Baryonic R-parity violation and its running

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Outline

R-parity violation

Still no signs of SUSY at the LHC:

- Current bounds are generally **at or above the TeV scale**

Turning on R-parity violation (RPV):

- Mass **bounds are relaxed**
- The lightest sparticle can decay
- MET signatures lost, **richer hadronic activities** expected

But...

- Generic RPV lead to **proton decay**, **neutron oscillations**...
- Light flavors RPV couplings should be tiny to pass those bounds
- Need **highly hierarchical** RPV couplings

Need an **alignment mechanism** with the **SM flavor structures**

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Flavor alignment

- The huge success of the SM in predicting flavor observables comes from its **highly hierarchical flavor structure**; the Yukawa couplings
- Need to **transmit** this **hierarchy** to the MSSM flavor couplings, *i.e.*, align the MSSM flavor couplings with the SM ones

We use the **minimal flavor violation** (**MFV**) approach to implement this flavor alignment within a well-defined **symmetry principle**.

- Under MFV, the $\Delta L=1$ couplings are proportionnal to the **Majorana neutrino masses**: either forbidden or of order $m_\nu/v \sim 10^{-12}$: not considered here.

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High scale alignment and low scale physics

Where does the alignment occur ?

- **High scale flavor dynamics** is yet unknown but well motivated
- Alignment is likely to derive from this flavor dynamics

We assume that it takes place at the **GUT scale**.

Is the alignment respected at the low scale ?

- Through the renormalization group (RG) evolution, the alignment does not need to remain valid
- If it does not, problems with flavor observables occur

Study of the RG behavior of the baryonic R-parity violating couplings (under MFV).

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Flavor symmetry in the SM, spurions

- The SM quark kinetic Lagrangian is invariant under the **global flavor symmetry** $G_F = U(3)^3 = U(3)_Q \times U(3)_U \times U(3)_D$:

$$\mathcal{L}_K = \sum_{k=Q,U,D} \bar{\psi}_k^I (i\not{D}_k \delta^{IJ}) \psi_k^J \xrightarrow{U(3)_k} \sum (\bar{\psi}_k g_k^\dagger)^I (i\not{D}_k \delta^{IJ})(g_k \psi_k)^J = \mathcal{L}_K.$$

- The Yukawa Lagrangian is the only source of **flavor breaking**:

$$\mathcal{L}_{Yukawa}^{quarks} = -U^I \mathbf{Y}_u^{IJ} Q^J H - D^I \mathbf{Y}_d^{IJ} Q^J H^* + h.c.$$

- **Recover** the flavor symmetry by assigning **well-chosen transformation properties** to the Yukawa couplings, *i.e.* promote them to **spurions**:

$$\mathbf{Y}_u \to g_U \mathbf{Y}_u g_Q^\dagger\,, \qquad \mathbf{Y}_d \to g_D \mathbf{Y}_d g_Q^\dagger.$$

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Minimal flavor violation

1. All flavor couplings are expressed in terms of the **Yukawa spurions** with the **appropriate G_F transformation**
2. **Naturality** criterion

- $\mathbf{F}^{\text{BSM}} = \sum_i c_i \mathcal{O}_i$ with $\mathcal{O}_i \sim \mathbf{F}^{\text{BSM}}$ under G_F
- **Minimal** violation of the flavor symmetry: only the **known flavor structures** at the origin of the observed masses and mixings are used to parametrize the flavor breaking: the Yukawa couplings
- **Natural** combinations ensure **alignment**, *i.e.*, the **SM flavor hierarchies** are **transmitted** to the BSM flavor couplings

R-parity violating MSSM

- RPV-MSSM (s)quark sector:

$$\mathcal{W}_{RPV} = U^I \mathbf{Y}_u^{IJ} Q^J H_u - D^I \mathbf{Y}_d^{IJ} Q^J H_d + \frac{1}{2} \mathbf{Y}_{udd}^{IJK} U^I D^J D^K$$

$$\mathcal{L}_{soft} = -\widetilde{Q}^\dagger \mathbf{m}_Q^2 \widetilde{Q} - \widetilde{U} \mathbf{m}_u^2 \widetilde{U}^\dagger - \widetilde{D} \mathbf{m}_d^2 \widetilde{D}^\dagger - \widetilde{U} \mathbf{A}_u \widetilde{Q} H_u - \widetilde{D} \mathbf{A}_d \widetilde{Q} H_d + \mathbf{A}_{udd}^{IJK} \widetilde{U}^I \widetilde{D}^J \widetilde{D}^K + h.c.$$

- 73 real RPC + 18 complex RPV flavor couplings, **all explicitly breaking $\mathbf{G_F}$**

$U(3)^3$ symmetry

- Generally used to bring all but either up- or down-type left quarks to their mass eigenstates:

$$v_u \mathbf{Y}_u = \mathbf{m}_u . \mathbf{V}_{CKM} \ , \quad v_d \mathbf{Y}_d = \mathbf{m}_d$$

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- Performing the same rotation on the squarks fields naturally **redefines** the $\mathbf{Y}_{udd}$ couplings and the soft terms

- The unitary matrices necessary to reach one of the two previous basis are **unknown**: **basis dependence** of all SUSY couplings

- Get around this dependence: express the **flavor couplings in terms of the Yukawa spurions**

Warm up: basis independent parametrisation of the soft terms

- Building block: $SU(3)_Q$ octets (**basis for $\mathcal{M}_3(\mathbb{C})$ matrices**)

$$\mathbf{O} = \mathbf{1} \oplus \mathbf{X}_u \oplus \mathbf{X}_d \oplus \mathbf{X}_u^2 \oplus \mathbf{X}_d^2 \oplus \{\mathbf{X}_u, \mathbf{X}_d\} \oplus i[\mathbf{X}_u, \mathbf{X}_d] \oplus i[\mathbf{X}_u^2, \mathbf{X}_d] \oplus i[\mathbf{X}_u, \mathbf{X}_d^2] \ ,$$

where $\mathbf{X}_{u,d} = \mathbf{Y}_{u,d}^\dagger \mathbf{Y}_{u,d}$ and $\mathbf{O} \to g_Q \mathbf{O} g_Q^\dagger$ under $g_Q \in U(3)_Q$.

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$$\mathbf{m}_Q^2/m_0^2 = a_1^q \mathbf{1} + a_2^q \mathbf{X}_u + a_3^q \mathbf{X}_d + a_4^q \mathbf{X}_u^2 + a_5^q \mathbf{X}_d^2 + a_6^q \{\mathbf{X}_u, \mathbf{X}_d\} + a_7^q i[\mathbf{X}_u, \mathbf{X}_d] + a_8^q i[\mathbf{X}_u^2, \mathbf{X}_d] + a_9^q i[\mathbf{X}_u, \mathbf{X}_d^2] = \mathbf{O}^{a^q}$$

$$\mathbf{A}_d/A_0 = \mathbf{Y}_d \mathbf{O}^{c^d}$$

MFV limit

$a_i^q, c_i^d \sim \mathcal{O}(1)$

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Basis independent parametrisation of the RPV sector

- Remember $\mathcal{W}_{RPV} \supset \frac{1}{2}\mathbf{Y}_{udd}^{IJK} U^I D^J D^K$, the 3 **simplest structures** having the right G_F transformation are:

$$(\mathbf{Y}_{udd}^{Q})^{IJK} \supset \epsilon_Q^{LMN} \mathbf{Y}_u^{IL} \mathbf{Y}_d^{JM} \mathbf{Y}_d^{KN}$$
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where either the ϵ tensor of $SU(3)_Q$, $SU(3)_U$, or $SU(3)_D$ is used.

- We will not study the $\mathbf{Y}_{udd}^{U}$ terms in the following
- The bases are then **completed** (insertion of $\mathbf{O}$ in all possible ways + Cayley-Hamilton theorem):

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MFV limit for the RPV couplings

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- Do we really need 2 $(+1)$ different bases to parametrize $\mathbf{Y}_{udd}$?
- One is obviously enough for generic couplings
- Need to be more careful when imposing MFV

Our expansions

- have the right G_F transformations,
- are built using the SM spurions.
- **What about the naturality criterion ?** Projecting **natural flavor structures** should return $\mathcal{O}(1)$ coefficients only.

Internal stability

$$(\mathbf{Y}^{Q}_{udd})^{IJK} = \epsilon_{Q}^{LMN}(\mathbf{Y}_u\,\mathbf{O}^{\lambda_q})^{IL}\,\mathbf{Y}_d^{JM}\,\mathbf{Y}_d^{KN}$$
$$(\mathbf{Y}^{D}_{udd})^{IJK} = \epsilon_{D}^{LJK}(\mathbf{Y}_u\,\mathbf{O}^{\lambda_d}\,\mathbf{Y}_d^{\dagger})^{IL}$$

- Within a given basis, the **stability** of the projection is assured by the use of the Cayley-Hamilton theorem. For instance,

$$\varepsilon_{Q}^{LMN}\mathbf{Y}_u^{IL}(\mathbf{Y}_d\mathbf{O})^{JM}(\mathbf{Y}_d\mathbf{O})^{KN} =$$
$$\varepsilon_{Q}^{LMN}(\mathbf{Y}_u[\mathbf{O}^2-\langle\mathbf{O}\rangle\mathbf{O}+\tfrac{1}{2}\langle\mathbf{O}\rangle^2-\tfrac{1}{2}\langle\mathbf{O}^2\rangle])^{IL}\mathbf{Y}_d^{JM}\mathbf{Y}_d^{KN}\ ,$$

where $\langle\mathbf{O}\rangle$, $\langle\mathbf{O}^2\rangle$ are of $\mathcal{O}(1)$ if MFV holds: can be absorbed in the projection coefficients without affecting their scaling.

$\Rightarrow$ Both the $\mathbf{Y}^{Q}_{udd}$ and $\mathbf{Y}^{D}_{udd}$ bases are **internally consistent**

Incompatibility between epsilon contractions

$$(\mathbf{Y}^{Q}_{udd})^{IJK} \ni \lambda_3^q \epsilon_Q^{LMN} (\mathbf{Y}_u \mathbf{Y}_d^\dagger \mathbf{Y}_d)^{IL} \mathbf{Y}_d^{JM} \mathbf{Y}_d^{KN}$$
$$(\mathbf{Y}^{D}_{udd})^{IJK} \ni \lambda_1^d \epsilon_D^{LJK} (\mathbf{Y}_u \mathbf{Y}_d^\dagger)^{IL}$$

- MFV stability between two bases cannot be ensured. For instance:

$$\varepsilon^{LMN} (\mathbf{Y}_u \mathbf{Y}_d^\dagger \mathbf{Y}_d)^{IL} \mathbf{Y}_d^{JM} \mathbf{Y}_d^{KN} = \det(\mathbf{Y}_d) \varepsilon^{LJK} (\mathbf{Y}_u \mathbf{Y}_d^\dagger)^{IL} .$$

$$\Rightarrow \lambda_3^q = \lambda_1^d / \det(\mathbf{Y}_d) \approx 10^{10} \lambda_1^d / \tan^3 \beta$$

- **MFV in one basis is not necessarily MFV in the other bases**.

RPV MFV principle

- **Stable RPV MFV formulation**: need to play with **only one basis** at a time.
- Only 1 basis = Only 1 type of ϵ tensor = Only 1 broken $U(1)$
- If two $U(1)$'s broken at a time, RG evolution generate **non usual RPC terms**, *e.g.*,

$$(\mathbf{m}_D^2)^{IJ}/m_0^2 \ni \varepsilon_Q^{LMN}\mathbf{Y}_u^{AL}\mathbf{Y}_d^{IM}\mathbf{Y}_d^{KN} \times \varepsilon_D^{RJK}(\mathbf{Y}_d\mathbf{Y}_u^\dagger)^{RA} \ ,$$

- Need only $\mathbf{SU(3)\otimes U(3)^2}$ to reach the standard Yukawa forms

$$V_R^{u,d}\mathbf{Y}_{u,d}V_L^{u,d\dagger} = \mathbf{m}_{u,d}/v_{u,d} \ , \ \mathbf{V}_{CKM} = V_L^u V_L^{d\dagger} \ ,$$

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- **Stable RPV MFV formulation**: need to play with **only one basis** at a time.
- Only 1 basis = Only 1 type of ϵ tensor = Only 1 broken $U(1)$
- If two $U(1)$'s broken at a time, RG evolution generate **non usual RPC terms**, *e.g.*,

$$(\mathbf{m}_D^2)^{IJ}/m_0^2 \ni \varepsilon_Q^{LMN}\mathbf{Y}_u^{AL}\mathbf{Y}_d^{IM}\mathbf{Y}_d^{KN} \times \varepsilon_D^{RJK}(\mathbf{Y}_d\mathbf{Y}_u^\dagger)^{RA} \ ,$$

- Need only $\mathbf{SU(3)\otimes U(3)^2}$ to reach the standard Yukawa forms

$$V_R^{u,d}\mathbf{Y}_{u,d}V_L^{u,d\dagger} = \mathbf{m}_{u,d}/v_{u,d} \ , \ \mathbf{V}_{CKM} = V_L^u V_L^{d\dagger} \ ,$$

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Two scenarios of interest

$$(\mathbf{Y}_{udd}^{Q})^{IJK} = \epsilon_Q^{LMN} (\mathbf{Y}_u \mathbf{O}^{\lambda_q})^{IL} \mathbf{Y}_d^{JM} \mathbf{Y}_d^{KN}$$
$$(\mathbf{Y}_{udd}^{D})^{IJK} = \epsilon_D^{LJK} (\mathbf{Y}_u \mathbf{O}^{\lambda_d} \mathbf{Y}_d^{\dagger})^{IL}$$

- **2 (+1) breaking patterns**, **2 (+1) typical hierarchies**

	Broken $U(1)_Q$			Broken $U(1)_D$		
	ds	sb	db	ds	sb	db
u	10^{-14}	10^{-9}	10^{-11}	10^{-9}	10^{-9}	10^{-9}
c	10^{-12}	10^{-7}	10^{-7}	10^{-5}	10^{-7}	10^{-5}
t	10^{-7}	10^{-6}	10^{-6}	0.1	10^{-6}	10^{-4}

Holomorphic MFV

- Motivated from the hypothesis that flavor symmetry is **dynamical** at a scale M_{flavor}
- Above M_{flavor} the Yukawa spurions are either **true dynamical fields** or related to **unknown fundamental flavor fields**
- Supersymmetry imposes **holomorphy** of the superpotential
- **Only one** structure involving only $\mathbf{Y}_u$ and $\mathbf{Y}_d$:

$$\mathbf{Y}_{udd}^{IJK} = \lambda \varepsilon^{LMN} \mathbf{Y}_u^{IL} \mathbf{Y}_d^{JM} \mathbf{Y}_d^{KN}$$

- Only $U(1)_Q$ broken: **MFV is stable and well-defined**

RG invariance of MFV holomorphy

- Holomorphy is supposed to hold above M_{flavor} but has **no reasons to hold through the RG evolution**
- Well it does, **MFV holomorphy is RG-invariant**

$$\mathbf{Y}_{udd}^{IJK} = \lambda \varepsilon^{LMN} \mathbf{Y}_u^{IL} \mathbf{Y}_d^{JM} \mathbf{Y}_d^{KN}$$

$$\frac{d\lambda}{dt} = -\lambda \beta_\lambda \;,\; \beta_\lambda = \gamma_{Q^P}^{Q^P} + \gamma_{H_2}^{H_2} + 2\gamma_{H_1}^{H_1}$$

- At one-loop:

$$\beta_\lambda = \frac{1}{32\pi^2}(4\langle \mathbf{Y}_u^\dagger \mathbf{Y}_u \rangle + 7\langle \mathbf{Y}_d^\dagger \mathbf{Y}_d \rangle + 2\langle \mathbf{Y}_e^\dagger \mathbf{Y}_e \rangle - g_1^2 - 9g_2^2 - 8g_3^2) \;,$$

- The low/GUT scale λ ratio is quite independent of the SUSY point:

$$\frac{\lambda[M_{\text{SUSY}}]}{\lambda[M_{\text{GUT}}]} = \exp\left\{ -\int_{\log M_{\text{SUSY}}^2}^{\log M_{\text{GUT}}^2} \beta_\lambda(t)\, dt \right\} \approx 1/5 - 1/4 \;,$$

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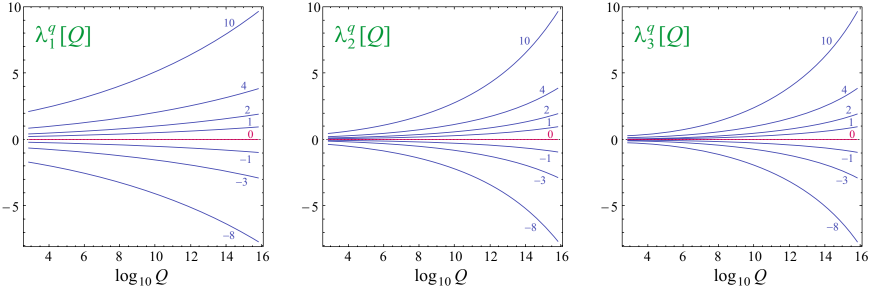
Broken $U(1)_Q$: $\mathbf{Y}_{udd}$ couplings

$$(\mathbf{Y}^Q_{udd})^{IJK} = \epsilon_Q^{LMN} (\mathbf{Y}_u \mathbf{O}^{\lambda^q})^{IL} \mathbf{Y}_d^{JM} \mathbf{Y}_d^{KN}$$

- Set $\lambda^q_i[M_{GUT}] = \lambda\delta_{i1}$ (left), $\delta_{i1} + \lambda_2\delta_{i2}$ (middle), $\delta_{i1} + \lambda_3\delta_{i3}$ (right)

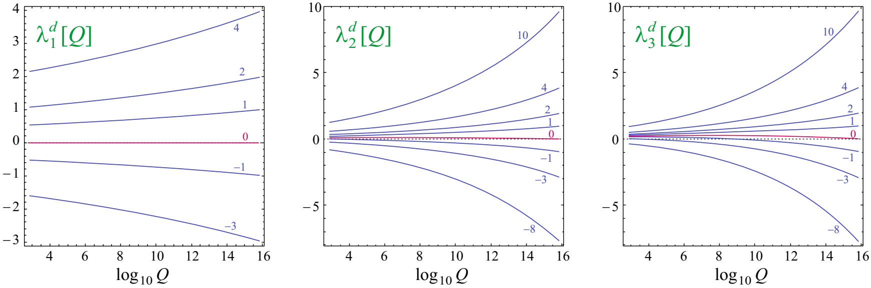


- Remarkably, **holomorphic MFV** appear as an **IR true fixed point**
- If MFV is active at a high scale and if $U(1)_Q$ is broken, $\mathbf{Y}_{udd}[M_{\text{SUSY}}]$ **is holomorphic** to an excellent approximation

Broken $U(1)_D$: $\mathbf{Y}_{udd}$ couplings

$$(\mathbf{Y}_{udd}^{D})^{IJK} = \epsilon_D^{LJK}(\mathbf{Y}_u \mathbf{O}^{\lambda_d} \mathbf{Y}_d^\dagger)^{IL}$$

- Set $\lambda_i^q[M_{gut}] = \lambda_1\delta_{i1}$ (left), $\delta_{i1} + \lambda_2\delta_{i2}$ (middle), $\delta_{i1} + \lambda_3\delta_{i3}$ (right)



- MFV is **reinforced** through the run and exhibit **quasi fixed points**
- **Same quasi-fixed point behavior** as the **RPC** flavor structures

Conclusions

Baryonic R-parity violation under the RG evolution

Need for a well-defined MFV formulation in the RPV sector:

- Construction of a **basis independent** parametrization of **generic RPV couplings**
- Unambiguously **set boundary conditions**,
- Restriction on the flavor group: **only one $U(1)$ broken at a time**

RG evolution study:

- Striking **IR fixed** or **quasi-fixed points**
- **Low scale RPV MFV** appears from **non high scale MFV**

Holomorphic MFV:

- **Analytical proof** of the **RG invariance**
- **Holomorphy as a powerful IR attractor**: low scale holomorphy to an excellent approximation

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Backup

SUSY point

- $\tan\beta = 10$,
- $m_{1/2} = m_0 = -A_0/2 = 1$ TeV,
- $m^2_{H_u} = m^2_{H_d} = (1.2 m_0)^2$,
- $\mathbf{m}^2_{Q,U,D,L,E} = m_0^2\ \mathbf{1}$,
- $\mathbf{A}_{u,d,e} = A_0 \mathbf{Y}_{u,d,e}$,

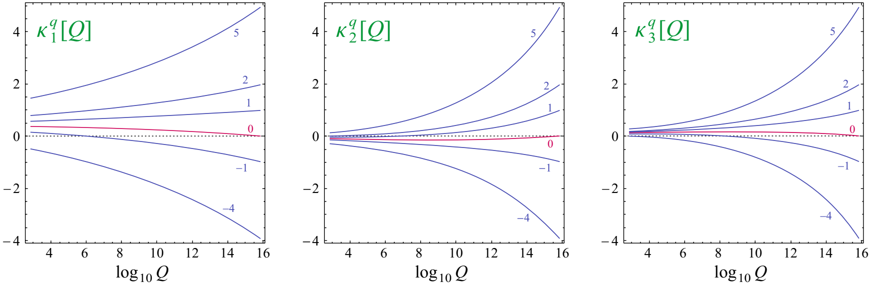
$m_h \approx 123$ GeV

$m_{\tilde{g}} = 2.2$ TeV , $m_{\tilde{\chi}^\pm} = (0.82,\ 1.5)$ TeV , $m_{\tilde{\chi}^0} = (0.43,\ 0.82,\ 1.5,\ 1.5)$ TeV ,
$m_{\tilde{u}} = (1.4,\ 1.9,\ 2.2,\ 2.2,\ 2.2,\ 2.2)$ TeV , $m_{\tilde{d}} = (1.9,\ 2.1,\ 2.1,\ 2.1,\ 2.2,\ 2.2)$ TeV ,
$m_{\tilde{e}} = (1.0,\ 1.1,\ 1.1,\ 1.2,\ 1.2,\ 1.2)$ TeV , $m_{\tilde{\nu}} = (1.2,\ 1.2,\ 1.2)$ TeV .

Broken $U(1)_Q$: $\mathbf{A}_{udd}$ term

$$(\mathbf{A}^{Q}_{udd})^{IJK} = \epsilon^{LMN}_{Q}(\mathbf{Y}_u \mathbf{O}^{\kappa^q})^{IL}\mathbf{Y}^{JM}_d \mathbf{Y}^{KN}_d$$

- Set $\lambda[M_{\mathbf{GUT}}] = 1$, $\kappa^q_i[M_{\mathbf{GUT}}] = \kappa\delta_{ia}$, $\kappa = \{-4, -1, 0, 1, 2, 5\}$



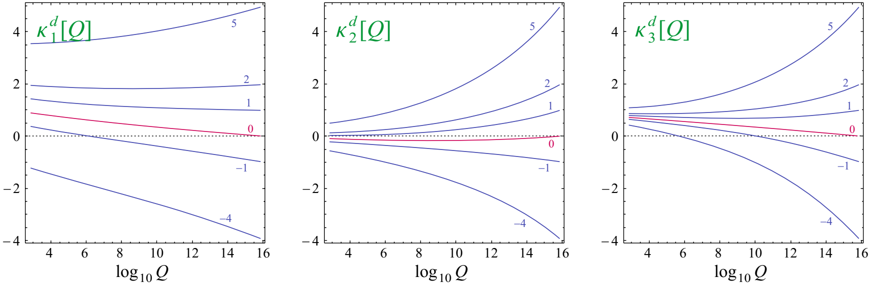
- Strong convergence towards the radiatively generated values

$$\kappa^q_{1,2,3}[M_{\text{SUSY}}] = (0.36,\ -0.12,\ 0.12)\ ,\ \ \kappa^q_{4,\ldots,9} \lesssim 10^{-3}$$

Broken $U(1)_D$: $\mathbf{A}_{udd}$ term

$$(\mathbf{A}^{D}_{udd})^{IJK} = \epsilon_D^{LJK} (\mathbf{Y}_u \mathbf{O}^{\kappa_d} \mathbf{Y}^{\dagger}_d)^{IL}$$

- Set $\lambda_1[M_{\mathbf{GUT}}] = 1$, $\kappa^q_i[M_{\mathbf{GUT}}] = \kappa\delta_{ia}$, $\kappa = \{-4, -1, 0, 1, 2, 5\}$



- Strong convergence towards the radiatively generated values
- Quasi fixed points are apparent