Impact of squark generation mixing on the search for squarks and gluinos at LHC

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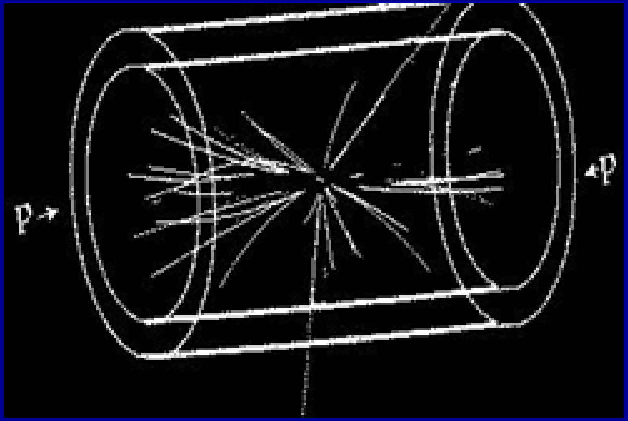

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Contents

1. Introduction

(1) Motivation;

- *Discovery of all SUSY partners and study of their properties are essential for testing the MSSM.*
- *Here we focus on SUSY partners of quraks and gluons (i.e. squarks and gluinos).*
- *With the start of the Large Hadron Collider (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 and gluinos 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. In this case quark-flavor violating (QFV) decays of squarks and gluinos could occur with a significant rate.
- *Here we study the effect of the mixing of charm-squark and top-squark on the production and decays of squarks and gluinos.*

(2)Purpose of this work;

- *In this work we study the effect of scharm-stop mixing on the squark and gluino decays at LHC in the general MSSM.*

- *We show that due to the mixing effect the branching ratios of QFV squark and gluino 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 gluinos and the MSSM parameter determination at LHC.*

2. MSSM with QFV

- ***The basic parameters of the MSSM with QFV:***

$\{\tan\beta, m_A, M_1, M_2, m_{gluino}, \mu, M^2_{Q\alpha\beta}, M^2_{U\alpha\beta}, M^2_{D\alpha\beta}, T_{U\alpha\beta}, T_{D\alpha\beta}\}$

(at weak scale) $(\alpha,\beta = 1,2,3 = u, c, t \text{ or } d, s, b)$

$\tan\beta$:	*ratio of VEV of the two Higgs doublets* $\langle H^0{}_2\rangle/\langle H^0{}_1\rangle$
m_A:	*CP odd Higgs boson mass*
M_1, M_2:	*U(1), SU(2) gaugino mass*
m_{gluino}:	*gluino mass*
μ:	*higgsino mass parameter*
$M^2_{Q\alpha\beta}$:	*left squark soft mass matrix*
$M^2_{U\alpha\beta}$:	*right up-type squark soft mass matrix*
$M^2_{D\alpha\beta}$:	*right down-type squark soft mass matrix*
$T_{U\alpha\beta}$:	*trilinear coupling matrix of up-type squark and Higgs boson*
$T_{D\alpha\beta}$:	*trilinear coupling matrix of down-type squark and Higgs boson*

- *Here we study* $\tilde{c}-\tilde{t}$ *mixing effect.*

QFV parameters ***in our study are:***

M^2_{Q23} : $\tilde{c}_L - \tilde{t}_L$ *mixing term* ($\tilde{s}_L - \tilde{b}_L$ *mixing term)*

M^2_{U23} : $\tilde{c}_R - \tilde{t}_R$ *mixing term*

T_{U23} : $\tilde{c}_L - \tilde{t}_R$ *mixing term*

T_{U32} : $\tilde{c}_R - \tilde{t}_L$ *mixing term*

(Note) We work in the ***super-CKM basis*** *of squarks:*

$$(\tilde{u}_L, \tilde{c}_L, \tilde{t}_L, \tilde{u}_R, \tilde{c}_R, \tilde{t}_R), (\tilde{d}_L, \tilde{s}_L, \tilde{b}_L, \tilde{d}_R, \tilde{s}_R, \tilde{b}_R).$$

In this basis we have $M^2_{Q_u} = K \cdot M^2_Q \cdot K^{-1}$ *due to the SU(2) symmetry,*

where $M^2_{Q_u}$ *is the soft mass matrix of left up-type squarks*

M^2_Q *is the soft mass matrix of left down-type squarks and*

K is the CKM matrix.

(Note) We have $M^2_{Q_u} \simeq M^2_Q$ *as* $K \simeq 1$.

3. *Constraints on the MSSM*

The following constraints are imposed in our analysis in order to respect experimental and theoretical constraints:

(a) Constraints from the B-physics experiments :

$2.92\times10^{-4} < B(b\to s\gamma) < 4.22\times10^{-4}$ (95% CL) (Lepton Photon2009)

$0.60\times10^{-6} < B(b\to s\,\ell^+\ell^-) < 2.60\times10^{-6}$ (with $\ell = e$ or μ) (95% CL) (BELLE, BABAR)

$B(B_s\to\mu^+\mu^-) < 4.3\times10^{-8}$ (95% CL) (CDF)

$B(B_u^+\to\tau^+\nu) = (1.73\pm0.35)\times10^{-4}$ (68% CL) (BELLE, BABAR)

$\Delta M_{B_s} = 17.77\pm0.12\ \mathrm{ps}^{-1}$ (68% CL) (CDF)

(b) LEP and Tevatron limits on sparticle masses

(ex) $m_{\tilde{\chi}_1^\pm} > 103\ GeV,\quad m_{\tilde{g}} > 308\ GeV$ ***etc.***

(c) The experimental limit on SUSY contributions to the electroweak ρ parameter:

$\Delta\rho(SUSY) < 0.0012$

(d) Vacuum stability conditions on trilinear couplings

(see J.A. Casas and S. Dimopoulos, Phys. Lett. B 387 (1996) 107 [hep-ph/9606237].)

(ex) $|T_{U\,23}|^2 < h_t^2\,(M_{Q_u\,22}^2 + M_{U\,33}^2 + m_2^2)$ ***etc.***

with $m_2^2 = (m_{H^*}^2 + m_Z^2\sin^2\theta_W)\cos^2\beta - \frac{1}{2}m_Z^2$

(Note) These constraints are very important:

$B(b \to s\gamma)$ *and* ΔM_{B_s} *data* => *strongly constrain the QFV squark parameters*

Vacuum stability conditions => *strongly constrain QFV trilinear couplings* $T_{U\alpha\beta}$

$B(B_u^+ \to \tau^+ \nu)$ *data* => *strongly constrain* $(m_{H^+}, \tan\beta)$

(Note) We use the public code SPheno v3.0 in the calculation of the B-physics observables.

4. QFV Benchmark Scenario

We take the following ***scharm-stop mixing scenario*** *as a* ***QFV benchmark scenario***:

$\tilde{c}_L - \tilde{t}_L$ *mixing term*

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

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

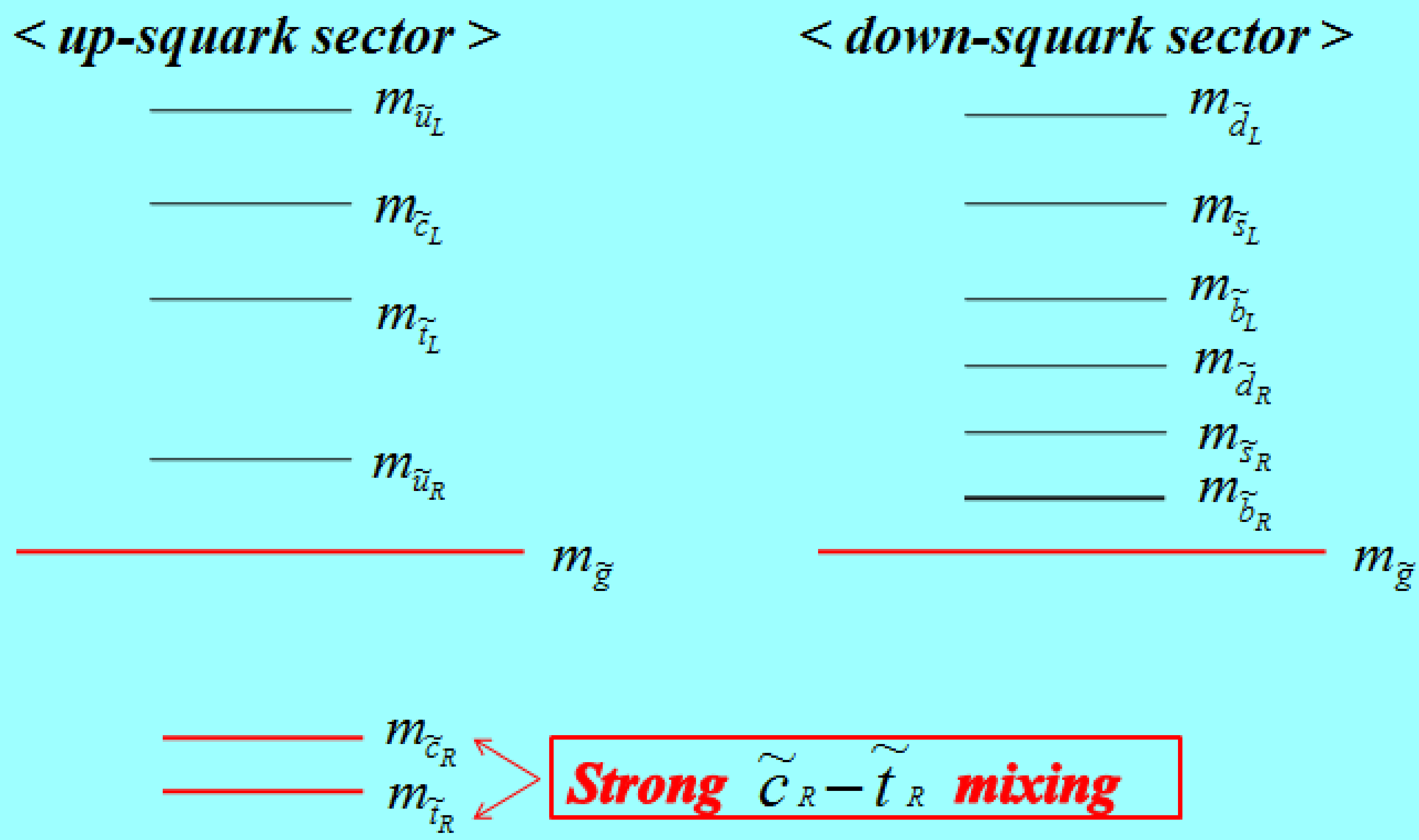
$\tilde{c}_R - \tilde{t}_R$ *mixing term*

$M^2_{D\alpha\beta}$	$\beta = 1$	$\beta = 2$	$\beta = 3$
$\alpha = 1$	$(830)^2$	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	$(600)^2$	$(224)^2$
$\alpha = 3$	0	$(224)^2$	$(580)^2$

Table 1: The basic MSSM parameters in our reference scenario with QFV. All of $T_{U\alpha\beta}$ and $T_{D\alpha\beta}$ are set to zero. All mass parameters are given in GeV.

QFV Benchmark Scenario



In this scenario, gluino can decay only into strong mixtures of $\tilde{c}_R$ and $\tilde{t}_R$!

$$\widetilde{u}_1 \approx 0.73\widetilde{c}_R - 0.69\widetilde{t}_R \qquad \widetilde{u}_2 \approx -0.69\widetilde{c}_R - 0.73\widetilde{t}_R$$

$\tilde{u}_1$	$\tilde{u}_2$	$\tilde{u}_3$	$\tilde{u}_4$	$\tilde{u}_5$	$\tilde{u}_6$	$\tilde{d}_1$	$\tilde{d}_2$	$\tilde{d}_3$	$\tilde{d}_4$	$\tilde{d}_5$	$\tilde{d}_6$
558	642	819	837	897	918	800	820	830	835	897	922

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

Table 2: Sparticles and corresponding masses (in GeV) in the scenario of Table 1.

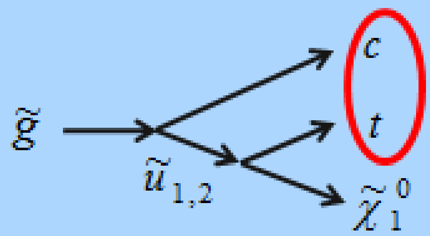
Our scenario is within the reach of LHC.

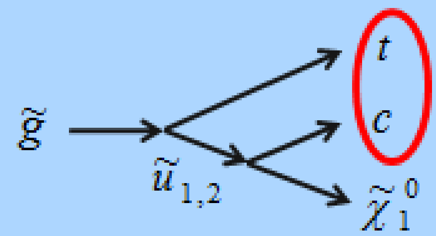
5. Impact of squark generation mixing on squark and gluino decays

- *We study the* *effect of squark generation mixing* *on the squark and gluino decays at LHC.*

- *In case of $\tilde{c}_R - \tilde{t}_R$ mixing, squarks and gluino could decay as follows:*

$$\tilde{g} \to \tilde{u}_i \; c \to c \; t \; \tilde{\chi}_1^0 \quad \text{and} \quad \tilde{g} \to \tilde{u}_i \; t \to c \; t \; \tilde{\chi}_1^0$$





$$\boxed{\tilde{g} \to c \; t \; \tilde{\chi}_1^0}$$

- ***Gluino decay branching ratios in our scenario:***

In our scenario we have:

$$B(\tilde{g} \to ct\tilde{\chi}_1^0) = \sum_{i=1,2} \left[B(\tilde{g} \to \tilde{u}_i c) B(\tilde{u}_i \to t\tilde{\chi}_1^0) + B(\tilde{g} \to \tilde{u}_i t) B(\tilde{u}_i \to c\tilde{\chi}_1^0) \right] = 0.463, \quad \left(QFV \right)$$

$$B(\tilde{g} \to cc\tilde{\chi}_1^0) = \sum_{i=1,2} \left[B(\tilde{g} \to \tilde{u}_i c) B(\tilde{u}_i \to c\tilde{\chi}_1^0) \right] = 0.380, \quad \left(QFC \right)$$

$$B(\tilde{g} \to tt\tilde{\chi}_1^0) = \sum_{i=1,2} \left[B(\tilde{g} \to \tilde{u}_i t) B(\tilde{u}_i \to t\tilde{\chi}_1^0) \right] = 0.120. \quad \left(QFC \right)$$

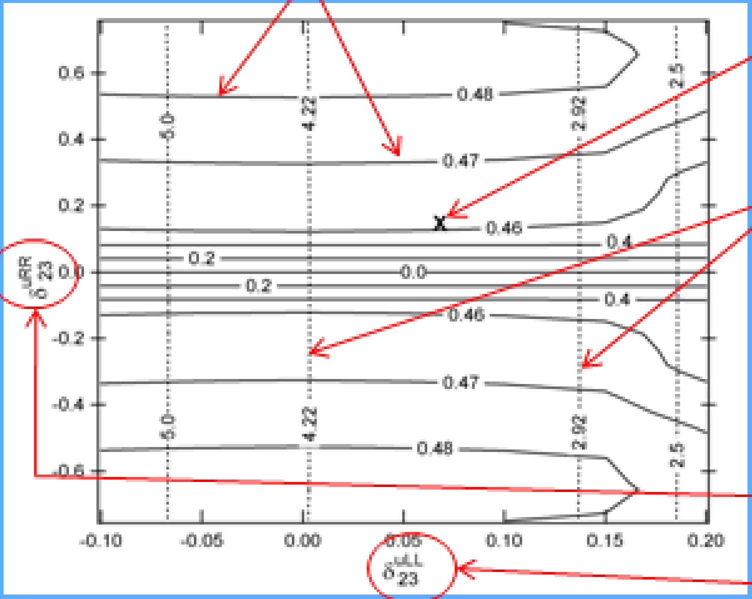
(Note) $\tilde{u}_1 \approx 0.73\tilde{c}_R - 0.69\tilde{t}_R$, $\tilde{u}_2 \approx -0.69\tilde{c}_R - 0.73\tilde{t}_R$

$\Downarrow$

We have very large QFV gluino decay branching ratio!

Contour plots of QFV BR in our scenario

$B(\tilde{g} \to ct\tilde{\chi}_1^0)$ ***contours***



our benchmark scenario

$\mathrm{B}(b \to s\gamma)\cdot 10^4$ ***contours***

$$\delta^{uLL}_{\alpha\beta} \equiv M^2_{Q\alpha\beta}/\sqrt{M^2_{Q\alpha\alpha}M^2_{Q\beta\beta}}$$

$$\delta^{uRR}_{\alpha\beta} \equiv M^2_{U\alpha\beta}/\sqrt{M^2_{U\alpha\alpha}M^2_{U\beta\beta}}$$

$\tilde{c}_R - \tilde{t}_R$ ***mixing parameter***

$\tilde{c}_L - \tilde{t}_L$ ***mixing parameter***

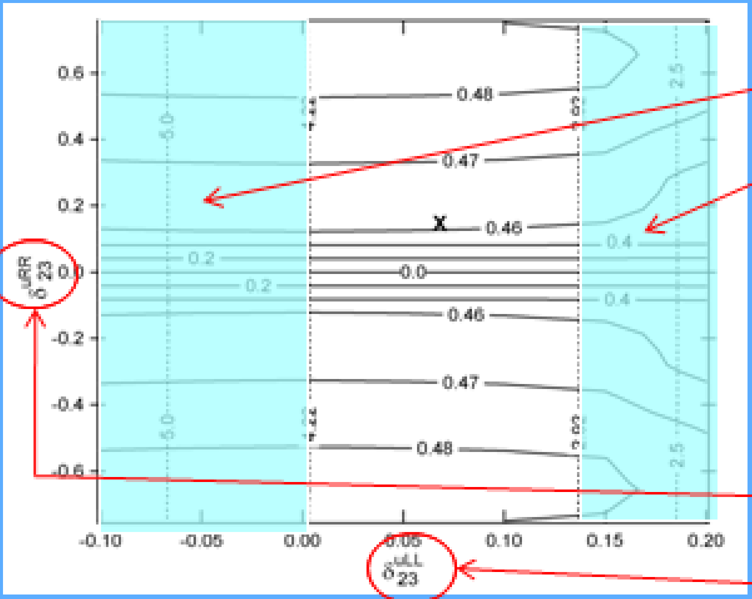
The QFV decay branching ratio $B(\tilde{g} \to ct\tilde{\chi}_1^0)$ ***can be very large in a significant part of the*** $\delta^{uLL}_{23} - \delta^{uRR}_{23}$ ***plane allowed by all of the constraints.***

This can lead to large QFV effects at LHC!

Contour plots of QFV BR in our scenario

$B(\tilde{g} \to ct\tilde{\chi}_1^0)$ ***contours***

excluded by $\mathrm{B}(b \to s\,\gamma)$ ***data***



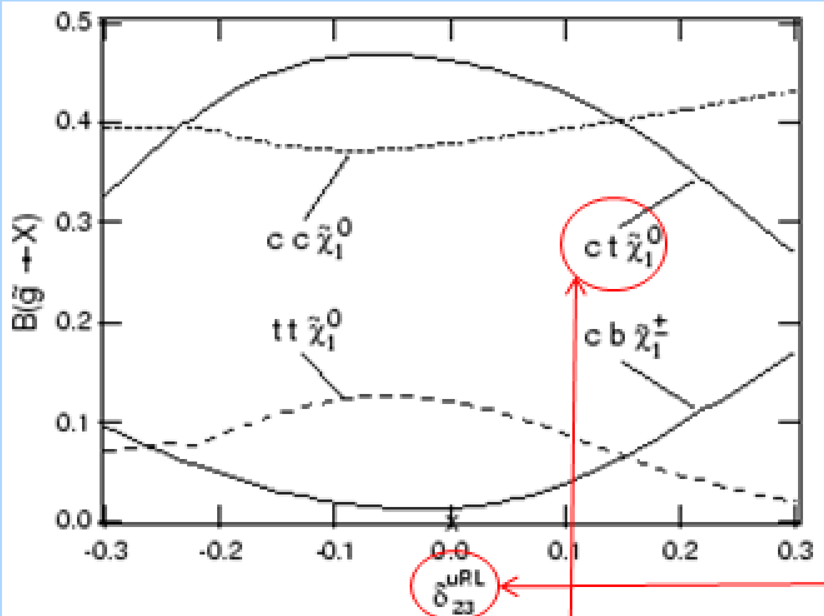
$\tilde{c}_R - \tilde{t}_R$ ***mixing parameter***

$\tilde{c}_L - \tilde{t}_L$ ***mixing parameter***

The QFV decay branching ratio $B(\tilde{g} \to ct\tilde{\chi}_1^0)$ ***can be very large in a significant part of the*** $\delta_{23}^{uLL} - \delta_{23}^{uRR}$ ***plane allowed by all of the constraints.***

This can lead to large QFV effects at LHC!

δ_{23}^{uRL} *dependences of gluino decay BR's in our scenario*

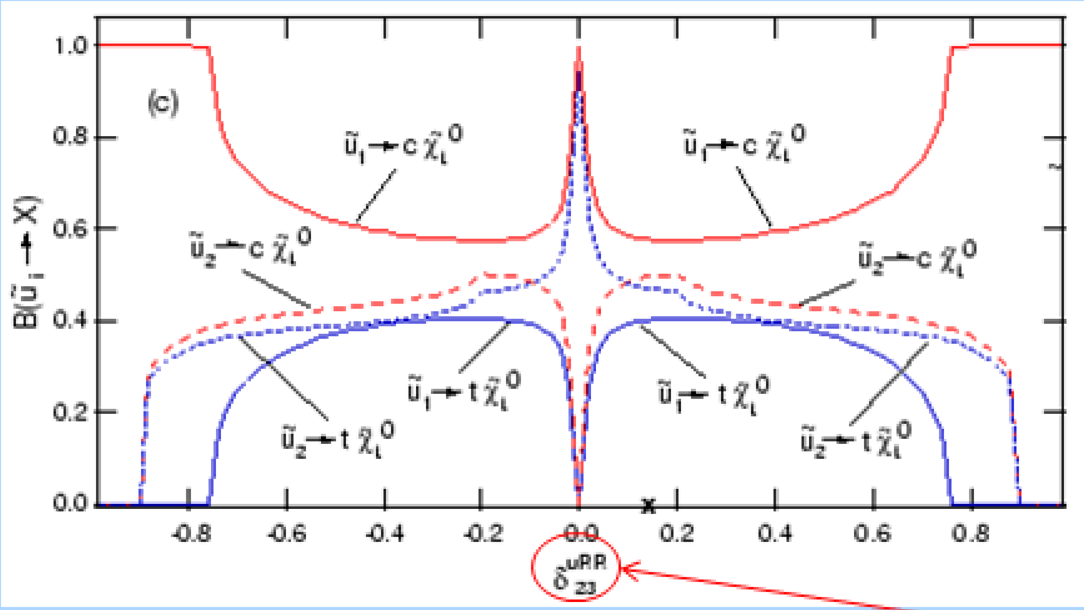


$$\delta_{\alpha\beta}^{uRL} \equiv (v_2/\sqrt{2}) T_{U\beta\alpha} / \sqrt{M_{U\alpha\alpha}^2 M_{Q\beta\beta}^2}$$

$\tilde{c}_R - \tilde{t}_L$ ***mixing parameter***

The QFV decay branching ratio $B(\tilde{g} \to c t \tilde{\chi}_1^0)$ ***can be very large (~30 - 50%) in a wide allowed range of*** $\tilde{c}_R - \tilde{t}_L$ ***mixing parameter*** δ_{23}^{uRL} ***.***

δ^{uRR}_{23} dependences of squark decay BR's in our scenario



$$\delta^{uRR}_{\alpha\beta} \equiv M^2_{\tilde{U}\alpha\beta} / \sqrt{M^2_{\tilde{U}\alpha\alpha} M^2_{\tilde{U}\beta\beta}}$$

$\tilde{c}_R - \tilde{t}_R$ mixing parameter

The QFV decay branching ratios $B(\tilde{u}_{1,2} \to c\tilde{\chi}_1^0)$ and $B(\tilde{u}_{1,2} \to t\tilde{\chi}_1^0)$ can be very large simultaneously in a wide allowed range of the $\tilde{c}_R - \tilde{t}_R$ mixing parameter δ^{uRR}_{23}.

This can lead to large QFV effects at LHC!

6. Impact on gluino signatures at LHC

Large $\tilde{c}_R - \tilde{t}_R$ ***mixing***

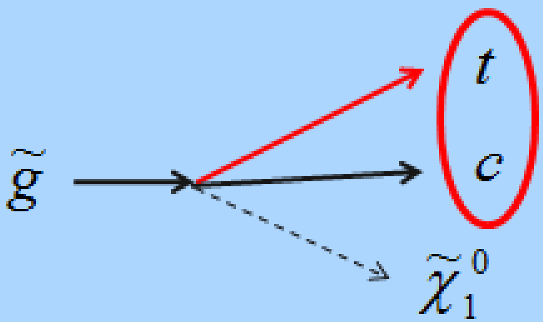
⇓

Large QFV BR $B(\tilde{g} \to t\bar{c}\tilde{\chi}_1^0)$

⇓

The signature of the QFV gluino decay $\tilde{g} \to t\bar{c}\tilde{\chi}_1^0$ ***at LHC:***

' top-quark + jet + missing-energy'



Example of QFV gluino signature at LHC

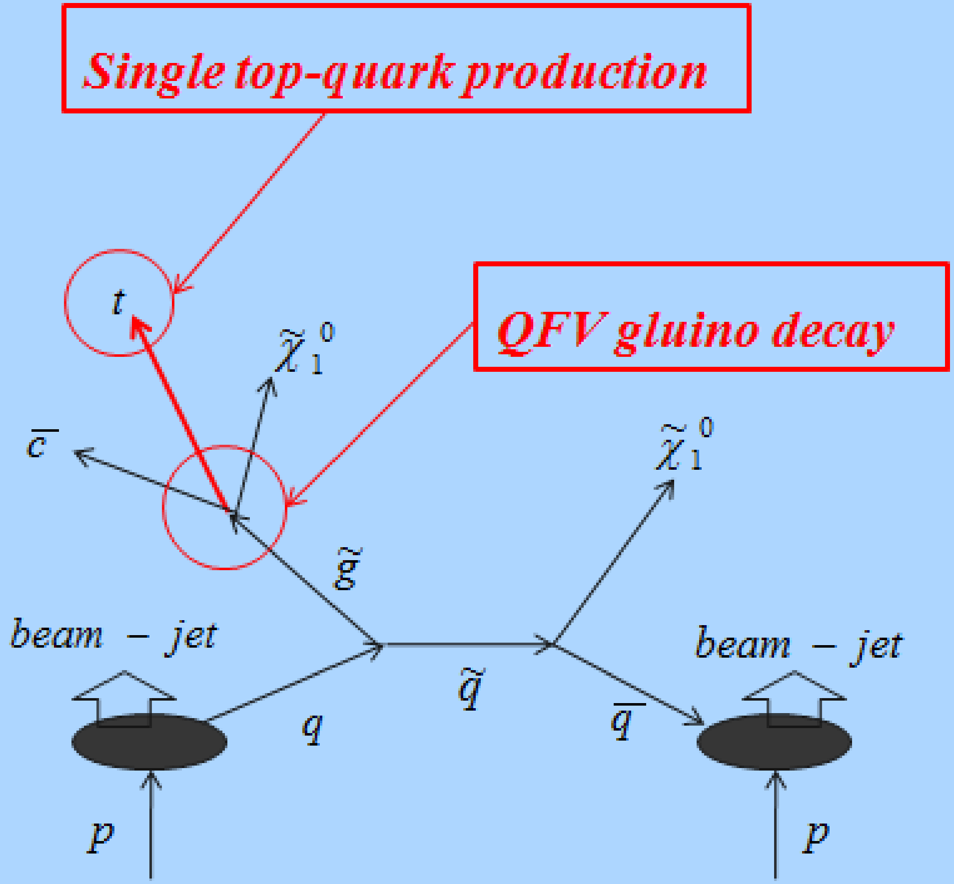
Example of QFV gluino decay signature at LHC :

$$pp \to \tilde{g}\tilde{\chi}_1^0 X \to t\bar{c}\tilde{\chi}_1^0\tilde{\chi}_1^0 X$$

⇓

'top-quark + jet + missing-E_T + beam-jets'

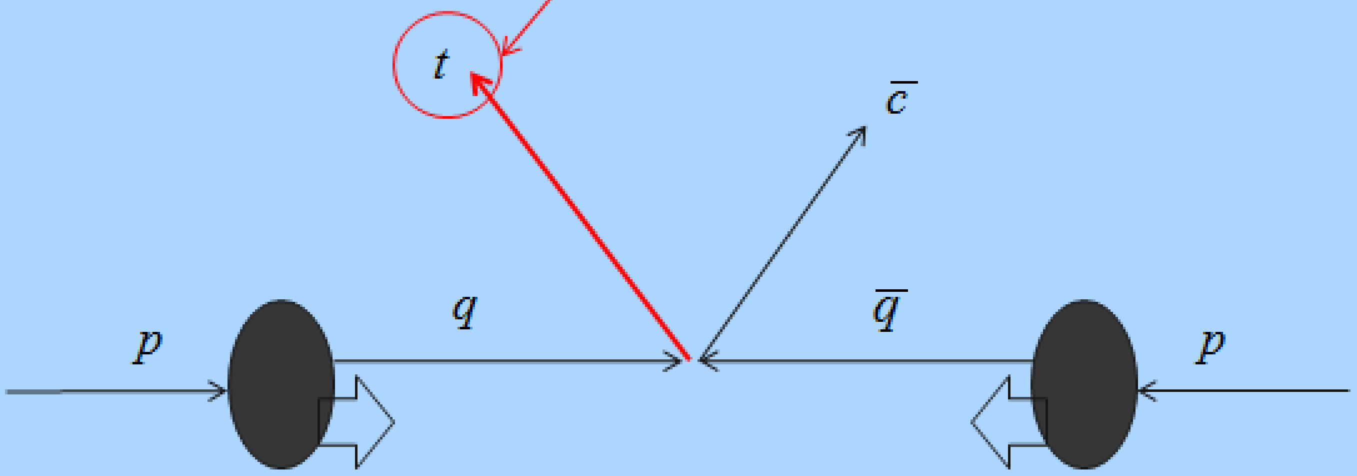
Example of QFV gluino signature at LHC



'top-quark + jet + missing-E_T + beam-jets'

Example of QFV gluino signature at LHC

Single top-quark production



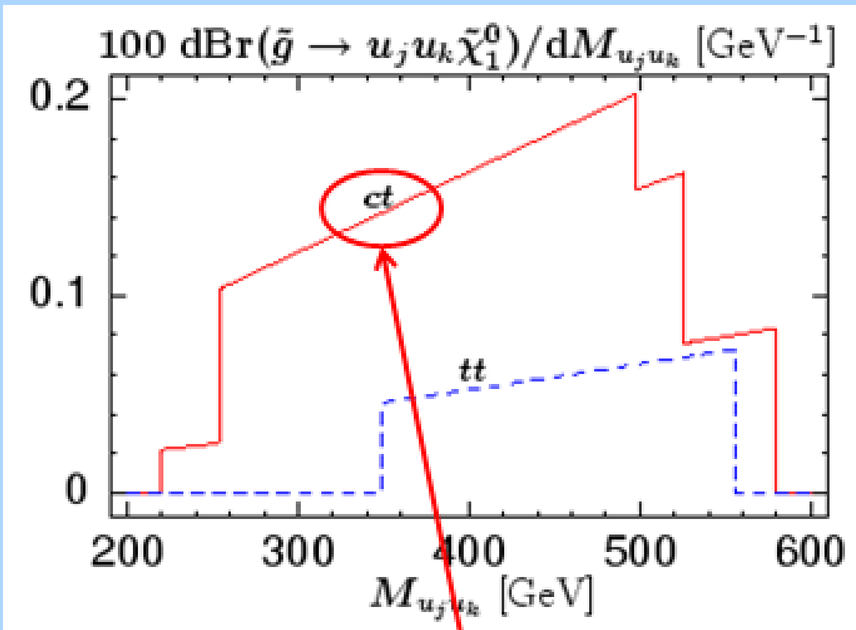
'top-quark + jet + missing-E_T + beam-jets'

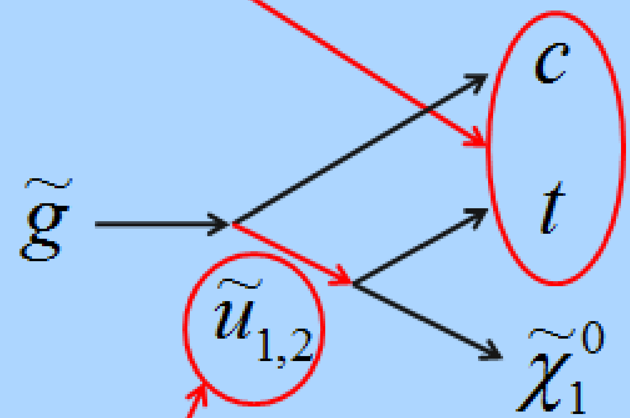
(Note) Single top–quark production $pp \to "W^{+}" Z^{0} X \to t\bar{b}\, \nu\bar{\nu} X$ *could be a SM BG.*

However the cross section of this process would be very small because it is a weak process.

Impact on invariant mass distribution

Invariant mass distribution of two quarks from gluino decay in our benchmark scenario





We have remarkable multi-edge structures in the invariant mass distribution of charm and top quarks!

This edge structure is due to the intermediate squark effect.

7. Impact on squark signatures at LHC

Large $\widetilde{c}_R - \widetilde{t}_R$ *mixing*

↓

Large QFV BR's $B(\widetilde{u}_{1,2} \to c\,\widetilde{\chi}_1^0)$, $B(\widetilde{u}_{1,2} \to t\,\widetilde{\chi}_1^0)$

↓

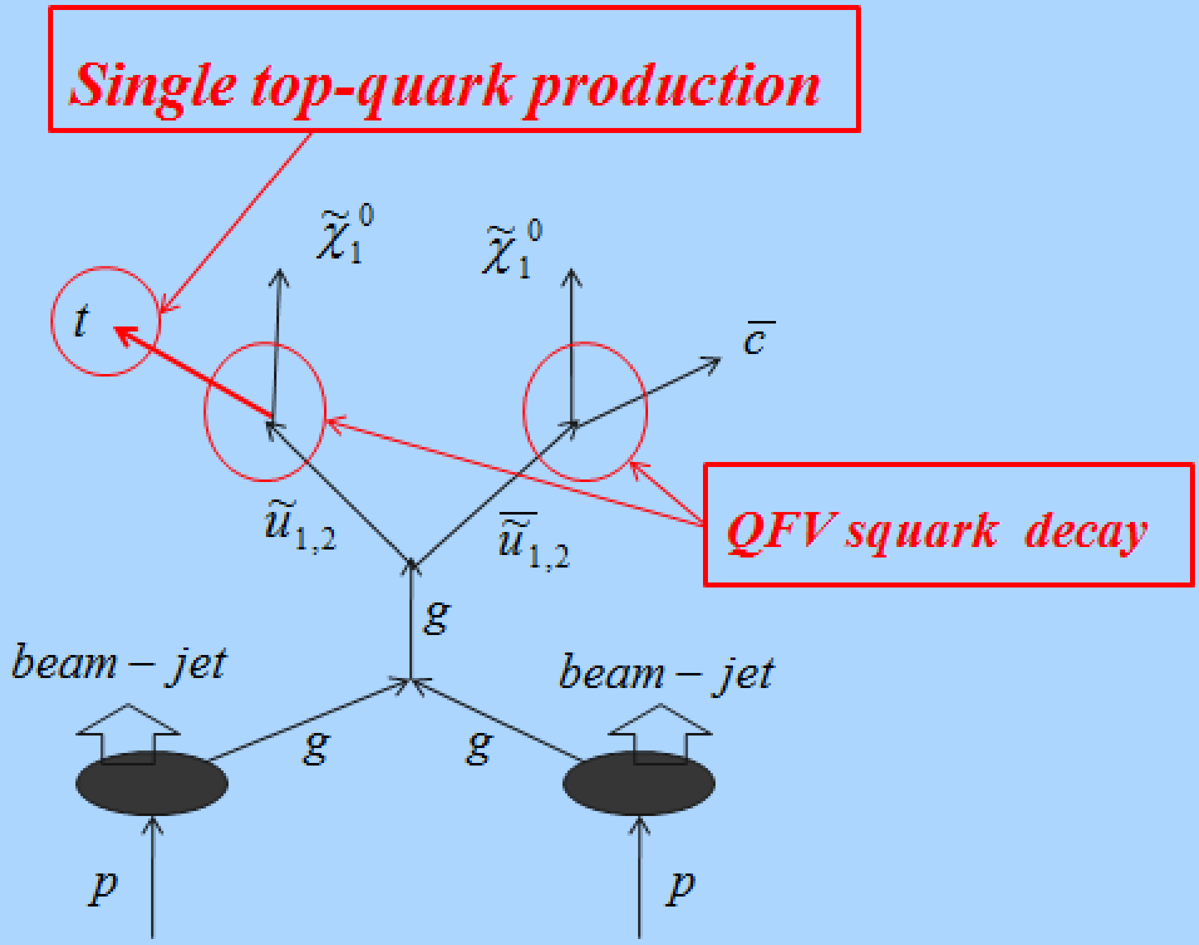
Large rate of QFV squark signature at LHC :

$$pp \to \widetilde{u}_{1,2}\overline{\widetilde{u}}_{1,2}X \to (t\,\widetilde{\chi}_1^0)(\overline{c}\,\widetilde{\chi}_1^0)X$$

↓

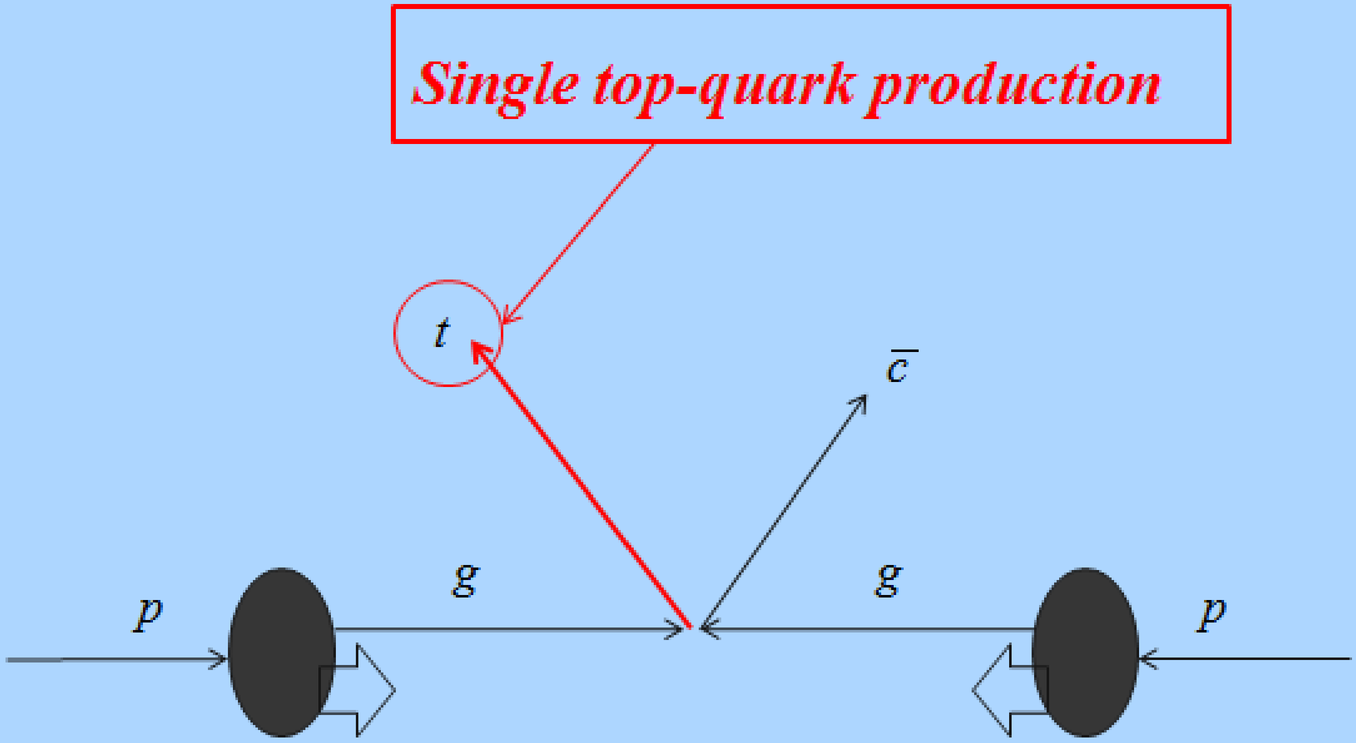
'top-quark + jet + missing-E_T + beam-jets'

QFV squark signature at LHC



'top-quark + jet + missing-E_T + beam-jets'

QFV squark signature at LHC



'top-quark + jet + missing-E_T + beam-jets'

(Note) Single top–quark production $pp \rightarrow "W^{+}" Z^{0} X \rightarrow t\bar{b}\, \nu\bar{\nu} X$ could be a SM BG.
However the cross section of this process would be very small because it is a weak process.

δ_{23}^{uRR} dependences of QFV cross sections at LHC in our benchmark scenario

$\sigma_{ct}^{11} \equiv \sigma(pp \to \tilde{u}_1 \bar{\tilde{u}}_1 X \to c\bar{t}(t\bar{c})\tilde{\chi}_1^0 \tilde{\chi}_1^0 X)(E_{cm} = 14TeV)$

$\sigma_{ct}^{22} \equiv \sigma(pp \to \tilde{u}_2 \bar{\tilde{u}}_2 X \to c\bar{t}(t\bar{c})\tilde{\chi}_1^0 \tilde{\chi}_1^0 X)(E_{cm} = 14TeV)$

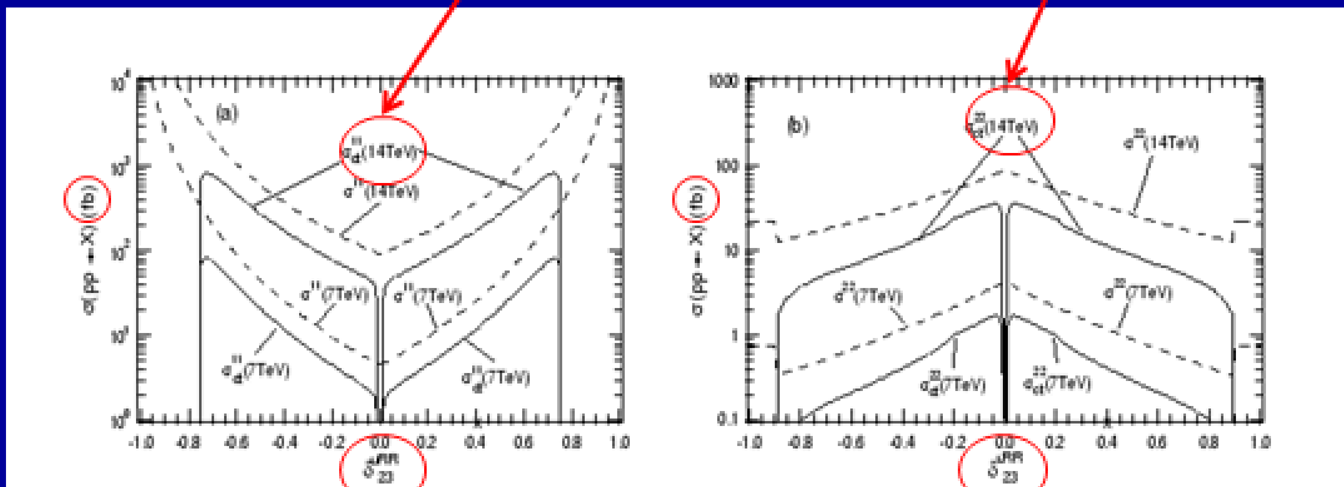


Figure 4: δ_{23}^{uRR} dependences of (a) $\sigma^{11} \equiv \sigma(pp \to \tilde{u}_1 \bar{\tilde{u}}_1 X)$, σ_{ct}^{11} and (b) $\sigma^{22} \equiv \sigma(pp \to \tilde{u}_2 \bar{\tilde{u}}_2 X)$, σ_{ct}^{22} at E_{cm} = 7 and 14 TeV.

$\delta_{\alpha\beta}^{uRR} \equiv M_{\tilde{U}\alpha\beta}^2 / \sqrt{M_{\tilde{U}\alpha\alpha}^2 M_{\tilde{U}\beta\beta}^2}$

$\tilde{c}_R - \tilde{t}_R$ mixing parameter

The QFV cross sections can be very large in a wide allowed range of the $\tilde{c}_R - \tilde{t}_R$ mixing parameter δ_{23}^{uRR}.

(Note) We have obtained similar results for the QFV cross sections in a QFV scenario based on the mSUGRA scenario SPS1a'.

Impact on squark and gluino search at LHC

Our analyses suggest the following:

- *One should take into account the possibility of significant contributions from QFV decays in the squark and gluino search at LHC.*
- *Moreover one should also include QFV squark parameters (i.e. squark generation mixing parameters) in the determination of the basic SUSY parameters at LHC.*
- *Detailed Monte Carlo studies including background processes and detector effects are necessary to identify the parameter region where the proposed QFV squark and gluino signals are observable with sufficient significance, e.g. the so-called "5 σ discovery region".*

8. Conclusion

- *We have studied production and decays of squarks and gluinos in the MSSM with* ***squark generation mixing****, especially* $\tilde{c}_{R/L} - \tilde{t}_{R/L}$ *mixing.*
- *We have shown that* ***QFV squark and gluino decay*** *branching ratios such as* $B(\tilde{g} \to ct\tilde{\chi}_1^0)$, $B(\tilde{u}_{1,2} \to c\tilde{\chi}_1^0)$, $B(\tilde{u}_{1,2} \to t\tilde{\chi}_1^0)$ *can be* ***very large (up to ~50%)*** *due to the* $\tilde{c}_R - \tilde{t}_R$ *mixing in a significant region of the QFV parameters despite the very strong constraints on QFV from experimental data on B mesons .*
- *This can result in remarkable* ***QFV squark and gluino signal*** *events such as* ‘ $pp \to t\bar{c} + E_T^{mis} + beam\text{-}jets$’ *with* ***a significant rate at LHC****.*
- *We have also studied the effect of the squark generation mixing on the invariant mass distributions of the two quarks from the* ***gluino decay*** *at LHC. We have found that it can result in novel and characteristic edge structures in the distributions. In particular,* ***multiple-edge (3- or 4-edge) structures*** *can appear in the* ***charm-top quark mass distribution****.*

- *These could have an important impact on the search for squarks and gluinos and the MSSM parameter determination at LHC.*

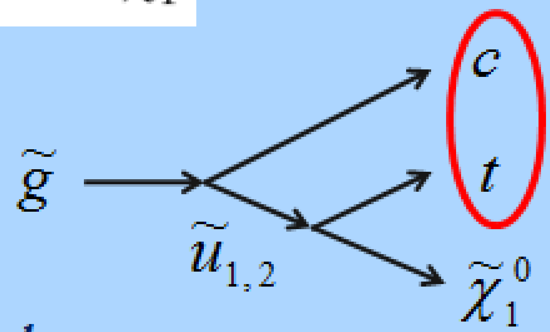
Backup Slides

5. *Impact of squark generation mixing on squark and gluino decays*

- *We study the* *effect of squark generation mixing* *on the squark and gluino decays at LHC.*
- *In case of* $\tilde{c}_R - \tilde{t}_R$ *mixing, gluino and squarks could decay as follows:*

$$\tilde{g} \to \tilde{u}_i\, c \to c\, t\, \tilde{\chi}_1^0 \quad \text{and} \quad \tilde{g} \to \tilde{u}_i\, t \to c\, t\, \tilde{\chi}_1^0$$

$$\boxed{\tilde{g} \to c\, t\, \tilde{\chi}_1^0}$$



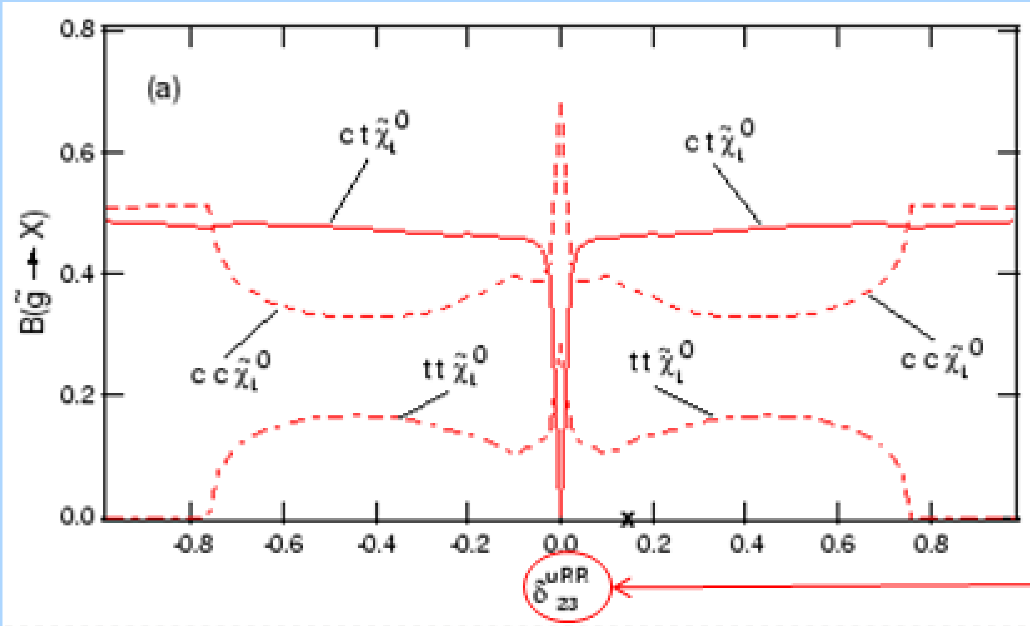
- *Possible two-body decays of the gluino and squarks are:*

$$\tilde{g} \;\to\; \tilde{u}_i\, u_k,\ \tilde{d}_i\, d_k,$$

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

$$u_k = (u, c, t) \text{ and } d_k = (d, s, b).$$

δ_{23}^{uRR} *dependences of* ***gluino decay*** *BR's in our scenario*



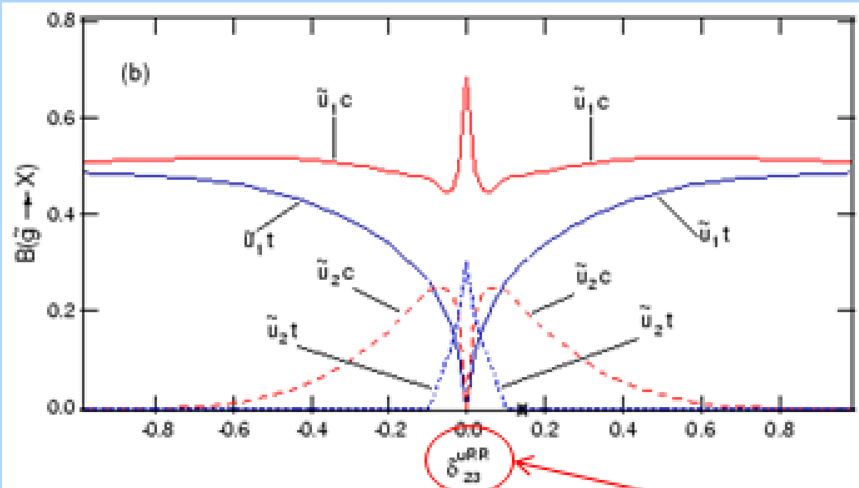
$$\delta_{\alpha\beta}^{uRR} \equiv M^2_{U\alpha\beta}/\sqrt{M^2_{U\alpha\alpha}M^2_{U\beta\beta}}$$

$\tilde{c}_R - \tilde{t}_R$ *mixing parameter*

The QFV decay branching ratio $B(\tilde{g} \to ct\tilde{\chi}_1^0)$ *increases quickly with increase of the* $\tilde{c}_R - \tilde{t}_R$ *mixing parameter* δ_{23}^{uRR} *and can be very large in a wide allowed range of* δ_{23}^{uRR}.

δ_{23}^{uRR} *dependences of gluino and squark two-body decay BR's*

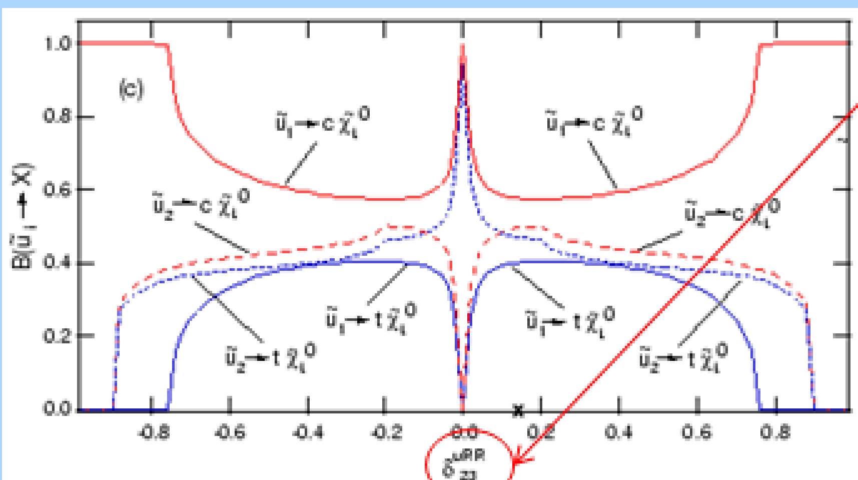
Gluino two-body decay BR's



$$\delta_{\alpha\beta}^{uRR} \equiv M_{\tilde{U}\alpha\beta}^2 / \sqrt{M_{\tilde{U}\alpha\alpha}^2 M_{\tilde{U}\beta\beta}^2}$$

$\tilde{c}_R - \tilde{t}_R$ ***mixing parameter***

Squark two-body decay BR's



6. Impact on gluino signatures at LHC

Gluino pair production and the QFV gluino decay $\tilde{g} \to t\bar{c}\tilde{\chi}_1^0$ *lead to*

QFV gluino signature at LHC :

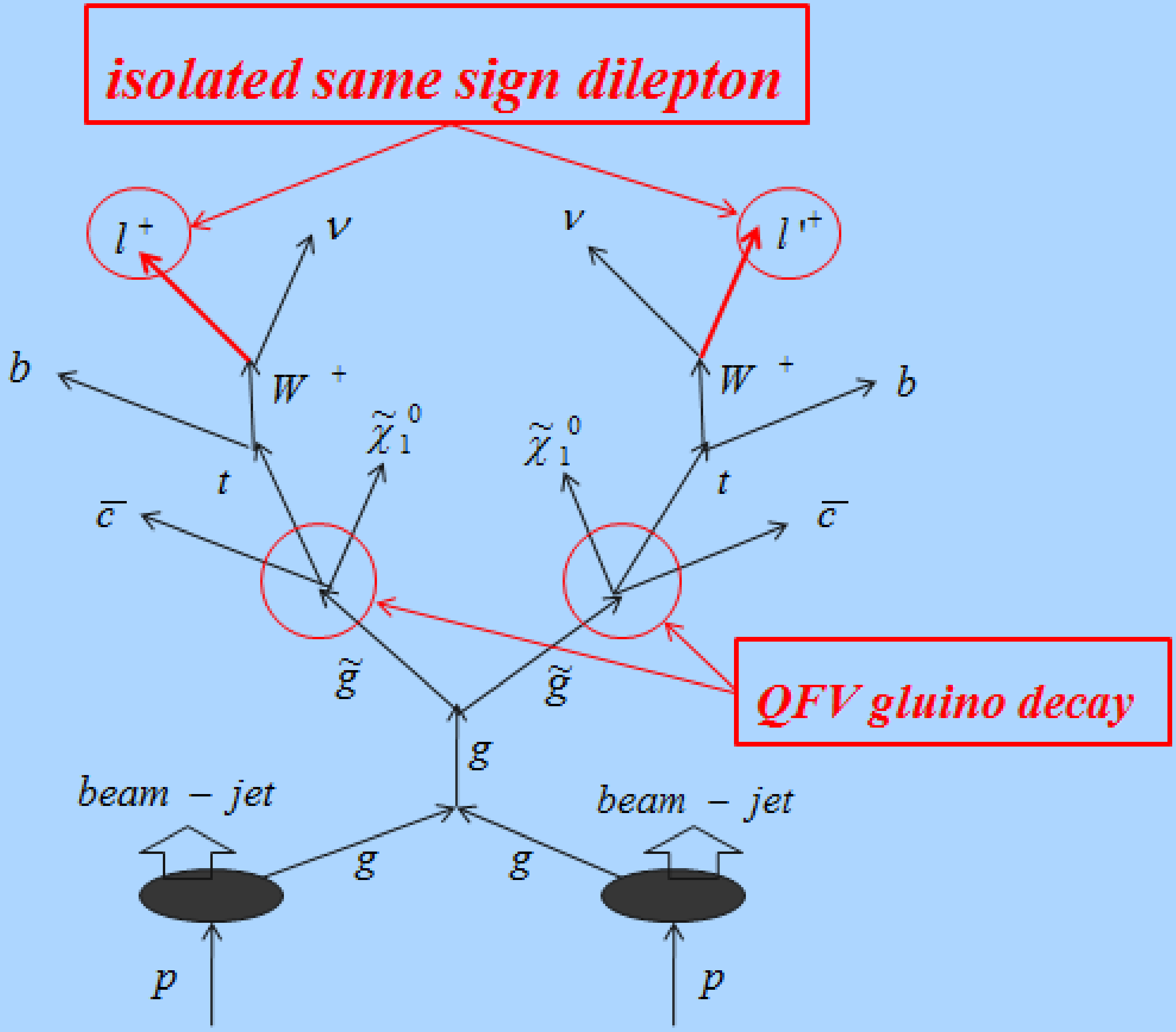
$$pp \to \tilde{g}\tilde{g}X \to (t\bar{c}\tilde{\chi}_1^0)(t\bar{c}\tilde{\chi}_1^0)X$$

'top-quark + top-quark + 2 jets + missing-E_T + beam-jets'

$$t \to bW^+ \to bl^+\nu$$

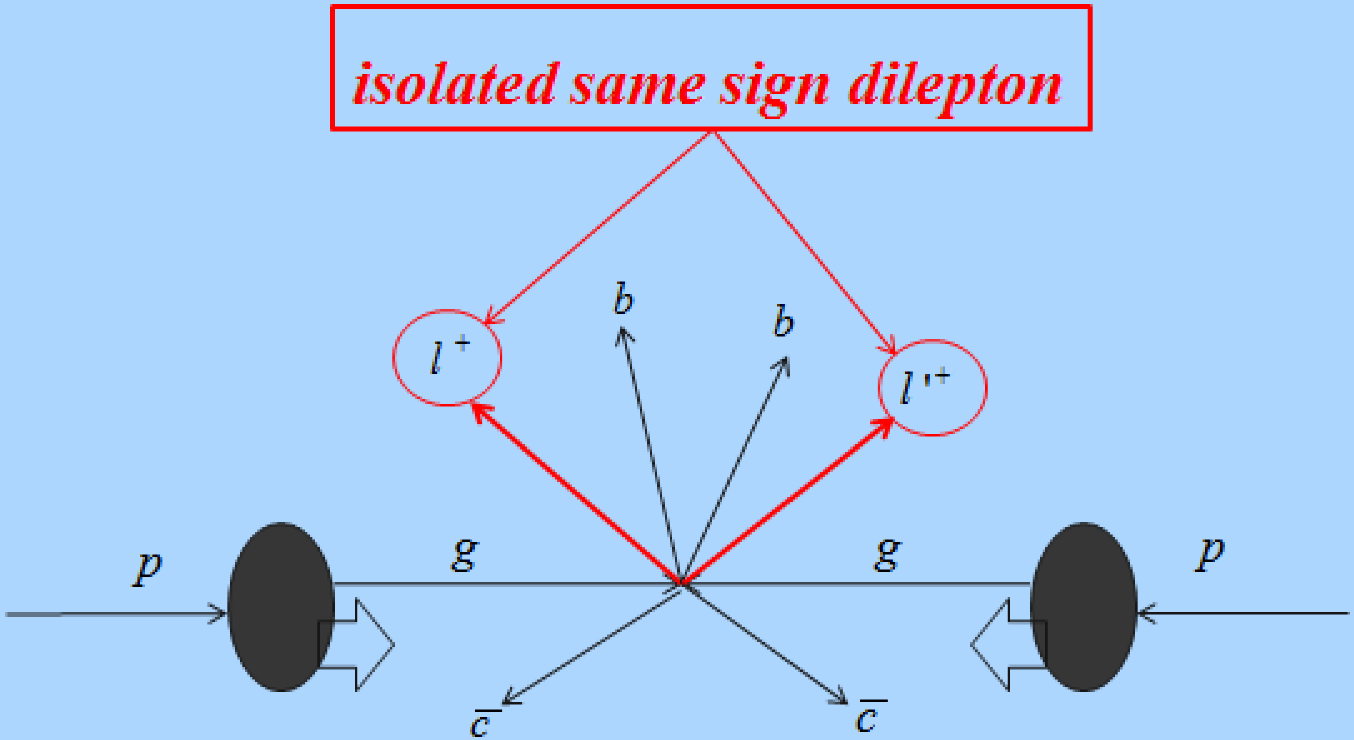
'isolated same sign dilepton + 4 jets + missing-E_T + beam-jets'

Example of QFV gluino signature at LHC



'isolated same sign dilepton + 4 jets + missing-E_T + beam-jets'

Example of QFV gluino signature at LHC



'isolated same sign dilepton + 4 jets + missing-E_T + beam-jets'

$$
\begin{aligned}
\sigma_{ct}^{ij} &\equiv \sigma(pp \to \tilde{u}_i \bar{\tilde{u}}_j X \to c\bar{t}(t\bar{c})\tilde{\chi}_1^0\tilde{\chi}_1^0 X) \\
&\equiv \sigma(pp \to \tilde{u}_i \bar{\tilde{u}}_j X \to c\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0 X) + \sigma(pp \to \tilde{u}_i \bar{\tilde{u}}_j X \to t\bar{c}\tilde{\chi}_1^0\tilde{\chi}_1^0 X) \\
&= \sigma(pp \to \tilde{u}_i \bar{\tilde{u}}_j X)[B(\tilde{u}_i \to c\tilde{\chi}_1^0) \cdot B(\bar{\tilde{u}}_j \to \bar{t}\tilde{\chi}_1^0) + B(\tilde{u}_i \to t\tilde{\chi}_1^0) \cdot B(\bar{\tilde{u}}_j \to \bar{c}\tilde{\chi}_1^0)]. \quad (15)
\end{aligned}
$$

We calculate the relevant squark-squark and squark-antisquark pair production cross-sections at leading order using the WHIZARD/O'MEGA packages [24, 25] where we have implemented the model described in Section 2 with squark generation mixing in its most general form. We use the CTEQ6L global parton density fit [26] for the parton distribution functions and take $Q = m_{\tilde{u}_i} + m_{\tilde{u}_j}$ for the factorization scale, where $\tilde{u}_i$ and $\tilde{u}_j$ are the squark pair produced. The QCD coupling $\alpha_s(Q)$ is also evaluated (at the two-loop level) at this scale Q. We have cross-checked our implementation of QFV by comparing with the results obtained using the public packages FeynArts [27] and FormCalc [28].