LPT - Orsay

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Minimal Flavor Violation in supersymmetry

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- Outline

Introduction: Flavors in the SM

I. New Physics flavor puzzles

II. Minimal Flavor Violation (MFV)

III. CP-violation under MFV

IV. RGE behavior of MFV

V. MFV and proton decay

Conclusion

Introduction

A. The Standard Model flavor symmetry

The three generations of quarks/leptons have *identical gauge interactions*

$$\mathcal{L}_{Kin} = \sum_{k,I=1,2,3} \bar{\psi}_k^I \, i\not{D}_k \, \psi_k^I , \qquad D_k^\mu \supset SU(3)_C \times SU(2)_L \times U(1)_Y$$

where $\psi_k \; : \; Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad U = u_R^\dagger, \quad D = d_R^\dagger, \quad L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}, \quad E = \ell_R^\dagger$

As a result, the SM gauge interactions exhibit the $U(3)^5$ *flavor symmetry*:

$$G_f = U(3)^5 = U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E$$

Chivukula, Georgi '87

With one $U(3)$ per fermion species, since under $g_k \in U(3)_k$

$$\psi_k^I \to (g_k)^{IJ} \psi_k^J \quad \Rightarrow \quad \mathcal{L}_{Kin} \to \sum_{k,I,J,K} \bar{\psi}_k^J \, (g_k^\dagger)^{JI} \, i\not{D}_k \, (g_k)^{IK} \, \psi_k^K = \mathcal{L}_{Kin}$$

B. In the SM, the flavor symmetry is broken in a very special way:

- *The only sources of breaking are the Yukawa couplings*:

$$\mathcal{L}_{Yukawa} = U^I \mathbf{Y}_u^{IJ} (Q^J H) + D^I \mathbf{Y}_d^{IJ} (Q^J H^\dagger) + E^I \mathbf{Y}_e^{IJ} (L^J H^\dagger)$$

which themselves are also *very special:*

- The *fermion masses* are highly hierarchical ($m_t \gg m_c \gg m_u$)
- The *CKM matrix* is highly hierarchical (close to unit matrix),
- The CKM phase is the *unique source for all CP-violation*.

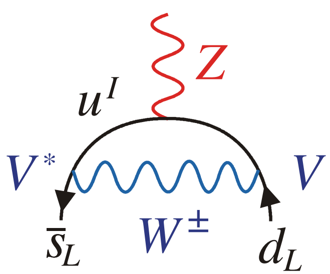
- Essential feature of *flavor physics* & *FCNC processes*:

$B \to X_{d,s} \ell^+ \ell^-$,

$B \to X_{d,s} \nu\bar{\nu}$,

$K \to \pi\nu\bar{\nu}$,

$K_L \to \pi^0 \ell^+ \ell^-$, ...



$\sim m_{u^I}^2$

$\Rightarrow$ top quark dominates

$b \to s : V_{tb}^* V_{ts} \sim 10^{-2}$

$b \to d : V_{tb}^* V_{td} \sim 10^{-3}$

$s \to d : V_{ts}^* V_{td} \sim 10^{-4}$

C. Warm-up: "MFV" in the Standard Model

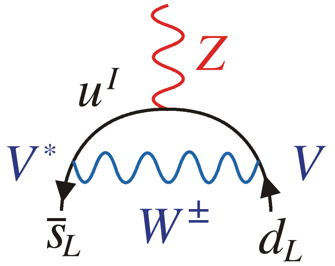
- The SM is made *artificially invariant under* G_f by forcing $\mathbf{Y}_{u,d,e}$ to transform as:

$$\mathbf{Y}_u \to g_U \mathbf{Y}_u g_Q^\dagger, \quad \mathbf{Y}_d \to g_D \mathbf{Y}_d g_Q^\dagger, \quad \mathbf{Y}_e \to g_E \mathbf{Y}_e g_L^\dagger$$

since then $\mathcal{L}_{Yukawa} = U\mathbf{Y}_u QH + D\mathbf{Y}_d QH^\dagger + E\mathbf{Y}_e LH^\dagger \xrightarrow{U(3)^5} \mathcal{L}_{Yukawa}$

Background values: $v\mathbf{Y}_u = m_u V_{CKM}$, $v\mathbf{Y}_d = m_d$, $v\mathbf{Y}_e = m_e$.

- All *SM amplitudes must then be invariant under* G_f, at all orders.



Example: The Z penguin:

$$\to \mathcal{O}_Z \sim \bar{Q}^I \gamma_\mu Q^I \underbrace{H^\dagger D^\mu H}_{\sim v^2 Z^\mu}$$

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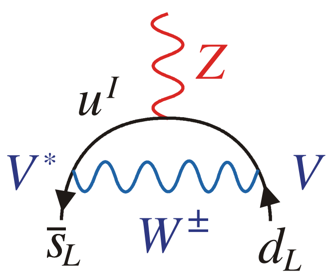

Example: The Z penguin:

$$\to \mathcal{O}_Z \sim \bar{Q}^I \gamma_\mu (\mathbf{Y}_u^\dagger \mathbf{Y}_u)^{IJ} Q^J \, v^2 Z^\mu$$

Predicts the CKM & quadratic ~~GIM~~ : $v^2 \mathbf{Y}_u^\dagger \mathbf{Y}_u \approx m_t^2 \begin{pmatrix} |V_{td}|^2 & V_{td}^* V_{ts} & V_{td}^* V_{tb} \\ V_{ts}^* V_{td} & |V_{ts}|^2 & V_{ts}^* V_{tb} \\ V_{tb}^* V_{td} & V_{tb}^* V_{ts} & |V_{tb}|^2 \end{pmatrix}$

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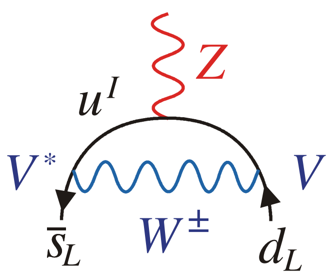

Example: The Z penguin:

$$\to \mathcal{O}_Z \sim \bar{Q}^I \gamma_\mu (\mathbf{Y}_u^\dagger \mathbf{Y}_u)^{IJ} Q^J \, v^2 Z^\mu$$

Suppressed by $\sim \dfrac{\mathrm{m}_{d^I}\mathrm{m}_{d^J}}{v^2}$

Right-handed currents? $\mathcal{O}_Z \sim D\gamma_\mu \mathbf{Y}_d \mathbf{Y}_u^\dagger \mathbf{Y}_u \mathbf{Y}_d^\dagger \bar{D} \, v^2 Z^\mu$

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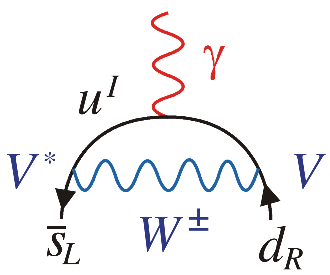

Example: The EM operator:

$$\to \begin{cases} \mathcal{O}_\gamma \sim D^I \sigma_{\mu\nu} Q^I \, H^\dagger F^{\mu\nu} \\ \mathcal{O}_\gamma \sim E^I \sigma_{\mu\nu} L^I \, H^\dagger F^{\mu\nu} \end{cases}$$

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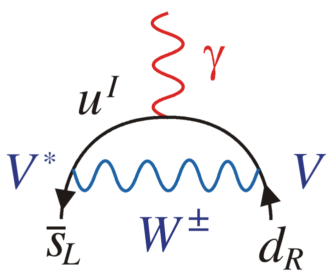


Example: The EM operator:

$$\to \begin{cases} \mathcal{O}_\gamma \sim D^I \sigma_{\mu\nu} (\mathbf{Y}_d \mathbf{Y}_u^\dagger \mathbf{Y}_u)^{IJ} Q^J \, H^\dagger F^{\mu\nu} \\ \mathcal{O}_\gamma \sim E^I \sigma_{\mu\nu} (\mathbf{Y}_e)^{IJ} L^J \, H^\dagger F^{\mu\nu} \end{cases}$$

No LFV, since $\mathbf{Y}_e$ is diagonal: $\mu \not\to e\gamma, \mu \not\to eee, \ldots$

Experimentally, $m_\nu \neq 0$ but extremely small $\Rightarrow B(\mu \to e\gamma) < 10^{-50}$.

I. The MSSM flavor puzzles

A. Flavors and New Physics

- There is some *New Physics* (dark matter, m_ν, unification, EW stability, gravity,...)

- Most New Physics models have either *new flavored particles*, or *new flavor-breaking interactions* between quarks and leptons.

- The (low-scale) Lagrangian of NP can always be made $U(3)^5$ *symmetric*, but at the cost of allowing for *new spurions* (= NP flavor-breaking couplings).

Ex: $\mathrm{X}_Q \to g_Q \mathrm{X}_Q g_Q^\dagger \quad \Rightarrow \quad \mathcal{O}_Z \sim \frac{1}{\Lambda_{NP}^2} \bar{Q}^I \gamma_\mu (\mathrm{X}_Q)^{IJ} Q^J \, v^2 Z^\mu$

- *Flavor experiments* $\Rightarrow$ either spurions non-natural, or NP scale very high.

Ex: $\mathcal{O}_Z \Rightarrow K \to \pi \nu \bar{\nu}$. With $(X_Q)^{12} \approx 1 \Rightarrow \Lambda \gtrsim 75\,\mathrm{TeV}$.

- Flavor structures of TeV-scale NP necessarily fine-tuned: *NP flavor puzzle.*

A. Flavors and New Physics: Situation in the MSSM

Essentially one superpartner for every SM particle, same gauge group.

Squarks and sleptons are *scalar flavored particles*.

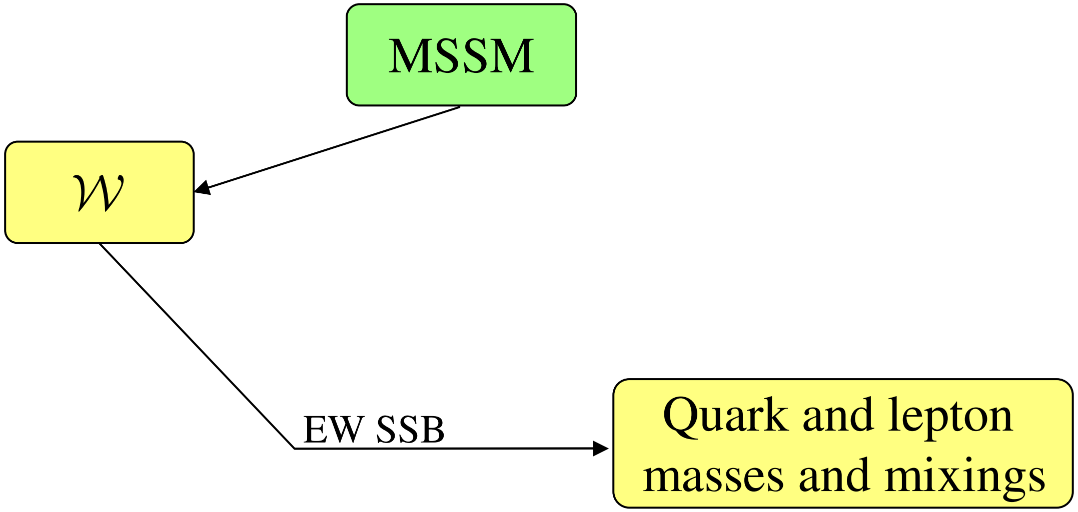
- MSSM gauge interactions still exhibit the $U(3)^5$ *flavor symmetry*.
- *Many new flavor couplings* ⇔ new spurions, a priori not hierarchical.
- *New contributions* to flavor transitions

e.g.: $\mathcal{L}_{MSSM} \supset \tilde{Q}^\dagger \mathbf{m}_Q^2 \tilde{Q} \quad \rightarrow \quad \mathcal{O}_Z \sim \frac{1}{\Lambda_{SUSY}^4} (\bar{Q}\gamma_\mu \mathbf{m}_Q^2 Q) v^2 Z^\mu$

$\mathcal{L}_{MSSM} \supset \tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} \quad \rightarrow \quad \mathcal{O}_\gamma \sim \frac{1}{\Lambda_{SUSY}^4} (E \mathbf{Y}_e \mathbf{m}_L^2 \sigma_{\mu\nu} L) H_d F^{\mu\nu}$

- Experimental data impose to *fine-tune those additional spurions*:

Approx. alignment with SM: $\mathbf{m}_Q^2 \sim \Lambda_{SUSY}^2 \mathbf{Y}_u^\dagger \mathbf{Y}_u\,,\ \ \mathbf{m}_L^2 \sim \Lambda_{SUSY}^2 \mathbf{Y}_e^\dagger \mathbf{Y}_e\,.$



1. Superpotential Yukawa couplings: set fermion masses and mixings.

$$\mathcal{W} = U\mathbf{Y}_u(QH_u) - D\mathbf{Y}_d(QH_d) - E\mathbf{Y}_e(LH_d) + \mu(H_u H_d)$$

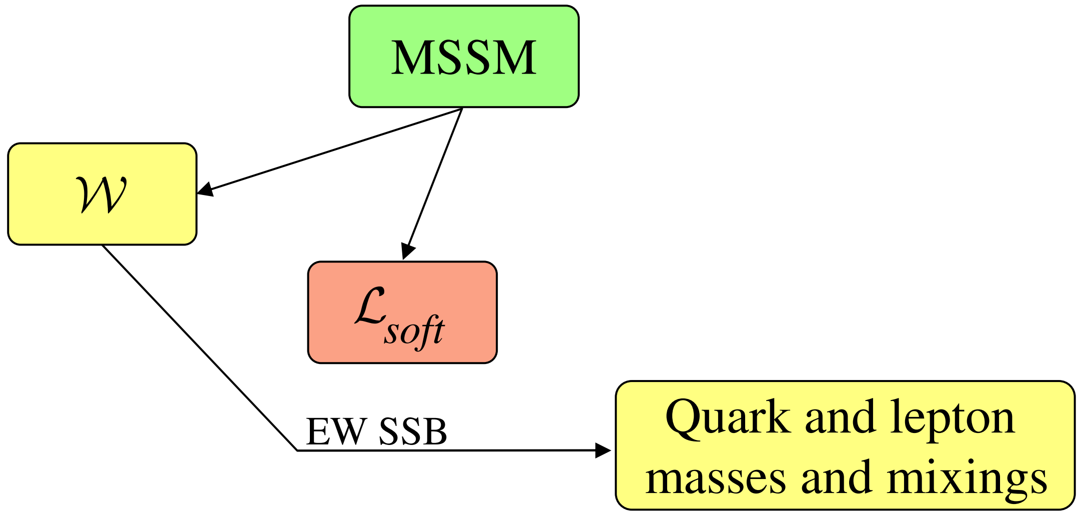
($Q, U, D, \ldots$ now denote *superfields*, with fermion & scalar components)

Analogues of the SM Yukawa couplings (but with two Higgs doublets).

→ *same hierachical fermion masses & CKM couplings*.

At this stage, perfect *alignment* of squarks with quarks, sleptons with leptons.

→ *same masses, same mixings.*



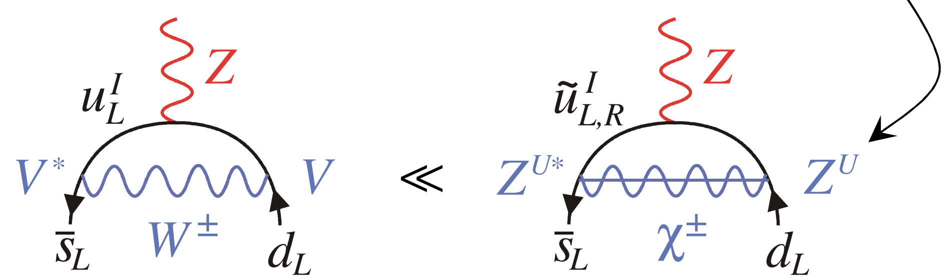
2. Squark soft-breaking terms: SUSY is broken, but the *exact mechanism is unclear*

- *Effective description*: $\mathcal{L}_{soft} \ni -\tilde{Q}^{\dagger}\mathbf{m}_Q^2\tilde{Q} - \tilde{U}\mathbf{m}_U^2\tilde{U}^{\dagger} - \tilde{U}\mathbf{A}_u(\tilde{Q}H_u) + \ldots$

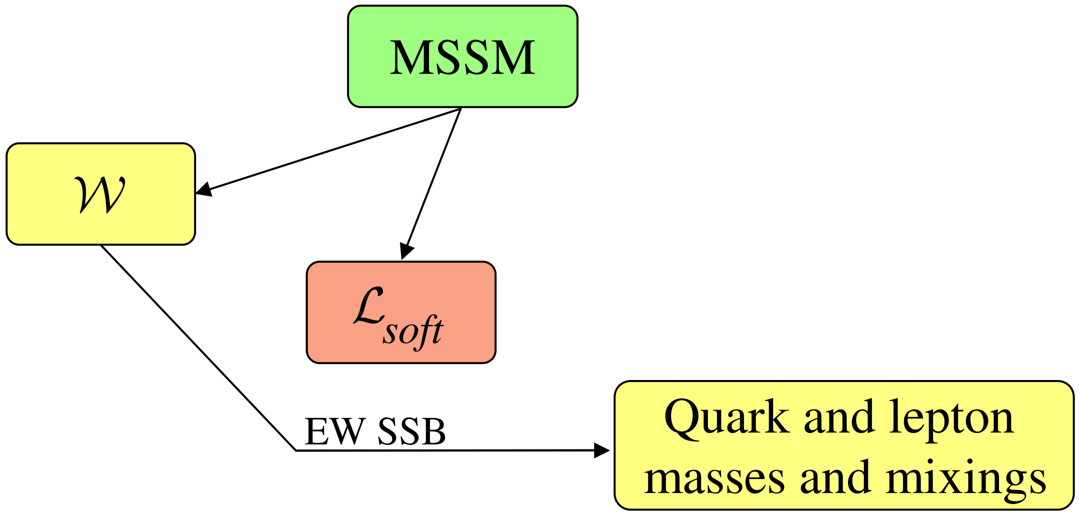
- *Squark mass terms*: $\delta M_{\tilde{u}}^2 = \begin{pmatrix} \mathbf{m}_Q^2 & v_u\mathbf{A}_u^{\dagger} \\ v_u\mathbf{A}_u & \mathbf{m}_U^2 \end{pmatrix}$

Large mass and gauge eigenstate mismatch?

- *Contributions to the FCNC*:



With sparticle masses < 1 TeV, the squark flavor mixings must be small.



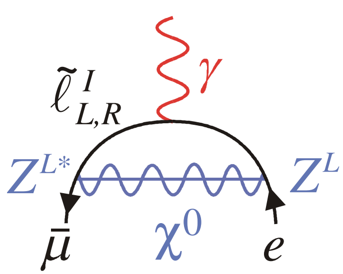
3. Slepton soft-breaking terms: similar situation as for squarks

- *Effective description*: $\mathcal{L}_{soft} \ni -\tilde{L}^\dagger \mathbf{m}_L^2 \tilde{L} - \tilde{E}\mathbf{m}_E^2 \tilde{E}^\dagger - \tilde{E}\mathbf{A}_e(\tilde{L}H_d) + \ldots$

- *Slepton mass terms*: $\delta M_{\tilde{\ell}}^2 = \begin{pmatrix} \mathbf{m}_L^2 & v_d \mathbf{A}_e^\dagger \\ v_d \mathbf{A}_e & \mathbf{m}_E^2 \end{pmatrix}$

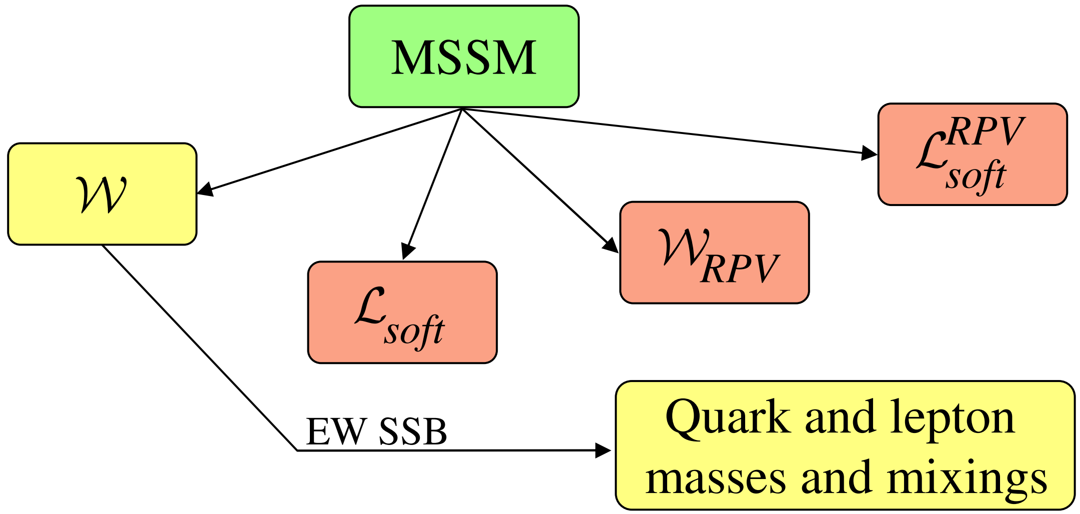
Large mass and gauge eigenstate mismatch?

- *New FCNC*:



With generic mixings, LFV much too large compared to experimental bounds.

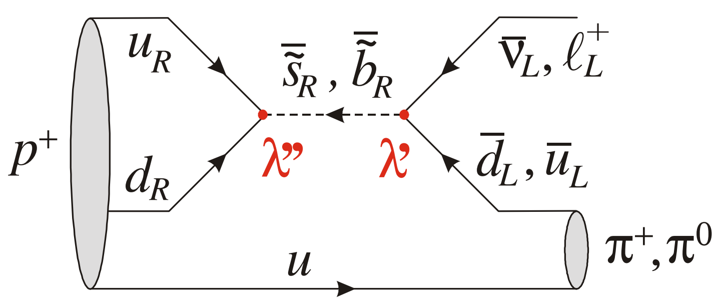
Again, sleptons and leptons must not be too misaligned.



4. $\mathcal{B}$ or $\mathcal{L}$ violating couplings are allowed (both supersymmetric and not):

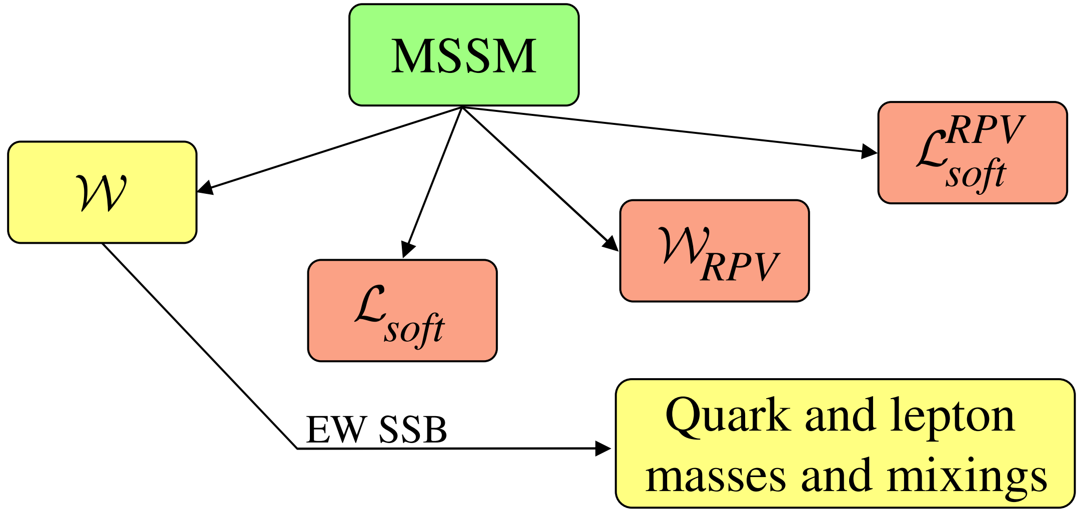
$$\mathcal{W}_{RPV} = \lambda^{IJK}(L^I L^J)E^K + \lambda'^{IJK}(L^I Q^J)D^K + \lambda''^{IJK}U^I D^J D^K + \mu'^I(L^I H_d)$$

These couplings induce *proton decay* (and associated) at tree-level:



$$p \to \pi^+\bar{\nu}_\ell, K^+\bar{\nu}_\ell, \pi^0\ell^+, \ldots$$
$$n \to \pi^0\bar{\nu}_\ell, K^0\bar{\nu}_\ell, \pi^-\ell^+, \ldots$$

But experimentally, $\tau_{p^+} > 10^{30}\ years$: $\Gamma_{p^+} \sim \dfrac{m_p^5}{M_{\tilde{d}}^4}|\lambda''\lambda'|^2 \quad \Rightarrow |\lambda'\lambda''| \leq 10^{-27}$?

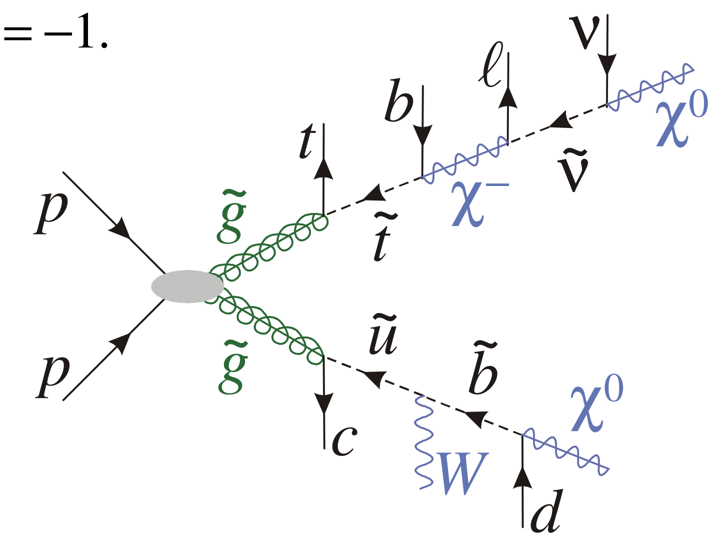


Usual escape route is to *impose R-parity*: *Farrar,Fayet '78*

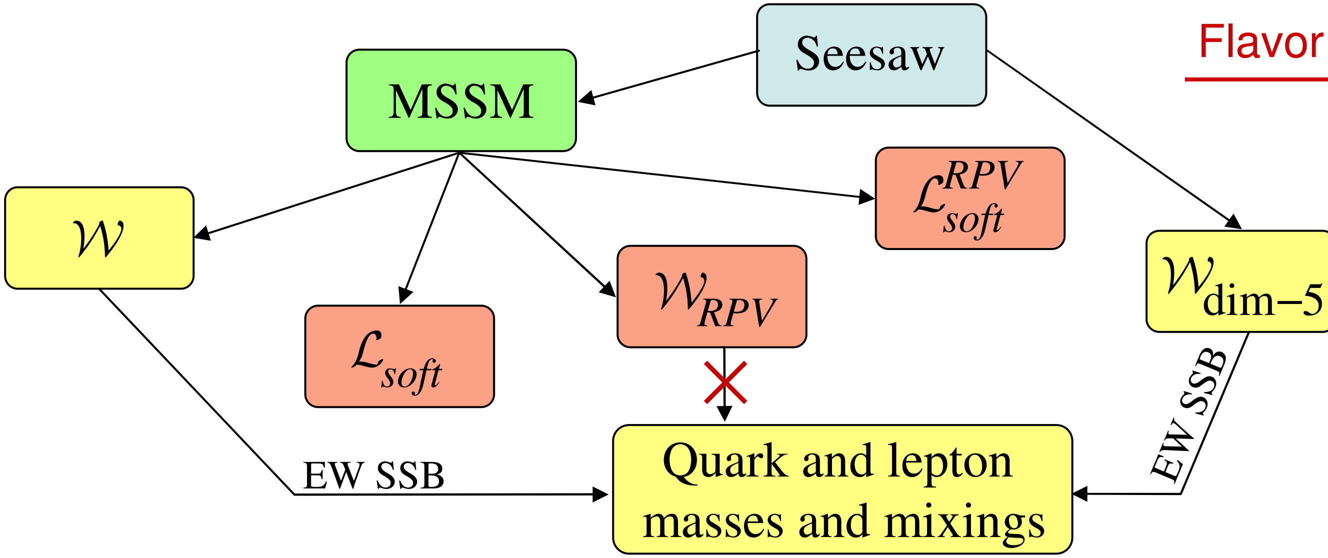
Assign $R(Particles) = +1$ and $R(Sparticles) = -1.$

→ $\mathcal{W}_{RPV}$ and $\mathcal{L}_{soft}^{RPV}$ couplings forbidden.

But also: sparticles produced in pairs, stable LSP (hence neutral LSP),...



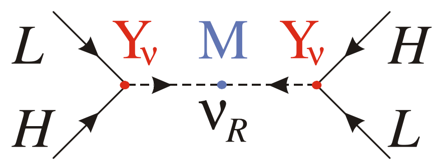
R-parity is a very (too?) tough constraint!



5. Seesaw mechanism to account for neutrino masses (not from $\mathcal{W}_{RPV}$):

- *Right-handed (s)neutrinos* are added: $\mathcal{W}_N = N\mathrm{M}N + N\mathrm{Y}_\nu(LH_u)$

- *Large $\mathcal{L}$ violating mass* M allowed → ν_R are integrated out:



$$\mathcal{W}_{\dim-5} = (\mathrm{Y}_\nu^T \mathrm{M}^{-1} \mathrm{Y}_\nu)^{IJ} (L^I H_u)(L^J H_u)$$

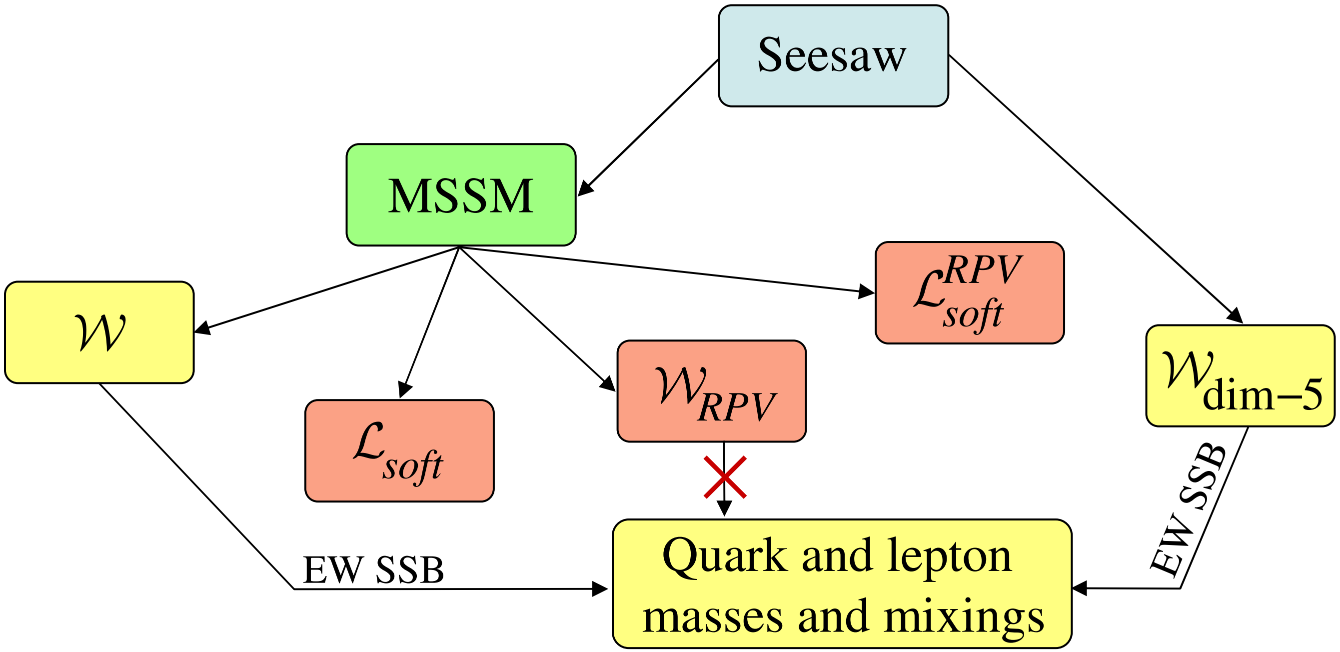
- *Effective Majorana mass term for ν_L*: $v_u^2 \mathrm{Y}_\nu^T \mathrm{M}^{-1} \mathrm{Y}_\nu = U_{PMNS}^* \cdot \mathrm{m}_\nu \cdot U_{PMNS}^\dagger$

Then, $\mathrm{m}_\nu \sim 1\,\mathrm{eV}$ with $\mathrm{Y}_\nu \sim \mathcal{O}(1)$ when $\mathrm{M} \sim 10^{13}\,\mathrm{GeV}$.

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

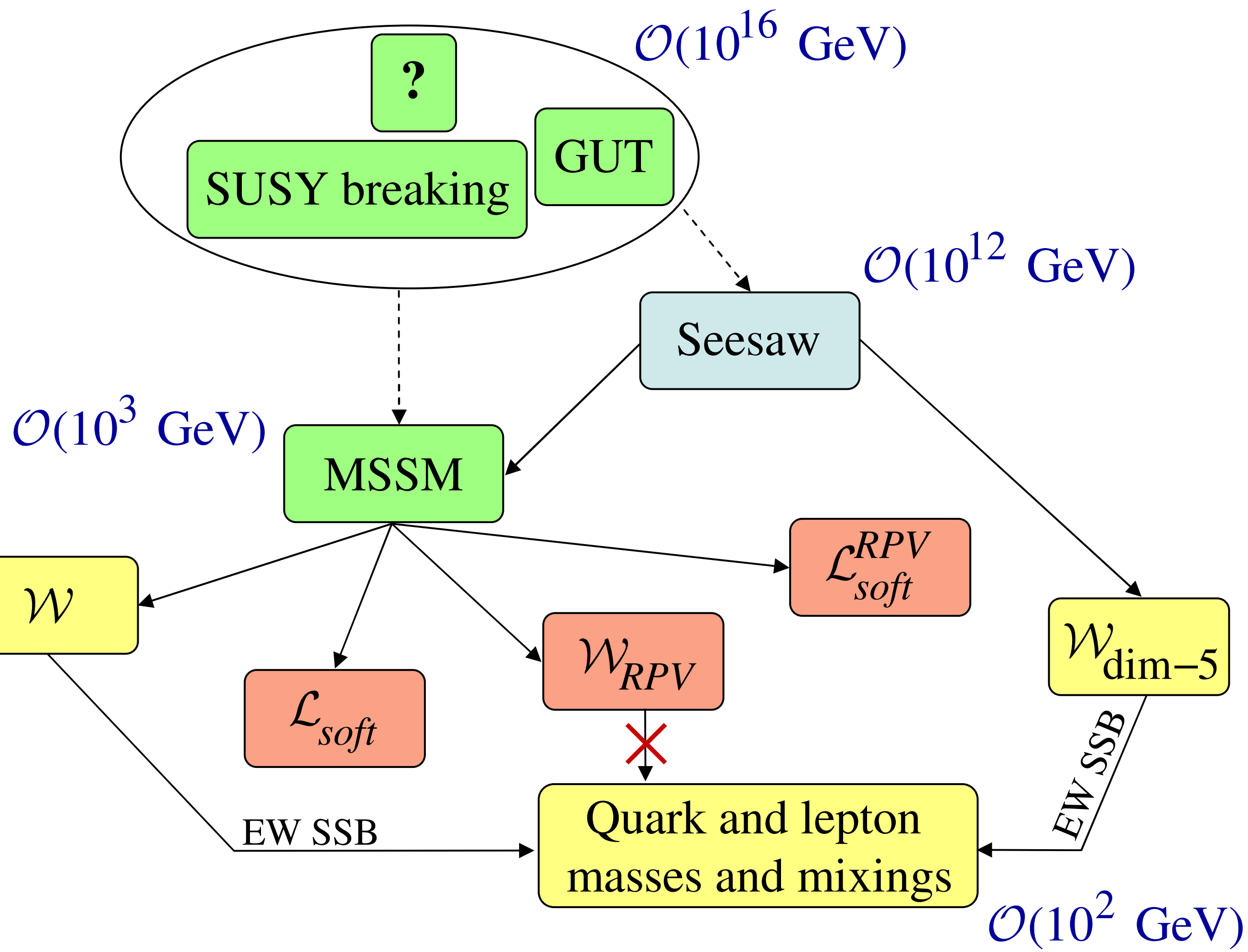
II. The MFV hypothesis

A. MFV and the origin of the flavor structures:



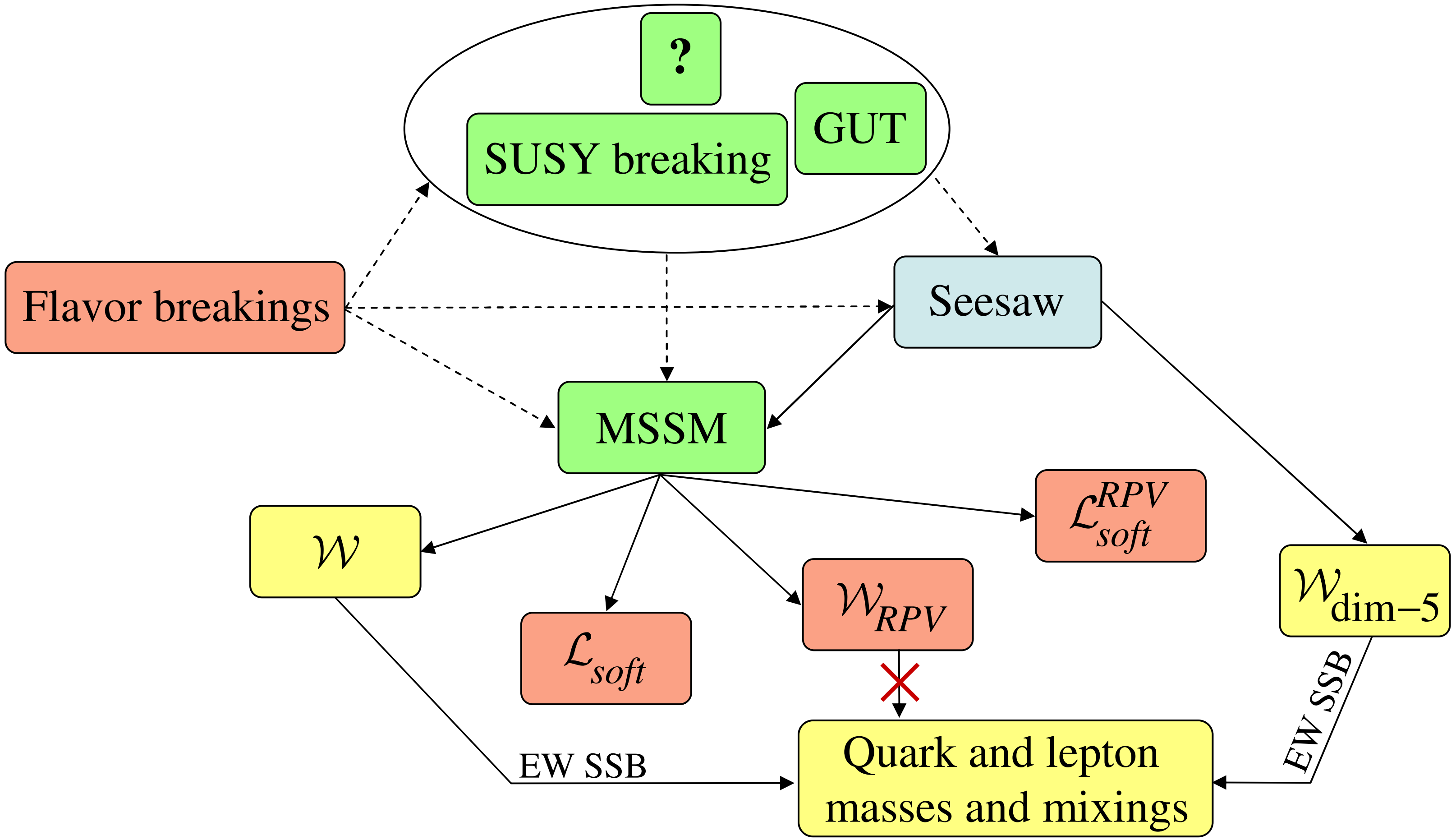
Only the flavor-breakings in the SM fermionic sector have been probed experimentally.

A. MFV and the origin of the flavor structures:



The MSSM is not the ultimate theory, but only a low-energy effective theory.

A. MFV and the origin of the flavor structures:



Some mechanism beyond the MSSM must explain the *origin of the flavor structures*.

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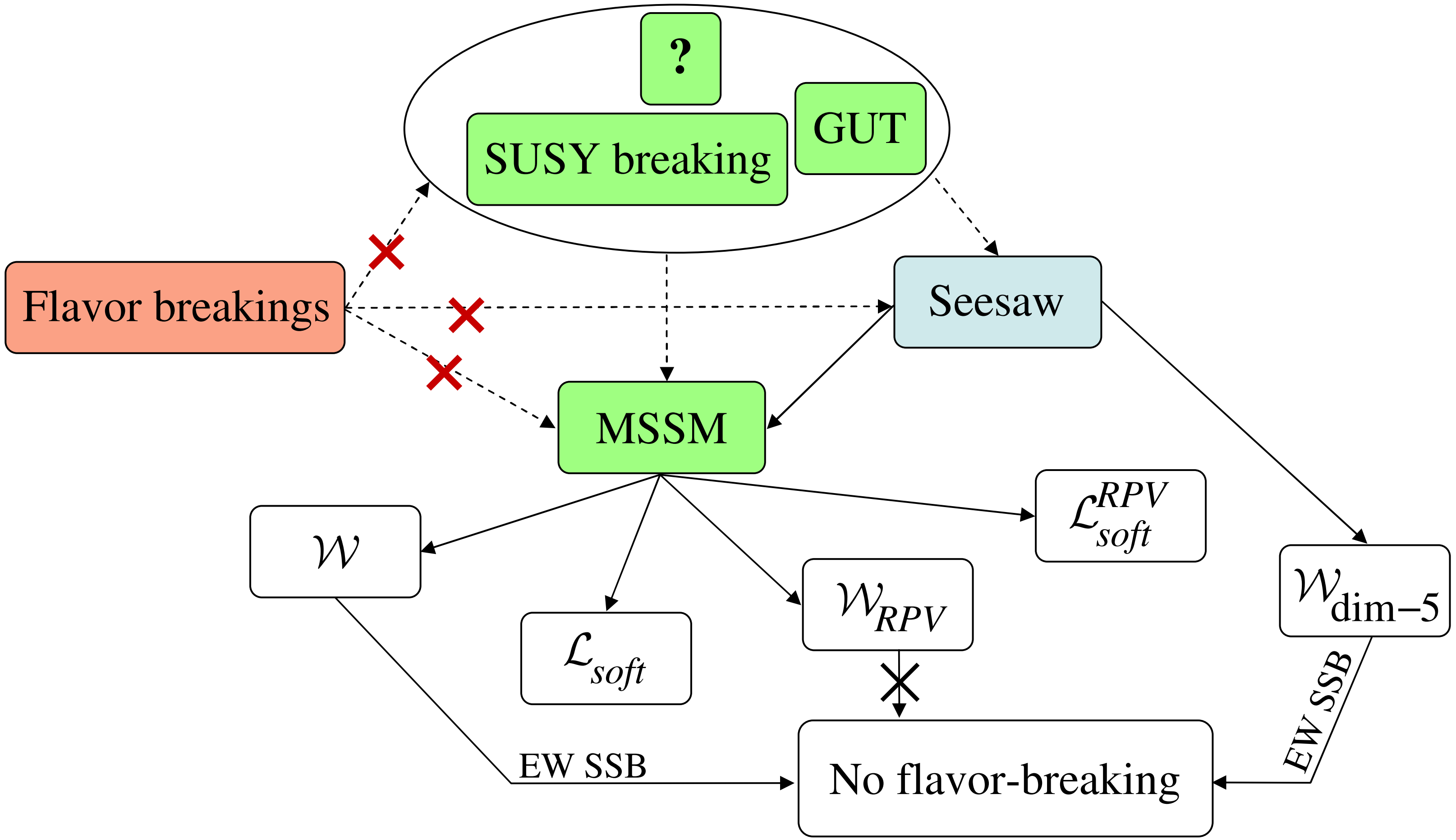

If this mechanism is turned off, *all* flavor-breaking terms become forbidden.

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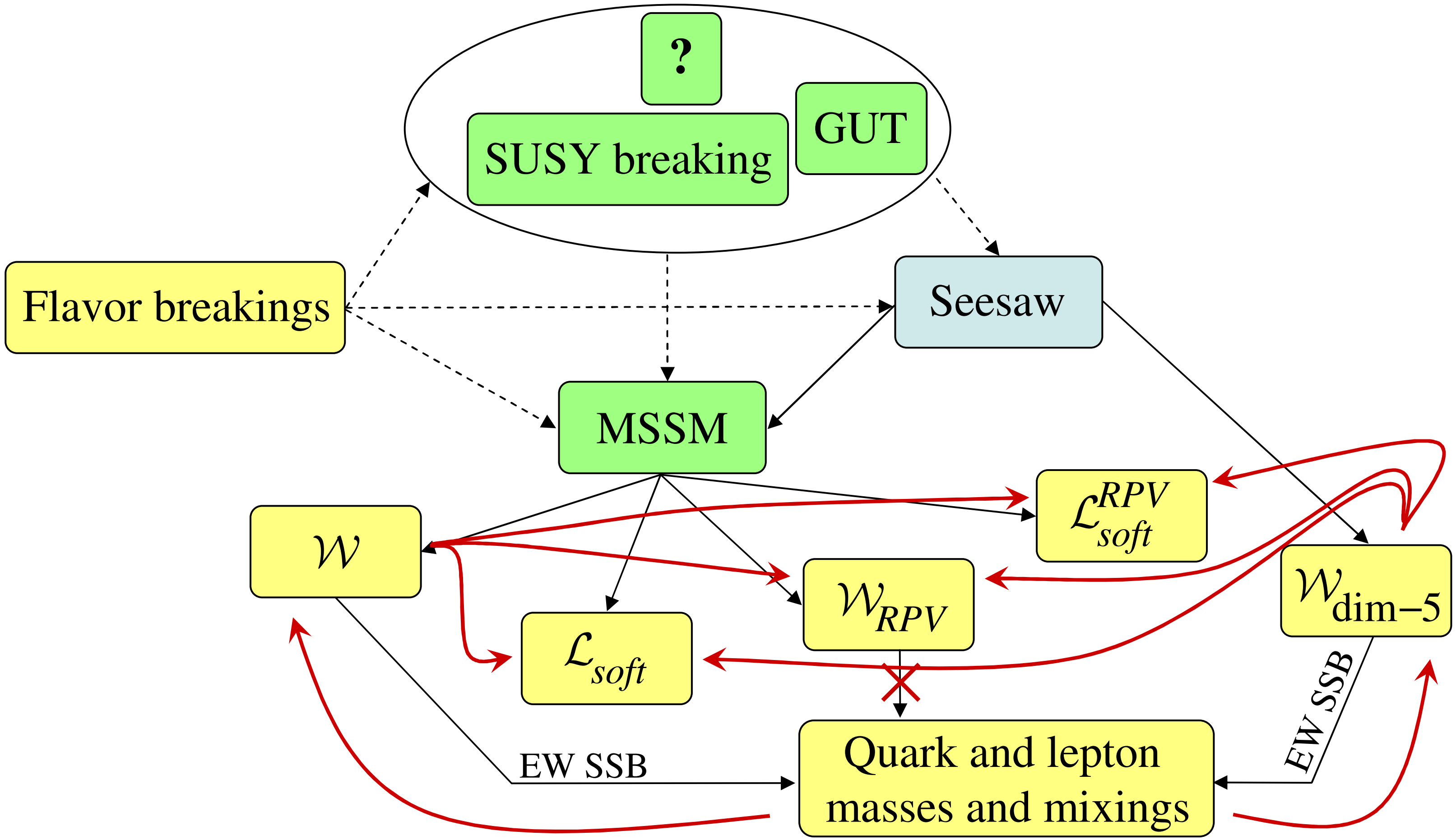


With MFV, all the flavor-breaking couplings are reconstructed in terms of the fermion masses and mixings, and become *naturally hierarchical*.

B. In practice:

- *Minimality hypothesis:* Minimal spurion content allowing for the known fermion masses and mixing - *this is the essence of MFV!*

Essentially, the Yukawas $\mathrm{Y}_u, \mathrm{Y}_d, \mathrm{Y}_e$ plus a few seesaw spurions.

- *Symmetry principle*: All Lagrangian couplings written as formal G_f -invariants

$$\mathbf{m}_Q^2 = m_0^2 (a_0 1 + a_1 \mathrm{Y}_u^\dagger \mathrm{Y}_u + a_2 \mathrm{Y}_d^\dagger \mathrm{Y}_d + \ldots) \quad \text{with} \quad a_i \sim \mathcal{O}(1) \quad \leftarrow \textit{naturality}$$

- *Freezing of the spurions* at their physical values:

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

$$\mathbf{m}_Q^2 \sim m_0^2 \left(\begin{pmatrix} 1 & 10^{-4} & 10^{-3} \\ 10^{-4} & 1 & 10^{-2} \\ 10^{-3} & 10^{-2} & 1 \end{pmatrix} + i \begin{pmatrix} 0 & 10^{-4} & 10^{-3} \\ 10^{-4} & 0 & 10^{-4} \\ 10^{-3} & 10^{-4} & 0 \end{pmatrix} \right)$$

These hierarchies come entirely from those of $\mathrm{Y}_u, \mathrm{Y}_d$.

C. MFV expansions in the quark sector

Hall,Randall '90, D'Ambrosio,Giudice, Isidori,Strumia '02, Colangelo,Nikolidakis,CS '08

- Only a *finite number* of terms thanks to Cayley-Hamilton identity:

$$\mathrm{X}^3 - \langle \mathrm{X} \rangle \mathrm{X}^2 + \tfrac{1}{2}\mathrm{X}(\langle \mathrm{X} \rangle^2 - \langle \mathrm{X}^2 \rangle) = \tfrac{1}{3}\langle \mathrm{X}^3 \rangle - \tfrac{1}{2}\langle \mathrm{X} \rangle \langle \mathrm{X}^2 \rangle + \tfrac{1}{6}\langle \mathrm{X} \rangle^3$$

- Use the large *mass hierarchy* to set $(\mathrm{Y}_i^\dagger \mathrm{Y}_i)^2 \sim \mathrm{Y}_i^\dagger \mathrm{Y}_i$, leaving:

$$\mathrm{A} \equiv \mathrm{Y}_u^\dagger \mathrm{Y}_u \qquad \mathrm{B} \equiv \mathrm{Y}_d^\dagger \mathrm{Y}_d$$

$$\mathbf{m}_Q^2 = m_0^2 (a_1 1 + a_2 \mathrm{A} + a_3 \mathrm{B} + a_4 \{\mathrm{A},\mathrm{B}\} + b_1 i[\mathrm{A},\mathrm{B}])$$

$$\mathbf{m}_U^2 = m_0^2 (a_5 1 + \mathrm{Y}_u (a_6 1 + a_7 \mathrm{B} + a_8 \{\mathrm{A},\mathrm{B}\} + b_2 i[\mathrm{A},\mathrm{B}]) \mathrm{Y}_u^\dagger)$$

$$\mathbf{m}_D^2 = m_0^2 (a_9 1 + \mathrm{Y}_d (a_{10} 1 + a_{11} \mathrm{A} + a_{12} \{\mathrm{A},\mathrm{B}\} + b_3 i[\mathrm{A},\mathrm{B}]) \mathrm{Y}_d^\dagger)$$

$$\mathbf{A}_u = A_0 \mathrm{Y}_u (c_1 1 + c_2 \mathrm{A} + c_3 \mathrm{B} + c_4 \{\mathrm{A},\mathrm{B}\} + d_1 i[\mathrm{A},\mathrm{B}])$$

$$\mathbf{A}_d = A_0 \mathrm{Y}_d (c_5 1 + c_6 \mathrm{A} + c_7 \mathrm{B} + c_8 \{\mathrm{A},\mathrm{B}\} + d_2 i[\mathrm{A},\mathrm{B}])$$

Using CH identities, all operators can be written as hermitian,

hence $a_i, b_i \in \mathbb{R}$, $c_i, d_i \in \mathbb{C}$ since scalar mass terms are hermitian.

D. MFV expansions in the lepton sector

- Integrating out the right-handed neutrinos:

Cirigliano,Grinstein Isidori,Wise '05

$$\mathrm{Y}_e\,,\qquad \mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu\,,\qquad \mathrm{Y}_\nu^T \mathrm{M}^{-1} \mathrm{Y}_\nu\,,\qquad \mathrm{Y}_\nu^\dagger \mathrm{M}^{-1*} \mathrm{M}^{-1} \mathrm{Y}_\nu\,,\quad \ldots$$

Lepton masses:

$$v_d \mathrm{Y}_e = \mathrm{m}_e$$

Neutrino masses:

$$v_u^2 \mathrm{Y}_\nu^T \mathrm{M}^{-1} \mathrm{Y}_\nu = U^* \mathrm{m}_\nu U^\dagger$$

Not completely fixed (we take $\mathrm{M} = M_R \mathbf{1}$):

$$v_u^2 \mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu = M_R U^* \mathrm{m}_\nu^{1/2} e^{2i\Phi} \mathrm{m}_\nu^{1/2} U^\dagger\,,\quad \Phi^{IJ} = \varepsilon^{IJK} \phi_K$$

Casas,Ibarra '01, Pascoli,Petcov, Yaguna '03,...

- More terms remain since there is no third-generation dominance for ν_L :

$$\mathbf{m}_L^2 = m_0^2 (a_1 \mathbf{1} + a_2 \mathrm{A} + a_3 \mathrm{B} + a_4 \mathrm{B}^2 + a_5 \{\mathrm{A},\mathrm{B}\} + a_6 \mathrm{BAB}$$
$$+ b_1 i[\mathrm{A},\mathrm{B}] + b_2 i[\mathrm{A},\mathrm{B}^2] + b_3 i(\mathrm{BAB}^2 - \mathrm{B}^2\mathrm{AB}))$$

$$\mathrm{A} \equiv \mathrm{Y}_e^\dagger \mathrm{Y}_e$$
$$\mathrm{B} \equiv \mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu$$

Similar for $\mathbf{m}_E^2$ and $\mathbf{A}_e$.

Mercolli,CS '09

E. How to test MFV?

Colangelo,Nikolidakis, CS '08
Nikolidakis '08, Mercolli, CS '09

Generically, all flavor couplings expanded under MFV involve:

$$Q = x_1 1 + x_2 \mathrm{A} + x_3 \mathrm{B} + x_4 \mathrm{B}^2 + x_5 \{\mathrm{A},\mathrm{B}\} + x_6 \mathrm{BAB} + x_7 i[\mathrm{A},\mathrm{B}] + x_8 i[\mathrm{A},\mathrm{B}^2] + x_9 i(\mathrm{BAB}^2 - \mathrm{B}^2\mathrm{AB})$$

$$(\mathrm{A} \equiv \mathrm{Y}_e^\dagger \mathrm{Y}_e, \mathrm{B} \equiv \mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu)$$

$$(\mathrm{A} \equiv \mathrm{Y}_d^\dagger \mathrm{Y}_d, \mathrm{B} \equiv \mathrm{Y}_u^\dagger \mathrm{Y}_u)$$

The MFV operators form a *complete basis* for the soft-breaking terms.

Allowing the coefficients to take any value → *full MSSM*.

However, the MFV basis is made of *nearly parallel operators*.

A generic matrix expanded in the MFV basis requires *huge coefficients*!

E. How to test MFV?

Generically, all flavor couplings expanded under MFV involve:

$$Q = x_1 1 + x_2 \mathrm{A} + x_3 \mathrm{B} + x_4 \mathrm{B}^2 + x_5 \{\mathrm{A},\mathrm{B}\} + x_6 \mathrm{BAB} \qquad (\mathrm{A} \equiv \mathrm{Y}_e^\dagger \mathrm{Y}_e, \mathrm{B} \equiv \mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu)$$

$$+ x_7 i[\mathrm{A},\mathrm{B}] + x_8 i[\mathrm{A},\mathrm{B}^2] + x_9 i(\mathrm{BAB}^2 - \mathrm{B}^2\mathrm{AB}) \qquad (\mathrm{A} \equiv \mathrm{Y}_d^\dagger \mathrm{Y}_d, \mathrm{B} \equiv \mathrm{Y}_u^\dagger \mathrm{Y}_u)$$

The MFV operators form a *complete basis* for the soft-breaking terms.

Allowing the coefficients to take any value → *full MSSM*.

MFV expansion coefficients versus Mass Insertions:

Same number of free parameters (choice of basis).

BUT: to each coefficient corresponds a *whole set of mass insertions*, with a *definite flavor pattern* inherited from those of the spurions.

↓

Permits to *test the naturality* of soft-breaking terms.

E. How to test MFV?

Generically, all flavor couplings expanded under MFV involve:

$$Q = x_1 1 + x_2 \mathrm{A} + x_3 \mathrm{B} + x_4 \mathrm{B}^2 + x_5 \{\mathrm{A},\mathrm{B}\} + x_6 \mathrm{BAB} + x_7 i[\mathrm{A},\mathrm{B}] + x_8 i[\mathrm{A},\mathrm{B}^2] + x_9 i(\mathrm{BAB}^2 - \mathrm{B}^2\mathrm{AB})$$

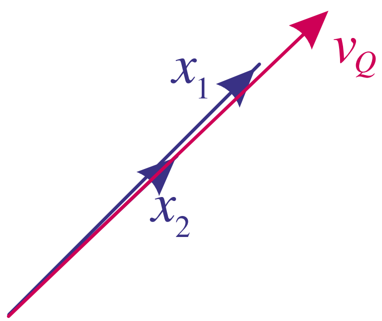
$$(\mathrm{A} \equiv \mathrm{Y}_e^\dagger \mathrm{Y}_e, \mathrm{B} \equiv \mathrm{Y}_\nu^\dagger \mathrm{Y}_\nu)$$

$$(\mathrm{A} \equiv \mathrm{Y}_d^\dagger \mathrm{Y}_d, \mathrm{B} \equiv \mathrm{Y}_u^\dagger \mathrm{Y}_u)$$

Imagine Q is constrained by experiment (collider + flavor).

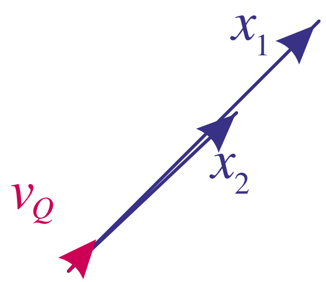
Three possible situations can arise when projecting Q in the MFV basis:

All the $x_i \sim O(1)$



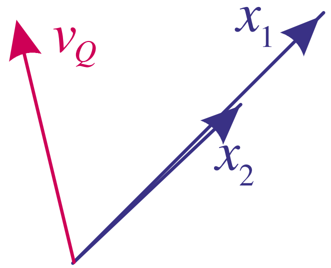
MFV flavor structure

Some of the $x_i \ll 1$



Fine-tuned flavor structure

Some of the $x_i \gg 1$



Generic flavor structure

E. How to test MFV?

Mercolli,C.S. '09

Current experimental constraints on the generic MSSM slepton sector:

m_L^2	(x_i / a_1)	m_R^2	(x_i / a_7)	$\mathrm{Re}\,A_e$	$(x_i / a_1 a_7)$	$\mathrm{Im}\,A_e$	$(x_i / a_1 a_7)$
a_1	*free*	a_7	*free*	$\mathrm{Re}\,c_1 \leq 10^2$	*stab.*	$\mathrm{Im}\,c_1 \leq 2$	d_e
$a_2 \leq 10^3$	*masses*	$a_8 \leq 10^3$	*masses*	$\mathrm{Re}\,c_2 \leq 10^3$	*stab.*	$\mathrm{Im}\,c_2 \leq 10^3$	*stab.*
$a_3 \leq 10$	$\mu \to e\gamma$	$a_9 \leq 10^6$	$\tau \to \mu\gamma$	$\mathrm{Re}\,c_3 \leq 10^3$	$\mu \to e\gamma$	$\mathrm{Im}\,c_3 \leq 10^3$	$\mu \to e\gamma$
$a_4 \leq 10^4$	$\mu \to e\gamma$	$a_{10} \leq 10^9$	$\tau \to \mu\gamma$	$\mathrm{Re}\,c_4 \leq 10^6$	$\mu \to e\gamma$	$\mathrm{Im}\,c_4 \leq 10^6$	$\mu \to e\gamma$
$a_5 \leq 10^3$	$\tau \to \mu\gamma$	$a_{11} \leq 10^7$	$\tau \to \mu\gamma$	$\mathrm{Re}\,c_5 \leq 10^5$	$\tau \to \mu\gamma$	$\mathrm{Im}\,c_5 \leq 10^5$	$\tau \to \mu\gamma$
$a_6 \leq 10^4$	$\mu \to e\gamma$	$a_{12} \leq 10^{11}$	$\tau \to \mu\gamma$	$\mathrm{Re}\,c_6 \leq 10^7$	$\mu \to e\gamma$	$\mathrm{Im}\,c_6 \leq 10^7$	$\mu \to e\gamma$
$b_1 \leq 10^3$	$\tau \to \mu\gamma$	$b_4 \leq 10^7$	$\tau \to \mu\gamma$	$\mathrm{Re}\,d_1 \leq 10^5$	$\tau \to \mu\gamma$	$\mathrm{Im}\,d_1 \leq 10^5$	$\tau \to \mu\gamma$
$b_2 \leq 10^6$	$\tau \to \mu\gamma$	$b_5 \leq 10^{10}$	$\tau \to \mu\gamma$	$\mathrm{Re}\,d_2 \leq 10^8$	$\tau \to \mu\gamma$	$\mathrm{Im}\,d_2 \leq 10^8$	$\tau \to \mu\gamma$
$b_3 \leq 10^8$	$\mu \to e\gamma$	$b_6 \leq 10^{13}$	$\tau \to \mu\gamma$	$\mathrm{Re}\,d_3 \leq 10^{10}$	$\mu \to e\gamma$	$\mathrm{Im}\,d_3 \leq 10^{10}$	$\mu \to e\gamma$

$M_{SUSY} \approx 500\,GeV,\ \tan\beta = 20,\ M_R = 10^{12}\,GeV, m_{L,R} \leq 4\,\mathrm{TeV}$

CPC *CPV*

F. Beyond MFV?

Within MFV, all flavor structures are related to that of the Yukawas.

Open questions:

- Why are the *Yukawa couplings so hierarchical*?
- Is there a *dynamical mechanism* behind MFV?

There is certainly something behind the Yukawa.

Explicit symmetry breaking ⟷ *Spontaneous symmetry breaking*

The approach followed here.

We assume a *minimal number of explicit breaking terms*.

Goldstone bosons?

Albrecht,Feldmann,Mannel '10

Discrete flavor symmetries?

Zwicky,Fischbacher '09

F. Beyond MFV?

C.S., in preparation

Even though the Yukawas are central for the MFV expansions, they need not be *the fundamental flavor structures!*

- Consider two low-energy flavor couplings A and B,
  (e.g., A = Yukawas, B = soft-breakings)

- Imagine there is a single fundamental spurion X at some high scale:

$$\mathrm{A} = x_0 1 + x_1 \mathrm{X} + x_2 \mathrm{X}^2 \quad \text{and} \quad \mathrm{B} = x'_0 1 + x'_1 \mathrm{X} + x'_2 \mathrm{X}^2 \quad \text{with} \quad x_i, x'_i \sim \mathcal{O}(1)$$

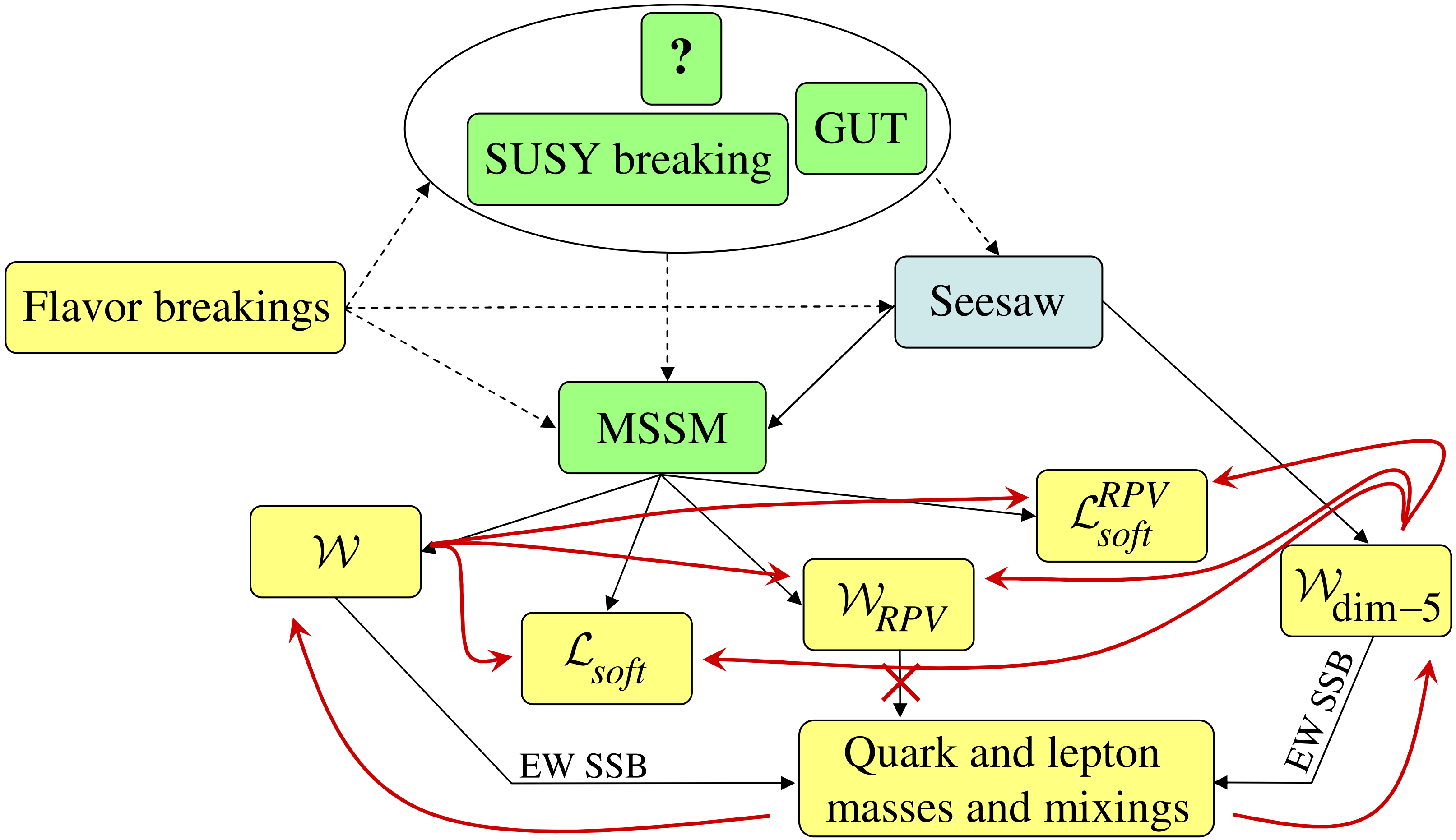
- Then, all that is observable is an MFV relation between A and B:

$$\mathrm{A} = a_0 1 + a_1 \mathrm{B} + a_2 \mathrm{B}^2 \quad \text{or} \quad \mathrm{B} = b_0 1 + b_1 \mathrm{A} + b_2 \mathrm{A}^2 \quad \text{with} \quad a_i, b_i \sim \mathcal{O}(1)$$

$\Longrightarrow$ *MFV only reflects a high-scale redundancy of the flavor structures*.

- Crucial to keep this in mind when trying to explain MFV or to extend it to GUT.

F. Beyond MFV?



The *flavor symmetry is always broken* (at all scale), but the *low-scale flavor structures are redundant*.

III. CP-violation under MFV

A. CP-violating phases in the MFV approach

Mercolli,C.S. '09

In the SM, CP-violation comes entirely from the phases in the spurions.

One in $\mathbf{Y}_u$ (Dirac), six in $\mathbf{Y}_\nu^\dagger \mathbf{Y}_\nu$ (1 Dirac, 2 Majorana, 3 from the ϕ_K)

Within MFV, there are several reasons for expecting *additional CP-phases*:

- The $U(3)^5$ does not say anything about CP-violating phases,

  All the *MFV coefficients are free complex parameters*.

- There can be new *CP-violating phases in other sectors*,

  CP-violation is a flavored phenomenon only in the SM!

- Potentially complex traces $\langle \mathbf{A}^l \mathbf{B}^m \mathbf{A}^n ... \rangle$ are $U(3)^5$ singlets,

  Absorbed in the coefficients: forcing them to stay real is a *fine-tuning*!

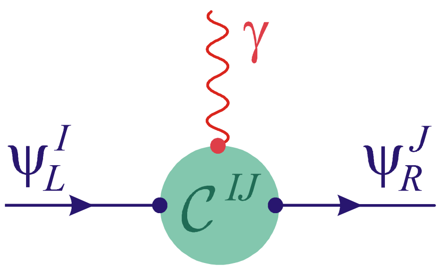
  (and is not RGE invariant)

B. Consequence: Is MFV breaking down?

MFV is very effective to *constrain flavor transitions* like $\ell^I \to \ell^J$ or $d^I \to d^J$.

But what about *flavor-diagonal* operators?

- Complex coefficients can induce additional *flavor-diagonal CP-phases*.
- Is this compatible with bounds on EDMs?



$$H_{eff} = C^{IJ}\,\bar{\psi}_L^I \sigma_{\mu\nu} \psi_R^J F^{\mu\nu} + C^{IJ*}\,\bar{\psi}_R^J \sigma_{\mu\nu} \psi_L^I F^{\mu\nu}$$

$I = J$ $\swarrow$ $\qquad$ $\searrow$ $I \neq J$

$$H_{eff} = C\,\bar{\psi}_L \sigma_{\mu\nu} \psi_R F^{\mu\nu} + C^*\,\bar{\psi}_L \sigma_{\mu\nu} \psi_R F^{\mu\nu}$$
$$= \mathrm{Re}\,C\,\bar{\psi}\sigma_{\mu\nu}\psi F^{\mu\nu} + i\,\mathrm{Im}\,C\,\bar{\psi}\sigma_{\mu\nu}\gamma_5\psi F^{\mu\nu}$$
$$\mathrm{Re}\,C \equiv e\frac{a}{4m} \qquad \mathrm{Im}\,C \equiv \frac{d}{2}$$

$$B(\psi^I \to \psi^J \gamma) \sim \left|C^{IJ}\right|^2$$

C. Classification of the CP-phases

$\mathbf{A} \equiv \mathbf{Y}_e^\dagger \mathbf{Y}_e$

$\mathbf{B} \equiv \mathbf{Y}_\nu^\dagger \mathbf{Y}_\nu$

MFV expansions, with $a_i, b_i \in \mathbb{R},\ c_i, d_i \in \mathbb{C}$:

$$\mathbf{m}_L^2 = m_0^2(a_1\mathbf{1} + a_2\mathbf{A} + a_3\mathbf{B} + a_5\{\mathbf{A},\mathbf{B}\} + a_6\mathbf{BAB} + b_1 i[\mathbf{A},\mathbf{B}] + \mathcal{O}(\mathbf{A}^2,\mathbf{B}^2)),$$

$$\mathbf{m}_E^2 = m_0^2(a_7\mathbf{1} + \mathbf{Y}_e(a_8\mathbf{1} + a_9\mathbf{B} + a_{11}\{\mathbf{A},\mathbf{B}\} + b_4 i[\mathbf{A},\mathbf{B}])\mathbf{Y}_e^\dagger + \mathcal{O}(\mathbf{A}^2,\mathbf{B}^2)),$$

$$\mathbf{A}_e = A_0\mathbf{Y}_e(c_1\mathbf{1} + c_2\mathbf{A} + c_3\mathbf{B} + c_5\{\mathbf{A},\mathbf{B}\} + d_1 i[\mathbf{A},\mathbf{B}] + \mathcal{O}(\mathbf{A}^2,\mathbf{B}^2))$$

C. Classification of the CP-phases

$\mathrm{A} \equiv \mathrm{Y}_e^\dagger \mathrm{Y}_e$

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MFV expansions, with $a_i, b_i \in \mathbb{R},\ c_i, d_i \in \mathbb{C}$:

$$\mathbf{m}_L^2 = m_0^2(a_1 1 + a_2 \mathrm{A} + a_3 \mathrm{B} + a_5\{\mathrm{A},\mathrm{B}\} + a_6 \mathrm{BAB} + b_1 i[\mathrm{A},\mathrm{B}] + \mathcal{O}(\mathrm{A}^2,\mathrm{B}^2)),$$

$$\mathbf{m}_E^2 = m_0^2(a_7 1 + \mathrm{Y}_e(a_8 1 + a_9 \mathrm{B} + a_{11}\{\mathrm{A},\mathrm{B}\} + b_4 i[\mathrm{A},\mathrm{B}])\mathrm{Y}_e^\dagger + \mathcal{O}(\mathrm{A}^2,\mathrm{B}^2)),$$

$$\mathbf{A}_e = A_0 \mathrm{Y}_e(c_1 1 + c_2 \mathrm{A} + c_3 \mathrm{B} + c_5\{\mathrm{A},\mathrm{B}\} + d_1 i[\mathrm{A},\mathrm{B}] + \mathcal{O}(\mathrm{A}^2,\mathrm{B}^2))$$

In the slepton sector: 15 CP-violating coefficients + 6 spurion phases

In the squark sector: 13 CP-violating coefficients + 1 spurion phase

$\Rightarrow$ *Plenty of new CP-phases in MFV!*

C. Classification of the CP-phases

$$\mathbf{A} \equiv \mathbf{Y}_e^\dagger \mathbf{Y}_e$$

$$\mathbf{B} \equiv \mathbf{Y}_\nu^\dagger \mathbf{Y}_\nu$$

MFV expansions, with $a_i, b_i \in \mathbb{R}$, $c_i, d_i \in \mathbb{C}$:

$$\mathbf{m}_L^2 = m_0^2 (a_1 \mathbf{1} + a_2 \mathbf{A} + a_3 \mathbf{B} + a_5 \{\mathbf{A},\mathbf{B}\} + a_6 \mathbf{BAB} + b_1 i[\mathbf{A},\mathbf{B}] + \mathcal{O}(\mathbf{A}^2,\mathbf{B}^2)),$$

$$\mathbf{m}_E^2 = m_0^2 (a_7 \mathbf{1} + \mathbf{Y}_e (a_8 \mathbf{1} + a_9 \mathbf{B} + a_{11} \{\mathbf{A},\mathbf{B}\} + b_4 i[\mathbf{A},\mathbf{B}]) \mathbf{Y}_e^\dagger + \mathcal{O}(\mathbf{A}^2,\mathbf{B}^2)),$$

$$\mathbf{A}_e = A_0 \mathbf{Y}_e (c_1 \mathbf{1} + c_2 \mathbf{A} + c_3 \mathbf{B} + c_5 \{\mathbf{A},\mathbf{B}\} + d_1 i[\mathbf{A},\mathbf{B}] + \mathcal{O}(\mathbf{A}^2,\mathbf{B}^2))$$

Flavor-blind

Overall phase, relative to $\mu, M_1, M_2, \ldots$

Contributes to $diag(\mathbf{A}_e)$.

Flavor-diagonal

Contribute to $diag(\mathbf{A}_e)$.

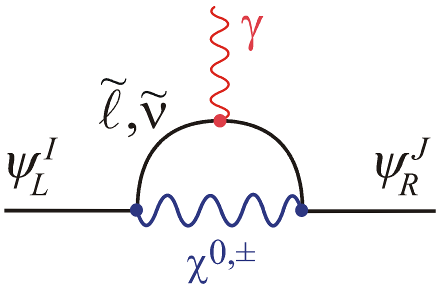
Flavor-off diagonal

Do not contribute to $diag(\mathbf{A}_e, \mathbf{m}_{L,E}^2)$.

(Remember: $\mathbf{Y}_i^\dagger \mathbf{Y}_i$ is hermitian)

D. Impact on the EDMs and LFV processes

A single operator dominates for $\mu \to e\gamma \sim |(\mathbf{m}_L^2 + \ldots)^{12}|^2$:



$$B(\mu \to e\gamma) \sim \frac{\alpha M_W^4 \tan^2\beta}{M_{SUSY}^4} \left| \frac{a_3}{a_1} (\mathbf{Y}_\nu^\dagger \mathbf{Y}_\nu)^{12} \right|^2$$

A single operator per type of phases dominates for $d_e \sim \operatorname{Im} diag(\mathbf{A}_e + \ldots)$:

$$\frac{d_e}{e} \sim \frac{\alpha m_e}{M_{SUSY}^2} \left(\frac{\operatorname{Im} c_1}{a_1 a_7} + \frac{\operatorname{Im} c_3}{a_1 a_7} \mathbf{Y}_\nu^\dagger \mathbf{Y}_\nu - \frac{b_1 \operatorname{Re} c_3}{a_1^2 a_7} [\mathbf{Y}_\nu^\dagger \mathbf{Y}_\nu, \mathbf{Y}_e^\dagger \mathbf{Y}_e] \mathbf{Y}_\nu^\dagger \mathbf{Y}_\nu + \ldots \right)^{11}$$

Flavor-blind

Flavor-diagonal

Flavor off-diagonal
(≥ neutrino phases)

Remark: $m_L^2 \approx m_0^2 a_1$, $m_R^2 \approx m_0^2 a_7$

D. Impact on the EDMs and LFV processes

A single operator dominates for $\mu \to e\gamma$:

$$B(\mu \to e\gamma) \sim \frac{\alpha M_W^4 \tan^2\beta}{M_{SUSY}^4} \left| \frac{a_3}{a_1} \frac{M_R \Delta m_{21}}{v_u^2} \right|^2$$

A single operator per type of phases dominates for d_e :

$$\frac{d_e}{e} \sim \frac{\alpha m_e}{M_{SUSY}^2} \left(\frac{\mathrm{Im}\, c_1}{a_1 a_7} + \frac{\mathrm{Im}\, c_3}{a_1 a_7} \frac{M_R \Delta m_{21}}{v_u^2} - \frac{b_1 \mathrm{Re}\, c_3}{a_1^2 a_7} \frac{m_\tau^2}{v_d^2} \left(\frac{M_R \Delta m_{21}}{v_u^2} \right)^2 + \ldots \right)^{11}$$

Flavor-blind → $M_{SUSY} \approx 500\, GeV$

Flavor-diagonal

Flavor off-diagonal
(≥ neutrino phases)

D. Impact on the EDMs and LFV processes

A single operator dominates for $\mu \to e\gamma$:

$$B(\mu \to e\gamma) \sim \frac{\alpha M_W^4 \tan^2\beta}{M_{SUSY}^4} \left| \frac{a_3}{a_1} \frac{M_R \Delta m_{21}}{v_u^2} \right|^2$$

$$\Rightarrow M_R \leq 10^{13}\, GeV$$

A single operator per type of phases dominates for d_e :

$$\frac{d_e}{e} \sim \frac{\alpha m_e}{M_{SUSY}^2} \left(\frac{\mathrm{Im}\, c_1}{a_1 a_7} + \frac{\mathrm{Im}\, c_3}{a_1 a_7} \frac{M_R \Delta m_{21}}{v_u^2} - \frac{b_1 \mathrm{Re}\, c_3}{a_1^2 a_7} \frac{m_\tau^2}{v_d^2} \left(\frac{M_R \Delta m_{21}}{v_u^2} \right)^2 + \ldots \right)^{11}$$

Flavor-blind — *Flavor-diagonal* — *Flavor off-diagonal* (≥ neutrino phases)

Flavor-blind ↓

$$M_{SUSY} \approx 500\, GeV$$

$$\Delta m_{21} \approx \sqrt{\Delta m_\odot^2} \approx 10^{-9} - 10^{-11}\, GeV$$

D. Impact on the EDMs and LFV processes

A single operator dominates for $\mu \to e\gamma$:

$$B(\mu \to e\gamma) \sim \frac{\alpha M_W^4 \tan^2\beta}{M_{SUSY}^4} \left| \frac{a_3}{a_1} \frac{M_R \Delta m_{21}}{v_u^2} \right|^2 \qquad \Rightarrow M_R \leq 10^{13}\, GeV$$

A single operator per type of phases dominates for d_e :

$$\frac{d_e}{e} \sim \frac{\alpha m_e}{M_{SUSY}^2} \left(\frac{\mathrm{Im}\, c_1}{a_1 a_7} + \frac{\mathrm{Im}\, c_3}{a_1 a_7} \frac{M_R \Delta m_{21}}{v_u^2} - \frac{b_1 \mathrm{Re}\, c_3}{a_1^2 a_7} \frac{m_\tau^2}{v_d^2} \left(\frac{M_R \Delta m_{21}}{v_u^2} \right)^2 + \ldots \right)^{11}$$

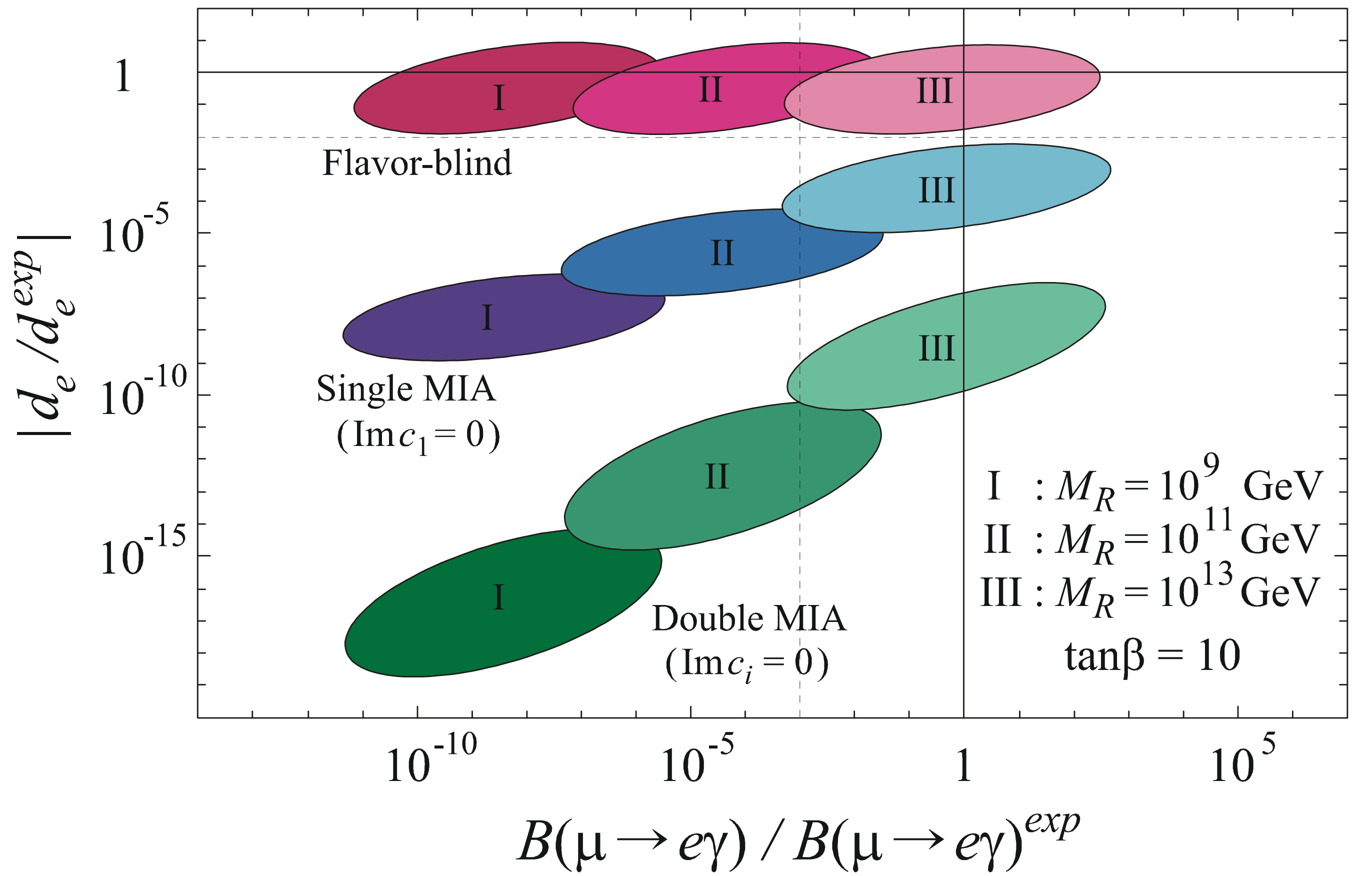
Flavor-blind $\gg$ *Flavor-diagonal* $\gg$ *Flavor off-diagonal* (≥ neutrino phases)

$$M_{SUSY} \approx 500\, GeV$$

$$\Delta m_{21} \approx \sqrt{\Delta m_\odot^2} \approx 10^{-9} - 10^{-11}\, GeV$$

D. Impact on the EDMs and LFV processes

Mercolli,C.S. '09



$$M_2 = \pm\mu = 2M_1 = 2/3m_0 = A_0 = 400\,GeV,\ a_i, b_i, c_i, d_i \in \pm[0.1, 8]$$

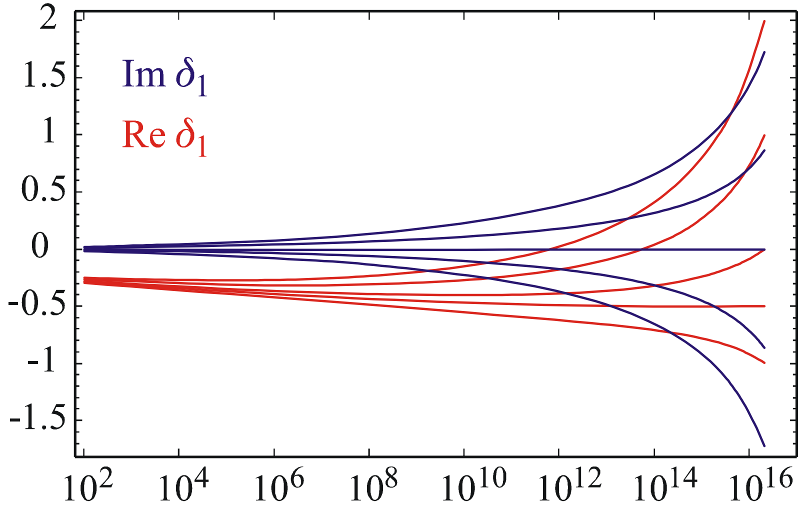
Exp. bounds: $B(\mu \to e\gamma) < 1.2\times10^{-11}$ and $d_e < 1.6\times10^{-27}\,e.cm.$

IV. RGE behavior

The MFV expansions are RGE invariant, but to get the RGE invariance of MFV itself requires in addition that the *coefficients must remain of $\mathcal{O}(1)$ at all scales*.

Running down from MFV at the GUT scale:

- *IR fixed-points* for ratios of coefficients ↔ predictions for *mass insertions.*
- In particular, all *CP-violating phases* run towards zero (in the quark sector).



$$\delta_1 \equiv \frac{(\delta^U_{RL})^{32}}{V_{ts}} = \frac{(\delta^U_{RL})^{31}}{V_{td}}$$

Paradisi,Ratz,Schieren,Simonetto '08
Colangelo,Nikolidakis,C.S. '08

Running up from MFV at the EW scale:

- MFV is lost at the GUT scale if one starts far enough from the fixed points.

(*some ratios of coefficients explode*)

V. MFV and proton decay

A. MFV expansions and the flavor U(1) symmetries

Assume that the high-energy dynamics violates $\mathcal{B}$ and/or $\mathcal{L}$.

We want to parametrize the RPV couplings in terms of the spurions:

$$\mathcal{W}_{RPV} = \underbrace{\mu'^{I} L^{I} H_{d} + \lambda^{IJK} L^{I} L^{J} E^{K} + \lambda'^{IJK} L^{I} Q^{J} D^{K}}_{\Delta\mathcal{L}=1} + \underbrace{\lambda''^{IJK} U^{I} D^{J} D^{K}}_{\Delta\mathcal{B}=1}$$

Odd number of flavor indices → *MFV under* $SU(3)^5$ instead of $U(3)^5$,

and *use ε–tensors* to form invariants.

Expected since $\mathcal{B}$ *and* $\mathcal{L}$ are combinations of the flavor $U(1)$'s:

$$\begin{aligned} G_f &= SU(3)^5 \times U(1)_Q \times U(1)_U \times U(1)_D \times U(1)_L \times U(1)_E \\ &= SU(3)^5 \times U(1)_{\mathcal{B}} \times U(1)_{\mathcal{L}} \times U(1)_Y \times U(1)_{PQ} \times U(1)_E \end{aligned}$$

But note: It is not needed to break all five $U(1)$'s!

B. Intrinsic difference between $\Delta\mathcal{L}=1$ and $\Delta\mathcal{B}=1$ couplings

- The $\Delta\mathcal{B}=1$ *couplings can be constructed* using $\Delta\mathcal{B}=0$ quark Yukawas:

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

- But $\Delta\mathcal{L}=1$ *couplings are strictly forbidden* as long as $m_\nu = 0$:

A $\Delta\mathcal{L}=0$ Dirac mass term for ν_L does not help either...

The SU(3) combinatorics demand a spurion transforming like a six.

The only such spurion available is the $\Delta\mathcal{L}=2$ Majorana mass term:

$$\Upsilon_\nu \equiv v_u \mathrm{Y}_\nu^T \mathrm{M}^{-1}\mathrm{Y}_\nu \to g_L^* \Upsilon_\nu g_L^\dagger \qquad \sim 6_{SU(3)_L} \otimes 1_{SU(3)_E}$$

All $\Delta\mathcal{L}=1$ couplings are suppressed by neutrino masses!!!

B. Intrinsic difference between $\Delta\mathcal{L}=1$ and $\Delta\mathcal{B}=1$ couplings

- The $\Delta\mathcal{B}=1$ *couplings can be constructed* using $\Delta\mathcal{B}=0$ quark Yukawas:

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$\cdots$

- But $\Delta\mathcal{L}=1$ *couplings are strictly forbidden* as long as $m_\nu = 0$*:*

Note: In some sense, $\Upsilon_\nu \equiv v_u \mathbf{Y}_\nu^T \mathbf{M}^{-1}\mathbf{Y}_\nu \sim \mathcal{O}(m_\nu / v_u) \ll 1$ by construction.

Why not take instead $\Upsilon'_\nu \equiv \langle\mathbf{M}\rangle\, \mathbf{Y}_\nu^T \mathbf{M}^{-1}\mathbf{Y}_\nu \sim \mathcal{O}(1)$ for example?

Davidson,Descotes-Genon '10

This ambiguity boils down to a question of scales:

$$\mu', \lambda, \lambda' = \frac{v_u}{\Lambda_{\Delta\mathcal{L}=1}}\Upsilon'_\nu(a_0 1 + \ldots) = \frac{\langle\mathbf{M}\rangle}{\Lambda_{\Delta\mathcal{L}=1}}\Upsilon_\nu(a_0 1 + \ldots) = \frac{\Lambda_{\Delta\mathcal{L}=2}}{\Lambda_{\Delta\mathcal{L}=1}}\Upsilon_\nu(a_0 1 + \ldots)$$

So, our normalization implicitly assumes $\Lambda_{\Delta\mathcal{L}=1} \approx \Lambda_{\Delta\mathcal{L}=2}$.

C. What happens in the SM? (Remember MFV is exact in the SM!)

- *No renormalizable interaction* can break $\mathcal{B}$ or $\mathcal{L}$.

- Simplest $\Delta\mathcal{B}$ and $\Delta\mathcal{L}$ *effective operators* are dimension-six:

$$\mathcal{L}_{\Delta(\mathcal{B}+\mathcal{L})} = \frac{1}{M_W^2}\left(c_1^{IJKL} L^I Q^J Q^K Q^L + c_2^{IJKL} E^I U^J U^K D^L + c_3^{IJKL} E^I U^J Q^{\dagger K} Q^{\dagger L} + c_4^{IJKL} L^I Q^J D^{\dagger K} U^{\dagger L}\right)$$

Weinberg '79

$\rightarrow$ Only generated when $m_\nu \neq 0$, and thus c_i *very suppressed!*

(here one automatically gets $\Lambda_{\Delta\mathcal{L}=1} \approx \Lambda_{\Delta\mathcal{L}=2}$)

Zwicky,CS, in preparation

- *Instanton effects* break $\mathcal{B}+\mathcal{L}$, exist for $m_\nu = 0$, but are $\mathcal{O}(10^{-165})$:

$$\mathcal{L}_{\Delta(\mathcal{B}+\mathcal{L})} \sim e^{-4\pi \sin^2\theta_W/\alpha}\left(\varepsilon_{IJK} L^I L^J L^K\right)\left(\varepsilon_{IJK} Q^I Q^J Q^K\right)^3$$

t'Hooft '76

Respect MFV but only under $G_f = SU(3)^5 \times U(1)_U \times U(1)_D \times U(1)_E$.

D. MFV for the R-parity violating terms of the MSSM:

Nikolidakis, C.S. '07

Structures ($\mathcal{W}_{RPV} = \mu' L H_d + \lambda LLE + \lambda' LQD + \lambda'' UDD$)		Scaling	Breaking
$\mu_1'^{I}$	$\mu\, \varepsilon^{STI} (Y_e^\dagger Y_e \Upsilon_\nu^\dagger)^{ST}, \ldots$	$\tan^2\beta$	$U(1)_L$
λ_1^{IJK}	$\varepsilon^{STI} (Y_e^\dagger Y_e \Upsilon_\nu^\dagger)^{ST} (Y_e)^{KJ}, \ldots$	$\tan^3\beta$	$U(1)_L$
λ_2^{IJK}	$\varepsilon^{IMJ} (Y_e \Upsilon_\nu^\dagger)^{KM}, \ldots$	$\tan\beta$	$U(1)_L$
λ_3^{IJK}	$\varepsilon^{STI} (Y_e^\dagger Y_e \Upsilon_\nu^\dagger)^{ST} \varepsilon^{LMJ} \varepsilon^{ABK} (Y_e^\dagger)^{LA} (Y_e^\dagger)^{MB}, \ldots$	$\tan^4\beta$	$U(1)_{L,E}$
$\lambda_1'^{IJK}$	$\varepsilon^{STI} (Y_e^\dagger Y_e \Upsilon_\nu^\dagger)^{ST} (Y_d)^{KJ}, \ldots$	$\tan^3\beta$	$U(1)_L$
$\lambda_2'^{IJK}$	$\varepsilon^{STI} (Y_e^\dagger Y_e \Upsilon_\nu^\dagger)^{ST} \varepsilon^{LMJ} \varepsilon^{ABK} (Y_d^\dagger)^{LA} (Y_d^\dagger)^{MB}, \ldots$	$\tan^4\beta$	$U(1)_{L,D,Q}$
$\lambda_1''^{IJK}$	$\varepsilon^{LJK} (Y_u Y_d^\dagger)^{IL}, \ldots$	$\tan\beta$	$U(1)_D$
$\lambda_2''^{IJK}$	$\varepsilon^{IMN} (Y_d Y_u^\dagger)^{JM} (Y_d Y_u^\dagger)^{KN}, \ldots$	$\tan^2\beta$	$U(1)_U$
$\lambda_3''^{IJK}$	$\varepsilon^{LMN} (Y_u)^{IL} (Y_d)^{JM} (Y_d)^{KN}, \ldots$	$\tan^2\beta$	$U(1)_Q$
$\lambda_4''^{IJK}$	$\varepsilon^{LMN} \varepsilon^{ABI} \varepsilon^{CJK} (Y_d^\dagger)^{LC} (Y_u^\dagger)^{MA} (Y_u^\dagger)^{NB}, \ldots$	$\tan\beta$	$U(1)_{Q,U,D}$

(Similar expansions for R-parity violating soft-breaking terms)

E. Check of the bounds on R-parity violating couplings

In addition to the *neutrino mass factor* $\Upsilon_\nu \sim \mathcal{O}(m_\nu / v_u) \sim \mathcal{O}(10^{-12})$, ε-tensor antisymmetry forces all couplings to be proportional to *light-fermion masses*:

Ex: $\varepsilon^{LMN}\mathbf{Y}_u^{IL}\mathbf{Y}_d^{JM}\mathbf{Y}_d^{KN} \to \varepsilon^{123}\mathbf{Y}_u^{I1}\mathbf{Y}_d^{J2}\mathbf{Y}_d^{K3} + \ldots \to \frac{m_u}{v_u}\frac{m_s}{v_d}\frac{m_b}{v_d} + \ldots$

Are these two mechanisms sufficient to pass experimental bounds ?

Hundreds of bounds, most rather weak and immediately satisfied.

(LFV & FCNC, EDM's, $n - \bar{n}$ oscillations, EWPO,...)

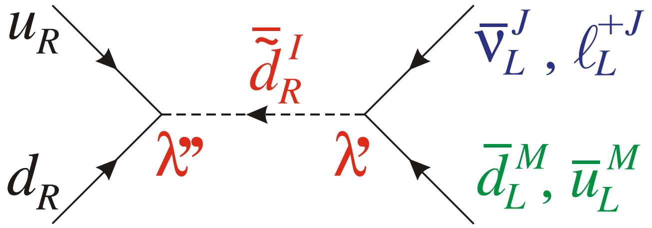
Toughest constraints from $\Delta\mathcal{B} = 1$ *nucleon decays, i.e.* $p, n \to \pi\nu, \pi\ell, K\nu, K\ell, \ldots$

Bounds on various combinations $|(\mu', \lambda, \lambda') \times \lambda''|$,

For some $IJK, I'J'K'$, as constraining as $|\lambda'_{IJK}\lambda''_{I'J'K'}| < 10^{-25} - 10^{-27}$.

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

Example of MFV suppression for a specific proton decay mechanism



$$\Rightarrow \left|\lambda'_{JMI}\lambda''^{*}_{11I}\right| < 10^{-26}\left(m[\tilde{d}_R^I]/300\,GeV\right)^2$$

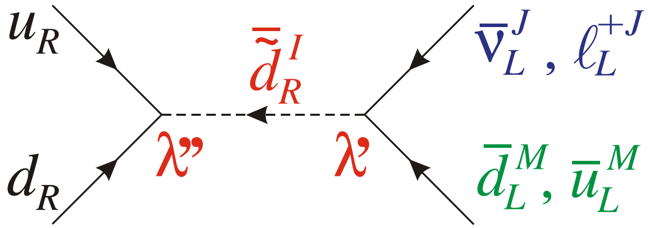
If the leading operators are: λ' : $\left(a_0\varepsilon^{LMI}\left(Y_e^\dagger Y_e \Upsilon_\nu^\dagger\right)^{LM}\left(Y_d Y_u^\dagger Y_u\right)^{KJ}\right) L^I Q^J D^K$

λ'' : $\left(a_1\varepsilon^{LJK}\left(Y_u Y_d^\dagger\right)^{IL} + a_2\varepsilon^{LMN} Y_u^{IL} Y_d^{JM} Y_d^{KN}\right) U^I D^J D^K$

The MFV prediction is then

$$\left|\lambda'_{JMI}\lambda''^{*}_{11I}\right| \approx \frac{\Delta m_{31}}{v_u}\frac{m_\tau^2}{v_d^2}\;\lambda^3\;\frac{m_b m_t^2 m_u}{v_d v_u^3}\left(a_0 a_1\frac{m_s}{v_d} + a_0 a_2\frac{m_d m_b}{v_d^2}\right)$$

Example of MFV suppression for a specific proton decay mechanism



$$\Rightarrow \left|\lambda'_{JMI}\lambda''^{*}_{11I}\right| < 10^{-26}\left(m[\tilde{d}_R^I]/300\,GeV\right)^2$$

If the leading operators are: $\lambda' \;:\; (a_0\varepsilon^{LMI}(\mathrm{Y}_e^\dagger \mathrm{Y}_e \Upsilon_\nu^\dagger)^{LM}(\mathrm{Y}_d \mathrm{Y}_u^\dagger \mathrm{Y}_u)^{KJ})\; L^I Q^J D^K$

$$\lambda'' \;:\; (a_1\varepsilon^{LJK}(\mathrm{Y}_u \mathrm{Y}_d^\dagger)^{IL} + a_2\varepsilon^{LMN}\mathrm{Y}_u^{IL}\mathrm{Y}_d^{JM}\mathrm{Y}_d^{KN})\; U^I D^J D^K$$

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Neutrino mass, related to $\Delta m^2_{atm} \approx 3\cdot 10^{-3}\,\mathrm{eV}^2$

Charged lepton mass

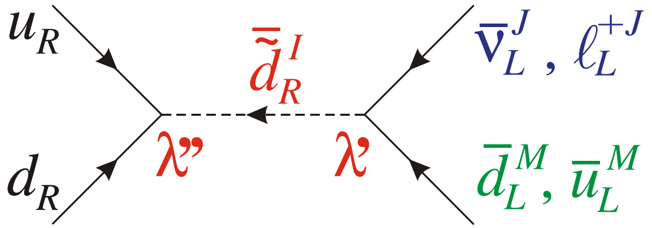
CKM factors

Light-quark masses

Symmetry of Υ_ν, the Majorana mass term

Antisymmetry of ε tensors

Example of MFV suppression for a specific proton decay mechanism



$$\Rightarrow \left|\lambda'_{JMI}\lambda''^{*}_{11I}\right| < 10^{-26}\left(m[\tilde{d}_R^I]/300\,GeV\right)^2$$

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$$\lambda''\ :\ (a_1\varepsilon^{LJK}(\mathrm{Y}_u \mathrm{Y}_d^\dagger)^{IL} + a_2\varepsilon^{LMN}\mathrm{Y}_u^{IL}\mathrm{Y}_d^{JM}\mathrm{Y}_d^{KN})\ U^I D^J D^K$$

The MFV prediction is then

$$\left|\lambda'_{JMI}\lambda''^{*}_{11I}\right| \approx \frac{\Delta m_{31}}{v_u}\frac{m_\tau^2}{v_d^2}\ \lambda^3\ \frac{m_b m_t^2 m_u}{v_d v_u^3}\left(a_0 a_1\frac{m_s}{v_d} + a_0 a_2\frac{m_d m_b}{v_d^2}\right)$$

$$\approx a_0 a_1 10^{-28}\tan^4\beta + a_0 a_2 10^{-31}\tan^5\beta \quad (for\ m_\nu^{lightest} = 0)$$

Conservatively, MFV can account for the necessary suppression.

- MFV coefficients of $\mathcal{O}(1)$, while $\mathcal{O}(\lambda)$ or $\mathcal{O}(g^2/4\pi)$ also natural,
- No GIM-like interferences, no cancellations among processes,

F. Where to expect significant experimental signals ?

1. Proton decay could be close to current bounds (worthy to pursue the search!)

2. Except for proton decay, lepton-number is effectively conserved.

(since $\mu', \lambda, \lambda' < \mathcal{O}(10^{-12})$)

3. MFV predictions for the baryonic couplings $\varepsilon^{abc} \lambda''^{IJK} U_a^I D_b^J D_c^K$:

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

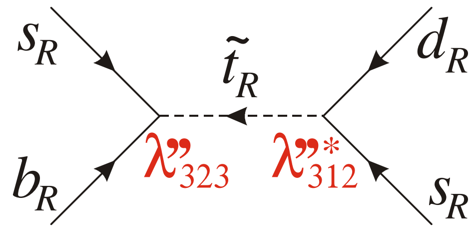
Notations : $x \equiv \mathcal{O}(10^{-x})$

$$\begin{pmatrix} 112 & 123 & 131 \\ 212 & 223 & 231 \\ 312 & 323 & 331 \end{pmatrix}$$

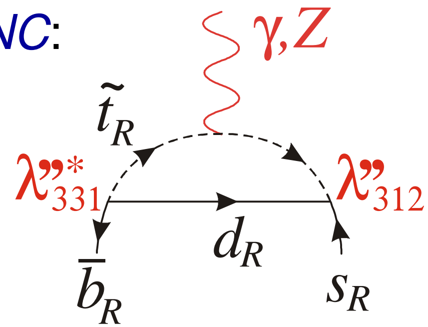
λ''_{312} → Sizeable $\tilde{t}_R d_R s_R$, $t_R \tilde{d}_R s_R$, $t_R d_R \tilde{s}_R$ couplings.

4. Probing $\Delta\mathcal{B} = 1$ interactions at low-energy:

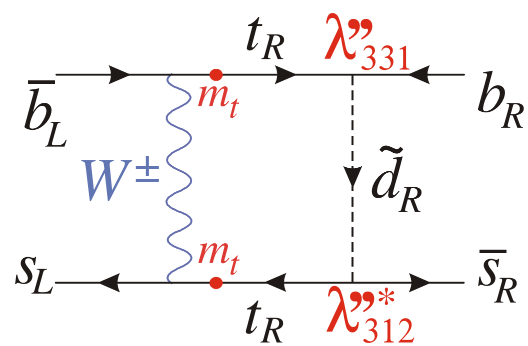
- Squarks as *diquark currents*:



- Induce *new FCNC*:



Chakraverty,Choudhury '01,...



...

Barbieri,Masiero '86, Slavich '00,...

- *With MFV,* these are *typically small* compared to the SM contributions:

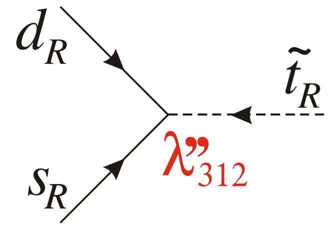
$$b \to s : \left|\lambda''_{312}\lambda''^{*}_{331}\right| < 10^{-3}, \quad b \to d : \left|\lambda''_{312}\lambda''^{*}_{323}\right| < 10^{-5}, \quad s \to d : \left|\lambda''_{313}\lambda''^{*}_{323}\right| < 10^{-8}$$

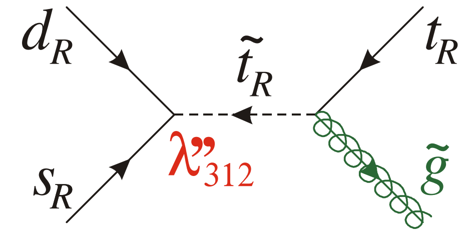
$$b \to s : \left|V^{*}_{tb}V_{ts}\right| \sim 10^{-2}, \qquad b \to d : \left|V^{*}_{tb}V_{td}\right| \sim 10^{-3}, \qquad s \to d : \left|V^{*}_{ts}V_{td}\right| \sim 10^{-4}$$

5. Probing $\Delta\mathcal{B}=1$ effects at colliders: drastic changes for the phenomenology.

- *Single stop* resonant production and associated *single gluino* production:

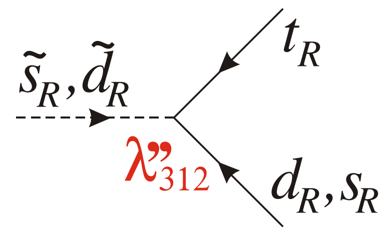
  Dimopoulos, Hall '88, Dreiner, Ross '91, Chaichan et al. '00, Allanach et al. '01,...



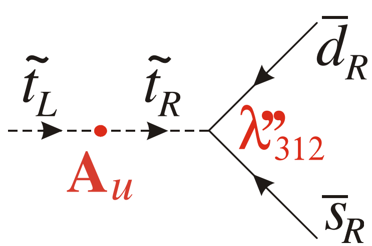


- *Top production*, from squark decay:

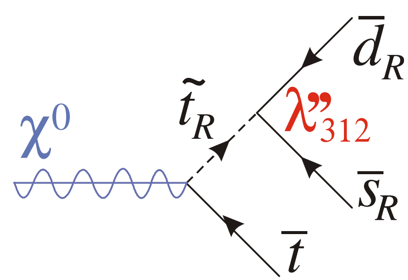
  Berger et al. '99, Chiappetta et al. '99,...



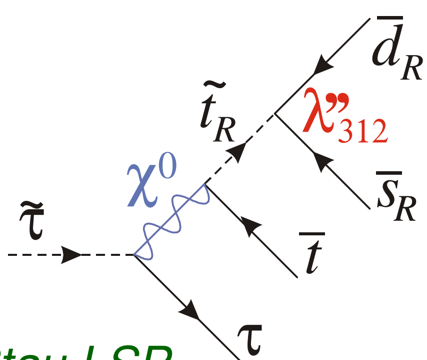
- *LSP* not necessarily colorless & neutral, and will *decay*, maybe in the detector:



Stop LSP



Neutralino LSP



Stau LSP

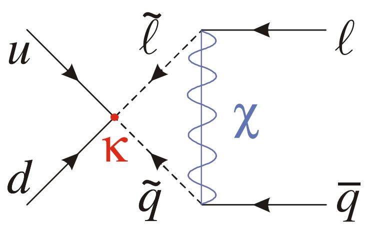
For a review of these and other possible signals, see e.g. Barbier et al. '05.

G. R-parity or not R-parity ?

- *Avoiding proton decay* is no longer a good motivation for R-parity.

- *Dim-5 R-parity conserving operators* can also induce proton decay:

Ibanez, Ross '92



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

MFV separately suppresses $\Delta\mathcal{L} = 1$ and $\Delta\mathcal{B} = 1$ effects.

- *GUT*: R-parity often built in ($SO(10)$-GUT) or required ($SU(5)$-GUT).

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

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

Cirigliano, Grinstein, Isidori, Wise '05

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

Baryon asymmetry generated from CPV, $\Delta\mathcal{B} = 1$ couplings?

Should experimentalists accept the burden of R-parity "only" for dark matter???

Conclusion

MFV, as a phenomenological hypothesis on the elementary flavor structures:

A single mechanism explaining: - *Smallness of susy effects in FCNC*
- *Extremely long proton lifetime*

Consequences of the *Yukawa hierarchies* and of the *small neutrino masses*.

MFV, as a window into physics beyond the MSSM:

It permits to *identify the flavor couplings which are fine-tuned* (none at present) out of those which are as "natural" as the SM Yukawas.

In particular, *the proton lifetime does not require fine-tuned RPV couplings*!

Since a *consistent picture emerges with only a few spurions*, the mechanism behind all the flavor structures could be relatively simple.

CP-violation is controlled by non-MFV physics, as expected from $Arg(\mu) \ll 1$.