Non-minimal flavour violation in supersymmetric models.

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Outline

The Minimal Supersymmetric Standard Model (MSSM)

- High energy extension to Standard Model (SM), **linking fermions and bosons.**
- Minimal Supersymmetric Standard Model: **one partner for each SM particle.**
  - Quarks ⇔ squarks.
  - Leptons ⇔ sleptons.
  - Gauge bosons ⇔ gauginos.
  - Higgs bosons ⇔ higgsinos.
  - Gluon ⇔ gluino.
  - Graviton ⇔ gravitino.
- **BUT no SUSY discovery until now!**
  - **SUSY must be broken** ⇒ SUSY masses shifted at a higher scale.
  - Assumptions on the breaking mechanism: 5-6 free parameters.
  - **These scenarios might be too constraining.**

Flavour violation in supersymmetry - generic features

- **Soft-supersymmetry breaking Lagrangian** in the squark sector.

$$-\mathcal{L}_{\rm Soft} \supset \sum_{i,j=1}^{3} \Bigg[\tilde{Q}^{0i\dagger} \, (\mathbf{m}^2_{\tilde{\mathbf{Q}}})_i{}^j \, \tilde{Q}^0_j + \tilde{u}^{0i\dagger}_R \, (\mathbf{m}^2_{\tilde{\mathbf{U}}})_i{}^j \, \tilde{u}^0_{Rj} + \tilde{d}^{0i\dagger}_R \, (\mathbf{m}^2_{\tilde{\mathbf{D}}})_i{}^j \, \tilde{d}^0_{Rj}$$

$$+ \left(\tilde{u}^{0i\dagger}_R \, (\mathbf{T^u})_i{}^j \, \tilde{u}^0_{Lj} + \tilde{d}^{0i\dagger}_R \, (\mathbf{T^d})_i{}^j \, \tilde{d}^0_{Lj} + h.c. \right) \Bigg].$$

- **All mass terms**.
  - New sources of flavour violation and CP violation.
  - **Could enhance processes severely restricted by experiment.**
    - $K^0 - \bar{K}^0$, $D^0 - \bar{D}^0$ and $B^0 - \bar{B}^0$ mixings.
    - Flavour-changing neutral-currents.
    - Rare B-meson decays.
    - *etc...*
  - **Strongly constrained**.
- **Several scenarios regarding flavour violation in supersymmetry.**

Constrained minimal flavour violation (cMFV)

- **No flavour violation** (CKM $\equiv$ identity).
- **Soft-supersymmetry breaking Lagrangian** in the squark sector.

$$-\mathcal{L}_{\rm Soft} \supset \sum_{i=1}^{3} \Bigg[\tilde{Q}^{0i\dagger} \left(\mathbf{m^2_{\tilde{Q}_i}}\right) \tilde{Q}^0_i + \tilde{u}^{0i\dagger}_R \left(\mathbf{m^2_{\tilde{U}_i}}\right) \tilde{u}^0_{Ri} + \tilde{d}^{0i\dagger}_R \left(\mathbf{m^2_{\tilde{D}_i}}\right) \tilde{d}^0_{Ri} + \left(\tilde{u}^{0i\dagger}_R \left(\mathbf{T^u_i}\right) \tilde{u}^0_{Li} + \tilde{d}^{0i\dagger}_R \left(\mathbf{T^d_i}\right) \tilde{d}^0_{Li} + h.c. \right) \Bigg].$$

- **6×6 mass matrices** (neglecting flavour conserving superpotential terms):

$$M^2_{\tilde{U}} = \begin{pmatrix} \left(\mathbf{m^2_{\tilde{Q}_i}}\,\delta_{ij}\right) & \left(\mathbf{T^u_i}^*\,\delta_{ij}\right) \\ \left(\mathbf{T^u_i}\,\delta_{ij}\right) & \left(\mathbf{m^2_{\tilde{U}_i}}\,\delta_{ij}\right) \end{pmatrix} \text{ and } M^2_{\tilde{D}} = \begin{pmatrix} \left(\mathbf{m^2_{\tilde{Q}_i}}\,\delta_{ij}\right) & \left(\mathbf{T^d_i}^*\,\delta_{ij}\right) \\ \left(\mathbf{T^d_i}\,\delta_{ij}\right) & \left(\mathbf{m^2_{\tilde{D}_i}}\,\delta_{ij}\right) \end{pmatrix}.$$

  - **All flavour-violating elements are zero**.
  - Sfermion mixing: $(\tilde{f}_L, \tilde{f}_R) \Rightarrow (\tilde{f}_1, \tilde{f}_2)$ with flavour conservation.
  - **Flavour-conserving mixing angles** (first two generations often neglected).
- **Scenario implemented in most Monte Carlo generators**.

Minimal flavour violation (MFV)

- **Flavour structure generated by the Yukawa couplings (and the CKM matrix)**.
- **Quark sector**.
  * **Diagonalization** of the Yukawa matrices.
  * Rotation from the gauge basis to the physical basis,

$$d^0_{Li} = V_d\, d_{Li}\ , \quad d^0_{Ri} = U_d\, d_R\ , \quad u^0_{Li} = V_u\, u_{Li}\ , \quad u^0_{Ri} = U_u\, u_R .$$

  * **The charged-current interactions are proportional to the CKM matrix**,

$$V_{CKM} = V_u^\dagger V_d .$$

- **Squark sector**.
  * The **Super-CKM basis**: the squarks undergo the same rotations,

$$\tilde d^0_{Li} = V_d\, \tilde d_{Li}\ , \quad \tilde d^0_{Ri} = U_d\, \tilde d_R\ , \quad \tilde u^0_{Li} = V_u\, \tilde u_{Li}\ , \quad \tilde u^0_{Ri} = U_u\, \tilde u_R .$$

  * **The mass matrices become**:

$$M^2_{\tilde U} = \begin{pmatrix} V_{CKM}\left(\mathbf{m}^2_{\tilde{\mathbf{Q}}_\mathbf{i}}\delta_{ij}\right)V^\dagger_{CKM} & \left(\mathbf{T}^{\mathbf{u}\,*}_\mathbf{i}\delta_{ij}\right) \\ \left(\mathbf{T}^\mathbf{u}_\mathbf{i}\delta_{ij}\right) & \left(\mathbf{m}^2_{\tilde{\mathbf{U}}_\mathbf{i}}\delta_{ij}\right)\end{pmatrix} \text{ and } M^2_{\tilde D} = \begin{pmatrix} \left(\mathbf{m}^2_{\tilde{\mathbf{Q}}_\mathbf{i}}\delta_{ij}\right) & \left(\mathbf{T}^{\mathbf{d}\,*}_\mathbf{i}\delta_{ij}\right) \\ \left(\mathbf{T}^\mathbf{d}_\mathbf{i}\delta_{ij}\right) & \left(\mathbf{m}^2_{\tilde{\mathbf{D}}_\mathbf{i}}\delta_{ij}\right)\end{pmatrix} .$$

  * **Flavour violation for the up squarks**,

$$\Big(\tilde u_1, \tilde u_2, \tilde u_3, \tilde u_4, \tilde u_5, \tilde u_6\Big)^T = R^{\tilde u}\Big(\tilde u_L, \tilde c_L, \tilde t_L, \tilde u_R, \tilde c_R, \tilde t_R\Big)^T .$$

Non-minimal flavour violation (NMFV)

- **We assume new sources of flavour violation**.
- **Soft-supersymmetry breaking Lagrangian** in the squark sector.

$$-\mathcal{L}_{\rm Soft} \supset \sum_{i,j=1}^{3} \Big[\tilde{Q}^{0i\dagger} (\mathbf{m}^2_{\tilde{\mathbf{Q}}})_i{}^j \tilde{Q}^0_j + \tilde{u}_R^{0i\dagger} (\mathbf{m}^2_{\tilde{\mathbf{U}}})_i{}^j \tilde{u}^0_{Rj} + \tilde{d}_R^{0i\dagger} (\mathbf{m}^2_{\tilde{\mathbf{D}}})_i{}^j \tilde{d}^0_{Rj} + \left(\tilde{u}_R^{0i\dagger} (\mathbf{T^u})_i{}^j \tilde{u}^0_{Lj} + \tilde{d}_R^{0i\dagger} (\mathbf{T^d})_i{}^j \tilde{d}^0_{Lj} + h.c. \right) \Big].$$

- **The squared squark mass matrices are**

$$M^2_{\tilde{U}} = \begin{pmatrix} V_{CKM} \left(\mathbf{m}^2_{\tilde{\mathbf{Q}}}\right) V^\dagger_{CKM} & \left(\mathbf{T^u}\right)^\dagger \\ \left(\mathbf{T^u}\right) & \left(\mathbf{m}^2_{\tilde{\mathbf{U}}}\right) \end{pmatrix} \text{ and } M^2_{\tilde{D}} = \begin{pmatrix} \left(\mathbf{m}^2_{\tilde{\mathbf{Q}}}\right) & \left(\mathbf{T^d}\right)^\dagger \\ \left(\mathbf{T^d}\right) & \left(\mathbf{m}^2_{\tilde{\mathbf{D}}}\right) \end{pmatrix}.$$

  * The off-diagonal elements consist in **21 new free parameters**,

$$(\mathbf{m}^2_{\tilde{\mathbf{Q}}})_i{}^j = \lambda^{\mathbf{ij}}_{\mathbf{LL}} \mathbf{m}_{\tilde{\mathbf{Q}}_\mathbf{i}} \mathbf{m}_{\tilde{\mathbf{Q}}_\mathbf{j}} \ldots$$

  * Diagonalization through 6×6 unitary rotation matrices R^u **and** R^d.

$$\begin{aligned} (\tilde{u}_1, \tilde{u}_2, \tilde{u}_3, \tilde{u}_4, \tilde{u}_5, \tilde{u}_6)^T &= R^u(\tilde{u}_L, \tilde{c}_L, \tilde{t}_L, \tilde{u}_R, \tilde{c}_R, \tilde{t}_R)^T, \\ (\tilde{d}_1, \tilde{d}_2, \tilde{d}_3, \tilde{d}_4, \tilde{d}_5, \tilde{d}_6)^T &= R^d(\tilde{d}_L, \tilde{s}_L, \tilde{b}_L, \tilde{d}_R, \tilde{s}_R, \tilde{b}_R)^T. \end{aligned}$$

Outline

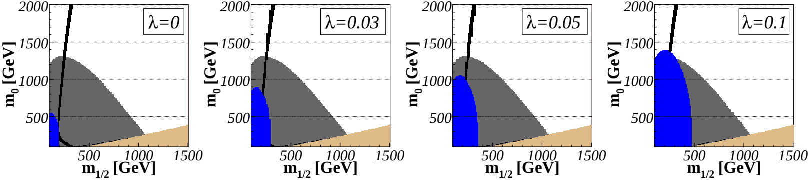
Constraints on NMFV SUSY models

- **Flavour changing neutral currents**.
  * Neutral kaon sector (Δm_K, ε, ε'/ε),
  * B-meson and D-meson oscillations (Δm_s, Δm_D),
  * Rare decays
  * Electric dipole moments (d_n and d_e).
- **Results for the second and third generation mixing**.
  [Gabbiani, Gabrielli, Masiero, Silvestrini (1996)]
  [Ciuchini, Masiero, Paradisi, Silvestrini, Vempati, Vives (2007)]

$$\boldsymbol{\lambda^{23}_{LL} \lesssim 2.10^{-1}}, \quad \lambda^{23}_{LR} \lesssim 5.10^{-3}, \quad \lambda^{23}_{RL} \lesssim 5.10^{-3}, \quad \boldsymbol{\lambda^{23}_{RR} \lesssim 2.10^{-1}}.$$

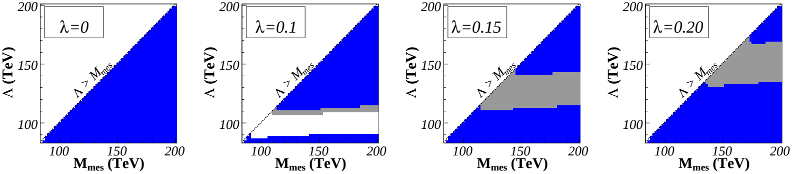
- **Mixing to the first generation more constrained** (and neglected here).

mSUGRA parameter space analysis



- $\tan\beta = 10$, $\mu > 0$, $A_0 = 0$ GeV, $0 \leq \lambda^{23}_{\rm LL} \equiv \lambda \leq 0.1$. [Bozzi, BenjF, Herrmann, Klasen (2007)]
- **Region favoured by a_μ @2σ (grey)**
  - * Experimental data: $\Delta a_\mu = (29.2 \pm 8.6) \times 10^{-10}$.
  - * Squarks contribute at **the two-loop level** only.
    $\Rightarrow$ Reduced squark vs. slepton one-loop contributions.
- **Region excluded by $b \to s\gamma$ @2σ (blue)**
  - * Experimental data (CLEO, Babar and Belle): $(3.55 \pm 0.26) \times 10^{-4}$.
  - * NMFV contributes at **one-loop** (as the SM) $\Rightarrow$ Very sensitive to λ.
- **Charged LSP (beige)**
  - * DM candidate $\Leftrightarrow$ **color singlet and electrically neutral** [Ellis *et al.* (1984)].
- **Region favoured by Ω_{CDM} (black)**
  - * Observation (WMAP, SDSS, SNLS, BAO): $0.095 < \Omega_{\rm CDM} h^2 < 0.136$.
  - * Not really sensitive to λ (many involved processes).

GMSB parameter space analysis



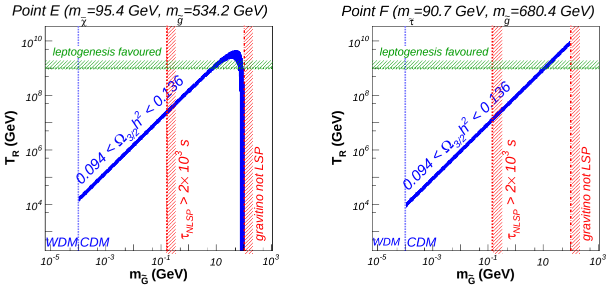
- $\tan\beta = 50, \mu > 0, N_{\rm mes} = 1, 0 \leq \lambda^{23}_{\bf LL} = \lambda^{23}_{\bf RR} \equiv \lambda \leq 0.2$.
  [BenjF, Herrmann, Klasen (2009)]

- **Region excluded by $b \to s\gamma$ @2σ (blue)**
  - NMFV contributes at the **one-loop level** (same as the SM contributions).
    $\Rightarrow$ Very sensitive to λ.

- **Region favoured by a_μ @2σ (grey)**
  - Squarks contribute at **the two-loop level** only.
    $\Rightarrow$ Reduced squark vs. slepton one-loop contributions.

- cMFV scenarios strongly disfavoured, but windows open at **larger λ**.

GMSB - cosmological constraints analysis

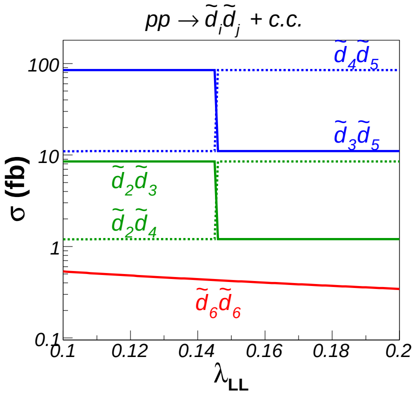


E/F: $\Lambda = 65/30$ TeV, $M_{\rm mes} = 90/80$ TeV, $N_{\rm mes} = 1/3$, $\tan\beta = 15$, $\mu > 0$, $0.03 \leq \lambda_{LL} = \lambda_{RR} \leq 0.068$ [BenjF, Herrmann, Klasen (2009)].

- **Gravitino LSP**: **cold dark matter candidate ($m_{\tilde G} \gtrsim 100$ keV)**.
- **Today's gravitino abundance**:
  - * Produced from thermal scattering in the very early Universe.
  - * Non-thermal production from NLSP decays (important for point E).
- $T_R \gtrsim 10^9$ **GeV: leptogenesis** ($\Rightarrow$ baryon asymmetry).
- $\tau_{\rm NLSP} \lesssim 2 \cdot 10^3$ **s: light element's abundance** (primordial nucleosynthesis).
- **Hard to fulfill all constraints** $\Rightarrow$ relaxation of the less stringent one: T_R.

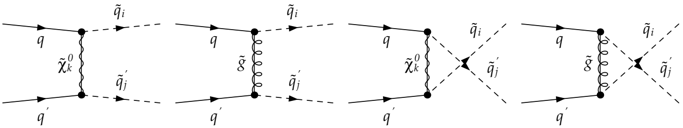
Outline

Squark pair production

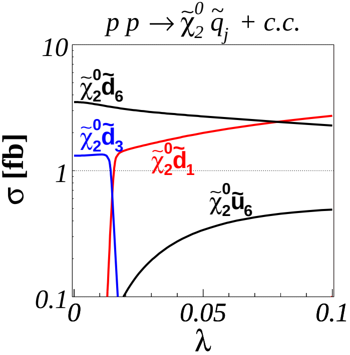


[BenjF, Herrmann, Klasen (2009)]

- **Benchmark scenario GMSB-E**:
  - * $\Lambda = 65$ TeV, $M_{\rm m} = 90$ TeV, $N_{\rm m} = 1$, $\tan\beta = 15, \mu > 0, \lambda_{RR} = 0$.
  - * Squark masses: 700-800 GeV.
- **LHC collider**:
  - * Large quark quark luminosity.
  - * **$\tilde{q}\tilde{q}'$ more easily produced than $\tilde{q}\tilde{q}'^*$** (non diagonal $\tilde{q}\tilde{q}'^*$ production).
  - * All QCD/EW diagrams considered.
- **Avoided crossings**:
  - * Mass flips between $\tilde{d}_3$ and $\tilde{d}_4$.
  - * **Sharp transitions with λ**.

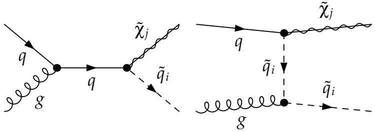


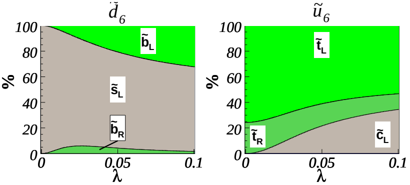
Associated squark-neutralino production



[Bozzi, BenjF, Herrmann, Klasen (2007)]

- **Benchmark scenario mSUGRA-B**:
  - * $m_0 = 100$ GeV, $m_{1/2} = 400$ GeV, $A_0 = 0$ GeV, $\tan\beta = 10$, $\mu > 0$.
  - * Squark masses: 700-900 GeV.
  - * Neutralino-2 mass: 300 GeV.
- **Quite sensitive to flavour violation**.
  - * $\tilde{d}_6\tilde{\chi}_2^0$ cross section decreases with λ (cf. $\tilde{d}_6$: $\tilde{s}/\tilde{b}$ content).
  - * $\tilde{u}_6\tilde{\chi}_2^0$ cross section increases with λ (cf. $\tilde{u}_6$: $\tilde{c}/\tilde{t}$ content).





Outline

Summary

- **Study of NMFV effects in SUSY models.**
  * Extended mSUGRA and GMSB scenarios investigated.
  * Low-energy, cosmological and electroweak constraints analyzed.
  * Production cross sections and decay widths studied.

- **Implementation of a multipurpose, flexible, computer program,** XSusy.
  * Interfaced with DarkSUSY, FeynHiggs, SPheno and SuSpect.
  * Generic and extended minimal SUSY scenarios implemented.
  * Allows for a detailed analysis of the NMFV parameter space.
  * Cross sections for SUSY particle pair-production processes.
  * SUSY particle two-body decays.