HEPHY VIENNA
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Impact of squark generation mixing on the search for squarks decaying into fermions at LHC

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Introduction

Motivation:

- Discovery of SUSY partners and study of their properties are essential for testing the MSSM.
- Here we focus on squarks – super partners of quarks
- With the start of the LHC at CERN a new era of particle physics has begun.
- If weak scale SUSY is realized in nature, squarks and gluinos will have high production rates for masses up to O(1) TeV at LHC.
- The main decay modes of squarks are usually assumed to be quark-flavor conserving (QFC).
- However, the squarks are not necessarily quark-flavor eigenstates. The flavor mixing in the squark sector may be stronger than that in the quark sector. Then quark-flavor violating (QFV) decays of squarks can occur with a significant rate.

Introduction

Purpose of this study:

- We study the effect of scharm-stop mixing on production and subsequent decays of squark at LHC in the general MSSM with R_P conserved.
- We show that due to the mixing effect the branching ratios of QFV squark decays can be very large in a significant region of the QFV parameters despite the very strong experimental constraints on QFV from B meson observables.
- This could have an important impact on the search for squarks and the MSSM parameter determination at LHC.

Quark Flavour Violation in the MSSM

In the Standard Model, all quark flavour-violating terms are prop. to CKM-matrix

Beyond Standard Model, e.g. Minimal Supersymmetric Standard Model (MSSM)

Minimal flavour-violation (MFV)

- no new sources of flavour violation
- in super-CKM basis squarks undergo same rotations as quarks
- all flavour-violating entries related to CKM-matrix
- Example: $\tilde{\chi}_i^\pm \tilde{q}_j q_k$ interaction proportional to $V_{q_j q'_k}$

Non-minimal flavour-violation (NMFV)

- new sources of flavour violation can appear within SUSY-GUTs
- e.g. gravity-mediation, messenger-matter mixing, flavour symmetries, ...
- corresponding flavour-violating entries not related to CKM-matrix
- considered as free parameters

The flavour-violating terms are incorporated in the 6x6 mass matrices at the electroweak scale, e.g.

$$M_{\tilde{u}}^2 = \begin{pmatrix} M_{\tilde{u}LL}^2 & (M_{\tilde{u}RL}^2)^\dagger \\ M_{\tilde{u}RL}^2 & M_{\tilde{u}RR}^2 \end{pmatrix}$$

Quark Flavour Violation in the MSSM

The 3x3 soft-breaking matrices can include off-diagonal, i.e. flavour-violating, entries

$$
\begin{aligned}
(M^2_{\tilde{u}LL})_{\alpha\beta} &= M^2_{Q_u\alpha\beta} + \left[(\frac{1}{2} - \frac{2}{3}\sin^2\theta_W)\cos 2\beta \; m_Z^2 + m_{u_\alpha}^2 \right] \delta_{\alpha\beta} \\
(M^2_{\tilde{u}RR})_{\alpha\beta} &= M^2_{U\alpha\beta} + \left[\frac{2}{3}\sin^2\theta_W \cos 2\beta \; m_Z^2 + m_{u_\alpha}^2 \right] \delta_{\alpha\beta} \\
(M^2_{\tilde{u}RL})_{\alpha\beta} &= (v_2/\sqrt{2}) T_{U\beta\alpha} - m_{u_\alpha}\mu^* \cot\beta \; \delta_{\alpha\beta}
\end{aligned}
$$

Introduce dimensionless parametrization for flavour-violating entries

$$
\begin{aligned}
\delta^{u\{LL,RR\}}_{\alpha\beta} &\equiv M^2_{\{Q,U\}\alpha\beta} / \sqrt{M^2_{\{Q,U\}\alpha\alpha} M^2_{\{Q,U\}\beta\beta}} \\
\delta^{uRL}_{\alpha\beta} &\equiv (v_2/\sqrt{2}) T_{U\beta\alpha} / \sqrt{M^2_{U\alpha\alpha} M^2_{Q\beta\beta}}
\end{aligned}
$$

Diagonalization through 6x6 rotation matrix leads to mass eigenstates

$$
\tilde{u}_i = R^{\tilde{u}}_{i\alpha} \tilde{u}_{0\alpha} \text{ and } R^{\tilde{u}} M^2_{\tilde{u}} R^{\tilde{u}\dagger} = \mathrm{diag}(m^2_{\tilde{u}_1}, \ldots, m^2_{\tilde{u}_6}), \text{ where } m_{\tilde{u}_i} < m_{\tilde{u}_j} \text{ for } i < j
$$

Constraints on the MSSM parameter space

- Mass limits from collider searches [PDG 2008-2010]
- only mixing between second and third generation squarks considered
- Electroweak precision and low-energy measurements [PDG 2008-2010; HFAG 2008-2010]

$$\begin{aligned} \mathrm{BR}(b \to s\gamma) &= (3.57 \pm 0.65)\cdot 10^{-4} \\ \Delta M_{B_s} &= (17.77 \pm 3.31)\mathrm{ps}^{-1} \\ \Delta\rho(\mathrm{SUSY}) &< 0.0012 \end{aligned}$$

Highly sensitive to QFV elements

$$\begin{aligned} \mathrm{BR}(b \to s\mu^+\mu^-) &= (1.60 \pm 1.00)\cdot 10^{-6} \\ \mathrm{BR}(b \to \mu^+\mu^-) &< 4.3 \cdot 10^{-8} \end{aligned}$$

$$\Delta a_\mu = a_\mu^{\mathrm{SM}} - a_\mu^{exp} = (29.0 \pm 8.6)\cdot 10^{-10}$$

Rather insensitive to QFV elements

- Cosmological constraints due to cold dark matter [WMAP 2010]

$$0.1018 < \Omega_{\mathrm{CDM}} h^2 < 0.1228$$

Squark decays

- The branching ratios of the squark decays

  $$\tilde{u}_{1,2} \to c\ \tilde{\chi}^0_1 \quad \text{and} \quad \tilde{u}_{1,2} \to t\ \tilde{\chi}^0_1$$

  are calculated by
- taking also into account

  $$\tilde{u}_i \quad \to \quad u_k\ \tilde{g},\ u_k\ \tilde{\chi}^0_n,\ d_k\ \tilde{\chi}^+_m,\ \tilde{u}_j\ Z^0,\ \tilde{d}_j\ W^+,\ \tilde{u}_j\ h^0$$

  where $u_k = (u, c, t)$ and $d_k = (d, s, b)$

Analytic formulas see G. Bozzi et al (2007), A. Bartl et al. (2004), M. Bruhnke, B. Herrrmann, W. Porod (2010)

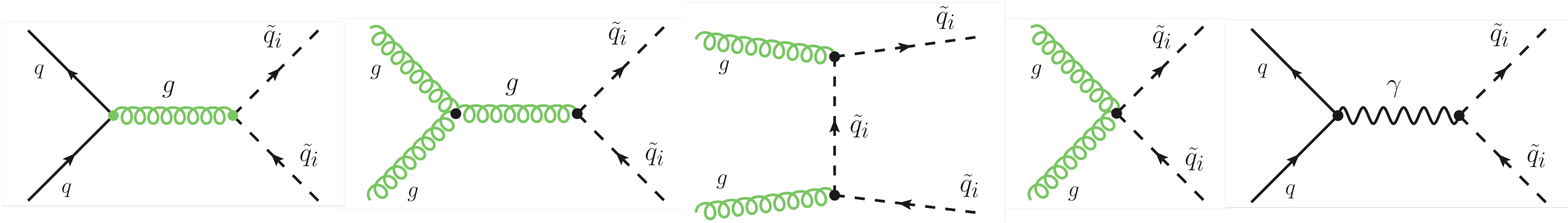
Squark Pair Production at Hadron Colliders

QCD factorization theorem

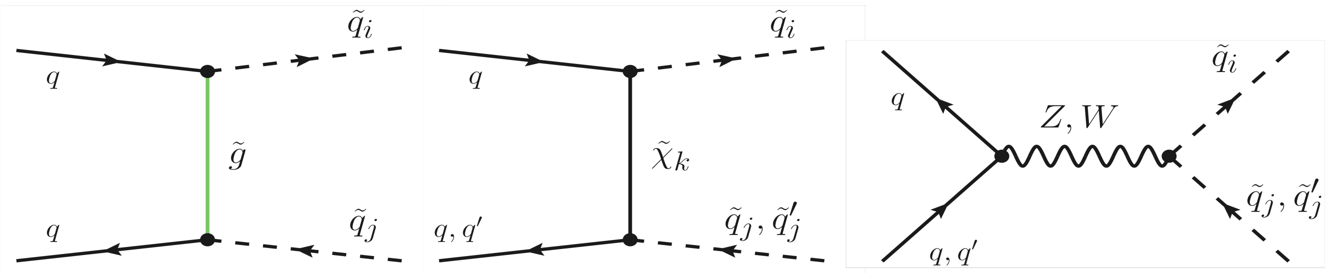
$$\boxed{\sigma = \int_{t_-}^{t_+} \mathrm{d}t \int_{\frac{4m^2}{s}}^{1} \mathrm{d}\tau \int_{-\frac{1}{2}\ln\tau}^{-\frac{1}{2}\ln\tau} \mathrm{d}y\, f_{a/A}(x_a, M_a^2)\, f_{b/B}(x_b, M_b^2)\, \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}t}}$$

$$x_{a,b} = \sqrt{\tau} e^{\pm y}$$

Flavour-conserving channels



Flavour-violating channels



Analytical expressions for squark production cross-sections and decays published in earlier works

Bozzi, Fuks, Herrmann, Klasen (2007); Fuks, Herrmann, Klasen (2008)

Production and Decays of Squarks at LHC

Interesting production signature due to potentially large squark branching ratios

$$\boxed{pp \to \tilde{u}_{1,2}\bar{\tilde{u}}_{1,2} \to c\bar{t}\,\tilde{\chi}_1^0\tilde{\chi}_1^0}$$

Calculation of the corresponding cross-sections

$$\sigma_{ct}^{ij} \equiv \sigma(pp \to \tilde{u}_i\bar{\tilde{u}}_j X)\times\Big(B(\tilde{u}_i \to c\tilde{\chi}_1^0)B(\bar{\tilde{u}}_j \to \bar{t}\tilde{\chi}_1^0)+B(\tilde{u}_i \to t\tilde{\chi}_1^0)B(\bar{\tilde{u}}_j \to \bar{c}\tilde{\chi}_1^0)\Big)$$

Numerical calculation

- SPheno3 for mass spectrum, constraints, and branching ratios [Porod 2003-2010]
- Whizard/O'Mega for production cross-sections [Kilian, Ohl, Reuter 2001-2010]
  (MSSM with QFV implemented!) [Herrmann 2009]
- Verification using FeynArts/FormCalc [Hahn 2001-2010]
- CTEQ6L parton distribution functions [Pumplin *et al.* (CTEQ)]

Numerical scenarios

- Input parameters:

  $\tan\beta, m_{A^0}, M_1, M_2, M_3, \mu, M^2_{Q\alpha\beta}, M^2_{U\alpha\beta}, M^2_{D\alpha\beta}, T_{U\alpha\beta}$ and $T_{D\alpha\beta}$

  (at the weak scale and real)

- QFV parameters:

  $M^2_{Q\alpha\beta}, M^2_{U\alpha\beta}, M^2_{D\alpha\beta}, T_{U\alpha\beta}$ and $T_{D\alpha\beta}$ with $\alpha \neq \beta$

- Two reference scenarios:

  – Scen1: QFV signals at LHC maximized:
  can serve as a benchmark scenario for further studies

  – Scen2: mSUGRA scenario SPS1a': has already served for
  several exp. studies

Scen I

$M^2_{Q\alpha\beta}$	$\beta=1$	$\beta=2$	$\beta=3$
$\alpha=1$	$(920)^2$	0	0
$\alpha=2$	0	$(880)^2$	$(224)^2$
$\alpha=3$	0	$(224)^2$	$(840)^2$

$\delta^{uLL}_{23} = \frac{(224)^2}{880\times840} = 0.068$

M_1	M_2	M_3	μ	$\tan\beta$	m_{A^0}
139	264	800	1000	10	800

All of $T_{U\alpha\beta}$ and $T_{D\alpha\beta}$ are set to zero

$M^2_{D\alpha\beta}$	$\beta=1$	$\beta=2$	$\beta=3$
$\alpha=1$	$(830)^2$	0	0
$\alpha=2$	0	$(820)^2$	0
$\alpha=3$	0	0	$(810)^2$

$M^2_{U\alpha\beta}$	$\beta=1$	$\beta=2$	$\beta=3$
$\alpha=1$	$(820)^2$	0	0
$\alpha=2$	0	$(600)^2$	$(373)^2$
$\alpha=3$	0	$(373)^2$	$(580)^2$

(all numbers in GeV, except $tan\beta$)

$\delta^{uRR}_{23} = \frac{(373)^2}{600\times580} = 0.4$

$\tilde{u}_1$	$\tilde{u}_2$	$\tilde{u}_3$	$\tilde{u}_4$	$\tilde{u}_5$	$\tilde{u}_6$
472	708	819	837	897	918

$\tilde{d}_1$	$\tilde{d}_2$	$\tilde{d}_3$	$\tilde{d}_4$	$\tilde{d}_5$	$\tilde{d}_6$
800	820	830	835	897	922

$\tilde{g}$	$\tilde{\chi}^0_1$	$\tilde{\chi}^0_2$	$\tilde{\chi}^0_3$	$\tilde{\chi}^0_4$	$\tilde{\chi}^\pm_1$	$\tilde{\chi}^\pm_2$
800	138	261	1003	1007	261	1007

h^0	H^0	A^0	$H^\pm$
122	800	800	804

Scen I

$\lvert R^{\tilde u}_{i\alpha}\rvert$	$\tilde u_L$	$\tilde c_L$	$\tilde t_L$	$\tilde u_R$	$\tilde c_R$	$\tilde t_R$
$\tilde u_1$	0.001	0.004	0.024	0	0.715	0.699
$\tilde u_2$	0.003	0.014	0.055	0	0.699	0.713
$\tilde u_3$	0	0	0	1.0	0	0
$\tilde u_4$	0.128	0.584	0.800	0	0.021	0.053
$\tilde u_5$	0.181	0.781	0.598	0	0.008	0.024
$\tilde u_6$	0.975	0.221	0.005	0	0	0

$$\tilde u_1 \sim -\frac{1}{\sqrt{2}}\tilde c_R + \frac{1}{\sqrt{2}}\tilde t_R$$
$$\tilde u_2 \sim +\frac{1}{\sqrt{2}}\tilde c_R + \frac{1}{\sqrt{2}}\tilde t_R$$

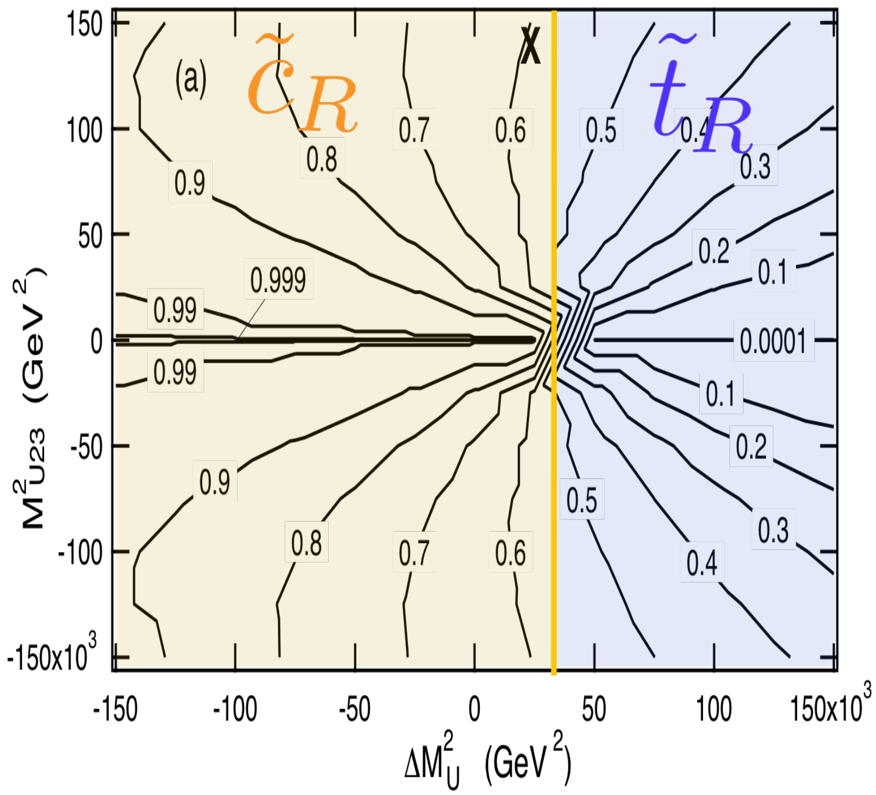
- Two main channels for $\tilde u_1$ and $\tilde u_2$:

(B – branching ratio)

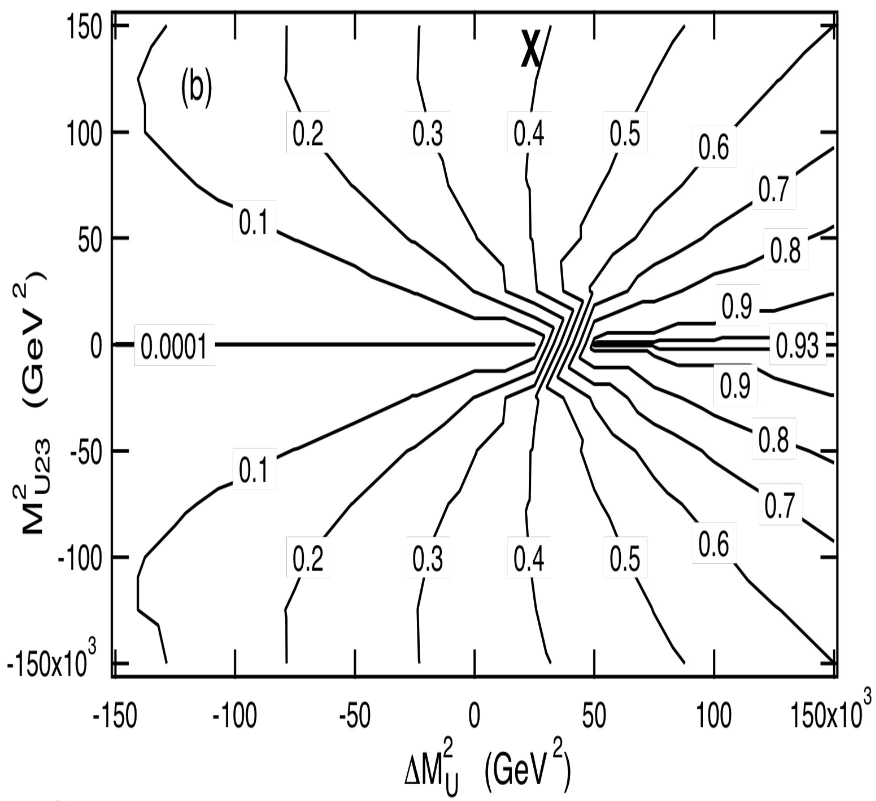
$$B(\tilde u_1 \to c\tilde\chi^0_1) = 0.59,\ \ B(\tilde u_1 \to t\tilde\chi^0_1) = 0.39$$
$$B(\tilde u_2 \to c\tilde\chi^0_1) = 0.44,\ \ B(\tilde u_2 \to t\tilde\chi^0_1) = 0.40$$

Squark decays

$B(\tilde{u}_1 \to c\tilde{\chi}^0_1)$



$B(\tilde{u}_1 \to t\tilde{\chi}^0_1)$



limit: $\tilde{t}_L$ - $\tilde{t}_R$ mixing ~ 0

$$\tan(2\theta^{eff}_{\tilde{c}_R\tilde{t}_R}) \equiv 2M^2_{U23}/(\Delta M^2_U - m_t^2)$$

$$\Delta M^2_U \equiv M^2_{U22} - M^2_{U33}$$

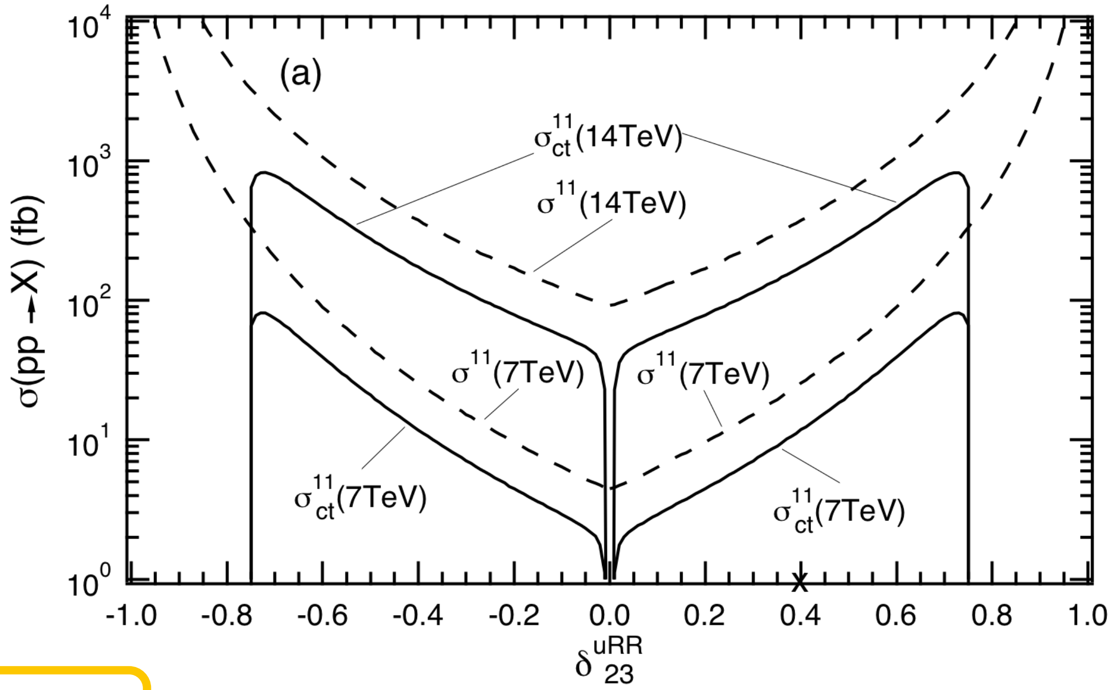
M^2_{U22} fixed

$\Delta M^2_U - m_t^2 > 0$: $\tilde{u}_1 \sim \tilde{t}_R \; (+\, \tilde{c}_R)$

$\Delta M^2_U - m_t^2 < 0$: $\tilde{u}_1 \sim \tilde{c}_R \; (+\, \tilde{t}_R)$

Scen I

- Charm-top associated production – interesting signature



$$\boxed{\sigma^{11} \equiv \sigma(pp \to \tilde{u}_1 \bar{\tilde{u}}_1 X)}$$

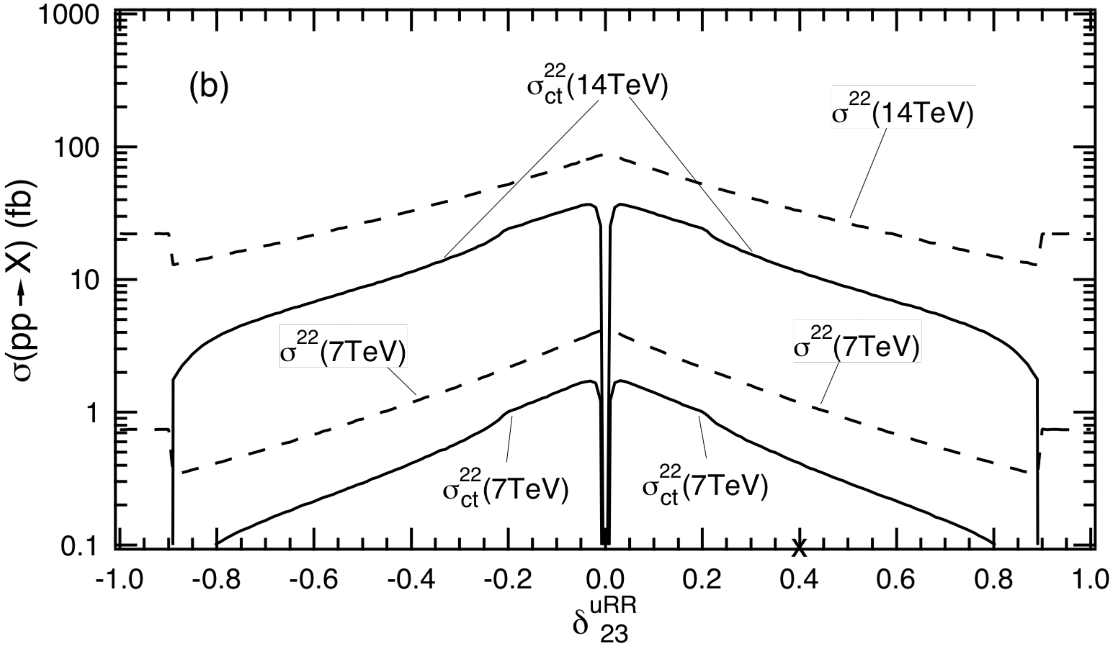
$$\boxed{\sigma^{11}_{ct} \equiv \sigma^{11} \times \left(B(\tilde{u}_1 \to c\tilde{\chi}^0_1) \cdot B(\bar{\tilde{u}}_1 \to \bar{t}\tilde{\chi}^0_1) + B(\tilde{u}_1 \to t\tilde{\chi}^0_1) \cdot B(\bar{\tilde{u}}_1 \to \bar{c}\tilde{\chi}^0_1) \right)}$$

Expect ~ O(10^4) events for "jet + top + E_T^{miss}" production at 100 fb^{-1} integrated luminosity

Loop corrections for dominant flavour-conserving channels enhance cross-section by ~ 30%

[Beenakker, Höpker, Spira, Zerwas (1997)]

Scen I



$$\sigma^{22} \equiv \sigma(pp \to \tilde{u}_2 \bar{\tilde{u}}_2 X)$$

$$\sigma^{22}_{ct} \equiv \sigma^{22} \times \Big(B(\tilde{u}_2 \to c \tilde{\chi}^0_1) \cdot B(\bar{\tilde{u}}_2 \to \bar{t} \tilde{\chi}^0_1) + B(\tilde{u}_2 \to t \tilde{\chi}^0_1) \cdot B(\bar{\tilde{u}}_2 \to \bar{c} \tilde{\chi}^0_1) \Big)$$

Scen II – SPS1a'

$M^2_{Q\alpha\beta}$	$\beta=1$	$\beta=2$	$\beta=3$
$\alpha=1$	$(526)^2$	0	0
$\alpha=2$	0	$(526)^2$	0
$\alpha=3$	0	0	$(471)^2$

M_1	M_2	M_3	μ	$\tan\beta$	m_{A^0}
103	193	572	398	10	373
T_{U11}	T_{U22}	T_{U33}	T_{D11}	T_{D22}	T_{D33}
-0.007	-2.68	-488	-0.19	-3.26	-128

$M^2_{D\alpha\beta}$	$\beta=1$	$\beta=2$	$\beta=3$
$\alpha=1$	$(505)^2$	0	0
$\alpha=2$	0	$(505)^2$	0
$\alpha=3$	0	0	$(501)^2$

$M^2_{U\alpha\beta}$	$\beta=1$	$\beta=2$	$\beta=3$
$\alpha=1$	$(508)^2$	0	0
$\alpha=2$	0	$(508)^2$	$(280)^2$
$\alpha=3$	0	$(280)^2$	$(387)^2$

$$\delta_{23}^{uRR} = \frac{(280)^2}{508\times387} = 0.4$$

(all numbers in GeV,
except $tan\beta$)

$\tilde{u}_1$	$\tilde{u}_2$	$\tilde{u}_3$	$\tilde{u}_4$	$\tilde{u}_5$	$\tilde{u}_6$
332	541	548	565	565	612

$\tilde{d}_1$	$\tilde{d}_2$	$\tilde{d}_3$	$\tilde{d}_4$	$\tilde{d}_5$	$\tilde{d}_6$
506	547	547	547	571	571

$\tilde{g}$	$\tilde{\chi}^0_1$	$\tilde{\chi}^0_2$	$\tilde{\chi}^0_3$	$\tilde{\chi}^0_4$	$\tilde{\chi}^\pm_1$	$\tilde{\chi}^\pm_2$
608	98	184	402	415	184	417

h^0	H^0	A^0	$H^\pm$
112	426	426	434

Scen II

$\lvert R^{\tilde{u}}_{i\alpha}\rvert$	$\tilde{u}_L$	$\tilde{c}_L$	$\tilde{t}_L$	$\tilde{u}_R$	$\tilde{c}_R$	$\tilde{t}_R$
$\tilde{u}_1$	0.010	0.032	0.457	0	0.369	0.809
$\tilde{u}_2$	0.014	0.015	0.691	0	0.720	0.062
$\tilde{u}_3$	0	0	0	1.0	0	0
$\tilde{u}_4$	0.896	0.444	0.011	0	0.003	0.001
$\tilde{u}_5$	0.443	0.893	0.036	0	0.062	0.008
$\tilde{u}_6$	0.021	0.058	0.559	0	0.585	0.585

$\tilde{u}_1 \sim (\tilde{t}_L, \tilde{c}_R, \tilde{t}_R)$

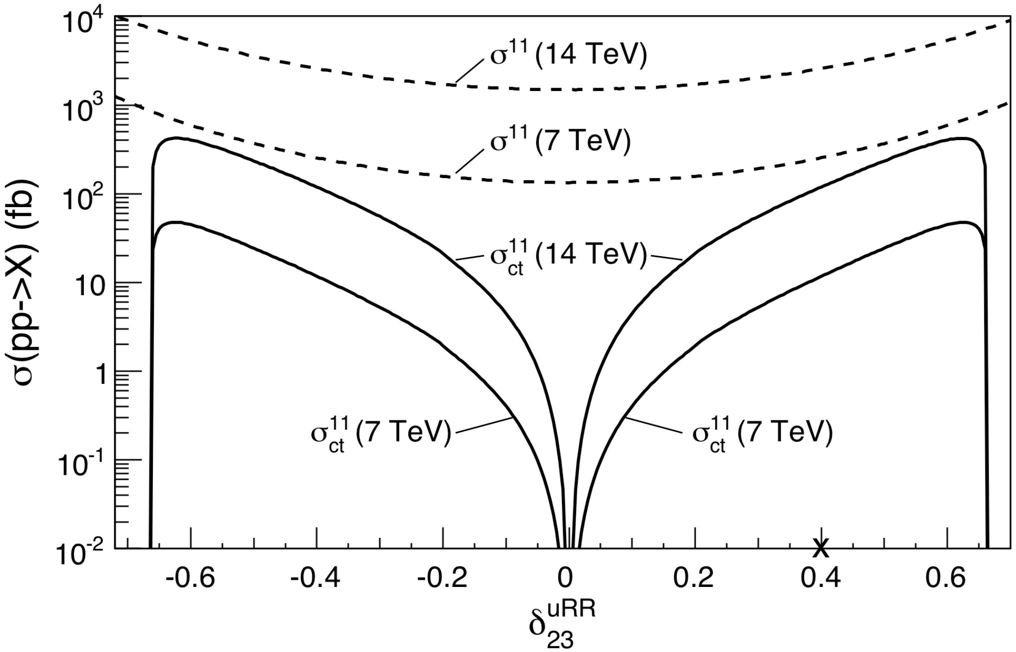
$\tilde{u}_2 \sim (\tilde{t}_L, \tilde{c}_R)$

- We get for $\tilde{u}_1$ and $\tilde{u}_2$: (B – branching ratio)

$$B(\tilde{u}_1 \to c\tilde{\chi}^0_1) = 0.10,\ \ B(\tilde{u}_1 \to t\tilde{\chi}^0_1) = 0.23$$

$$B(\tilde{u}_2 \to c\tilde{\chi}^0_1) = 0.15,\ \ B(\tilde{u}_2 \to t\tilde{\chi}^0_1) = 0.004$$

Scen II



$$\boxed{\sigma^{11} \equiv \sigma(pp \to \tilde{u}_1 \bar{\tilde{u}}_1 X)}$$

$$\boxed{\sigma^{11}_{ct} \equiv \sigma^{11} \times \Big(B(\tilde{u}_1 \to c\tilde{\chi}^0_1) \cdot B(\bar{\tilde{u}}_1 \to \bar{t}\tilde{\chi}^0_1) + B(\tilde{u}_1 \to t\tilde{\chi}^0_1) \cdot B(\bar{\tilde{u}}_1 \to \bar{c}\tilde{\chi}^0_1) \Big)}$$

Again, expect up to O(10^4) events for "jet + top + E_T^{miss}" production at 100 fb^{-1} integrated luminosity

Signal and Background

$pp \to \tilde{u}_{1,2}\bar{\tilde{u}}_{1,2} \to c\bar{t}\,(t\bar{c})\,\tilde{\chi}_1^0\tilde{\chi}_1^0$? $pp \to \tilde{u}_{1,2}\bar{\tilde{u}}_{1,2} \to t\bar{t}\,\tilde{\chi}_1^0\tilde{\chi}_1^0$

Main SUSY background

Identification of top-quark crucial: $t \to b\,W^+ \to bq\bar{q}$

Efficient charm-tagging useful, otherwise search for $pp \to \tilde{u}_{1,2}\bar{\tilde{u}}_{1,2} \to q\bar{t}\,(t\bar{q})\,\tilde{\chi}_1^0\tilde{\chi}_1^0$

$pp \to \tilde{u}_{1,2}\bar{\tilde{u}}_{1,2} \to c\bar{t}\,(t\bar{c})\,\tilde{\chi}_1^0\tilde{\chi}_1^0$? $pp \to \tilde{g}\tilde{\chi}_1^0 \to c\bar{t}\,(t\bar{c})\,\tilde{\chi}_1^0\tilde{\chi}_1^0$

Xsection very small in our scenarios

SM background: $pp \to t\bar{t}Z^0X \to t\bar{t}\nu\bar{\nu}X$

$pp \to W^{+*}Z^0X \to t\bar{b}\nu\bar{\nu}X$

However, these Xsections are very small because they involve weak processes.

Conclusions and Outlook

Conclusions:

- effects of squark mixing of 2nd and 3rd generation $\tilde{c}_{L/R}$ - $\tilde{t}_{L/R}$ on squark production and decays at LHC in the MSSM studied
- branching ratios $\mathrm{B}(\tilde{u}_{1,2} \to c/t\tilde{\chi}^0_1)$ can be up to 50% simultaneously
- QFV signal events '$pp \to c\bar{t}\ (t\bar{c}) + E_T^{mis}$ + beam-jets' with a significant rate at LHC with rather low background
- Next step: detailed Monte Carlo study

Outlook:

- Study of further squark and gluino decays …
- Inclusion of higher order corrections in production and decays …
- Study of lepton flavour violating processes and signatures …