Flavour violating squark and gluino decays


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Flavour problem of New Physics

\[ \mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \sum_i \frac{c_i^{New}}{\Lambda_{NP}} O_i^{(5)} + ... \]

- SM as effective theory valid up to cut-off scale \( \Lambda_{NP} \)
- Typical example: \( K^0 - \bar{K}^0 \)-mixing \( O^6 = (\bar{s}d)^2 \):
  \[
  c^{SM}/M_W^2 \times (\bar{s}d)^2 + c^{New}/\Lambda_{NP}^2 \times (\bar{s}d)^2 \quad \Rightarrow \quad \Lambda_{NP} > 10^4 \text{ TeV}
  \]
  (tree-level, generic new physics)

- Natural stabilisation of Higgs boson mass (hierarchy problem)
  (i.e. supersymmetry, little Higgs, extra dimensions) \( \Rightarrow \Lambda_{NP} \leq 1 \text{ TeV} \)

- EW precision data ↔ little hierarchy problem \( \Rightarrow \Lambda_{NP} \sim 3 - 10 \text{ TeV} \)

Possible New Physics at the TeV scale has to have a nongeneric flavour structure.

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Interplay of high-$p_T$ and flavour physics

- Dynamics of flavour ↔ mechanism of SUSY breaking
  \((BR(b \rightarrow s\gamma) = 0\) in exact supersymmetry\)

\[\Rightarrow\text{ Discrimination between various SUSY-breaking mechanism}\]

\[\delta S(K_{S\pi^0\gamma}) = \pm 0.03\ (50\text{ab}^{-1})\]

\[\text{Expected Super-B sensitivity (50ab}^{-1}) \quad \text{Goto, Okada, Shindou, Tanaka, arXiv:0711.2935}\]

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Can we ignore flavour when analysing possible new physics at the electroweak scale?

Correlations between flavour and high-$p_T$ physics via squark mixing

- In the unconstrained MSSM new contributions to flavour violation
  - CKM-induced contributions from $H^+, \chi^+$ exchanges
  - flavour mixing in the sfermion mass matrix

- Possible disalignment of quarks and squarks

- Squark decays:
  
  $$\tilde{u}_i \rightarrow u_j \tilde{\chi}_k^0, \quad d_j \tilde{\chi}_l^+ \quad \tilde{d}_i \rightarrow d_j \tilde{\chi}_k^0, \quad u_j \tilde{\chi}_l^-$$

  with $i = 1, \ldots, 6$, $j = 1, 2, 3$, $k = 1, \ldots, 4$ and $l = 1, 2$.

- These tree decays are governed by the same mixing matrices as the contributions to flavour violating low-energy observables

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Squark and gluino decays

- $m_{\tilde{g}} > m_{\tilde{q}_i}$ ($q = d, u; i = 1, \ldots, 6$) the gluino will mainly decay according to
  \[ \tilde{g} \rightarrow d_j \tilde{d}_i, \quad \tilde{g} \rightarrow u_j \tilde{u}_i \]

followed by squark decays into neutralino and charginos
  \[ \tilde{u}_i \rightarrow u_j \tilde{\chi}_k^0, \quad \tilde{d}_i \rightarrow d_j \tilde{\chi}_k^0, \quad u_j \tilde{\chi}_l^- \]

or into gauge- and Higgs bosons if kinematically allowed
  \[ \tilde{u}_i \rightarrow Z \tilde{u}_k, \quad H^0_r \tilde{u}_k, \quad W^+ \tilde{d}_j, \quad H^+ \tilde{d}_j; \quad \tilde{d}_i \rightarrow Z \tilde{d}_k, \quad H^0_r \tilde{d}_k, \quad W^- \tilde{u}_j, \quad H^- \tilde{u}_j \]

Due to left-right squark mixing

flavour changing neutral decays into $Z$-bosons at tree-level

- $m_{\tilde{g}} < m_{\tilde{q}_i}$ the squarks decay mainly into a gluino
  \[ \tilde{u}_i \rightarrow u_j \tilde{g}, \quad \tilde{d}_i \rightarrow d_j \tilde{g} \]

the gluino decays into charginos and neutralinos via three-body decays and loop-induced two-body decays
  \[ \tilde{g} \rightarrow d_j d_i \tilde{\chi}_k^0, \quad u_j u_i \tilde{\chi}_k^0, \quad \tilde{g} \rightarrow u_j d_i \tilde{\chi}_l^\pm, \quad \tilde{g} \rightarrow g \tilde{\chi}_k^0 \]

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Squark mixing

Squark mass matrices \((f = u, d)\):

\[
\mathcal{M}_f^2 \equiv \begin{pmatrix}
M_{f,LL}^2 + F_{f,LL} + D_{f,LL} & M_{f,LR}^2 + F_{f,LR} \\
(M_{f,LR}^2)^\dagger + F_{f,RL}^* & M_{f,RR}^2 + F_{f,RR} + D_{f,RR}
\end{pmatrix}
\]

In the super-CKM basis  \(F\)- and \(D\)-terms are flavour diagonal:

\[
D_{f,LL} = (T_{3,f} - e_f \sin^2 \theta_W) \cos(2\beta)m_Z^2, \quad D_{f,RR} = e_f \sin^2 \theta_W \cos(2\beta)m_Z^2
\]

\[
F_{f,LL,ij} = F_{f,RR,ij} = m_i^2 \delta_{ij}, \quad F_{f,RL,ij} = -\mu m_i \delta_{ij} (\tan \beta)^{-2T_{3,f}}
\]

All flavour violation beyond the CKM in the soft SUSY breaking terms:

\[
M_{d,LL}^2 = V_{CKM}^\dagger M_{u,LL}^2 V_{CKM} = \hat{m}_Q^2 \equiv V_d^\dagger m_Q^2 V_d,
\]

\[
M_{d,RR}^2 = \hat{m}_d^2 \equiv U_d^\dagger m_d^2 U_d,
\]

\[
M_{d,LR}^2 = v_1/\sqrt{2} \hat{T}_D \equiv v_1/\sqrt{2} U_d^\dagger T_D^T V_d,
\]

\[
M_{u,LR}^2 = v_2/\sqrt{2} \hat{T}_U \equiv v_2/\sqrt{2} U_u^\dagger T_U^T V_u
\]

Observables as functions of the normalized off-diagonal elements:

\[
\delta_{LL,ij} = \frac{(M_{f,LL}^2)_{ij}}{m_q^2}, \quad \delta_{f,RR,ij} = \frac{(M_{f,RR}^2)_{ij}}{m_f^2}, \quad (i \neq j)
\]
Experimental and theoretical constraints

- Vacuum stability constraints
- Electroweak precision data: $m_{h_0}$, $\rho$ parameter
- Squark Tevatron bounds
- Bounds from flavour observables:
  - Data from $K$ and $B_d$ physics strongly constrain new sources of flavour violation in $s \rightarrow d$ and $b \rightarrow d$ sector
  - Possibility of sizable new contributions to $b \rightarrow s$ remains open.
  - In SUSY-GUTs the large mixing angle in the neutrino sector relates to large mixing in the right-handed $b$-$s$ sector

\[
2.67 < \quad Br(\bar{B} \rightarrow X_s \gamma) \times 10^4 \quad < 4.29 \\
13.5 < \quad \Delta M_{B_s} \quad ps \quad < 21.1 \\
1.05 < \quad BR(\bar{B} \rightarrow X_s l^+ l^-)_{\text{low } q^2} \times 10^6 \quad \times \quad < 2.15 \\
BR(B_s \rightarrow \mu^+ \mu^-) \times 10^8 \quad \leq 5.8
\]
Strategy:

- Take susy benchmark points: SPS1a', γ, and I''
- Vary flavour nondiagonal parameters
  (off-diagonal squark mass entries)
- Use all experimental and theoretical bounds

⇒ Bounds on δ parameters

<table>
<thead>
<tr>
<th></th>
<th>SPS1a'</th>
<th>γ</th>
<th>I''</th>
</tr>
</thead>
<tbody>
<tr>
<td>δ_{LL,23}</td>
<td>(-0.05,0.03)</td>
<td>(-0.037,0.005)</td>
<td>(-0.06,0.001)</td>
</tr>
<tr>
<td>δ_{d,RR,23}</td>
<td>(-0.43,0.66)</td>
<td>(-0.29,0.48)</td>
<td>(-0.5,0.45)</td>
</tr>
<tr>
<td>δ_{u,RR,23}</td>
<td>(-0.7,0.7)</td>
<td>(-0.54,0.43)</td>
<td>(-0.55,0.45)</td>
</tr>
<tr>
<td>δ_{u,LR,23}</td>
<td>(-0.16,0.08)</td>
<td>(-0.16,0.06)</td>
<td>(-0.35,0.05)</td>
</tr>
<tr>
<td>δ_{u,LR,32}</td>
<td>(-0.7,0.54)</td>
<td>(-0.5,0.2)</td>
<td>(-0.7,0.27)</td>
</tr>
<tr>
<td>δ_{d,LR,23}</td>
<td>(-0.0047,0.0046)</td>
<td>(-0.006,0.001)</td>
<td>(-0.01,0.0015)</td>
</tr>
<tr>
<td>δ_{d,LR,32}</td>
<td>(-0.019,0.02)</td>
<td>(-0.015,0.015)</td>
<td>(-0.004,0.003)</td>
</tr>
</tbody>
</table>

Assumption used that only one flavour-mixing parameter is present (regions 95% CL.)
Allowed regions for SPS1a'

a) in the $\delta_{d,RR,23}-\delta_{LL,23}$

(b $\rightarrow s\gamma$ red lines, $\Delta M_{B_s}$ magenta)

b) in the $\delta_{D,LR,23}-\delta_{D,LR,32}$ plane

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### Typical results for squark and gluino decays

<table>
<thead>
<tr>
<th>decaying particle</th>
<th>final states and corresponding branching ratios in % for.</th>
<th>II. $\delta_{LL,23} = 0.04, \delta_{D,RR23} = 0.45$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{d}_1 \rightarrow$</td>
<td>$\tilde{\chi}_1^0 b$, 4.4</td>
<td>$\tilde{\chi}_1^0 s$, 36.8</td>
</tr>
<tr>
<td>I: $\tilde{b}_L(\tilde{b}_R)$</td>
<td>$\tilde{u}_1 W^-$, 27.7</td>
<td>$\tilde{\chi}_1^- t$, 9.6</td>
</tr>
<tr>
<td>$\tilde{d}_2 \rightarrow$</td>
<td>$\tilde{\chi}_1^0 s$, 8.0</td>
<td>$\tilde{\chi}_1^0 b$, 27.3</td>
</tr>
<tr>
<td>I: $\tilde{b}_R(\tilde{b}_L, \tilde{s}_R)$</td>
<td>$\tilde{\chi}_3^0 b$, 1.1</td>
<td>$\tilde{\chi}_1^- t$, 34.6</td>
</tr>
<tr>
<td>$\tilde{d}_4 \rightarrow$</td>
<td>$\tilde{\chi}_1^- u$, 2.1</td>
<td>$\tilde{\chi}_1^- c$, 2.3</td>
</tr>
<tr>
<td>I: $\tilde{s}_R(\tilde{s}_L, \tilde{b}_R)$</td>
<td>$\tilde{\chi}_1^0 s$, 9.1</td>
<td>$\tilde{\chi}_1^- c$, 3.0</td>
</tr>
<tr>
<td>$\tilde{d}_5 \rightarrow$</td>
<td>$\tilde{\chi}_1^0 d$, 2.3</td>
<td>$\tilde{\chi}_2^- d$, 31.7</td>
</tr>
<tr>
<td>I: $\tilde{d}_L$</td>
<td>$\tilde{\chi}_1^- u$, 2.3</td>
<td>$\tilde{\chi}_1^- u$, 59.7</td>
</tr>
<tr>
<td>$\tilde{d}_6 \rightarrow$</td>
<td>$\tilde{\chi}_1^- c$, 58.1</td>
<td>$\tilde{\chi}_1^- u$, 2.9</td>
</tr>
<tr>
<td>I: $\tilde{s}_L(\tilde{s}_R)$</td>
<td>$\tilde{\chi}_2^- c$, 2.4</td>
<td>$\tilde{\chi}_2^- c$, 2.3</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow$</td>
<td>$\tilde{g} b$, 39.8</td>
<td>$\tilde{g} s$, 2.2</td>
</tr>
</tbody>
</table>

II: $\tilde{d}_1 \simeq \tilde{b}_L, \tilde{s}_R(\tilde{b}_L), \tilde{d}_6 \simeq \tilde{s}_R, \tilde{b}_R(\tilde{b}_L), \tilde{d}_2 \simeq \tilde{b}_L, \tilde{d}_3 \simeq \tilde{d}_R, \tilde{d}_4 \simeq \tilde{d}_L$ and $\tilde{d}_5 \simeq \tilde{s}_L$
Squark masses in GeV for SPS1a’ and the two points I and II

<table>
<thead>
<tr>
<th></th>
<th>$m_{\tilde{d}_1}$</th>
<th>$m_{\tilde{d}_2}$</th>
<th>$m_{\tilde{d}_3}$</th>
<th>$m_{\tilde{d}_4}$</th>
<th>$m_{\tilde{d}_5}$</th>
<th>$m_{\tilde{d}_6}$</th>
<th>$m_{\tilde{u}_1}$</th>
<th>$m_{\tilde{u}_2}$</th>
<th>$m_{\tilde{u}_4}$</th>
<th>$m_{\tilde{u}_6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS1a’</td>
<td>506</td>
<td>546</td>
<td>547</td>
<td>547</td>
<td>570</td>
<td>570</td>
<td>367</td>
<td>547</td>
<td>565</td>
<td>586</td>
</tr>
<tr>
<td>I. $\delta_{LL,23} = 0.01$, $\delta_{d,RR,23} = 0.1$</td>
<td>503</td>
<td>525</td>
<td>547</td>
<td>569</td>
<td>570</td>
<td>570</td>
<td>366</td>
<td>547</td>
<td>565</td>
<td>586</td>
</tr>
<tr>
<td>II. $\delta_{LL,23} = 0.04$, $\delta_{d,RR,23} = 0.45$</td>
<td>422</td>
<td>509</td>
<td>547</td>
<td>570</td>
<td>572</td>
<td>641</td>
<td>366</td>
<td>547</td>
<td>565</td>
<td>587</td>
</tr>
</tbody>
</table>

Note that $m_{\tilde{u}_2} \simeq m_{\tilde{u}_3}$ and $m_{\tilde{u}_4} \simeq m_{\tilde{u}_5}$

Composition of a) $\tilde{d}_{i=1}$ and b) $\tilde{d}_{i=2}$ as a function of $\delta_{d,RR,23}$

red: $|R_{i,\tilde{s}_R}^d|^2$  blue: $|R_{i,\tilde{b}_R}^d|^2$  green: $|R_{i,\tilde{b}_L}^d|^2$  $\tilde{d}_k = R_{k,j}^d \tilde{d}_j^{ew}$

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Impact on LHC and ILC

Flavour tagging at LHC important, but difficult

This can complicate determination of sparticle masses:

\[ \tilde{g} \rightarrow b\tilde{b}_j \rightarrow b\tilde{b}\tilde{\chi}_k^0 \]

\[ 10^4 \frac{d(\text{BR}(\tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0))}{dm_{bb}} \]

\[ 10^4 \frac{d(\text{BR}(\tilde{g} \rightarrow bs\tilde{\chi}_1^0))}{dm_{bs}} \]

\[ m_{bb} = \sqrt{(p_b + p_{\tilde{b}})^2} \]

Differential distributions

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Conclusions

- Flavour-violating squark and gluino decays can be typically of order of 10%, consistent with the present flavour data.
- Common feature for a couple of SUSY benchmark points like SPS1a’, γ, and I’
- Even 40% possible for large new physics contributions

- Impact on the discovery strategies at the LHC
  - Flavour tagging at LHC important but difficult
  - Detailed Monte-Carlo analysis of differential distributions needed

- Additional information from flavour factories or ILC will be necessary to interpret LHC data properly
Immense potential for synergy and complementarity between high-$p_T$ and flavour physics within the search for new physics

The indirect information will be most valuable when the general nature of new physics will be identified in the direct search.