Flavour violating squark and gluino decays

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Flavour problem of New Physics

$$\mathcal{L} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \sum_i \frac{c_i^{New}}{\Lambda_{\rm NP}} \mathcal{O}_i^{(5)} + \ldots$$

- SM as effective theory valid up to cut-off scale $\Lambda_{\rm NP}$
- Typical example: $K^0 - \bar{K}^0$-mixing $\mathcal{O}^6 = (\bar{s}\, d)^2$:

  $c^{SM}/M_W^2 \times (\bar{s}\, d)^2 + c^{New}/\Lambda_{\rm NP}^2 \times (\bar{s}\, d)^2$ $\Rightarrow$ $\Lambda_{\rm NP} > 10^4\,{\rm TeV}$

  (tree-level, generic new physics)

- Natural stabilisation of Higgs boson mass (hierarchy problem)

  (i.e. supersymmetry, little Higgs, extra dimensions) $\Rightarrow$ $\Lambda_{\rm NP} \leq 1{\rm TeV}$

- EW precision data $\leftrightarrow$ little hierarchy problem $\Rightarrow \Lambda_{\rm NP} \sim 3 - 10{\rm TeV}$

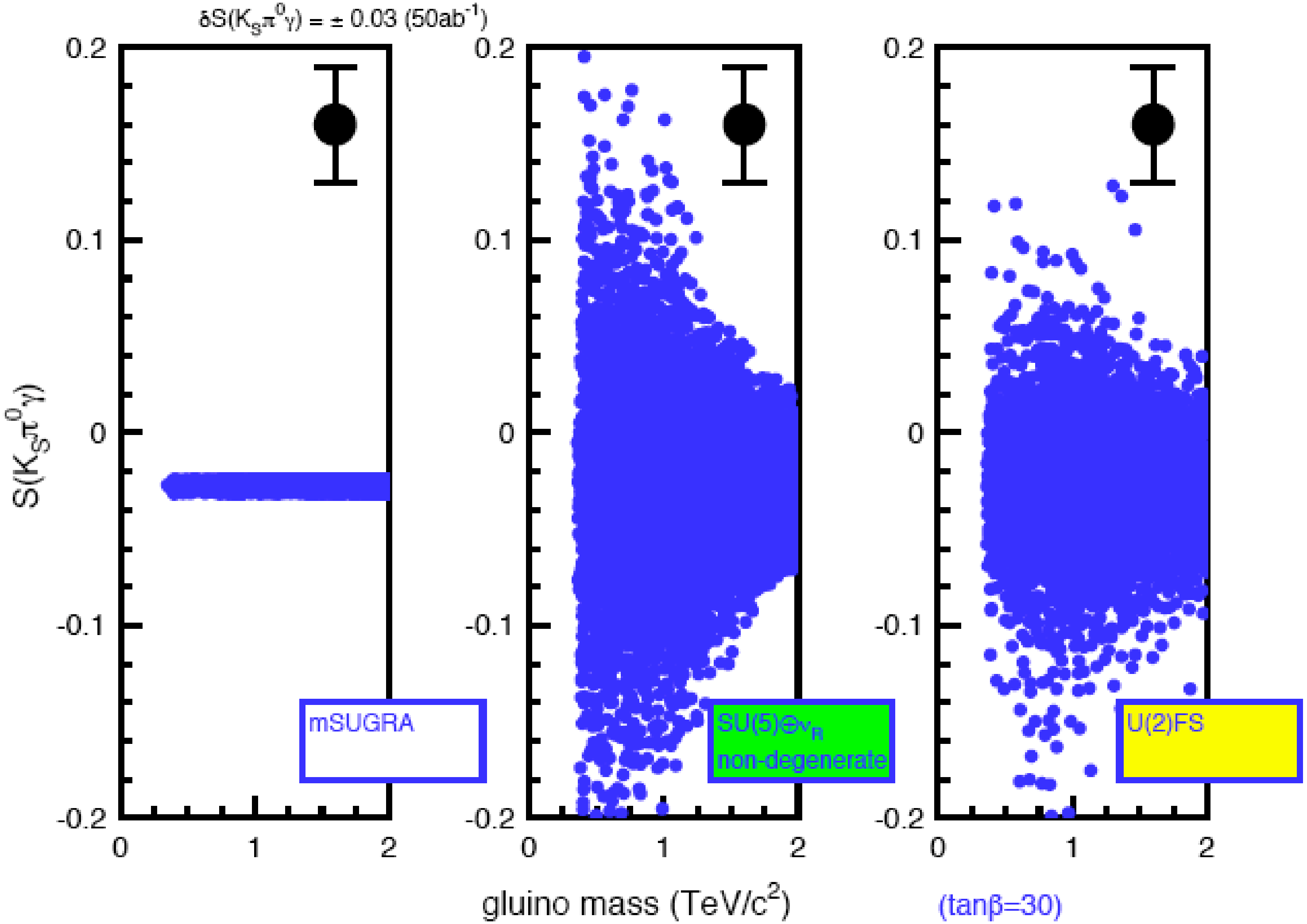
Possible New Physics at the TeV scale has to have

a nongeneric flavour structure

Interplay of high-p_T and flavour physics

- Dynamics of flavour $\leftrightarrow$ mechanism of SUSY breaking
  ($BR(b \to s\gamma) = 0$ in exact supersymmetry)

  $\Rightarrow$ Discrimination between various SUSY-breaking mechanism



Expected Super-B sensitivity ($50ab^{-1}$) Goto,Okada,Shindou,Tanaka,arXiv:0711.2935

- 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^+, χ^+ exchanges
  - flavour mixing in the sfermion mass matrix
- Possible disalignement of quarks and squarks
- Squark decays:

$$\tilde{u}_i \to u_j \tilde{\chi}^0_k \,,\; d_j \tilde{\chi}^+_l \qquad \tilde{d}_i \to d_j \tilde{\chi}^0_k \,,\; u_j \tilde{\chi}^-_l$$

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

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

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

$$\tilde{g} \to d_j\, \tilde{d}_i\,, \quad \tilde{g} \to u_j\, \tilde{u}_i$$

followed by squark decays into neutralino and charginos

$$\tilde{u}_i \to u_j \tilde{\chi}^0_k\,, d_j \tilde{\chi}^+_l\,, \quad \tilde{d}_i \to d_j \tilde{\chi}^0_k\,, u_j \tilde{\chi}^-_l$$

or into gauge- and Higgs bosons if kinematically allowed

$$\tilde{u}_i \to Z \tilde{u}_k\,,\ H^0_r \tilde{u}_k\,,\ W^+ \tilde{d}_j\,,\ H^+ \tilde{d}_j; \qquad \tilde{d}_i \to Z \tilde{d}_k\,,\ H^0_r \tilde{d}_k\,,\ W^- \tilde{u}_j\,,\ H^- \tilde{u}_j$$

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

$$\tilde{u}_i \to u_j \tilde{g}\,, \quad \tilde{d}_i \to d_j \tilde{g}$$

the gluino decays into charginos and neutralinos

via three-body decays and loop-induced two-body decays

$$\tilde{g} \to d_j\, d_i\, \tilde{\chi}^0_k\,,\ u_j\, u_i\, \tilde{\chi}^0_k\,, \quad \tilde{g} \to u_j\, d_i\, \tilde{\chi}^\pm_l\,, \quad \tilde{g} \to g\, \tilde{\chi}^0_k$$

Squark mixing

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

$$\mathcal{M}_f^2 \equiv \begin{pmatrix} M^2_{f,\,LL} + F_{f\,LL} + D_{f\,LL} & M^2_{f,\,LR} + F_{f\,LR} \\ \left(M^2_{f,\,LR}\right)^\dagger + F^*_{f\,RL} & M^2_{f,\,RR} + F_{f\,RR} + D_{f\,RR} \end{pmatrix}$$

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:

$$\begin{aligned} M^2_{d,LL} &= V^\dagger_{CKM} M^2_{u,LL} V_{CKM} = \hat{m}^2_{\tilde{Q}} \equiv V_d^\dagger\, m^2_{\tilde{Q}}\, V_d \,, \\ M^2_{d,RR} &= \hat{m}^2_{\tilde{d}} \equiv U_d^\dagger\, m^{2\,T}_{\tilde{d}}\, U_d \;, \qquad M^2_{u,RR} = \hat{m}^2_{\tilde{u}} \equiv U_u^\dagger\, m^{2\,T}_{\tilde{u}}\, U_u \,, \\ M^2_{d,LR} &= v_1/\sqrt{2}\,\hat{T}_D \equiv v_1/\sqrt{2}\, U_d^\dagger\, T_D^T\, V_d \;, \qquad M^2_{u,LR} = v_2/\sqrt{2}\,\hat{T}_U \equiv v_2/\sqrt{2}\, U_u^\dagger\, T_U^T\, V_u \end{aligned}$$

Observables as functions of the normalized off-diagonal elements:

$$\delta_{LL,ij} = \frac{(M^2_{f,\,LL})_{ij}}{m^2_{\tilde{q}}} \,, \qquad \delta_{f,RR,ij} = \frac{(M^2_{f,\,RR})_{ij}}{m^2_{\tilde{f}}} \,, \qquad (i \neq j)$$

Experimental and theoretical constraints

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

$$
\begin{array}{lcl}
2.67 < & Br(\bar{B} \to X_s \gamma) \times 10^4 & < 4.29 \\
13.5 < & \Delta M_{B_S}\ ps & < 21.1 \\
1.05 < & BR(\bar{B} \to X_s l^+ l^-)_{\mathrm{low}_{q^2}} \times 10^6 & < 2.15 \\
 & BR(B_s \to \mu^+ \mu^-) \times 10^8 & \leq 5.8
\end{array}
$$

Strategy:

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

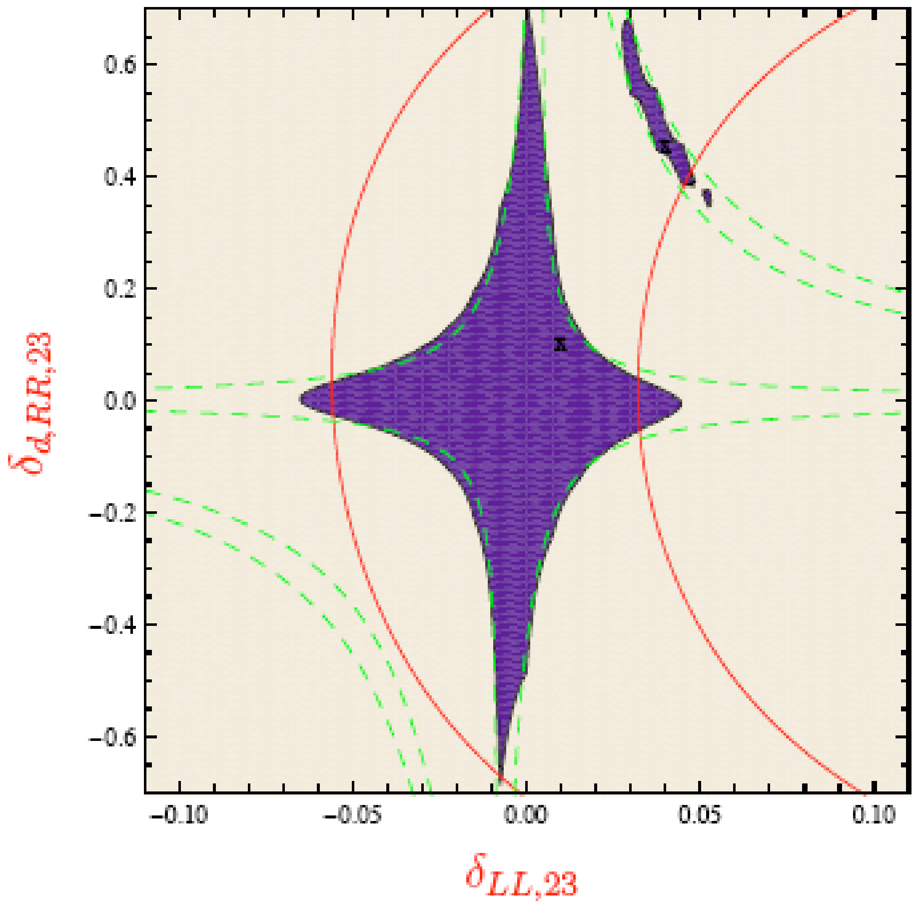
$\Rightarrow$ Bounds on δ parameters

	SPS1a'	γ	I''
$\delta_{LL,23}$	(-0.05,0.03)	(-0.037,0.005)	(-0.06,0.001)
$\delta_{d,RR,23}$	(-0.43,0.66)	(-0.29,0.48)	(-0.5,0.45)
$\delta_{u,RR,23}$	(-0.7,0.7)	(-0.54,0.43)	(-0.55,0.45)
$\delta_{u,LR,23}$	(-0.16,0.08)	(-0.16,0.06)	(-0.35,0.05)
$\delta_{u,LR,32}$	(-0.7,0.54)	(-0.5,0.2)	(-0.7,0.27)
$\delta_{d,LR,23}$	(-0.0047,0.0046)	(-0.006,0.001)	(-0.01,0.0015)
$\delta_{d,LR,32}$	(-0.019,0.02)	(-0.015,0.015)	(-0.004,0.003)

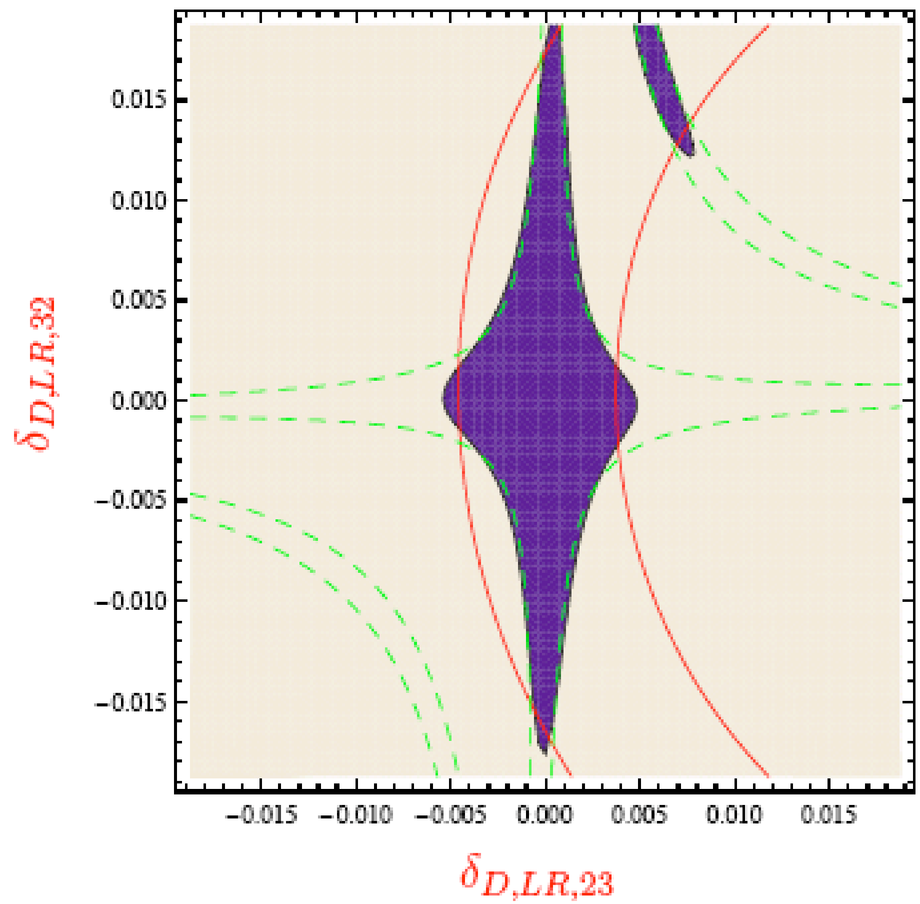
Assumption used that only one flavour-mixing parameter is present (regions 95% CL.)

Allowed regions for SPS1a'

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



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



($b \to s\gamma$ red lines, ΔM_{B_s} magenta)

Typical results for squark and gluino decays

decaying particle	final states and corresponding branching ratios in % for.					
	I. $\delta_{LL,23} = 0.01, \delta_{D,RR23} = 0.1$			II. $\delta_{LL,23} = 0.04, \delta_{D,RR23} = 0.45$		
$\tilde{d}_1 \to$ I: $\tilde{b}_L (\tilde{b}_R)$	$\tilde{\chi}^0_1 b$, 4.4 $\tilde{u}_1 W^-$, 27.7	$\tilde{\chi}^0_2 b$, 29.8	$\tilde{\chi}^-_1 t$, 37.0	$\tilde{\chi}^0_1 s$, 36.8 $\tilde{\chi}^-_1 t$, 9.6	$\tilde{\chi}^0_1 b$, 42.2	$\tilde{\chi}^0_2 b$, 10.9
$\tilde{d}_2 \to$ I: $\tilde{b}_R(\tilde{b}_L, \tilde{s}_R)$	$\tilde{\chi}^0_1 s$, 8.0 $\tilde{\chi}^0_3 b$, 1.1 $\tilde{u}_1 W^-$, 38.9	$\tilde{\chi}^0_1 b$, 6.4 $\tilde{\chi}^0_4 b$, 1.8	$\tilde{\chi}^0_2 b$, 19.0 $\tilde{\chi}^-_1 t$, 24.6	$\tilde{\chi}^0_1 b$, 2.1 $\tilde{u}_1 W^-$, 33.2	$\tilde{\chi}^0_2 b$, 27.3	$\tilde{\chi}^-_1 t$, 34.6
$\tilde{d}_4 \to$ I: $\tilde{s}_R(\tilde{s}_L, \tilde{b}_R)$	$\tilde{\chi}^0_1 s$, 9.1 $\tilde{\chi}^-_1 u$, 2.1	$\tilde{\chi}^0_1 b$, 6.3 $\tilde{\chi}^-_1 c$, 47.3	$\tilde{\chi}^0_2 s$, 25.3 $\tilde{u}_1 W^-$, 4.8	$\tilde{\chi}^0_1 d$, 2.3 $\tilde{\chi}^-_1 c$, 3.0	$\tilde{\chi}^0_2 d$, 31.7 $\tilde{\chi}^-_2 u$, 2.3	$\tilde{\chi}^-_1 u$, 59.7
$\tilde{d}_5 \to$ I: $\tilde{d}_L$	$\tilde{\chi}^0_1 d$, 2.3 $\tilde{\chi}^-_1 c$, 2.8	$\tilde{\chi}^0_2 d$, 31.7 $\tilde{\chi}^-_2 u$, 2.3	$\tilde{\chi}^-_1 u$, 59.9	$\tilde{\chi}^0_1 s$, 2.2 $\tilde{\chi}^-_1 c$, 58.5	$\tilde{\chi}^0_2 s$, 30.7 $\tilde{\chi}^-_2 c$, 2.3	$\tilde{\chi}^-_1 u$, 2.9
$\tilde{d}_6 \to$ I: $\tilde{s}_L (\tilde{s}_R)$	$\tilde{\chi}^0_1 s$, 3.1 $\tilde{\chi}^-_1 c$, 58.1	$\tilde{\chi}^0_2 s$, 30.6 $\tilde{\chi}^-_2 c$, 2.4	$\tilde{\chi}^-_1 u$, 2.7	$\tilde{\chi}^0_1 s$, 19.7 $\tilde{\chi}^0_4 b$, 2.9 $\tilde{g} b$, 39.8	$\tilde{\chi}^0_1 b$, 18.8 $\tilde{\chi}^-_2 t$, 5.8 $\tilde{u}_1 W^-$, 5.5	$\tilde{\chi}^0_3 b$, 2.9 $\tilde{g} s$, 2.2
$\tilde{g} \to$	$\tilde{u}_1 t$, 19.2 $\tilde{u}_4 u$, 4.2 $\tilde{d}_1 s$, 1.4 $\tilde{d}_2 s$, 6.3 $\tilde{d}_4 s$, 2.3	$\tilde{u}_2 c$, 8.2 $\tilde{u}_5 c$, 4.2 $\tilde{d}_1 b$, 20.6 $\tilde{d}_2 b$, 9.0 $\tilde{d}_4 b$, 1.3	$\tilde{u}_3 u$, 8.3 $\tilde{d}_3 d$, 8.3 $\tilde{d}_6 s$, 2.8	$\tilde{u}_1 t$, 13.5 $\tilde{u}_4 c$, 2.6 $\tilde{d}_1 s$, 21.1 $\tilde{d}_2 b$, 14.0 $\tilde{d}_4 d$, 2.3	$\tilde{u}_2 c$, 5.8 $\tilde{u}_5 u$, 2.6 $\tilde{d}_1 b$, 22.7 $\tilde{d}_5 d$, 3.3	$\tilde{u}_3 u$, 5.8 $\tilde{d}_3 d$, 5.9

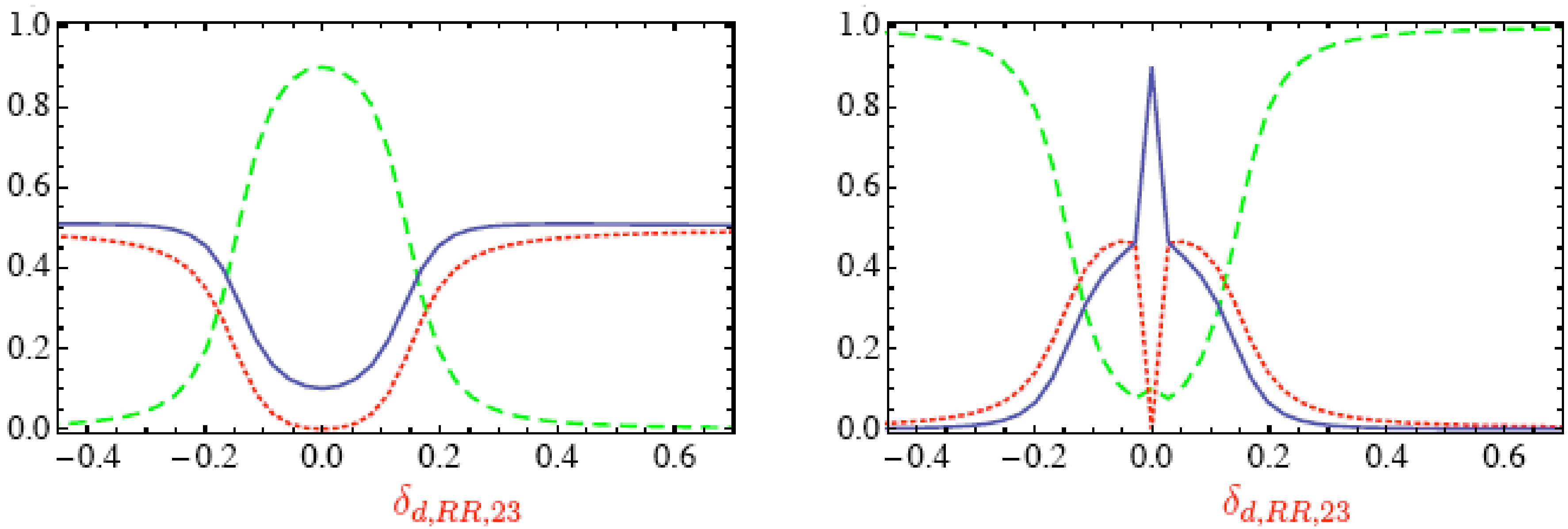
II: $\tilde{d}_1 \simeq \tilde{b}_R, \tilde{s}_R(\tilde{b}_L)$, $\tilde{d}_6 \simeq \tilde{s}_R, \tilde{b}_R(\tilde{b}_L)$, $\tilde{d}_2 \simeq \tilde{b}_L$, $\tilde{d}_3 \simeq \tilde{d}_R$, $\tilde{d}_4 \simeq \tilde{d}_L$ and $\tilde{d}_5 \simeq \tilde{s}_L$

Squark masses in GeV for SPS1a' and the two points I and II

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

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: $|R^d_{i,\tilde{s}_R}|^2$ **blue:** $|R^d_{i,\tilde{b}_R}|^2$ **green:** $|R^d_{i,\tilde{b}_L}|^2$ $\tilde{d}_k = R^d_{kj} \tilde{d}^{ew}_j$

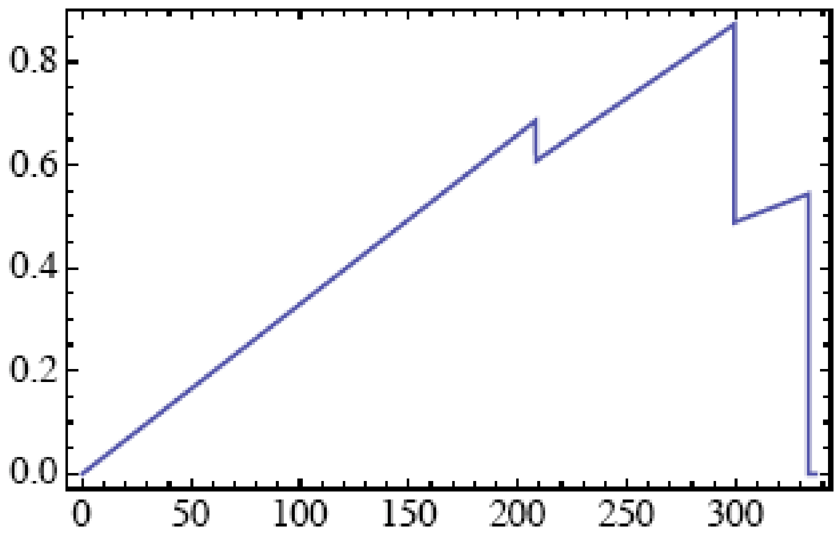
Impact on LHC and ILC

Flavour tagging at LHC important, but difficult

This can complicate determination of sparticle masses:

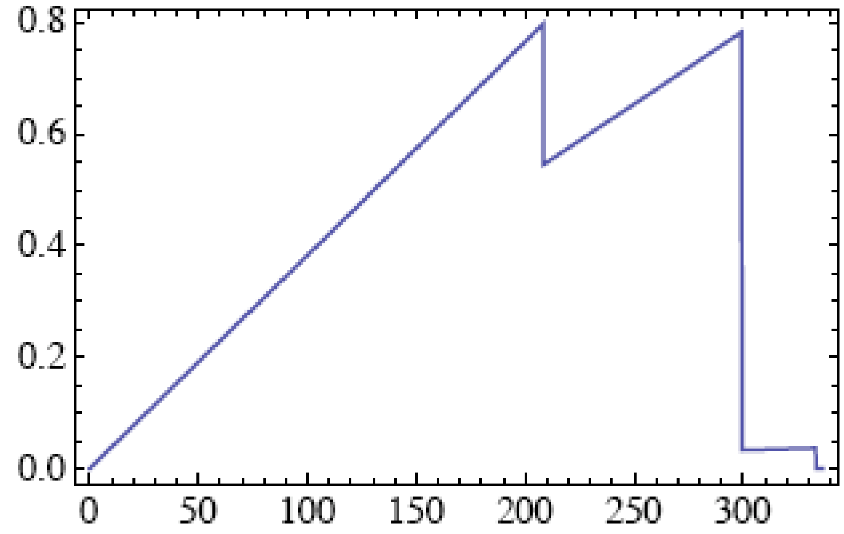
$$\tilde{g} \longrightarrow b\tilde{\bar{b}}_j \longrightarrow b\bar{b}\tilde{\chi}^0_k$$

$10^4\ d(\mathrm{BR}(\tilde{g} \to b\bar{b}\tilde{\chi}^0_1)/dm_{bb}$



$m_{bb} = \sqrt{(p_b + p_{\bar{b}})^2}$

$10^4\ d(\mathrm{BR}(\tilde{g} \to bs\tilde{\chi}^0_1)/dm_{bs}$



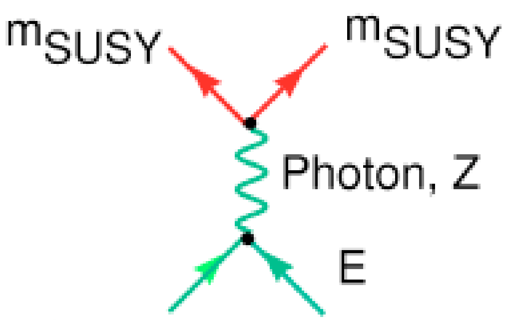
m_{bs}

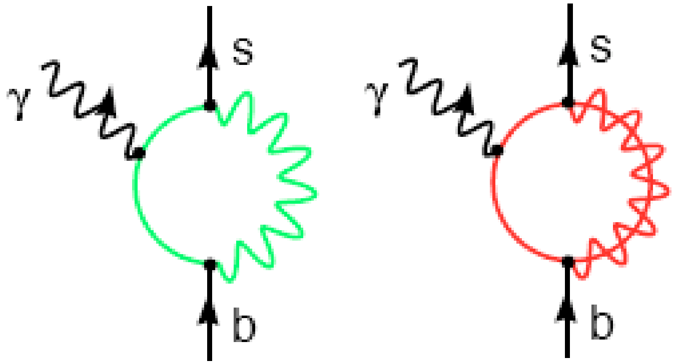
Differential distributions

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

Flavour@high-p_T





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.