluated given the MFV predictions for the RPV couplings.

(See e.g. the review of Barbier et al. '05)

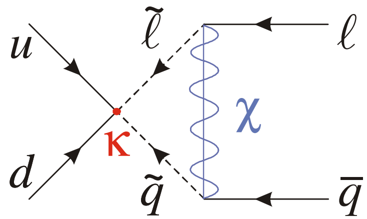
→ Scenarios for specific searches?

4. Other seesaw types: Stability of MFV predictions, at least to a large extent.

Seesaw
→ Majorana mass for ν_L: $\Upsilon_\nu \sim (\bar{6},1)$
→ Other unsuppressed spurions (here $Y_\nu^\dagger Y_\nu \sim (8,1)$)

MFV stability implies that no unsuppressed spurion can transform as $(\bar{6},1)$.

5. Dim-5 RPC operators: MFV separately suppresses $\Delta L = 1$ and $\Delta B = 1$ effects,



$$\mathcal{W}_{\text{dim}-5} \ni \frac{\kappa_1^{IJKL}}{\Lambda_{\Delta L=1}}(Q^I Q^J)(Q^K L^L) + \frac{\kappa_2^{IJKL}}{\Lambda_{\Delta L=1}}(D^I U^J U^K)E^L$$

Ibanez,Ross '92

Loop-level κ_1, κ_2 should be subleading compared to $\lambda \times \lambda''$, $\lambda' \times \lambda''$ contributions.

6. GUT flavor groups: leptons and quarks flavor-groups not necessarily factorized.

Example: $G_f = U(3)_{\bar{5}} \times U(3)_{10}$: $Y_{\bar{5}} \sim (\bar{3}, \bar{3}), Y_{10} \sim (1, \bar{6})$

Cirigliano,Grinstein, Isidori,Wise '05

Seesaw spurions not required for $\mathcal{W}_{RPV} = \Lambda^{IJK} \bar{5}^I \bar{5}^J 10^K + \dots$

But: - Antisymmetric ε-tensors still needed → some suppression remains,

- Flavor-group much smaller, with $U(1)_D \sim U(1)_{\bar{5}}$, $U(1)_{U,E} \sim U(1)_{10}$

→ $\mathcal{W}_{RPV}$ may then only arise after $SU(5)$ is broken.

7. Cosmology

MSSM-LSP not stable → nature of dark matter still to be resolved.

Could the baryon asymmetry be generated from MFV $\Delta B = 1$ couplings?

Backup

Backup 1. Expansions for RPC soft-breaking terms

Cayley-Hamilton: $A^3 - \langle A\rangle A^2 + \frac{1}{2}A(\langle A\rangle^2 - \langle A^2\rangle) - \frac{1}{3}\langle A^3\rangle + \frac{1}{2}\langle A\rangle\langle A^2\rangle - \frac{1}{6}\langle A\rangle^3 = 0$,

Third generation dominance: $(Y^\dagger_{u,d,\ell} Y_{u,d,\ell})^2 = y^2_{t,b,\tau} Y^\dagger_{u,d,\ell} Y_{u,d,\ell}$,

$\Rightarrow$ Octet terms: $R_q = 1, X_u, X_d, X_u X_d, X_d X_u$, $R_{u,d} = 1, Y_{u,d} R_q Y^\dagger_{u,d}$, $R_e = 1, Y_\ell R_\ell Y^\dagger_\ell$,

$(X_i \equiv Y_i^\dagger Y_i)$ $R_\ell = 1,\ X_\ell,\ X_\nu,\ X_\ell X_\nu,\ X_\nu X_\ell,\ X_\nu^2,\ X_\ell X_\nu^2,\ X_\nu^2 X_\ell,\ X_\nu^2 X_\ell X_\nu$,

RPC soft-terms: $m_Q^2 = m_0^2[R_q]_{h.c.},\ m_U^2 = m_0^2[R_u]_{h.c.},\ m_D^2 = m_0^2[R_d]_{h.c.}$,

$$m_L^2 = m_0^2[R_\ell]_{h.c.},\ m_E^2 = m_0^2[R_e]_{h.c.}$$

$$A_u^{IJ} = A_0((Y_u R_q)^{IJ} + \varepsilon^{LMN}\varepsilon^{ABC} R_u^{KA}(R_q Y_u^\dagger)^{LB}(R_q Y_u^\dagger)^{MC} R_q^{NJ})$$

$$A_d^{IJ} = A_0((Y_d R_q)^{IJ} + \varepsilon^{LMN}\varepsilon^{ABC} R_d^{KA}(R_q Y_d^\dagger)^{LB}(R_q Y_d^\dagger)^{MC} R_q^{NJ})$$

$$A_\ell^{IJ} = A_0((Y_\ell R_\ell)^{IJ} + \varepsilon^{LMN}\varepsilon^{ABC} R_e^{KA}(R_\ell Y_\ell^\dagger)^{LB}(R_\ell Y_\ell^\dagger)^{MC} R_\ell^{NJ})$$

- Sum with $O(1)$ MFV coefficents,
- For trilinear terms, the ε-structures are new, though small but for 11 mixings,
- LFV effects tuned by $Y_\nu^\dagger Y_\nu$, and only a finite number of terms. *Borzumati,Masiero '86*
- Suppression of the FCNC's analyzed in *Isidori et al. '06 / Altmannshofer,Buras,Guadagnoli '07*

Backup 2. MFV predictions and bounds on $\Delta B = 1$ nucleon decays

Approximate bounds $(I, J = 1,2,3, M = 1,2)$	I A	I B	I C	II A	II B	II C	III A	III B	III C	IV A	IV B	IV C
$\lvert\lambda'_{JMI}\lambda''^{*}_{11I}, \lambda'_{M1I}\lambda''^{*}_{12I}\rvert < 10^{-27}\,\tilde{d}_R^I$	24	25	28	20	20	23	23	24	27	18	19	22
$\lvert\lambda'_{IJM}\lambda''^{*}_{11J}\rvert < 10^{-27}\,\tilde{d}_L^J(\delta_J^D)^{-1}$	24	28	31	20	23	25	23	27	29	19	21	24
$\lvert\lambda'_{MJ1}\lambda''^{*}_{J12}\rvert < 10^{-26}\,\tilde{u}_L^J(\delta_J^U)^{-1}$	23	29	29	18	23	23	21	27	27	16	22	22
$\lvert\lambda_{212,322}\lambda''^{*}_{112}\rvert < 10^{-20}(\tilde{m}\sim 1\,\mathrm{TeV})$	21	27	30	19	23	26	20	26	28	18	22	25
$\lvert\lambda_{133,323}\lambda''^{*}_{112}\rvert < 10^{-21}(\tilde{m}\sim 1\,\mathrm{TeV})$	20	26	28	18	22	25	19	25	27	17	21	24
$\lvert\lambda''_{112}\mu'_I/\mu\rvert < 10^{-23}\,\tilde{u}_R$	22	27	30	19	23	26	20	26	29	17	21	24
$\lvert\lambda''_{312}\mu'_I/\mu\rvert < 10^{-16}\,\tilde{d}_R$	18	23	23	14	18	18	16	22	22	13	17	17

$(x \equiv O(10^{-x}))$

$$\tilde{q} \equiv m_{\tilde{q}}^2/(100\,\mathrm{GeV})^2, \quad \delta_J^X \equiv (m_X^2)_{LR}^{JJ}/(m_X^2)_R^J$$

I : $\tan\beta = 5$, $M_R = 10^{12}\,GeV$, $m_\nu = 0.5\,eV$,

II : $\tan\beta = 50$, $M_R = 10^{12}\,GeV$, $m_\nu = 0.5\,eV$,

III : $\tan\beta = 5$, $M_R = 2\cdot 10^{14}\,GeV$, $m_\nu = 0\,eV$,

IV : $\tan\beta = 50$, $M_R = 2\cdot 10^{14}\,GeV$, $m_\nu = 0\,eV$,

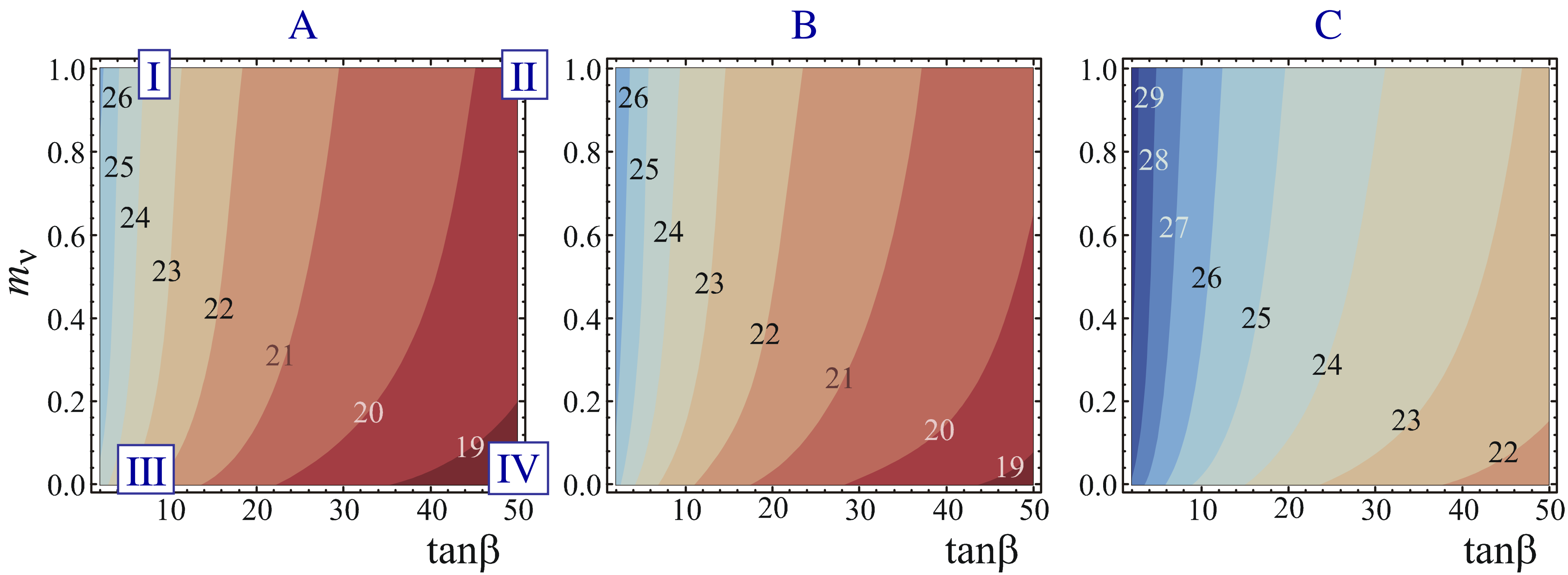
A : $SU(3)^5$

B : $SU(3)^5 \times U(1)_D \times U(1)_E$

C : $SU(3)^5 \times U(1)_D \times U(1)_E \times U(1)_U$

Backup 3. $(\tan\beta, m_\nu)$ behavior of the MFV prediction for $|\lambda'_{M1I}\lambda''^{*}_{12I}|$

(others are similar)



$(x \equiv O(10^{-x}))$

I : $\tan\beta = 5$, $M_R = 10^{12}\ GeV$, $m_\nu = 0.5\,eV$,

II : $\tan\beta = 50$, $M_R = 10^{12}\ GeV$, $m_\nu = 0.5\,eV$,

III : $\tan\beta = 5$, $M_R = 2\cdot 10^{14}\ GeV$, $m_\nu = 0\,eV$,

IV : $\tan\beta = 50$, $M_R = 2\cdot 10^{14}\ GeV$, $m_\nu = 0\,eV$,

A : $SU(3)^5$

B : $SU(3)^5 \times U(1)_D \times U(1)_E$

C : $SU(3)^5 \times U(1)_D \times U(1)_E \times U(1)_U$