Brussels, November 2007

Minimal Flavor Violation, Seesaw, and R-parity

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

- Outline

A - Motivation and generalities

B - Minimal Flavor Violation: spurions and expansions

C - Phenomenological consequences

D - Conclusion

Motivation and generalities

• A few generalities about the MSSM

Supersymmetry: Unify matter (fermions) and interactions (bosons).

MSSM: the simplest (phenomenologically viable) realization of supersymmetry

Characteristics:
- Doubling of matter & gauge degrees of freedom,
- Specific Higgs sector (2HDM - type II),
- Few free parameters in its supersymmetric sector.

Flavor-symmetry: three generations of (s)quarks and (s)leptons (exact replicas) with identical gauge interactions → Invariance under: *Chivukula,Georgi '87*

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

$$Q \xrightarrow{G_f} g_Q Q,\;\; U \xrightarrow{G_f} U g_U^\dagger,\;\; D \xrightarrow{G_f} D g_D^\dagger,\;\; L \xrightarrow{G_f} g_L L,\;\; E \xrightarrow{G_f} E g_E^\dagger$$

Superpotential breaks G_f: it sets (but does not explain) the masses and mixings

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

All (s)quark/(s)lepton masses/interactions in terms of the *Yukawas* (alignment).

- The flavor-related puzzles

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

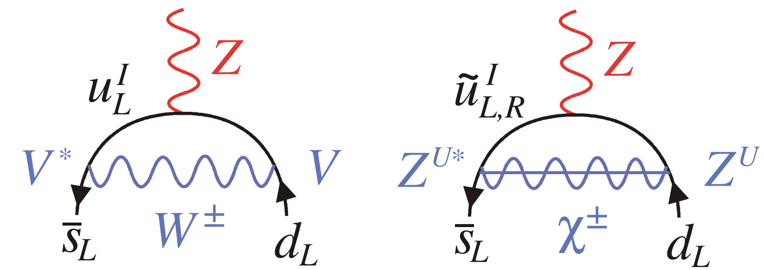
$$\mathcal{L}_{soft}^{RPC} \ni -\tilde{Q}^{\dagger}\mathbf{m}_{Q}^{2}\tilde{Q} - \tilde{U}\mathbf{m}_{U}^{2}\tilde{U}^{\dagger} - \tilde{D}\mathbf{m}_{D}^{2}\tilde{D}^{\dagger} - \tilde{U}\mathbf{A}_{u}(\tilde{Q}H_{u}) + \tilde{D}\mathbf{A}_{d}(\tilde{Q}H_{d}) + \ldots$$

Now: $\varepsilon_K, \Delta M_{Bs,Bd}, b \to s\gamma, B \to \psi K, \ldots$

Soon: $B_{s,d} \to \ell^+\ell^-, B \to X\ell^+\ell^-, K \to \pi\nu\bar{\nu}, \ldots$

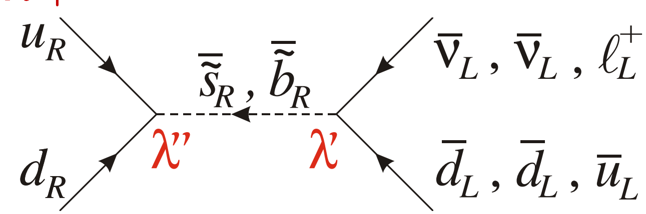
MFV to enforce sufficient alignment.

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



2. 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

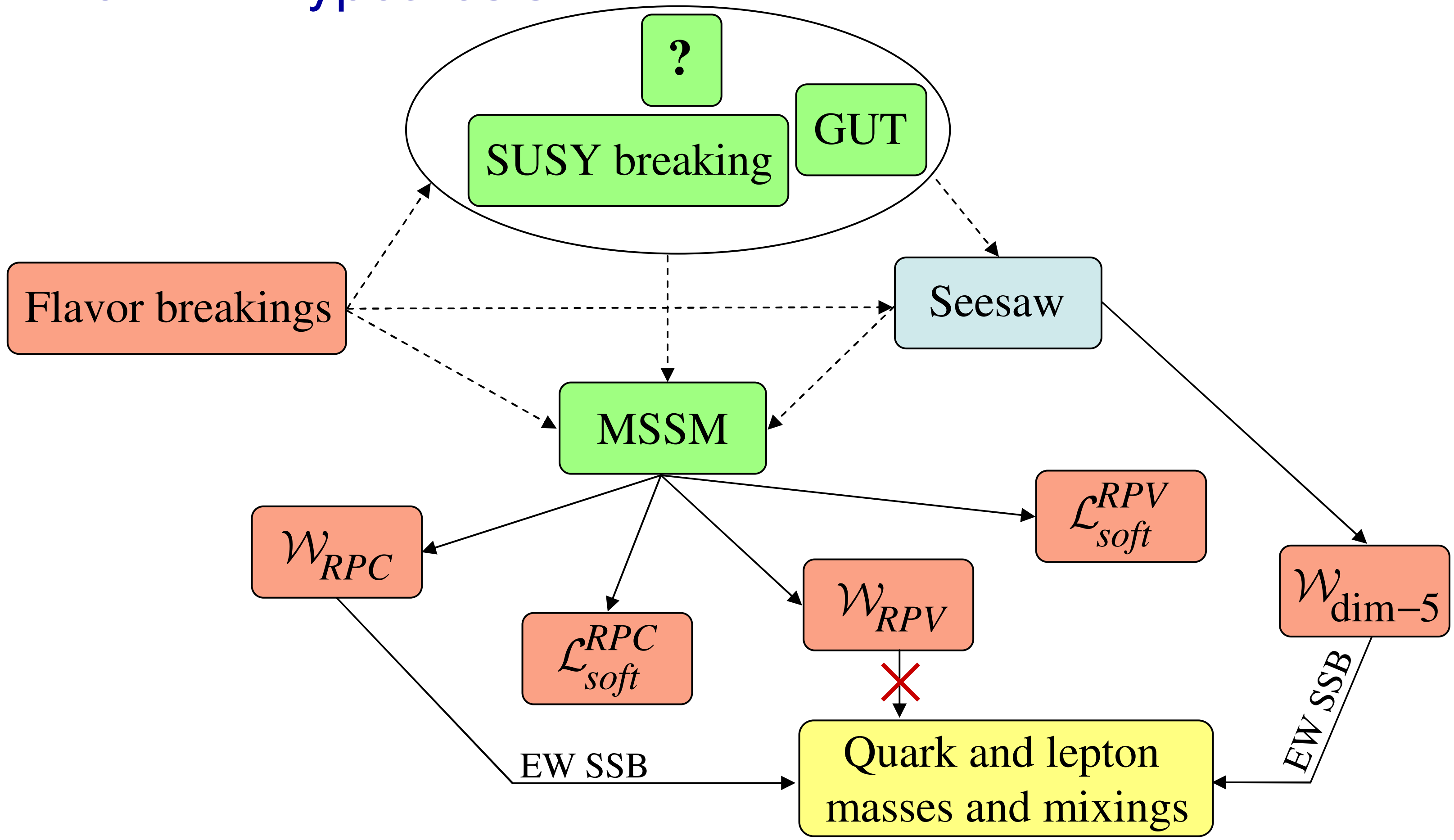
3. Seesaw and neutrino masses: In the MSSM, no ν_R and ν_L massless.

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,...

- The 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.

Goal: To show that when MFV is enforced, R-parity is no longer needed.

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

1. Which spurions to choose: Minimal set able to induce the known flavor-structures.

Yukawas: $\mathbf{Y}_u \xrightarrow{G_f} g_U \mathbf{Y}_u g_Q^\dagger,\ \mathbf{Y}_d \xrightarrow{G_f} g_D \mathbf{Y}_d g_Q^\dagger,\ \mathbf{Y}_\ell \xrightarrow{G_f} g_E \mathbf{Y}_\ell g_L^\dagger \quad \Rightarrow \mathcal{W}_{RPC}$ invariant.

Neutrino: $\mathbf{Y}_\nu \xrightarrow{G_f \times U(3)_N} g_N \mathbf{Y}_\nu g_L^\dagger$

$U(3)_N$ singlets: $\begin{cases} \Upsilon_\nu \equiv v_u \mathbf{Y}_\nu^T \mathbf{M}^{-1} \mathbf{Y}_\nu \xrightarrow{G_f} g_L^* \Upsilon_\nu g_L^\dagger, \\ \mathbf{Y}_\nu^\dagger \mathbf{Y}_\nu \xrightarrow{G_f} g_L \mathbf{Y}_\nu^\dagger \mathbf{Y}_\nu g_L^\dagger \end{cases}$

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

Cirigliano,Grinstein,Isidori,Wise '05

	G_q $U(3)_{Q,U,D}$	G_ℓ $U(3)_{L,E}$
$\mathbf{Y}_u$	$(\bar{3},3,1)$	$(1,1)$
$\mathbf{Y}_d$	$(\bar{3},1,3)$	$(1,1)$
$\mathbf{Y}_\ell$	$(1,1,1)$	$(\bar{3},3)$
Υ_ν	$(1,1,1)$	$(\bar{6},1)$
$\mathbf{Y}_\nu^\dagger \mathbf{Y}_\nu$	$(1,1,1)$	$(8,1)$

Background: $\mathbf{Y}_u = \frac{\mathbf{m}_u}{v_u} V,\ \mathbf{Y}_d = \frac{\mathbf{m}_d}{v_d},\ \mathbf{Y}_\ell = \frac{\mathbf{m}_\ell}{v_d},\ \Upsilon_\nu = U^* \frac{\mathbf{m}_\nu}{v_u} U^\dagger,\ \mathbf{Y}_\nu^\dagger \mathbf{Y}_\nu \overset{CP}{=} \frac{M_R}{v_u} \Upsilon_\nu$

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

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

→ Where $a_i \sim O(1)$ MFV coefficents,
→ The CKM matrix remains the only source of flavor-breaking.

Sometimes large (but always *finite*!) number of possible terms.
(*Cayley-Hamilton Theorem* + *Third generation dominance for* u,d,ℓ)

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

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).

Structures and MFV terms		Scaling	Breaking
$\mu_1'^I$	$\mu\bar{\Upsilon}_\nu^I,\ \ \bar{\Upsilon}_\nu^I \equiv \varepsilon^{QMJ}(\mathrm{R}_\ell \Upsilon_\nu^\dagger \mathrm{R}_\ell^T)^{QM}\mathrm{R}_\ell^{JI}$	$\tan^2\beta$	$U(1)_L$
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 $m_\nu = 0$.

MFV expansion

Structures and MFV terms		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}	$\bar{\Upsilon}_\nu^I \varepsilon^{LMN}\varepsilon^{ABC}\mathrm{R}_e^{KA}(\mathrm{R}_\ell \mathrm{Y}_\ell^\dagger)^{LB}(\mathrm{R}_\ell \mathrm{Y}_\ell^\dagger)^{MC}\mathrm{R}_\ell^{NJ},\ldots$	$\tan^4\beta$	$U(1)_{L,E}$
$\lambda_1'^{IJK}$	$\bar{\Upsilon}_\nu^I(\mathrm{Y}_d \mathrm{R}_q)^{KJ}$	$\tan^3\beta$	$U(1)_L$
$\lambda_2'^{IJK}$	$\bar{\Upsilon}_\nu^I \varepsilon^{LMN}\varepsilon^{ABC}\mathrm{R}_d^{KA}(\mathrm{R}_q \mathrm{Y}_d^\dagger)^{LB}(\mathrm{R}_q \mathrm{Y}_d^\dagger)^{MC}\mathrm{R}_q^{NJ}$	$\tan^4\beta$	$U(1)_{L,D,Q}$
$\lambda_1''^{IJK}$	$\varepsilon^{LMN}(\mathrm{Y}_u \mathrm{R}_q \mathrm{Y}_d^\dagger)^{IL}\mathrm{R}_d^{JM}\mathrm{R}_d^{KN}$	$\tan\beta$	$U(1)_D$
$\lambda_2''^{IJK}$	$\varepsilon^{LMN}\mathrm{R}_u^{IL}(\mathrm{Y}_d \mathrm{R}_q \mathrm{Y}_u^\dagger)^{JM}(\mathrm{Y}_d \mathrm{R}_q \mathrm{Y}_u^\dagger)^{KN}$	$\tan^2\beta$	$U(1)_U$
$\lambda_3''^{IJK}$	$\varepsilon^{LMN}(\mathrm{Y}_u \mathrm{R}_q)^{IL}(\mathrm{Y}_d \mathrm{R}_q)^{JM}(\mathrm{Y}_d \mathrm{R}_q)^{KN}$	$\tan^2\beta$	$U(1)_Q$
$\lambda_4''^{IJK}$	$\varepsilon^{LMN}\varepsilon^{ABC}\varepsilon^{DEF}(\mathrm{R}_q \mathrm{Y}_d^\dagger)^{LD}(\mathrm{R}_q \mathrm{Y}_u^\dagger)^{MA}(\mathrm{R}_q \mathrm{Y}_u^\dagger)^{NB}\mathrm{R}_u^{IC}\mathrm{R}_d^{JE}\mathrm{R}_d^{KF}$	$\tan\beta$	$U(1)_{Q,U,D}$

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

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

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

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

- The invariance under some $U(1)$'s can be enforced.
  Does not forbid any structure, but suppresses them by $\det(\mathbf{Y}_{u,d,\ell})$ factors.

- Similar expansions for RPV soft-breaking terms (up to their normalization).

Structures and MFV terms		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}	$\overline{\Upsilon}_\nu^I \varepsilon^{LMN}\varepsilon^{ABC}\mathrm{R}_e^{KA}(\mathrm{R}_\ell \mathrm{Y}_\ell^\dagger)^{LB}(\mathrm{R}_\ell \mathrm{Y}_\ell^\dagger)^{MC}\mathrm{R}_\ell^{NJ},\ldots$	$\tan^4\beta$	$U(1)_{L,E}$
$\lambda_1'^{IJK}$	$\overline{\Upsilon}_\nu^I(\mathrm{Y}_d \mathrm{R}_q)^{KJ}$	$\tan^3\beta$	$U(1)_L$
$\lambda_2'^{IJK}$	$\overline{\Upsilon}_\nu^I \varepsilon^{LMN}\varepsilon^{ABC}\mathrm{R}_d^{KA}(\mathrm{R}_q \mathrm{Y}_d^\dagger)^{LB}(\mathrm{R}_q \mathrm{Y}_d^\dagger)^{MC}\mathrm{R}_q^{NJ}$	$\tan^4\beta$	$U(1)_{L,D,Q}$
$\lambda_1''^{IJK}$	$\varepsilon^{LMN}(\mathrm{Y}_u \mathrm{R}_q \mathrm{Y}_d^\dagger)^{IL}\mathrm{R}_d^{JM}\mathrm{R}_d^{KN}$	$\tan\beta$	$U(1)_D$
$\lambda_2''^{IJK}$	$\varepsilon^{LMN}\mathrm{R}_u^{IL}(\mathrm{Y}_d \mathrm{R}_q \mathrm{Y}_u^\dagger)^{JM}(\mathrm{Y}_d \mathrm{R}_q \mathrm{Y}_u^\dagger)^{KN}$	$\tan^2\beta$	$U(1)_U$
$\lambda_3''^{IJK}$	$\varepsilon^{LMN}(\mathrm{Y}_u \mathrm{R}_q)^{IL}(\mathrm{Y}_d \mathrm{R}_q)^{JM}(\mathrm{Y}_d \mathrm{R}_q)^{KN}$	$\tan^2\beta$	$U(1)_Q$
$\lambda_4''^{IJK}$	$\varepsilon^{LMN}\varepsilon^{ABC}\varepsilon^{DEF}(\mathrm{R}_q \mathrm{Y}_d^\dagger)^{LD}(\mathrm{R}_q \mathrm{Y}_u^\dagger)^{MA}(\mathrm{R}_q \mathrm{Y}_u^\dagger)^{NB}\mathrm{R}_u^{IC}\mathrm{R}_d^{JE}\mathrm{R}_d^{KF}$	$\tan\beta$	$U(1)_{Q,U,D}$

- "Asymmetry" in the treatment of RPV and RPC is spurious:

  Spurions and Yukawas can be identified: $a_1\mathrm{Y}_u + a_2\mathrm{Y}_u\mathrm{Y}_u^\dagger\mathrm{Y}_u + a_3\mathrm{Y}_u\mathrm{Y}_d^\dagger\mathrm{Y}_d + \ldots \rightarrow \mathrm{Y}_u$

- Properties and extensions

1. Bilinears and Higgs-lepton mixings: Separation RPV – RPC is basis-dependent

Hall,Suzuki '84

$$\begin{pmatrix} H'_d \\ L'^I \end{pmatrix} = U \begin{pmatrix} H_d \\ L^I \end{pmatrix},\ U \in SU(4) \Rightarrow \quad \lambda'^{IJK}(L^I Q^J)D^K \leftrightarrow D^I \mathbf{Y}_d^{IJ}(Q^J H_d)\ ,\ \ldots$$

Near-alignment: $\mu'^I = \mu \overline{\Upsilon}_\nu^I, b'^I = b\overline{\Upsilon}_\nu^I, m_{Ld}^I = m_{H_d}^2 \overline{\Upsilon}_\nu^I \quad \Rightarrow \langle \tilde{\nu}^I \rangle = v_d \overline{\Upsilon}_\nu^I$ Banks,Grossman, Nardi,Nir '95

MFV is stable if the sneutrino vev's are rotated away: $\lambda'^{IJK} \to \lambda'^{IJK} + \mathbf{Y}_d^{KJ} \langle \tilde{\nu}^I \rangle / v_d$

Physical $\Delta L = 1$ Higgs-slepton mixing $O(\overline{\Upsilon}_\nu)$, and RPV corrections to $m_\nu \sim O(m_\nu^2)$.

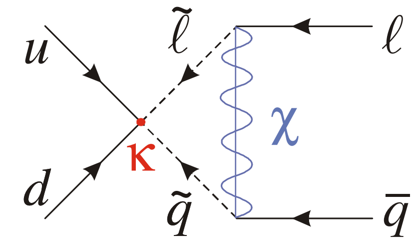
Banks,Grossman,Nardi,Nir '95, Davidson,Ellis '97, Grossman,Haber '99

2. Factorization $G_q \times G_\ell$: MFV separately suppresses $\Delta L = 1$ and $\Delta B = 1$ effects, even if arising from a single, higher-dimensional operator.

$$\mathcal{W}_{\dim-5} \ni \frac{\kappa_1^{IJKL}}{\Lambda_{\Delta L=1}}(Q^I Q^J)(Q^K L^L) + \frac{\kappa_2^{IJKL}}{\Lambda_{\Delta L=1}}(D^I U^J U^K)E^L + \frac{\kappa_5^{IJ}}{\Lambda_{\Delta L=2}}(L^I H_u)(L^J H_u)$$

Ibanez,Ross '92

If $\Lambda_{\Delta L=1} \approx \Lambda_{\Delta L=2}$, and since κ_1, κ_2 are RPC, these operators should be subleading compared to the tree-level $\lambda \times \lambda''$, $\lambda' \times \lambda''$ contributions.



Phenomenological consequences

- Numerical estimates: Preliminaries

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.

The precise dependences are exactly predicted by MFV.

$$\lambda'^{IJK} \neq O(m_e^I m_u^J m_d^K), \quad \lambda''^{IJK} \neq O(m_u^I m_d^J m_d^K)$$

Reduced basis: Not all operators of equal size, some can always be neglected.

- However: the reduced basis, with the minimal number of operators, strongly depends on $\tan\beta$, lightest neutrino mass m_ν, and the seesaw scale M_R.
- For $\tan\beta < 20$, $M_R < 2\cdot 10^{13}\,GeV$, $m_\nu > 0.05\,eV$: only 10 to 20 dominant terms.

Numerical estimates for the maximal order of magnitudes in four extreme scenarios:

$$\begin{array}{llll}
\text{Case I}: & \tan\beta = 5 & M_R = 10^{12}\,GeV & m_\nu = 0.5\,eV \\
\text{Case II}: & \tan\beta = 50 & M_R = 10^{12}\,GeV & m_\nu = 0.5\,eV \\
\text{Case III}: & \tan\beta = 5 & M_R = 2\cdot 10^{14}\,GeV & m_\nu = 0\,eV \\
\text{Case IV}: & \tan\beta = 50 & M_R = 2\cdot 10^{14}\,GeV & m_\nu = 0\,eV
\end{array}$$

Case II & IV: maximize H_d Yukawa couplings Y_d, Y_ℓ,

Case III & IV: maximize neutrino spurions Υ_ν and $\mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu$.

- Freezing the spurions

Our goal: Leading, order-of-magnitude estimates in terms of $\tan\beta, M_R, m_\nu$, assuming MFV coefficients are not larger than about one.

1. Quark and charged lepton Yukawas fixed from the PDG masses and CKM:

$$\mathrm{Y}_u = \frac{\mathrm{m}_u}{v_u} V,\ \mathrm{Y}_d = \frac{\mathrm{m}_d}{v_u}\tan\beta,\ \mathrm{Y}_\ell = \frac{\mathrm{m}_\ell}{v_u}\tan\beta$$

2. Neutrino masses: set $\theta_{13} \approx 0, \theta_{atm} \approx 45^\circ$ and $\tan\theta_\odot \approx 2/3$ such that

$$\Upsilon_\nu = U^* \frac{\mathrm{m}_\nu}{v_u} U^\dagger \approx \frac{1}{v_u}\left(m_\nu 1 + \frac{\Delta m_{21}}{3}\begin{pmatrix} 1 & 1 & -1 \\ 1 & 1 & -1 \\ -1 & -1 & 1 \end{pmatrix} + \frac{\Delta m_{31}}{2}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}\right)$$

- As $m_\nu \equiv m_{\nu 1}$ decreases, Υ_ν gets less diagonal (normal spectrum for larger effects) for fixed $\Delta m_\odot^2 \approx 8\cdot 10^{-5}\ \mathrm{eV}^2$, $\Delta m_{atm}^2 \approx 2.6\cdot 10^{-3}\ \mathrm{eV}^2$.
- For most operators, the piece ~ 1 drops out since $\bar{\Upsilon}_\nu^I = \varepsilon^{QMI}(\mathrm{Y}_\ell^\dagger \mathrm{Y}_\ell \Upsilon_\nu^\dagger)^{QM} + \ldots$

3. Neutrino octet spurion fixed in the CP-limit: $\mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu \overset{CP}{=} \frac{M_R}{v_u}\Upsilon_\nu$

Perturbative bound: $\mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu \leq 1 \to \frac{\max[m_\nu, \Delta m_{31}]}{1\,\mathrm{eV}} \frac{M_R}{10^{13}\,\mathrm{GeV}} \leq 3$

- Order-of-magnitude estimates

Example 1: Auxiliary neutrino spurion

$$\overline{\Upsilon}_\nu^I = \begin{pmatrix}17\\19\\21\end{pmatrix}, \underbrace{\overbrace{\begin{pmatrix}15\\17\\19\end{pmatrix}, \begin{pmatrix}16\\17\\18\end{pmatrix}}^{\text{large } \tan\beta}, \begin{pmatrix}14\\15\\16\end{pmatrix}}_{\text{large } M_R,\text{small } m_\nu},$$

- Inverted hierarchy,
- Significantly suppressed ($M_R = 10^{12-14}\,\mathrm{GeV}$),
- Quadratic in $\tan\beta$,
- $M_R \nearrow$ and/or $m_\nu \searrow$: hierarchies softened,
- Tunes μ' and λ', and similar for λ.

Example 2: Baryonic couplings

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

Structure	λ''_1	λ''_2	λ''_3	$\lambda''_{4,5}$
Broken $U(1)$	$U(1)_D$	$U(1)_U$	$U(1)_Q$	$U(1)_{U,D,Q}$
Scaling	$\tan\beta$	$\tan^2\beta$	$\tan^2\beta$	$\tan\beta$
$\tan\beta = 5$	$\begin{pmatrix}8&8&8\\4&6&5\\1&6&4\end{pmatrix}$	$\begin{pmatrix}11&6&7\\12&9&9\\13&12&13\end{pmatrix}$	$\begin{pmatrix}13&8&10\\10&6&7\\6&5&6\end{pmatrix}$	$\begin{pmatrix}5&5&5\\7&9&7\\7&12&10\end{pmatrix}$
$\tan\beta = 50$	$\begin{pmatrix}7&7&7\\3&5&4\\0&5&3\end{pmatrix}$	$\begin{pmatrix}9&4&5\\10&7&7\\11&10&11\end{pmatrix}$	$\begin{pmatrix}11&6&8\\8&4&5\\4&3&4\end{pmatrix}$	$\begin{pmatrix}4&4&4\\6&8&6\\6&11&9\end{pmatrix}$

$X^{IJ} \equiv \lambda''^{I(JK)}$,
$(JK) = 12, 23, 31$

- Bounds on RPV couplings

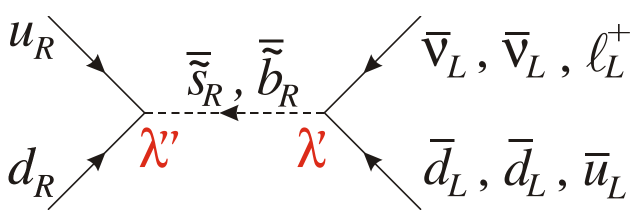
Barbier et al. '05

1. Bounds from $\Delta L = 1$, $\Delta B = 0$ processes:

All easily satisfied, because $\Delta L = 1$ couplings $\mu', \lambda, \lambda' < O(10^{-13})$

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

Tree-level:



Very constraining (see next slide)

Loop-level:

$$|\lambda'_{IJK}\lambda''_{I'J'K'}| < O(10^{-9} - 10^{-11})$$

Automatic since $\lambda' < O(10^{-13})$

3. Bounds from neutron oscillations:

Tree-level (very approximative):

$$|\lambda''_{11I}| < (10^{-8} - 10^{-7})\,\frac{10^8 s}{\tau_{osc}}\left(\frac{\tilde{m}}{100\,\text{GeV}}\right)^{5/2}$$

Loop-level:

$$|\lambda''_{312}| < [10^{-3}, 10^{-2}]\left(\frac{200\,\text{MeV}}{m_s}\right),$$
$$\tilde{m}_q \sim [100\,\text{GeV}, 200\,\text{GeV}]$$

Not very constraining for squark masses above a few hundred GeV.

4. 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

$\tilde{q} \equiv m_{\tilde{q}}^2/(100\,\mathrm{GeV})^2$

$\delta_J^X \equiv (m_X^2)_{LR}^{JJ}/(m_X^2)_R^J$

Case II,IV : large $\tan\beta$

Case III, IV : $\begin{cases}\text{large } M_R \\ \text{small } m_\nu\end{cases}$

A : $SU(3)^5$

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

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

Conservative: - Light-quark masses at 2 GeV, on-shell lepton masses,

- MFV coefficients of $O(1)$, while $O(\lambda)$ or $O(g^2/4\pi)$ equally natural,
- No GIM-like interferences for a given mechanism, and no cancellations among possible mechanisms for a given final state.

• Consequences

1. FCNC and LFV: - Moderate $\tan\beta$ preferred → suppresses Higgs FCNC.
- Large m_ν preferred → suppresses LFV effects.
- Alternative: if $U(1)_L$ imposed, additional factor $\det(\mathbf{Y}_\ell) < 10^{-6}$.

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

$$\frac{\left|\lambda''_{IJK}\lambda''^{*}_{LMN}\right|}{\tilde{m}_q^2} \leq 10^{-8}\,\mathrm{GeV}^{-2}\frac{(100\,\mathrm{GeV})^2}{\tilde{m}_q^2} \quad \leftrightarrow \quad G_F \sim 10^{-5}\,\mathrm{GeV}^{-2}$$

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.

3. $\Delta B = 1$ 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 $(\tilde{d},\tilde{s},\tilde{b}) \to t + (d,s,b)$.
- …

- A few thoughts about possible extensions

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

Seesaw → Majorana mass for ν_L: $\Upsilon_\nu \sim (\bar{6},1)$

Seesaw → Other unsuppressed spurions (here $Y_\nu^\dagger Y_\nu \sim (8,1)$)

But MFV stability implies that no other spurion can contribute as $(\bar{6},1)$.

Then, this suppressed $(\bar{6},1)$ remains the essential building block.

2. 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

$$\mathcal{W}_{RPV} = \Lambda^{IJK}\,\bar{5}^I\,\bar{5}^J\,10^K + \ldots$$

Seesaw spurions not required to construct invariants.

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.

MFV still useful in the GUT context, especially if the $U(3)^5$ group re-emerges.

Conclusion

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.

Extensions: Consequences still to be investigated. In particular:

- In *GUT's/SUSY-breaking*: ensuring the emergence of MFV is a powerful method towards satisfying low-energy constraints.
- For *cosmology*, MSSM-LSP not stable, and baryon number violated?

Backup

Backup 1. Expansions for RPC soft-breaking terms

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

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

Octets: $\mathrm{X}_i \equiv \mathrm{Y}_i^\dagger \mathrm{Y}_i$, $\mathrm{R}_\ell = 1, \mathrm{X}_\ell, \mathrm{X}_\nu, \mathrm{X}_\ell\mathrm{X}_\nu, \mathrm{X}_\nu\mathrm{X}_\ell, \mathrm{X}_\nu^2, \mathrm{X}_\ell\mathrm{X}_\nu^2, \mathrm{X}_\nu^2\mathrm{X}_\ell, \mathrm{X}_\nu^2\mathrm{X}_\ell\mathrm{X}_\nu$,

$\mathrm{R}_q = 1, \mathrm{X}_u, \mathrm{X}_d, \mathrm{X}_u\mathrm{X}_d, \mathrm{X}_d\mathrm{X}_u$, $\mathrm{R}_{u,d} = 1, \mathrm{Y}_{u,d}\mathrm{R}_q\mathrm{Y}^\dagger_{u,d}$, $\mathrm{R}_e = 1, \mathrm{Y}_\ell\mathrm{R}_\ell\mathrm{Y}^\dagger_\ell$

RPC-terms: $\mathrm{m}_Q^2 = m_0^2[\mathrm{R}_q]_{h.c.}$, $\mathrm{m}_U^2 = m_0^2[\mathrm{R}_u]_{h.c.}$, $\mathrm{m}_D^2 = m_0^2[\mathrm{R}_d]_{h.c.}$,

$\mathrm{m}_L^2 = m_0^2[\mathrm{R}_\ell]_{h.c.}$, $\mathrm{m}_E^2 = m_0^2[\mathrm{R}_e]_{h.c.}$

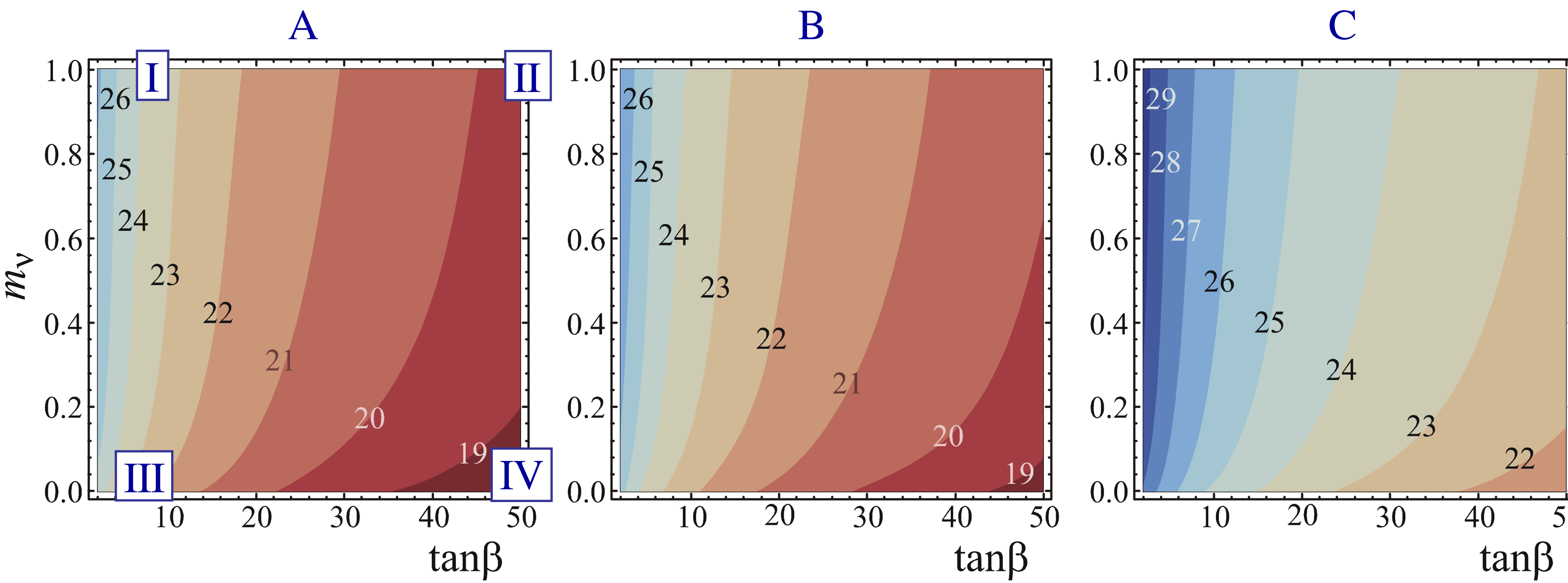
$$\mathrm{A}_u^{IJ} = A_0((\mathrm{Y}_u\mathrm{R}_q)^{IJ} + \varepsilon^{LMN}\varepsilon^{ABC}\mathrm{R}_u^{KA}(\mathrm{R}_q\mathrm{Y}_u^\dagger)^{LB}(\mathrm{R}_q\mathrm{Y}_u^\dagger)^{MC}\mathrm{R}_q^{NJ})$$

$$\mathrm{A}_d^{IJ} = A_0((\mathrm{Y}_d\mathrm{R}_q)^{IJ} + \varepsilon^{LMN}\varepsilon^{ABC}\mathrm{R}_d^{KA}(\mathrm{R}_q\mathrm{Y}_d^\dagger)^{LB}(\mathrm{R}_q\mathrm{Y}_d^\dagger)^{MC}\mathrm{R}_q^{NJ})$$

$$\mathrm{A}_\ell^{IJ} = A_0((\mathrm{Y}_\ell\mathrm{R}_\ell)^{IJ} + \varepsilon^{LMN}\varepsilon^{ABC}\mathrm{R}_e^{KA}(\mathrm{R}_\ell\mathrm{Y}_\ell^\dagger)^{LB}(\mathrm{R}_\ell\mathrm{Y}_\ell^\dagger)^{MC}\mathrm{R}_\ell^{NJ})$$

- Sum with $O(1)$ MFV coefficents,
- For trilinear terms, the ε-structures are new, though small but for 11 mixing,
- LFV effects tuned by $\mathrm{Y}_\nu^\dagger\mathrm{Y}_\nu$, 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. Behavior of the bound $|\lambda'_{M1I}\lambda''^{*}_{12I}|$ (others are similar)



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

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