Flavour violating gluino and squark decays @ LHC

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in collaboration with
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- Introduction
- Squark generation mixing in the MSSM
- Theoretical and experimental constraints
- Quark flavour violating (QFV) three-body decays of gluino
- QFV bosonic decays of squarks
- Measurability @ the LHC
- Summary and conclusions
Introduction

- The LHC has started its operation aiming at a direct verification of the predictions of the different theories of particle physics.
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- In particular, it was built with the main purposes:
  - To prove or disprove the existence of the SM Higgs boson.
  - To prove or disprove the existence of the numerous new particles predicted by supersymmetric theories.
  - If weak scale SUSY is realized in Nature, gluinos and squarks will be observed with high statistical significance for masses up to $O(1)\text{ TeV}$.
  - The decays of gluinos and squarks are usually assumed to be quark-flavour conserving (QFC).
  - However, the squarks are not necessarily quark-flavour eigenstates. Flavour mixing in the squark sector may be stronger than in the quark sector. QFV decays can then occur with significant rates.
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- The decays of gluinos and squarks are usually assumed to be quark-flavour conserving (QFC).
- The squark are, however, not necessarily quark-flavour eigenstates. Flavour mixing in the squark sector may be stronger than in the quark sector. QFV decays can then occur with significant rates.
In the SM: all QFV terms are proportional to the CKM matrix

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In the general MSSM - two concepts

* Minimal flavour violation (MFV)
  - No new sources of QFV; in the super CKM-basis the squarks undergo the same rotations as the quarks; all flavour-violating entries related to the CKM matrix (e.g. \( \tilde{\chi}^\pm i \tilde{\chi}^q j \tilde{\chi}^q k \sim V_q^j q^\dagger q^k \))

* Non-minimal flavour violation (NMFV)
  - New sources of flavour violation appear; corresponding flavour-violating entries not connected to the CKM matrix; considered as free parameters in the theory

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- In the following we assume NMFV
The flavour-violating terms are contained in the mass matrices of the squarks at the electroweak scale

\[ \mathcal{M}^2_{\tilde{q}} = \begin{pmatrix} \mathcal{M}^2_{\tilde{q} \text{LL}} & (\mathcal{M}^2_{\tilde{q} \text{RL}})^\dagger \\ \mathcal{M}^2_{\tilde{q} \text{RL}} & \mathcal{M}^2_{\tilde{q} \text{RR}} \end{pmatrix}, \quad q = u, d. \]

The 3 × 3 soft-breaking matrices can introduce flavour violating (off-diagonal) terms, e.g. in the up-squark sector

\[
\begin{align*}
(M^2_{\tilde{u} \text{LL}})_{\alpha\beta} &= M^2_{Q_{u\alpha\beta}} + \left[ \left( \frac{1}{2} - \frac{2}{3} \sin^2 \theta_W \right) \cos 2\beta \ m_Z^2 + m_{u\alpha}^2 \right] \delta_{\alpha\beta} \\
(M^2_{\tilde{u} \text{RR}})_{\alpha\beta} &= M^2_{U_{\alpha\beta}} + \left[ \left( \frac{2}{3} \sin^2 \theta_W \right) \cos 2\beta \ m_Z^2 + m_{u\alpha}^2 \right] \delta_{\alpha\beta} \\
(M^2_{\tilde{u} \text{RL}})_{\alpha\beta} &= \left( \frac{v_2}{\sqrt{2}} \right) T_{U_{\beta\alpha}} - m_{U_{\alpha}} \mu^* \cot \beta \ \delta_{\alpha\beta}
\end{align*}
\]

After diagonalization with a 6 × 6 rotation matrix \( R_{\tilde{u}} \), the mass eigenstates are obtained \( \tilde{u}_i = R_{\tilde{u}}^{i\alpha} \tilde{u}_{0\alpha} \), where \( R_{\tilde{u}} M^2_{\tilde{u}} R_{\tilde{u}}^\dagger = \text{diag}(m_{\tilde{u}_1}, \ldots, m_{\tilde{u}_6}) \), with \( m_{\tilde{u}_i} < m_{\tilde{u}_j} \) for \( i < j \).
• Dimentionless QFV parameters are introduced, in the up-type squark sector \((\alpha \neq \beta)\)

\[
\begin{align*}
\delta_{\alpha\beta}^{LL} & \equiv \frac{M_{Q\alpha\beta}^2}{\sqrt{M_{Q\alpha\alpha}^2 M_{Q\beta\beta}^2}} \\
\delta_{\alpha\beta}^{uRR} & \equiv \frac{M_{U\alpha\beta}^2}{\sqrt{M_{U\alpha\alpha}^2 M_{U\beta\beta}^2}} \\
\delta_{\alpha\beta}^{uRL} & \equiv \frac{(v_2/\sqrt{2}) T_{U_{\beta\alpha}}}{\sqrt{M_{U\alpha\alpha}^2 M_{Q\beta\beta}^2}}
\end{align*}
\]

• Analogously in the down-type squark sector

\[
\begin{align*}
\delta_{\alpha\beta}^{dRR} & \equiv \frac{M_{D\alpha\beta}^2}{\sqrt{M_{D\alpha\alpha}^2 M_{D\beta\beta}^2}} \\
\delta_{\alpha\beta}^{dRL} & \equiv \frac{(v_2/\sqrt{2}) T_{D_{\beta\alpha}}}{\sqrt{M_{D\alpha\alpha}^2 M_{Q\beta\beta}^2}}
\end{align*}
\]
From the vacuum stability conditions, the trilinear coupling matrices are constrained as follows

\[
|T_{U\alpha\alpha}|^2 < 3 \ Y_{U\alpha}^2 \left( M_{Q\alpha\alpha}^2 + M_{U\alpha\alpha}^2 + m_2^2 \right),
\]

\[
|T_{D\alpha\alpha}|^2 < 3 \ Y_{D\alpha}^2 \left( M_{Q\alpha\alpha}^2 + M_{D\alpha\alpha}^2 + m_1^2 \right),
\]

\[
|T_{U\alpha\beta}|^2 < Y_{U\gamma}^2 \left( M_{Q\alpha\alpha}^2 + M_{U\beta\beta}^2 + m_2^2 \right),
\]

\[
|T_{D\alpha\beta}|^2 < Y_{D\gamma}^2 \left( M_{Q\alpha\alpha}^2 + M_{D\beta\beta}^2 + m_1^2 \right),
\]

where \(\alpha, \beta = 1, 2, 3, \ \alpha \neq \beta; \ \gamma = \text{Max}(\alpha, \beta)\) and

\[
m_1^2 = (m_{H\pm}^2 + m_Z^2 \sin^2 \theta_W) \sin^2 \beta - \frac{1}{2} m_Z^2,
\]

\[
m_2^2 = (m_{H\pm}^2 + m_Z^2 \sin^2 \theta_W) \cos^2 \beta - \frac{1}{2} m_Z^2.
\]

\(Y_{U\alpha}\) and \(Y_{D\alpha}\) are the Yukawa couplings of the up-type and down-type quarks.
Constraints on the MSSM parameters

Experimental constraints

- Strong constraints on mixing involving the first generation from precision measurements of K and B meson decays.
- Only mixing between second and third generation squarks considered. Despite the constraints from B physics still allows appreciable mixing.
- SUSY mass limits from direct collider searches.
- Electroweak precision and low-energy measurements.

\[
B(b \rightarrow s\gamma) = (3.37 \pm 0.23) \times 10^{-4}
\]
\[
\Delta M_{B_s} = (17.725 \pm 0.049) \text{ ps}^{-1}
\]
\[
\Delta \rho \ (\text{SUSY}) < 0.0012
\]
\[
B(b \rightarrow s\mu^+\mu^-) = (1.60 \pm 0.50) \times 10^{-6}
\]
\[
B(B_s \rightarrow \mu^+\mu^-) < 4.2 \times 10^{-9}
\]
We consider the case:

- All squarks are heavier than the gluino ⇒ only three-body decays to quark pairs + chargino/neutralino possible
- Squark generation mixing occurs only between the 2nd and 3rd generation ⇒ One has the following QFV three-body decays into quarks and neutralino:
  \[
  \tilde{g} \rightarrow c \bar{t} \tilde{\chi}_0^i, \quad \bar{c}t \tilde{\chi}_0^i, \quad \tilde{g} \rightarrow s \bar{b} \tilde{\chi}_0^i, \quad \bar{s}b \tilde{\chi}_0^i.
  \]

We will mainly focus on decays into the lightest neutralino, \( \tilde{\chi}_0^1 \).
We consider the case:

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\[ \tilde{g} \rightarrow c \bar{t} \tilde{\chi}^0_i, \bar{c} t \tilde{\chi}^0_i, \tilde{g} \rightarrow s \bar{b} \tilde{\chi}^0_i, \bar{s} b \tilde{\chi}^0_i. \]
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$$\tilde{g} \rightarrow c \bar{t} \tilde{\chi}^0_i, \quad \bar{c} t \tilde{\chi}^0_i, \quad \tilde{g} \rightarrow s \bar{b} \tilde{\chi}^0_i, \quad \bar{s} b \tilde{\chi}^0_i.$$ 

We will mainly focus on decays into the lightest neutralino, $\tilde{\chi}^0_1$
QVF three-body decays of gluino
Reference scenario

- Basic MSSM input parameters (at the weak scale and real)

\[ \{ \tan \beta, m_{A0}, M_1, M_2, M_3, \mu, M_{Q\alpha\beta}^2, M_{U\alpha\beta}^2, M_{D\alpha\beta}^2, T_{U\alpha\beta}, T_{D\alpha\beta} \} \]

- Quark-flavour violating parameters

\[ M_{Q\alpha\beta}^2, M_{U\alpha\beta}^2, M_{D\alpha\beta}^2, T_{U\alpha\beta}, T_{D\alpha\beta}, \alpha \neq \beta \]

- Reference scenario

<table>
<thead>
<tr>
<th>( M_1 )</th>
<th>( M_2 )</th>
<th>( M_3 )</th>
<th>( \mu )</th>
<th>( \tan \beta )</th>
<th>( m_{A0} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>139 GeV</td>
<td>264 GeV</td>
<td>800 GeV</td>
<td>1000 GeV</td>
<td>10</td>
<td>800 GeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( M_{Q\alpha\beta}^2 )</th>
<th>( M_{U\alpha\beta}^2 )</th>
<th>( M_{D\alpha\beta}^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>((3150)^2 ) GeV(^2)</td>
<td>((3100)^2 ) GeV(^2)</td>
<td>((3050)^2 ) GeV(^2)</td>
</tr>
<tr>
<td>((3000)^2 ) GeV(^2)</td>
<td>((2200)^2 ) GeV(^2)</td>
<td>((2150)^2 ) GeV(^2)</td>
</tr>
<tr>
<td>((3000)^2 ) GeV(^2)</td>
<td>((2990)^2 ) GeV(^2)</td>
<td>((2980)^2 ) GeV(^2)</td>
</tr>
</tbody>
</table>

- All constraints are satisfied, \( T_{\{U,D\}\alpha\alpha} = 0 \)
QVF three-body decays of gluino

Physical output

- The numerical calculations of the decay BRs and physical masses are performed with \textit{Spheno v3.0}
- Physical masses of the SUSY particles in the reference scenario chosen (Fairly insensitive to the QFV parameters)

\begin{table}[h]
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
Particle & $m_{\tilde{\chi}^0_1}$ & $m_{\tilde{\chi}^0_2}$ & $m_{\tilde{\chi}^0_3}$ & $m_{\tilde{\chi}^0_4}$ & $m_{\tilde{\chi}^+_1}$ & $m_{\tilde{\chi}^+_2}$ & $m_{\tilde{g}}$ \\
\hline
Ph. mass [GeV] & 139 & 281.3 & 1017.9 & 1021.7 & 281.5 & 1022.7 & 975 \\
\hline
\end{tabular}
\end{table}

\begin{table}[h]
\begin{tabular}{|c|c|c|c|}
\hline
Particle & $m_{h^0}$ & $m_{H^0}$ & $m_{A^0}$ & $m_{H^+}$ \\
\hline
Ph. mass [GeV] & 121.1 & 800.3 & 800 & 804 \\
\hline
\end{tabular}
\end{table}

up-squark sector \hspace{1cm} down-squark sector

\begin{itemize}
\item $m_{\tilde{u}_L}$, $m_{\tilde{c}_L}$, $m_{\tilde{t}_L}$, $m_{\tilde{u}_R}$, $m_{\tilde{c}_R}$, $m_{\tilde{t}_R}$
\item \{\ $m_{\tilde{d}_L}$, $m_{\tilde{s}_L}$, $m_{\tilde{b}_L}$, $m_{\tilde{d}_R}$, $m_{\tilde{s}_R}$, $m_{\tilde{b}_R}$ \}
\end{itemize}

- $m_{\tilde{u}_1}$ \hspace{1cm} $m_{\tilde{g}}$ \hspace{1cm} $m_{\tilde{g}}$ \hspace{1cm} ~3 TeV \hspace{1cm} \sim 3 \text{ TeV}

- mass splitting due to $\tilde{c}_R - \tilde{t}_R$ mixing
QVF three-body decays of gluino

Relevant QFV parameters

- QFV left-right mixing is not relevant for our study
  * We show this for the left-right mixing parameter $\delta_{23}^{uRL}$

Due to the vacuum stability condition we have

$$|T_{U32}|^2 \lesssim Y_{U3}^2 (M_{Q33}^2 + M_{U22}^2 + m_2) \approx M_{Q33}^2 + M_{U22}^2 \approx O(10\text{TeV}^2),$$

because $Y_{U3} \approx 1$ and $m_2 \ll M_{Q33}^2 + M_{U22}^2$.

$$\implies |\delta_{23}^{uRL}| = \frac{v_2}{\sqrt{2}} \frac{|T_{U32}|}{\sqrt{M_{U22}^2 M_{Q33}^2}} \lesssim \frac{v_2}{\sqrt{2}} \sqrt{\frac{M_{U22}^2 + M_{Q33}^2}{M_{U22}^2 M_{Q33}^2}} \approx 0.1$$

Analogously, the parameters $\delta_{23}^{uLR}$, $\delta_{23}^{dRL}$, $\delta_{23}^{dLR}$ are also constrained to be very small.

- Relevant QFV parameters for our study are $\delta_{23}^{LL} (\tilde{c}_L - \tilde{t}_L)$, $\delta_{23}^{uRR} (\tilde{c}_R - \tilde{t}_R)$, $\delta_{23}^{dRR} (\tilde{s}_R - \tilde{b}_R)$
Squark and guino masses

All squarks but $\tilde{u}_1$ are heavy $\implies$ gluino decay is dominated by virtual $\tilde{u}_1$ exchange

$\tilde{u}_1$ is a strong mixture of $\tilde{c}_R$ and $\tilde{t}_R$ $\implies$ QFV branching ratio

$B(\tilde{g} \to c\bar{t}\tilde{\chi}_1^0)$ can be large
Due to the effective $\tilde{c} - \tilde{t}$ mixing

$$\tilde{u}_1 \sim \cos \theta \tilde{c}_R + \sin \theta \tilde{t}_R$$
$$\tilde{u}_2 \sim - \sin \theta \tilde{c}_R + \cos \theta \tilde{t}_R$$

there can be a strong destructive interference between $\tilde{u}_1$ and $\tilde{u}_2$ if their masses are similar.

In order to suppress such cancelations large mass splitting is required and hence large values of the mixing term $M_{U23}^2 \sim \delta_{23}^{uRR}$.
- Up-type squark masses and flavour decomposition of $\tilde{u}_1$ as a function of $\delta^{uRR}_{23}(\tilde{c}_R - \tilde{t}_R)$, all other QFV parameters are zero.
QVF three-body decays of gluino

Numerical results

- QFV decay branching ratio \( B(\tilde{g} \to ct\tilde{\chi}_1^0) \) \{ \( B(\tilde{g} \to \tilde{b}\tilde{\chi}_1^0) \) \} in the \( \delta_{23}^{uRR} \{ \delta_{23}^{dRR} \} - \delta_{23}^{LL} \) plane

\[
B(\tilde{g} \to ct\tilde{\chi}_1^0) \equiv B(\tilde{g} \to ct\tilde{\chi}_1^0) + B(\tilde{g} \to \bar{c}t\tilde{\chi}_1^0) \\
B(\tilde{g} \to sb\tilde{\chi}_1^0) \equiv B(\tilde{g} \to sb\tilde{\chi}_1^0) + B(\tilde{g} \to \bar{s}b\tilde{\chi}_1^0)
\]
Branching ratios of the decays $\tilde{g} \rightarrow ct\tilde{\chi}_1^0$, $\tilde{g} \rightarrow c\bar{c}\tilde{\chi}_1^0$ and $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ as functions of $\delta_{23}^{uRR}$, the other QFV parameters are zero.
Squark generation mixing enters also the squark-quark-neutralino couplings

The neutralino/chargino parameters can also influence the QFV gluino three-body decays

Contour plot for $B(\tilde{g} \rightarrow c t \tilde{\chi}_1^0)$ in the $\mu - M_2$ plane for $\delta_{23}^{uRR} = 0.8$, the other QFV parameters being zero, Region A: bino-like LSP, Region B: wino-like LSP, Region C: higgsino-like LSP
QVF three-body decays of gluino
Influence of the neutralino/chargino parameters on the QFV three-body decays of gluino

- $\mu$ dependence of the QFV and QFC gluino decay branching ratios for $\delta_{23}^{uRR} = 0.8$, the other QFV parameters being zero

- The $M_2$ dependence of the QFV gluino decay branching ratios for $M_1 = 264$ GeV, $\mu = 600$ GeV, $\delta_{23}^{uRR} = 0.8$, the other QFV parameters being zero
QVF three-body decays of gluino

Influence of the neutralino/chargino parameters on the QFV three-body decays of gluino

- Weak scale parameters, the corresponding neutralino and chargino masses and some important branching ratios for a scenario with a higgsino-like LSP ($\mu < M_1, M_2$)

<table>
<thead>
<tr>
<th>$M_1$</th>
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<th>$\mu$</th>
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<th>$m_{\tilde{\chi}^+_1}$</th>
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<tr>
<td>87.0 GeV</td>
<td>133.1 GeV</td>
<td>158.3 GeV</td>
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<th>$B(\tilde{g} \rightarrow c\tilde{\chi}^0_1)$</th>
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<th>$B(\tilde{g} \rightarrow b\tilde{c}\tilde{\chi}^+_1)$</th>
<th>$B(\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 \nu\bar{\nu})$</th>
<th>$B(\tilde{\chi}^+_1 \rightarrow \mu^+ \nu\mu \tilde{\chi}^0_1)$</th>
</tr>
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<tr>
<td>3.4 %</td>
<td>6.1 %</td>
<td>11.2 %</td>
<td>18.4 %</td>
<td>11.2 %</td>
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$\delta_{23}^{uRR} = 0.8$, the other QFV parameters being zero

- Signature from $\tilde{g} \rightarrow \tilde{\chi}^\pm + b\bar{c}(\bar{b}c) + \mu^\pm (e^\pm) + E_T^{miss}$ with $\approx 5\%$ probability

(from MFV $\approx 10^{-4}$)
QVF three-body decays of gluino
Influence of the neutralino/chargino parameters on the QFV three-body decays of gluino

Weak scale parameters, the corresponding neutralino and chargino masses and some important branching ratios for a scenario with a wino-like LSP \((M_2 < M_1, \mu)\)

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<tr>
<td>275.5 GeV</td>
<td>362.6 GeV</td>
<td>376.4 GeV</td>
<td>433.1 GeV</td>
<td>280.0 GeV</td>
<td>407.1 GeV</td>
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<th>(B(\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1\nu\bar{\nu}))</th>
<th>(B(\tilde{\chi}^+_1 \rightarrow \mu^+\nu\mu\tilde{\chi}^0_1))</th>
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<tr>
<td>2.5 %</td>
<td>6.3 %</td>
<td>5.8 %</td>
<td>4.1 %</td>
<td>13.2 %</td>
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\(\delta_{23}^{uRR} = 0.8\), the other QFV parameters being zero

Signature from \(\tilde{g} \rightarrow \tilde{\chi}^\pm + b\bar{c}(\bar{b}c) + \mu^\pm(e^\pm) + E_T^{\text{miss}}\) with \(\approx 3\%\) probability
QVF three-body decays of gluino
Measurability

- Production cross section calculated at leading order with WHIZARD/O’MEGA packages, CTEQ6L parton density fit with PDFs factorization scale \( Q = m_{\tilde{p}_1} + m_{\tilde{p}_2} \), \( \alpha_s(Q) \) evaluated at two-loop level
- Dominant production process \( pp \to \tilde{g}\tilde{g}X \), with \( X \) containing beam jets only
- In our scenario gluino production cross section practically independent on \( \delta_{uRR}^{23} \), at the reference point \( \approx 170 \text{ fb} \) (3 fb) for \( \sqrt{s} = 14 \text{ TeV} \) (7 TeV)
- Signal rates for \( pp \to \tilde{g}\tilde{g}X \) at \( \sqrt{s} = 14 \text{ TeV} \) where at least one of the gluinos decays as \( \tilde{g} \to c\bar{t}(\bar{c}t)\tilde{\chi}_1^0 \), as a function of \( \delta_{uRR}^{23} \)
QVF three-body decays of gluino

Measurability

- Invariant mass distributions of two up-type quarks from the decay $\tilde{g} \rightarrow u_j \bar{u}_k \tilde{\chi}_1^0$, $d\Gamma(\tilde{g} \rightarrow u_j \bar{u}_k \tilde{\chi}_1^0)/(\Gamma_{tot}(\tilde{g}) \ dM_{u_j \bar{u}_k})$, where $M_{u_j \bar{u}_k}$ is the invariant mass of the two-quark system $u_j \bar{u}_k$, $M^2_{u_j \bar{u}_k} = (p_{u_j} + p_{\bar{u}_k})^2$, $\delta_{23}^{uRR} = 0.8$

- Endpoint at $(m_{\tilde{g}} - m_{\tilde{\chi}_1^0})$, thresholds at $2m_c, m_c + m_t$ and $2m_t$

- No edge structure, in contrast to two-body gluino decays, where the gluino first decays into real squark

- Measuring can help distinguishing QFV from QFC decays
QVF three-body decays of gluino

Measurability

- A typical $\tilde{g}\tilde{g}$ production even contains at least 4 large-$p_T$ jets + large $E_T^{\text{miss}}$

- An event with a QFV gluino decay $\tilde{g} \rightarrow c\bar{t}\tilde{\chi}_1^0 (\bar{c}t\tilde{\chi}_1^0)$ should contain at least 1 top (anti-top) in the final state to be identified, possible with $t \rightarrow bW^\pm$ or c-tagging

- Typical signatures of QFV $\tilde{g}$ pair events are: $t (\text{or } \bar{t}) + 3$ jets + $E_T^{\text{mis}} + X$, $t + t$ (or $\bar{t} + \bar{t}$) + 2 jets + $E_T^{\text{mis}} + X$ and $t + t + \bar{t}$ (or $\bar{t} + \bar{t} + t$) + 1 jet + $E_T^{\text{mis}} + X$, where $X$ contains beam-jets only

- $t + t$ (or $\bar{t} + \bar{t}$) + 2 jets + $E_T^{\text{mis}} + X$ can only be produced in the MSSM with QFV

- Small background
At the reference point $m_{h^0} = 121.1$ GeV

In order to get $m_{h^0} = 125$ GeV we have to switch on $T_{U33} = h_t A_t = -2350$

The new elements in the $6 \times 6$ up-squark mass matrix are small in comparison with the diagonal ones $\implies$ small effect on the flavour decomposition of up-type squarks

Small influence on the theoretical predictions of B-physics observables

Small influence on the predictions for the QFV gluino three-body decay BRs
If kinematically allowed, the following QFV bosonic squark decays are possible

\[
\tilde{q}_i \to \tilde{q}_j + h^0, H^0, A^0 \\
\tilde{q}_i \to \tilde{q}'_j + H^+ \\
\tilde{q}_i \to \tilde{q}_j + Z^0 \\
\tilde{q}_i \to \tilde{q}'_j + W^+
\]

with \( i, j = 1, \ldots, 6 \)
If kinematically allowed, the following QFV bosonic squark decays are possible

\[ \tilde{q}_i \to \tilde{q}_j + h^0, H^0, A^0 \]

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\[ \tilde{q}_i \to \tilde{q}_j + Z^0 \]

\[ \tilde{q}_i \to \tilde{q}'_j + W^+ \]

with \( i, j = 1, ..., 6 \)

We will concentrate on up-type squark decays
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$$\tilde{q}_i \rightarrow \tilde{q}'_j + H^+$$
$$\tilde{q}_i \rightarrow \tilde{q}_j + Z^0$$
$$\tilde{q}_i \rightarrow \tilde{q}'_j + W^+$$

with $i, j = 1, ..., 6$

- We will concentrate on **up-type** squark decays

- In particular, we consider $\tilde{u}_{1,2,3}$ decays in scenarios where their decays into charged bosons $W^\pm, H^\pm$ and those into the heavier Higgs bosons $H^0$ and $A^0$ are kinematically forbidden
QVF bosonic squark decays

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\]

with \( i, j = 1, \ldots, 6 \)

- We will concentrate on **up-type** squark decays

- In particular, we consider \( \tilde{u}_{1,2,3} \) decays in scenarios where their decays into charged bosons \( W^\pm, H^\pm \) and those into the heavier Higgs bosons \( H^0, A^0 \) are kinematically forbidden

- Furthermore, we will focus on decays into \( h^0 \), \( \tilde{q}_i \rightarrow \tilde{q}_j h^0 \), as they offer the best possibility to determine the MSSM trilinear coupling \( \tilde{q}_i - \tilde{q}_j - h^0 \)
QVF bosonic squark decays

- In the super-CKM basis, the Lagrangian including the coupling of up-type squarks to $h^0$ contains the trilinear couplings $(T_U)_{ij}$ which are explicitly flavour-breaking terms that couple left-handed to right-handed squarks

\[
\mathcal{L} \supset -\frac{g_2}{2m_W} h^0 \left[ \bar{\tilde{u}}_i^R \tilde{u}_j L \left( \mu^* \frac{\sin \alpha}{\sin \beta} m_{u,i} \delta_{ij} + \frac{\cos \alpha}{\sin \beta} \frac{v_2}{\sqrt{2}} (T_U)_{ji} \right) \right] + \text{h.c.}
\]

- Our QFV parameters are those ones related to the up-type sector

\[
\begin{align*}
\delta^{LL}_{\alpha\beta} &\equiv M^2_{Q_{\alpha\beta}} / \sqrt{M^2_{Q_{\alpha\alpha}} M^2_{Q_{\beta\beta}}} \\
\delta^{uRR}_{\alpha\beta} &\equiv M^2_{U_{\alpha\beta}} / \sqrt{M^2_{U_{\alpha\alpha}} M^2_{U_{\beta\beta}}} \\
\delta^{uRL}_{\alpha\beta} &\equiv (v_2 / \sqrt{2}) T_{U_{\beta\alpha}} / \sqrt{M^2_{U_{\alpha\alpha}} M^2_{Q_{\beta\beta}}} \\
\delta^{uLR}_{\alpha\beta} &\equiv \delta^{uRL*}_{\beta\alpha}
\end{align*}
\]

for $\alpha, \beta = 2, 3, \alpha \neq \beta$
Numerical calculations performed with SPheno v3.1, we also use SSP package

Results presented for three scenarios, A, B, and C. All corresponding theoretical and experimental constraints are satisfied. Relatively large $\mu, M_1, M_2$ in order to avoid dominance of the fermionic squark decays. $M_3$ is chosen so that the guino is within the reach of the LHC. $M_1, M_2$ and $M_3$ do not fulfill gaugino mass unification at the GUT scale, except for scenario B.

For our scenarios the mass of the lightest Higgs $h_0 = 126$ GeV and hence it is SM-like.
Numerical calculations performed with SPheno v3.1, we also use SSP package

Results presented for three scenarios, A, B, and C
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QVF bosonic squark decays

Scenario A

- Weak scale basic MSSM parameters at $Q = 1$ TeV and physical masses in GeV of the SUSY particles for Scenario A

$T_{\{U,D\}}_{\alpha\alpha} = 0$, except for $T_{U33} = -2100$ ($\delta_{33}^{uRL} = -0.34$)

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<th>$m_{\tilde{u}_2}$</th>
<th>$m_{\tilde{u}_3}$</th>
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**QVF bosonic squark decays**

**Numerical results, Scenario A**

- Dependence of the masses of $\tilde{u}_1$ and $\tilde{u}_2$ on $\delta_{23}^{uRL}$ and $\delta_{23}^{uLR}$

- $m_{h^0}$, as a function of $T_{U33}$ and $\mu$ and as a function of $\delta_{23}^{uRL}$ and $\delta_{23}^{uLR}$
QVF bosonic squark decays
Numerical results, Scenario A

- In the following we concentrate on $\tilde{u}_2 \to \tilde{u}_1 h^0$
- The coupling $|c(\tilde{u}_2 \tilde{u}_1 h^0)|^2$ as a function of $\delta_{23}^{uRL}$ and $\delta_{23}^{uLR}$ and as a function of $\delta_{23}^{uRL}$ and $\delta_{33}^{uRL}$

$$B(\tilde{u}_2 \to \tilde{u}_1 h^0)$$ as a function of $\delta_{23}^{uRL}$ and $\delta_{23}^{uLR}$ and as a function of $\delta_{23}^{uRL}$ and $\delta_{33}^{uRL}$
At the reference point $B(\tilde{u}_3 \to \tilde{u}_1 h^0) = 22\%$, can go up to 30\%.
$B(\tilde{u}_3 \to \tilde{u}_2 h^0) = 10\%$. The branching ratios of $\tilde{u}_3 \to \tilde{u}_1 Z^0$ and $\tilde{u}_3 \to \tilde{u}_2 Z^0$ at the reference point are about 28\% and 14\%, respectively.

- $B(\tilde{g} \to \tilde{u}_2 \bar{c}) + B(\tilde{g} \to \tilde{u}_2 c)$ and $B(\tilde{g} \to \tilde{u}_2 \bar{t}) + B(\tilde{g} \to \tilde{u}_2 t)$ as functions of $\delta^{u_{RL}}_{23}$ and $\delta^{u_{RL}}_{33}$.
Scenario B, GUT-inspired: $M_1 \approx 0.5 M_2$, $M_3/M_2 = g_3^2/g_2^2$, where $g_2$ and $g_3$ are the SU(2) and SU(3) gauge coupling constants, respectively.

- Only $M_1$, $M_2$ and $M_3$ are changed with respect to scenario A, $M_1 = 250$ GeV, $M_2 = 500$ GeV and $M_3 = 1500$ GeV

- Large $m_{\tilde{g}} = 1626$ GeV $\Longrightarrow$ small production cross section

- The dependences of the QFV parameters are similar like in scenario A
Scenario C, parameters changed with respect to scenario A

\[ M_{U22}^2 = (650 \text{ GeV})^2, \quad M_{U33}^2 = (1600 \text{ GeV})^2, \quad M_{Q33}^2 = (780 \text{ GeV})^2, \]

\[ \delta_{23}^{uLL} = 0, \quad \delta_{23}^{uRR} = 0, \quad \delta_{23}^{uRL} = -0.17, \quad \delta_{33}^{uRL} = -0.3 \]

\[ \delta_{23}^{uRL} (\sim T_{U32}) \] much larger than that in Scenario A

Physical masses and branching ratios

\[ m_{\tilde{g}} = 1134 \text{ GeV}, m_{\tilde{u}_1} = 651 \text{ GeV}, m_{\tilde{u}_2} = 800 \text{ GeV}, m_{\tilde{u}_3} = 1580 \text{ GeV}, m_{h^0} = 125.3 \text{ GeV} \]

\[ B(\tilde{u}_2 \to \tilde{u}_1 h^0) = 43\%, B(\tilde{u}_2 \to \tilde{u}_1 Z^0) = 34\%, B(\tilde{g} \to \tilde{u}_2 \tilde{c}) + B(\tilde{g} \to \tilde{u}_2 \tilde{c}) = 8\%, \]

\[ B(\tilde{g} \to \tilde{u}_2 \tilde{t}) + B(\tilde{g} \to \tilde{u}_2 \tilde{t}) = 15\%, B(\tilde{u}_1 \to \tilde{\chi}_1^0 \tilde{c}) = 96\%, B(\tilde{u}_1 \to \tilde{\chi}_1^0 \tilde{t}) = 4\% \]

Both \( B(\tilde{u}_2 \to \tilde{u}_1 h^0) \) and \( B(\tilde{u}_2 \to \tilde{u}_1 Z^0) \) are very large, leading to the dominance of the QFV bosonic decays of \( \tilde{u}_2 \).
QVF bosonic squark decays
Signatures

- Lighter squark states can be produced directly, $pp \rightarrow \tilde{u}_1 \tilde{u}_1 X$, $pp \rightarrow \tilde{u}_2 \tilde{u}_2 X$, or via gluino production, $pp \rightarrow \tilde{g} \tilde{g} X$, where at least one of the gluino decays into $\tilde{u}_1$ or $\tilde{u}_2$, $\tilde{g} \rightarrow \tilde{u}_{1,2} u; \tilde{u}_{1,2} c; \tilde{u}_{1,2} t$, with $q$ being a light quark.
- We assume that the $t$-quark can be identified, but the $c$-quark not.
- Possible signatures expected from the QFV decays of $\tilde{u}_2$ into the lightest Higgs boson $h^0$, $t$ denotes top or anti-top, $j$ denotes a $c$-quark jet.

<table>
<thead>
<tr>
<th>processes</th>
<th>final states containing $h^0$</th>
</tr>
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<tbody>
<tr>
<td>$pp \rightarrow \tilde{u}_2 \tilde{u}_2 X$</td>
<td>$2j + h^0 + E_T^{\text{miss}} + X$ (1.4 fb)</td>
</tr>
<tr>
<td></td>
<td>$j + t + h^0 + E_T^{\text{miss}} + X$ (2.8 fb)</td>
</tr>
<tr>
<td></td>
<td>$j + t + 2h^0 + E_T^{\text{miss}} + X$ (1 fb)</td>
</tr>
<tr>
<td></td>
<td>$2j + Z^0 + h^0 + E_T^{\text{miss}} + X$</td>
</tr>
<tr>
<td></td>
<td>$2j + 2h^0 + E_T^{\text{miss}} + X$</td>
</tr>
<tr>
<td></td>
<td>$2t + h^0 + E_T^{\text{miss}} + X$</td>
</tr>
<tr>
<td></td>
<td>$2t + 2h^0 + E_T^{\text{miss}} + X$</td>
</tr>
<tr>
<td>$pp \rightarrow \tilde{g} \tilde{g} X$</td>
<td>$4j + h^0 + E_T^{\text{miss}} + X$ (2 fb)</td>
</tr>
<tr>
<td></td>
<td>$3j + t + h^0 + E_T^{\text{miss}} + X$ (8 fb)</td>
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<td></td>
<td>$2j + 2t + h^0 + E_T^{\text{miss}} + X$ (4 fb)</td>
</tr>
<tr>
<td></td>
<td>$4j + Z^0 + h^0 + E_T^{\text{miss}} + X$</td>
</tr>
<tr>
<td></td>
<td>$4j + 2h^0 + E_T^{\text{miss}} + X$</td>
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<tr>
<td></td>
<td>$3j + t + 2h^0 + E_T^{\text{miss}} + X$</td>
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<td>$2j + 2t + 2h^0 + E_T^{\text{miss}} + X$</td>
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<td>$2j + 2t + Z^0 + h^0 + E_T^{\text{miss}} + X$</td>
</tr>
<tr>
<td></td>
<td>$4t + h^0/Z^0 (+h^0/Z^0) + E_T^{\text{miss}} + X$</td>
</tr>
</tbody>
</table>

- In scenario A, summing up the cross sections for all QFV final states with at least one $h^0$ one gets 19 fb $\Rightarrow$ one could expect about 1900 of such events assuming an integrated luminosity of 100 fb.
Signal rates for the QVF bosonic squark decay signatures from gluino pair production in Scenario A and in Scenario C as functions of $\delta_{uRL}^{23}$. The red solid (dashed) line corresponds to the pure QVF one $t$ final state $3j + t + h^0 (Z^0) + E_T^{\text{miss}} + X$. The green solid (dashed) line corresponds to the QVF signal events with $2t$ coming from $tt/\bar{t}t/\bar{t}\bar{t} + 2j + h^0 (Z^0) + E_T^{\text{miss}} + X$. The blue solid line corresponds to the QFC signal events $t + \bar{t} + 2j + h^0 + E_T^{\text{miss}} + X$. The violet dashed line corresponds to the pure QVF one $t$ final state $3j + t + h^0 + Z^0 + E_T^{\text{miss}} + X$. 

![Graphs showing signal rates](image-url)
We have studied QFV in the decays of

- Gluino in the case that all squarks are heavier than the gluino and the gluino dominantly decays into three particles, \( \tilde{g} \rightarrow q \bar{q} \tilde{\chi}_0^k \), \( q \bar{q}' \tilde{\chi}_0^\pm l \)

- Bosonic squark decays
  - \( \tilde{u}_2 \rightarrow \tilde{u}_1 h_0/Z_0 \)
  - \( \tilde{u}_3 \rightarrow \tilde{u}_1, 2 h_0/Z_0 \)

All constraints from theory and experiments on SUSY particle searches, Higgs searches and precision data in the B meson sector are taken into account.

Mixing is considered only between second and third generations of squarks.

In the case of gluino decays, the QFV parameters \( \delta_{uRR}^{23}, \delta_{dRR}^{23} \) and \( \delta_{LL}^{23} \) are important.

We have focused on \( \tilde{g} \rightarrow c \bar{t} (\bar{c}t) \tilde{\chi}_0^1 \) and \( \tilde{g} \rightarrow s \bar{b} (\bar{c}t) \tilde{\chi}_0^1 \) decays, their QFV decay BRs can reach 40% and 35%, respectively.

We have shown that the parameter of the neutralino/chargino sector can have also important influence on the decays studied.

The dominant production process is \( pp \rightarrow \tilde{g} \tilde{g}X \) and the QFV signatures \( pp \rightarrow tc \bar{c} \bar{c}E_{miss} \) and \( pp \rightarrow tt \bar{c} \bar{c}E_{miss} \) can be significant at the LHC.
We have studied QFV in the decays of

* Gluino in the case that all squarks are heavier than the gluino and the gluino dominantly decays into three particles, $\tilde{g} \to q\bar{q}\tilde{\chi}^0_k$, $q\bar{q}'\tilde{\chi}^\pm_l$
We have studied QFV in the decays of

- Gluino in the case that all squarks are heavier than the gluino and the gluino dominantly decays into three particles, \( \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_k^0, \; q\bar{q}'\tilde{\chi}_l^{\pm} \)
- Bosonic squark decays \( \tilde{u}_2 \rightarrow \tilde{u}_1 h^0/Z^0 \) and \( \tilde{u}_3 \rightarrow \tilde{u}_{1,2} h^0/Z^0 \)
We have studied QFV in the decays of

* Gluino in the case that all squarks are heavier than the gluino and the gluino dominantly decays into three particles, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_k^0$, $q\bar{q}'\tilde{\chi}_l^\pm$

* Bosonic squark decays $\tilde{u}_2 \rightarrow \tilde{u}_1h^0/Z^0$ and $\tilde{u}_3 \rightarrow \tilde{u}_{1,2}h^0/Z^0$

All constraints from theory and experiments on SUSY particle searches, Higgs searches and precision data in the B meson sector are taken into account
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All constraints from theory and experiments on SUSY particle searches, Higgs searches and precision data in the B meson sector are taken into account

Mixing is considered only between second and third generations of squarks
QVF bosonic squark decays

Summary

- We have studied QFV in the decays of
  - Gluino in the case that all squarks are heavier than the gluino and the gluino dominantly decays into three particles, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_k^0$, $q\bar{q}'\tilde{\chi}_l^{\pm}$
  - Bosonic squark decays $\tilde{u}_2 \rightarrow \tilde{u}_1 h^0/Z^0$ and $\tilde{u}_3 \rightarrow \tilde{u}_{1,2} h^0/Z^0$
- All constraints from theory and experiments on SUSY particle searches, Higgs searches and precision data in the B meson sector are taken into account
- Mixing is considered only between second and third generations of squarks
- In the case of gluino decays the QFV parameters $\delta_{23}^{uRR}$, $\delta_{23}^{dRR}$ and $\delta_{23}^{LL}$ are important
- We have focused on $\tilde{g} \rightarrow c\bar{t}(\bar{c}t)\tilde{\chi}_1^0$ and $\tilde{g} \rightarrow s\bar{b}(\bar{s}b)\tilde{\chi}_1^0$ decays, their QFV decay BRs can reach 40% and 35%, respectively
- We have shown that the parameter of the neutralino/chargino sector can have also important influence on the decays studied
- The dominant production process is $pp \rightarrow \tilde{g}\tilde{g}X$ and the QFV signatures $pp \rightarrow tcc\bar{c}E_T^{\text{miss}} X$ and $pp \rightarrow tt\bar{c}\bar{c}E_T^{\text{miss}} X$ can be significant at the LHC
In the case of $\tilde{u}_2 \rightarrow \tilde{u}_1 h^0/Z^0$ the branching ratio $B(\tilde{u}_2 \rightarrow \tilde{u}_1 h^0)$ can be larger than in the QFC case, and can go up to 60%, and, hence, this decay gives access to the QFV trilinear couplings $T_{U32}$ and $T_{U23}$.

We have studied the signatures expected from the QFV decay $\tilde{u}_2 \rightarrow \tilde{u}_1 h^0$ at LHC with $\sqrt{s} = 14$ TeV in three different scenarios.

We have considered direct $\tilde{u}_2$ production $pp \rightarrow \tilde{u}_2 \tilde{u}_2 X$ as well as $\tilde{u}_2$ production in $\tilde{g}$ decays via $pp \rightarrow \tilde{g}\tilde{g}X$.

The most pronounced QFV signature is $3j + t + h^0 + E_T^{\text{miss}} + X$, for example coming from $pp \rightarrow \tilde{g}\tilde{g}X \rightarrow \tilde{u}_{1,2} t\tilde{u}_2 cX \rightarrow \tilde{u}_{1,2} \tilde{t}\tilde{u}_1 h^0 cX \rightarrow c\bar{t}c\bar{c} h^0 E_T^{\text{miss}} X$, which can have a cross section up to 8 fb in Scenario A. A further interesting QFV signature coming from gluino pair production is $2j + 2t + h^0 + E_T^{\text{miss}} + X$ with a cross section in Scenario A of about 4 fb.
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Our analyses suggest that QFV decays shall be taken into account as they can have an important influence on the search of squarks and gluinos at the LHC as well as on the determination of the MSSM parameters.
Thank you for your attention!!!