Flavour-violating squark and gaugino production at the LHC

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Outline

SUSY-breaking

- Unconstrained MSSM: intergenerational mixing, complex phases
  $\longrightarrow$ huge number of new free parameters.

- Constrained MSSM: assumptions $\longrightarrow$ less parameters.
  - No new source of *CP*-violation
    $\longrightarrow$ only real parameters.
  - No intergenerational mixing in sfermion sector
    $\longrightarrow$ no FCNC at tree-level.
  - Masses of $1^{\rm st}$ and $2^{\rm nd}$ fermion generation neglected to simplify
    $\longrightarrow$ Sfermion universality at low energy for light flavours.

$\Longrightarrow$ 22 new free parameters.

Minimal supergravity (mSUGRA)

- SUSY-breaking through gravitational-strength interactions.
- Boundary conditions at the GUT scale:
  - ◇ Universal gaugino mass $m_{1/2}$.
  - ◇ Universal scalar mass m_0.
  - ◇ Universal trilinear coupling A_0.

$\Rightarrow$ Four new free parameters ($m_{1/2}$, m_0, A_0, $\tan\beta$) and a sign (μ).

- Strongly constrained:
  - ◇ Electroweak precision measurements.
  - ◇ Direct searches.
  - ◇ Dark matter searches.

$\Rightarrow$ Maybe too strong restrictions on the parameter space?

Sources of flavour-violation in the MSSM

- Diagonalization of the quark mass matrices.
  - ◇ Rotation from the interaction- to the mass-eigenstate basis.
  - ◇ Misalignment between up- and down-type rotations.
    $\longrightarrow$ parameterized by the CKM matrix.
- Diagonalization of the squark mass matrices.
  - ◇ Misalignment between the quark and squark sector.
  - ◇ CKM rotations not sufficient.
  - ◇ Additional rotations needed.
- Possible flavour-violation in the slepton sector not considered (stringently constrained by $\mu \to \gamma e$, $\tau \to \gamma e$, $\tau \to \gamma\mu$).

The Super-CKM basis (1)

- Diagonalization of the quark sector
  - Rotation of the up-type (down-type) quark fields from the interaction-eigenstate basis $U_{L,R}$ ($D_{L,R}$) to the mass-eigenstate basis $U^0_{L,R}$ ($D^0_{L,R}$):

$$\begin{aligned} U^0_L &= V^u_L\, U_L \quad , \quad & D^0_L &= V^d_L\, D_L, \\ U^0_R &= V^u_R\, U_R \quad \text{and} \quad & D^0_R &= V^d_R\, D_R. \end{aligned}$$

  - Squark interaction-eigenstates $(\widetilde{U}_{L,R},\ \widetilde{D}_{L,R})$ are rotated parallel to the quarks fields:

$$\begin{aligned} \widetilde{U}^0_L &= V^u_L\, \widetilde{U}_L \quad , \quad & \widetilde{D}^0_L &= V^d_L\, \widetilde{D}_L, \\ \widetilde{U}^0_R &= V^u_R\, \widetilde{U}_R \quad \text{and} \quad & \widetilde{D}^0_R &= V^d_R\, \widetilde{D}_R. \end{aligned}$$

$\equiv$ Super-CKM basis $(U^0_L, U^0_R, D^0_L, D^0_R, \widetilde{U}^0_L, \widetilde{U}^0_R, \widetilde{D}^0_L, \widetilde{D}^0_R,)$.

The Super-CKM basis (2)

- The squark fields are not the physical eigenstates.
- The squark mass matrices are not flavour-diagonal.

- Very useful basis: the charged current interactions couple with a strength given by the CKM matrix

$$V = V_L^u \, V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} .$$

Examples: $W^\pm q q'$, $H^\pm q q'$, $\tilde{\chi} q \tilde{q}'$, ...

The squark mass matrices (1)

- In the Super-CKM basis, the up-type squark mass matrix is given by

$$M^2_{\tilde{U}} = \left(\begin{array}{ccc|ccc} M^2_{LL,u} & \Delta^{uc}_{LL} & \Delta^{ut}_{LL} & m_u\, m_{LR,u} & \Delta^{uc}_{LR} & \Delta^{ut}_{LR} \\ \Delta^{cu}_{LL} & M^2_{LL,c} & \Delta^{ct}_{LL} & \Delta^{cu}_{RL} & m_c\, m_{LR,c} & \Delta^{ct}_{LR} \\ \Delta^{tu}_{LL} & \Delta^{tc}_{LL} & M^2_{LL,t} & \Delta^{tu}_{RL} & \Delta^{tc}_{RL} & m_t\, m_{LR,t} \\ \hline m_u\, m_{RL,u} & \Delta^{uc}_{RL} & \Delta^{ut}_{RL} & M^2_{RR,u} & \Delta^{uc}_{RR} & \Delta^{ut}_{RR} \\ \Delta^{cu}_{LR} & m_c\, m_{RL,c} & \Delta^{ct}_{RL} & \Delta^{cu}_{RR} & M^2_{RR,c} & \Delta^{ct}_{RR} \\ \Delta^{tu}_{LR} & \Delta^{tc}_{LR} & m_t\, m_{RL,t} & \Delta^{tu}_{RR} & \Delta^{tc}_{RR} & M^2_{RR,t} \end{array}\right) .$$

- In the MSSM with MFV:
  - ◇ The 1st and 2nd generation flavour-conserving off-diagonal entries are neglected ($m_{\{u,c\}} \to 0$).
  - ◇ The flavour-violating off-diagonal entries are not considered ($\Delta \to 0$).
  - ◇ Diagonalization performed with only one angle, $\theta_{\tilde{t}}$.
  - ◇ Same pattern for down-type squarks.

The squark mass matrices (2)

- In the Super-CKM basis, the up-type squark mass matrix is given by

$$M^2_{\tilde{U}} = \left(\begin{array}{ccc|ccc} M^2_{LL,u} & \Delta^{uc}_{LL} & \Delta^{ut}_{LL} & m_u\, m_{LR,u} & \Delta^{uc}_{LR} & \Delta^{ut}_{LR} \\ \Delta^{cu}_{LL} & M^2_{LL,c} & \Delta^{ct}_{LL} & \Delta^{cu}_{RL} & m_c\, m_{LR,c} & \Delta^{ct}_{LR} \\ \Delta^{tu}_{LL} & \Delta^{tc}_{LL} & M^2_{LL,t} & \Delta^{tu}_{RL} & \Delta^{tc}_{RL} & m_t\, m_{LR,t} \\ \hline m_u\, m_{RL,u} & \Delta^{uc}_{RL} & \Delta^{ut}_{RL} & M^2_{RR,u} & \Delta^{uc}_{RR} & \Delta^{ut}_{RR} \\ \Delta^{cu}_{LR} & m_c\, m_{RL,c} & \Delta^{ct}_{RL} & \Delta^{cu}_{RR} & M^2_{RR,c} & \Delta^{ct}_{RR} \\ \Delta^{tu}_{LR} & \Delta^{tc}_{LR} & m_t\, m_{RL,t} & \Delta^{tu}_{RR} & \Delta^{tc}_{RR} & M^2_{RR,t} \end{array}\right) .$$

- In the MSSM with NMFV:
  - All entries are kept.
  - Diagonalization is performed through a 6×6 rotation matrix R^u

$$\mathrm{diag}(m^2_{\tilde{u}_1}, \ldots, m^2_{\tilde{u}_6}) = R^u\, M^2_{\tilde{U}}\, R^{u\dagger}$$

  - Same pattern for down-type squarks.

Mass eigenstates

- Each mass eigenstate contents all flavours and both chiralities

$$\begin{pmatrix}\tilde{u}_1\\ \tilde{u}_2\\ \tilde{u}_3\\ \tilde{u}_4\\ \tilde{u}_5\\ \tilde{u}_6\end{pmatrix} = R^u \begin{pmatrix}\tilde{u}_L\\ \tilde{c}_L\\ \tilde{t}_L\\ \tilde{u}_R\\ \tilde{c}_R\\ \tilde{t}_R\end{pmatrix} \quad \text{and} \quad \begin{pmatrix}\tilde{d}_1\\ \tilde{d}_2\\ \tilde{d}_3\\ \tilde{d}_4\\ \tilde{d}_5\\ \tilde{d}_6\end{pmatrix} = R^d \begin{pmatrix}\tilde{d}_L\\ \tilde{s}_L\\ \tilde{b}_L\\ \tilde{d}_R\\ \tilde{s}_R\\ \tilde{b}_R\end{pmatrix}.$$

- The masses are ordered as

$$m_{\tilde{u}_1} < \ldots < m_{\tilde{u}_6}$$
$$m_{\tilde{d}_1} < \ldots < m_{\tilde{d}_6}$$

Constraints and simplifications

- The scaling of the Δ terms with the SUSY-breaking scale implies the hierarchy

$$\Delta_{LL} \gg \Delta_{LR,RL} \gg \Delta_{RR}$$

[Hikasa, Kobayashi (1987); Gabbiani, Masiero (1989); Brax, Savoy (1995)]

- Mixing of the first generation to any other:
  - Expected to be suppressed
    - small Yukawa couplings involved.
  - Stringently constrained experimentally
    - $K^0 - \bar{K}^0$ and $D^0 - \bar{D}^0$ precision measurements.

$\Rightarrow$ Simplifications:

$$\Delta^{ct}_{LL} = \Delta^{tc}_{LL} \equiv \lambda\, M_{LL,t}\, M_{LL,c} \quad , \quad \Delta^{bs}_{LL} = \Delta^{sb}_{LL} \equiv \lambda\, M_{LL,s}\, M_{LL,b},$$

and the other $\Delta \to 0$.

NMFV in mSUGRA

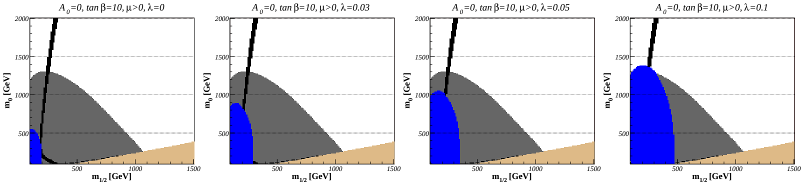
- GUT scale:
  - Four free parameters ($m_{1/2}$, m_0, A_0, $\tan\beta$) and a sign (μ).
  - Evolution down to electroweak scale: `SPheno` 2.2.3. [Porod (2005)]
- Electroweak scale:
  - Generalization of the squark mass matrices: one additional free parameter (λ).
  - SUSY spectrum: `FeynHiggs` 2.5.1. [Heinemeyer *et al.* (2006)]
- Constraints:
  - EW constraints: `FeynHiggs` 2.5.1.
  - Dark matter: `DarkSUSY` 4.1. [Gondolo *et al.* (2004)]

Constraints on flavour-violation

- $b \to s\gamma$:
  - ▷ $\mathrm{BR}(b \to s\gamma) = (3.55 \pm 0.26) \times 10^{-4}$ [Barbiero *et al.* (2006)]
  - ▷ NMFV contributes at one-loop level (same as SM).
- $\Delta\rho$:
  - ▷ $\Delta\rho = \frac{\Sigma_Z(0)}{M_Z^2} - \frac{\Sigma_W(0)}{M_W^2} = 0.00102 \pm 0.00086$ [PDG (2006)] (fits of EW parameters).
  - ▷ Sensitive to squark mass splitting within isospin doublets.[Veltman (1977)]
  - ▷ Influence on m_W and $\sin^2\theta_W$.
- a_μ:
  - ▷ $a_\mu = (22 \pm 10) \times 10^{-10}$ [PDG (2006)] (BNL data vs SM).
  - ▷ Squarks contribute at the two-loop level.
- LSP:
  - ▷ Color singlet and electrically neutral. [Ellis *et al.* (1984)]
- $\Omega_{CDM}\, h^2$:
  - ▷ $0.094 < \Omega_{CDM}\, h^2 < 0.136$ [Hamann, Hannestad, Sloth, Wong (2007)] (WMAP, SDSS, SNLS, Baryon Acoustic Oscillations).

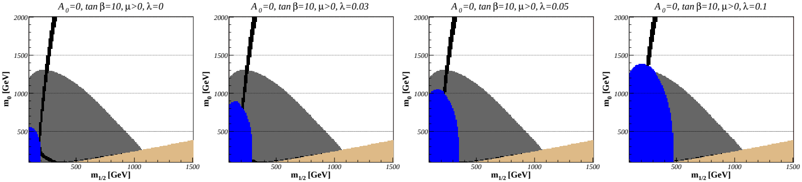
Outline

$\tan\beta = 10, \mu > 0, A_0 = 0$ GeV (1)



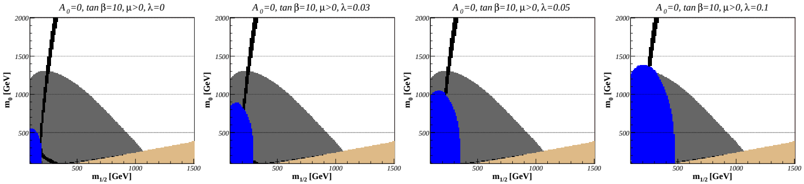
- Region favoured by a_μ @2σ (grey):
  - ▷ Dominated by slepton-loops.
  - ▷ Squarks contribute at two-loops.
- Region excluded by $b \to s\gamma$ @2σ (blue):
  - ▷ Very sensitive to λ.
  - ▷ Same level as SM.
- Region excluded by $\Delta\rho$ @2σ:
  - ▷ Parameter space constrained outside the regions shown (high masses).

$\tan\beta = 10, \mu > 0, A_0 = 0$ GeV (2)



- Charged LSP (beige):
- Regions favoured by Ω_{CDM} (black):
  - ▷ 1. Coannihilation between the LSP and the NLSP.
  - ▷ 2. *Focus point*-like region (LSP with sizeable Higgsino component).
  - ▷ Not really sensitive to λ.

$\tan\beta = 10, \mu > 0, A_0 = 0$ GeV (3)

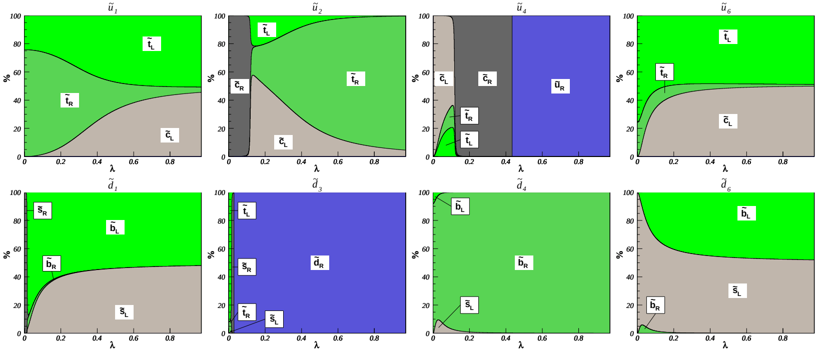


- Proposal of a benchmark point:

m_0 [GeV]	$m_{1/2}$ [GeV]	A_0 [GeV]	$\tan\beta$	$sign(\mu)$
100	400	0	10	$+$

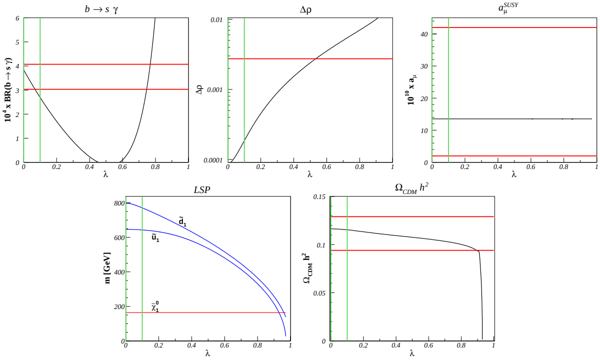
- ▷ LSP and NLSP almost mass degenerate.
  $\rightarrow$ Coannihilation region.
- ▷ Light sleptons and gauginos.
- ▷ Rather light squarks and gluino.
  $\rightarrow$ Collider friendly.

Heavy flavour content



- The chirality and (heavy) flavour decomposition:
  - ▷ Mostly smooth changes.
  - ▷ Sometimes dramatically (mass flips).
  - ▷ Large mixing between 2^{nd} and 3^{rd} generation, even for small λ.

Constraints



- $b \to s\gamma$ and $\Delta\rho$ very sensitive on λ.
- a_μ not sensitive on λ.
- Ω_{CDM} falls at large λ (very light squarks).
- Allowed region: close to MFV.

Outline

Processes

- Studied (partonic) processes :

$$a_{h_a}(p_a)\, b_{h_b}(p_b) \quad \to \quad \begin{cases} \tilde{q}_i^{(*)}(p_1)\, \tilde{q}_j^{\prime(*)}(p_2), \\ \tilde{\chi}_j^{\pm(0)}(p_1)\, \tilde{q}_i^{(*)}(p_2), \\ \tilde{\chi}_i^{\pm(0)}(p_1)\, \tilde{\chi}_j^{\pm(0)}(p_2), \end{cases}$$

- Hadronic cross section (QCD factorization theorem)

$$\sigma = \sum_{a,b} \int_\tau^1 \mathrm{d}x_a \int_{\tau/x_a}^1 \mathrm{d}x_b\, f_{a/H_a}(x_a, \mu_F^2)\; f_{b/H_b}(x_b, \mu_F^2)$$
$$\times \quad \hat{\sigma}_{ab}(z, M^2; \alpha_s(\mu_R^2), \frac{M^2}{\mu_F^2}, \frac{M^2}{\mu_R^2})$$

▷ Partonic cross sections taken at leading order in α_s.

▷ PDFs: MRST 2001 LO.

(Some) NMFV couplings (1)

- Recall:

$$\begin{pmatrix}\tilde{u}_1\\ \tilde{u}_2\\ \tilde{u}_3\\ \tilde{u}_4\\ \tilde{u}_5\\ \tilde{u}_6\end{pmatrix} = R^u \begin{pmatrix}\tilde{u}_L\\ \tilde{c}_L\\ \tilde{t}_L\\ \tilde{u}_R\\ \tilde{c}_R\\ \tilde{t}_R\end{pmatrix} \quad \text{and} \quad \begin{pmatrix}\tilde{d}_1\\ \tilde{d}_2\\ \tilde{d}_3\\ \tilde{d}_4\\ \tilde{d}_5\\ \tilde{d}_6\end{pmatrix} = R^d \begin{pmatrix}\tilde{d}_L\\ \tilde{s}_L\\ \tilde{b}_L\\ \tilde{d}_R\\ \tilde{s}_R\\ \tilde{b}_R\end{pmatrix}.$$

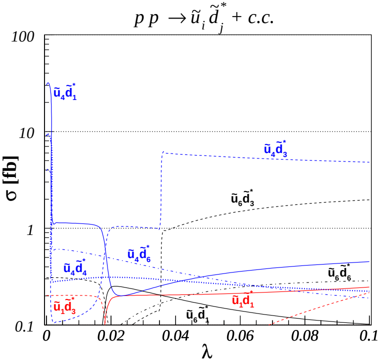
- squark-squark-gauge boson:

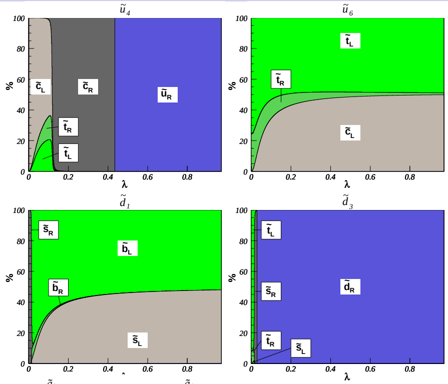
$$\{L_{\tilde{q}_i \tilde{q}_j Z}, R_{\tilde{q}_i \tilde{q}_j Z}\} = (2\,T^3_{\tilde{q}} - 2\,e_{\tilde{q}}\,x_W) \times \sum_{k=1}^{3} \{R^u_{ik}\,R^{u*}_{jk},\, R^u_{i(3+k)}\,R^{u*}_{j(3+k)}\},$$

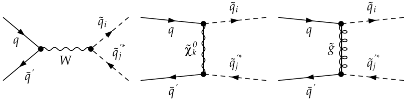
$$\{L_{\tilde{u}_i \tilde{d}_j W}, R_{\tilde{u}_i \tilde{d}_j W}\} = \sum_{k,l=1}^{3} \{\sqrt{2}\,c_W\,V_{u_k d_l}\,R^u_{ik}\,R^{d*}_{jl},\, 0\},$$

▷ NMFV contributions.

Squark-antisquark pair production at the LHC (1)

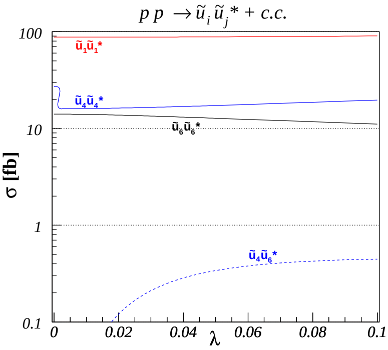


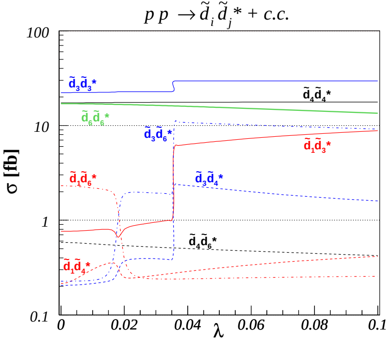


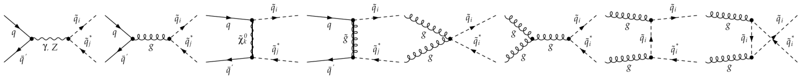


- Only heavy flavours production is considered.
- The three diagrams contribute (only one dominant for MFV).
- Very sensitive to NMFV.

Squark-antisquark pair production at the LHC (2)

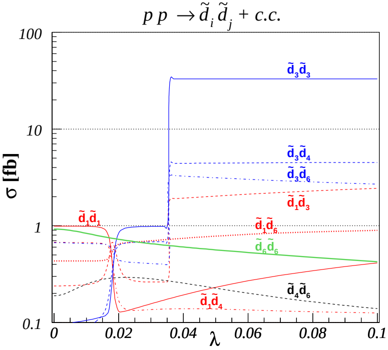


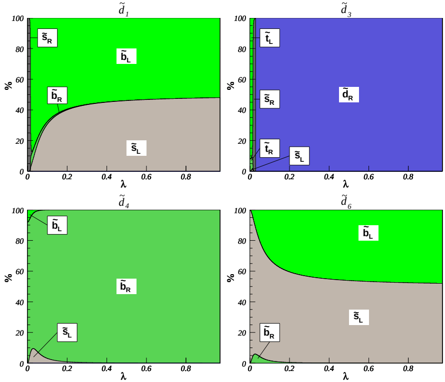


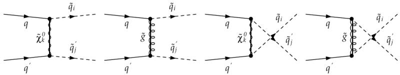


- Diagonal production dominates (QCD diagrams).

Squark-pair production at the LHC

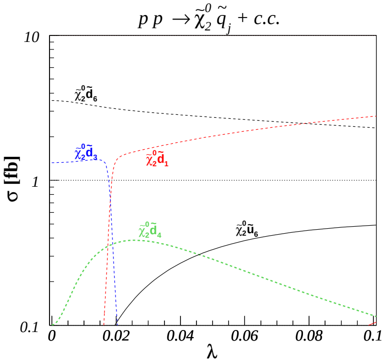


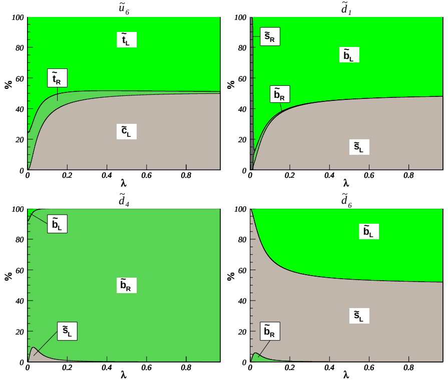


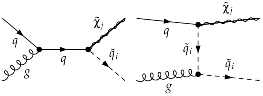


- Higher cross sections, due to new opened channels.
- Gluino diagrams dominate.

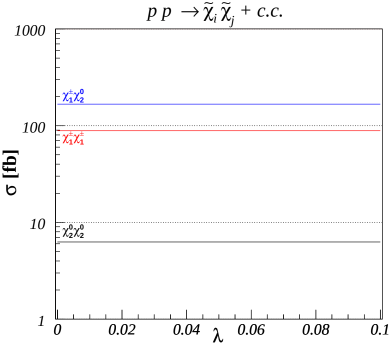
Associated squark-neutralino production at the LHC

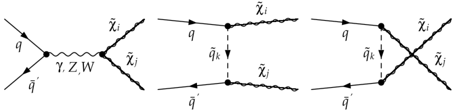






Gaugino-pair production at the LHC





- Z and γ diagrams dominate.
- NMFV-sensitive t- and u-channels negligible.

Other scenarios

- Three other benchmark points

m_0 [GeV]	$m_{1/2}$ [GeV]	A_0 [GeV]	$\tan\beta$	$sign(\mu)$
700	200	0	10	+
230	590	0	30	+
600	700	0	50	+

- Heavier squarks (bigger m_0 and/or $m_{1/2}$).
- Results:
  - ▷ Scenario 1: Reduced sensitivity to NMFV.
  - ▷ Scenario 2: Quite sensitive to NMFV, and lower cross sections.
  - ▷ Scenario 3: Visible cross sections not sensitive to NMFV.

Outline

Summary

- Scan of the mSUGRA parameter space:
  - ▷ Search for regions allowed by EW and dark matter constraints.
  - ▷ Benchmark points proposals.
  - ▷ Study of flavour and chirality content.
- Cross sections for :

$$a_{h_a}(p_a)\, b_{h_b}(p_b) \quad \to \quad \left\{ \begin{array}{l} \tilde{q}_i^{(*)}(p_1)\, \tilde{q}_j^{\prime(*)}(p_2), \\ \tilde{\chi}_j^{\pm(0)}(p_1)\, \tilde{q}_i^{(*)}(p_2), \\ \tilde{\chi}_i^{\pm(0)}(p_1)\, \tilde{\chi}_j^{\pm(0)}(p_2), \end{array} \right.$$

- Perspectives:
  - ▷ Public code for the LO cross sections.
  - ▷ Studies of new benchmark points: MSSM with NMFV, higher number of NMFV parameters,...