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

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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 quarks 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:**

\[
\{ \tan \beta, m_A, M_1, M_2, m_{\text{gluino}}, \mu, M^2_{Q\alpha\beta}, M^2_{U\alpha\beta}, M^2_{D\alpha\beta}, T_{U\alpha\beta}, T_{D\alpha\beta} \} \\
\text{(at weak scale)}
\]

- **\( \tan \beta \):** 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

- **\( m_{\text{gluino}} \):** gluino mass

- **\( \mu \):** 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:

\[
M_{Q_{23}}^2 : \quad \tilde{C}_L - \tilde{t}_L \quad \text{mixing term} \quad (\tilde{S}_L - \tilde{b}_L \quad \text{mixing term}) \\
M_{U_{23}}^2 : \quad \tilde{C}_R - \tilde{t}_R \quad \text{mixing term} \\
T_{U_{23}} : \quad \tilde{C}_L - \tilde{t}_R \quad \text{mixing term} \\
T_{U_{32}} : \quad \tilde{C}_R - \tilde{t}_L \quad \text{mixing term}
\]

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

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

In this basis we have \( M_{Q_u}^2 = K \cdot M_Q^2 \cdot K^{-1} \) due to the SU(2) symmetry,

where \( M_{Q_u}^2 \) is the soft mass matrix of left up-type squarks

\( M_Q^2 \) is the soft mass matrix of left down-type squarks and

\( K \) is the CKM matrix.

(Note) We have \( M_{Q_u}^2 \equiv M_Q^2 \) as \( K \equiv 1 \).
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:*

- $2.92 \times 10^{-4} < B(b \to s \gamma) < 4.22 \times 10^{-4}$ (95% CL) (Lepton Photon 2009)
- $0.60 \times 10^{-4} < B(b \to s \ell^+ \ell^-) < 2.60 \times 10^{-4}$ (with $\ell = e$ or $\mu$) (95% CL) (BELLE, BABAR)
- $B(B_s \to \mu^+ \mu^-) < 4.3 \times 10^{-4}$ (95% CL) (CDF)
- $B(B_s^+ \to \tau^+ \nu) = (1.73 \pm 0.35) \times 10^{-4}$ (68% CL) (BELLE, BABAR)
- $\Delta M_{b_s} = 17.77 \pm 0.12 \text{ ps}^{-1}$ (68% CL) (CDF)

(b) *LEP and Tevatron limits on sparticle masses*

- $(m_{\tilde{\chi}^\pm_1} > 103 \text{ GeV}, m_{\tilde{g}} > 308 \text{ GeV} \text{ etc.})$

(c) *The experimental limit on SUSY contributions to the electroweak $\rho$ parameter:*

- $\Delta \rho(\text{SUSY}) < 0.0012$

(d) *Vacuum stability conditions on trilinear couplings*


- $(| T_{\nu 23} |^2 < h_i^2 (M_{\tilde{\nu}_{22}}^2 + M_{\tilde{\nu}_{33}}^2 + m_{\tilde{\chi}^\pm_1}^2) \text{ etc.})$

  *with*  
  
  $m_{\tilde{\chi}^\pm_1} = (m_{\tilde{\nu}_e}^2 + m_{\tilde{\nu}_\mu}^2 \sin^2 \theta_W) \cos^2 \beta - \frac{1}{4} m_{\tilde{\nu}_\tau}^2$
(Note) These constraints are very important:

\[ B(b \rightarrow s \gamma) \text{ and } \Delta M_{B_s}, \text{ data } \Rightarrow \text{ strongly constrain the QFV squark parameters} \]

Vacuum stability conditions \Rightarrow \text{ strongly constrain } QFV \text{ trilinear couplings } T_{Ua\beta} \]

\[ B(B^+_u \rightarrow \tau^+ \nu) \text{ data } \Rightarrow \text{ strongly constrain } (m_{H^+}, \tan \beta) \]

(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:

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

\[
\tilde{g} \rightarrow \tilde{u}_i \ c \rightarrow c \ t \ \tilde{\chi}_1^0 \quad \text{and} \quad \tilde{g} \rightarrow \tilde{u}_i \ t \rightarrow c \ t \ \tilde{\chi}_1^0
\]
In our scenario we have:

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

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

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

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

We have very large QFV gluino decay branching ratio!
Contour plots of $QFV$ BR in our scenario

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

This can lead to large $QFV$ effects at LHC!
The QFV decay branching ratio $B(\tilde{g} \rightarrow ct\tilde{\chi}_1^0)$ can be very large in a significant part of the $\delta_{23}^{uL} - \delta_{23}^{uR}$ plane allowed by all of the constraints. This can lead to large QFV effects at LHC!
The QFV decay branching ratio $B(\tilde{g} \rightarrow ct\tilde{\chi}_1^0)$ can be very large (~30 - 50%) in a wide allowed range of $\tilde{c}_R - \tilde{t}_L$ mixing parameter $\delta_{23}^{uRL}$. 
The QFV decay branching ratios $B(\tilde{u}_{1,2} \rightarrow c\tilde{\chi}_1^0)$ and $B(\tilde{u}_{1,2} \rightarrow t\tilde{\chi}_1^0)$ can be very large simultaneously in a wide allowed range of the $c_R - t_R$ mixing parameter $\delta_{23}$. 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 $B(\tilde{g} \rightarrow t\bar{c}\tilde{\chi}_1^0)$

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

' top-quark + jet + missing-energy'
Example of QFV gluino signature at LHC

Example of QFV gluino decay signature at LHC:

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

‘top-quark + jet + missing-$$E_T$$ + beam-jets‘
Example of QFV gluino signature at LHC

- Single top-quark production

- QFV gluino decay

- 'top-quark + jet + missing-$E_T$ + beam-jets'
Single top-quark production

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

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

Large rate of QFV squark signature at LHC:

$pp \rightarrow \tilde{u}_{1,2} \tilde{u}_{1,2} X \rightarrow (t\tilde{\chi}_1^0)(c\tilde{\chi}_1^0)X$

‘top-quark + jet + missing-$E_T$ + beam-jets‘
**QFV squark signature at LHC**

- **Single top-quark production**
- **QFV squark decay**

'**top-quark + jet + missing-\(E_T\) + beam-jets**'
Single top-quark production

(Note) Single top–quark production $pp \rightarrow W^+ Z^0 X \rightarrow t\bar{b} \nu \sqrt{s}X$ could be a SM BG. However the cross section of this process would be very small because it is a weak process.
The QFV cross sections can be very large in a wide allowed range of the $\tilde{c}_R - \tilde{t}_R$ mixing parameter $\delta_{uRR}^{23}$.

(Note) We have obtained similar results for the QFV cross sections in a QFV scenario based on the mSUGRA scenario SPS1a'.
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 $B(\tilde{g} \to ct\chi_1^0)$, $B(\tilde{u}_{1,2} \to c\tilde{\chi}_1^0)$, $B(\tilde{u}_{1,2} \to t\chi_1^0)$ 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 $pp \to t\bar{c} + E_T^{mis} + beam-jets$ 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
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:

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

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

$$\tilde{g} \rightarrow \tilde{u}_i \ u_k, \ \tilde{d}_i \ d_k, \ \tilde{c}_i$$

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

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

5. Impact of squark generation mixing on squark and gluino decays
dependence of gluino decay BR's in our scenario

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

$\delta_{uRR}^{23} = M_{U_{\alpha\beta}}^{2} / \sqrt{M_{U_{\alpha\alpha}}^{2} M_{U_{\beta\beta}}^{2}}$
dependences of gluino and squark two-body decay BR’s

Gluino two-body decay BR’s

\[ \delta_{23}^{uRR} \]

\[ \text{mixing parameter} \]

Squark two-body decay BR’s

\[ \tilde{C}_R - \tilde{t}_R \]
6. Impact on gluino signatures at LHC

Gluino pair production and the QFV gluino decay \( \tilde{g} \rightarrow t\bar{c}\tilde{\chi}_1^0 \) lead to QFV gluino signature at LHC:

\[ pp \rightarrow \tilde{g}\tilde{g}X \rightarrow (t\bar{c}\tilde{\chi}_1^0)(t\bar{c}\tilde{\chi}_1^0)X \]

\textit{top-quark + top-quark + 2 jets + missing-}\( E_T \text{ + beam-jets}^\prime \)

\[ t \rightarrow bW^+ \rightarrow bl^+\nu \]

\textit{isolated same sign dilepton + 4 jets + missing-}\( E_T \text{ + beam-jets}^\prime \)
Example of QFV gluino signature at LHC

isolated same sign dilepton

QFV gluino decay

'isolated same sign dilepton + 4 jets + missing-\(E_T\) + beam-jets'
Example of QFV gluino signature at LHC

isolated same sign dilepton

\[ l^+ \quad b \quad b \quad l'^+ \]

\[ p \quad g \quad g \quad p \]

\[ c \quad \bar{c} \quad \bar{c} \]

'isolated same sign dilepton + 4 jets + missing-$E_T$ + beam-jets'
\[ \sigma_{ct}^{ij} \equiv \sigma(pp \to \tilde{u}_i \tilde{u}_j X \to c\bar{t}(t\bar{c})\tilde{\chi}_1^0 \tilde{\chi}_1^0 X) \]

\[ \equiv \sigma(pp \to \tilde{u}_i \tilde{u}_j X \to c\bar{t}\tilde{\chi}_1^0 \tilde{\chi}_1^0 X) + \sigma(pp \to \tilde{u}_i \tilde{u}_j X \to t\bar{c}\tilde{\chi}_1^0 \tilde{\chi}_1^0 X) \]

\[ = \sigma(pp \to \tilde{u}_i \tilde{u}_j X)[B(\tilde{u}_i \to c\tilde{\chi}_1^0) \cdot B(\tilde{u}_j \to \tilde{\chi}_1^0) + B(\tilde{u}_i \to \tilde{\chi}_1^0) \cdot B(\tilde{u}_j \to t\tilde{\chi}_1^0)]. \tag{15} \]

We calculate the relevant squark-squark and squark-antiquark 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].