Impact of generation mixing on the search for squarks at the LHC

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Outline

1. Flavour violation in the MSSM
2. Fermionic squark decays
3. Bosonic squark decays
4. Conclusion and Outlook

Flavour violation in the MSSM

In the Standard Model, quark flavour violation interactions are parametrized through CKM-matrix

$$\boxed{V_{\mathrm{CKM}} = V_u^\dagger V_d}$$

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Minimal flavour-violation (MFV)

- no new sources of flavour violation
- in super-CKM basis squarks undergo same rotations as quarks
- all flavour-violating entries related to CKM-matrix
- Example: $\tilde{\chi}_i^{\pm} \tilde{q}_j q_k$ interaction proportional to $V_{q_j q'_k}$

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Non-minimal flavour-violation (NMFV)

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- e.g. gravity-mediation, messenger-matter mixing, ...
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Flavour-violating terms incorporated in the mass matrices at the electroweak scale

$$\mathcal{M}^2_{\tilde{u}} = \begin{pmatrix} \mathcal{M}^2_{LL} & \left(\mathcal{M}^2_{RL}\right)^{\dagger} \\ \mathcal{M}^2_{RL} & \mathcal{M}^2_{RR} \end{pmatrix}$$

Focus here on flavour violation in the squark sector (slepton sector analogously with PMNS-matrix)

Squark sector with flavour violation

Soft-breaking matrices may include off-diagonal, i.e. flavour-violating, entries

$$
\begin{aligned}
\mathcal{M}^2_{LL,\alpha\beta} &= M^2_{Q,\alpha\beta} + \frac{1}{2}\left[m^2_{u,\alpha} + \left(\frac{1}{2} - \frac{2}{3}s^2_W\right) m^2_Z c_{2\beta}\right]\delta_{\alpha\beta} \\
\mathcal{M}^2_{RR,\alpha\beta} &= M^2_{U,\alpha\beta} + \frac{1}{2}\left[m^2_{u,\alpha} + \frac{2}{3}s^2_W m^2_Z c_{2\beta}\right]\delta_{\alpha\beta} \\
\mathcal{M}^2_{RL,\alpha\beta} &= \frac{v_u}{\sqrt{2}} T_{U,\alpha\beta} - m_{u,\alpha}\frac{\mu^*}{\tan\beta}\delta_{\alpha\beta}
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Introduce dimensionless parametrization through normalization w.r.t. diagonal elements

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\delta^{u\{LL,RR\}}_{\alpha\beta} &= M^2_{\{Q,U\},\alpha\beta}\Big/\sqrt{M^2_{\{Q,U\},\alpha\alpha} M^2_{\{Q,U\},\beta\beta}} \\
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Diagonalization through 6x6 rotation matrices leads to mass eigenstates ($m_{\tilde{u}_1} < \ldots < m_{\tilde{u}_6}$)

$$\mathcal{R}_{\tilde{u}} \mathcal{M}^2_{\tilde{u}} \mathcal{R}^\dagger_{\tilde{u}} = \mathrm{diag}\left(m^2_{\tilde{u}_1}, m^2_{\tilde{u}_2}, m^2_{\tilde{u}_3}, m^2_{\tilde{u}_4}, m^2_{\tilde{u}_5}, m^2_{\tilde{u}_6}\right)$$

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$$\begin{aligned}
\mathrm{BR}(b \to s\gamma) &= (3.57 \pm 0.65) \cdot 10^{-4} \\
\Delta M_{B_s} &= (17.77 \pm 3.31)\ \mathrm{ps}^{-1} \\
\mathrm{BR}(b \to s\mu^+\mu^-) &= (1.60 \pm 1.00) \cdot 10^{-6} \\
\mathrm{BR}(B_s \to \mu^+\mu^-) &< 4.3 \cdot 10^{-8} \\
\Delta a_\mu = a_\mu^{\mathrm{SM}} - a_\mu^{\mathrm{exp}} &= (29.0 \pm 8.6) \cdot 10^{-10}
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Highly sensitive to QFV elements

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Rather insensitive to QFV elements

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[e.g. Bozzi, Fuks, Herrmann, Klasen 2007; Fuks, Herrmann, Klasen 2008; Bartl, Hidaka, Hohenwarter-Sodek, Kernreiter, Majerotto, Porod 2009; Hurth, Porod 2009; Bruhnke, Herrmann, Porod 2010; Bartl, Eberl, Herrmann, Hidaka, Majerotto, Porod 2010]

Constraints on quark flavour violation

[Bruhnke, Herrmann, Porod (2010)]

Reference scenario for following studies: SPS1a' [Aguilar-Saavedra *et al.* 2006]

$$\boxed{m_0 = 70\ \mathrm{GeV}, m_{1/2} = 250\ \mathrm{GeV}, A_0 = -300\ \mathrm{GeV}, \tan\beta = 10, \mu > 0}$$

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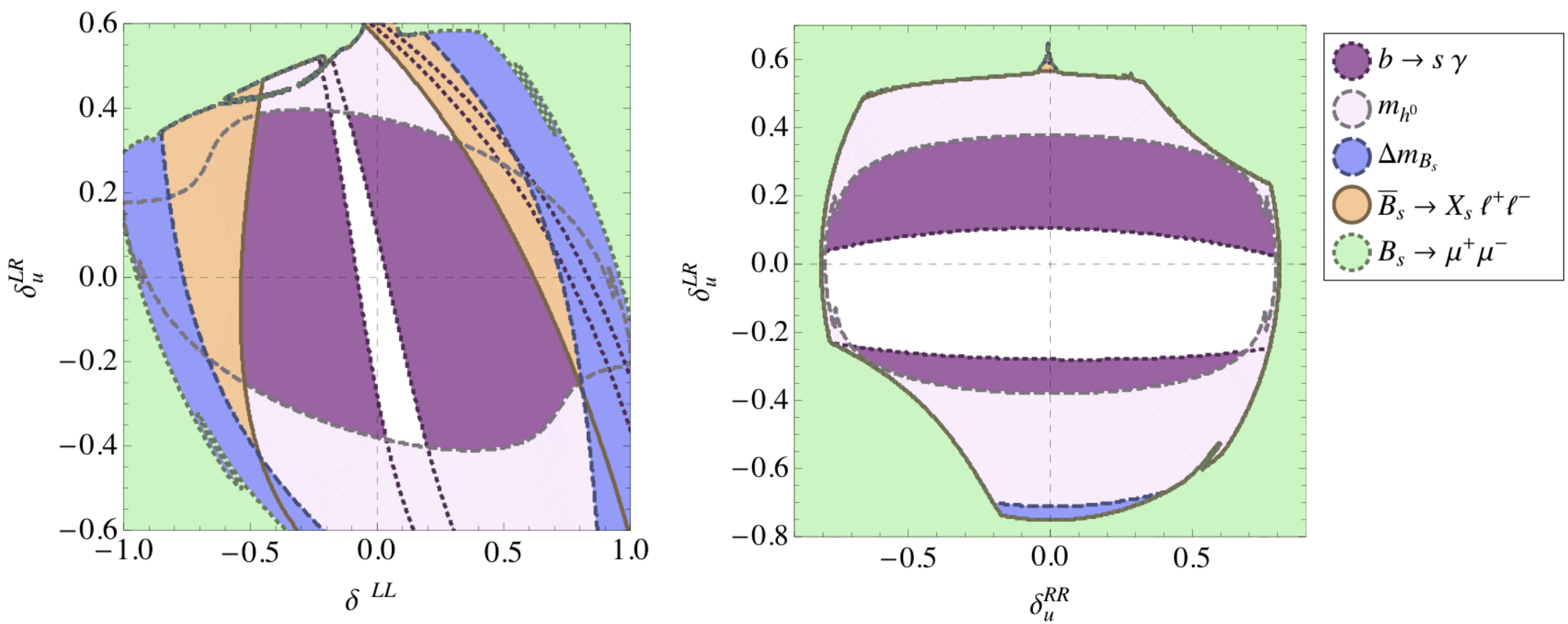
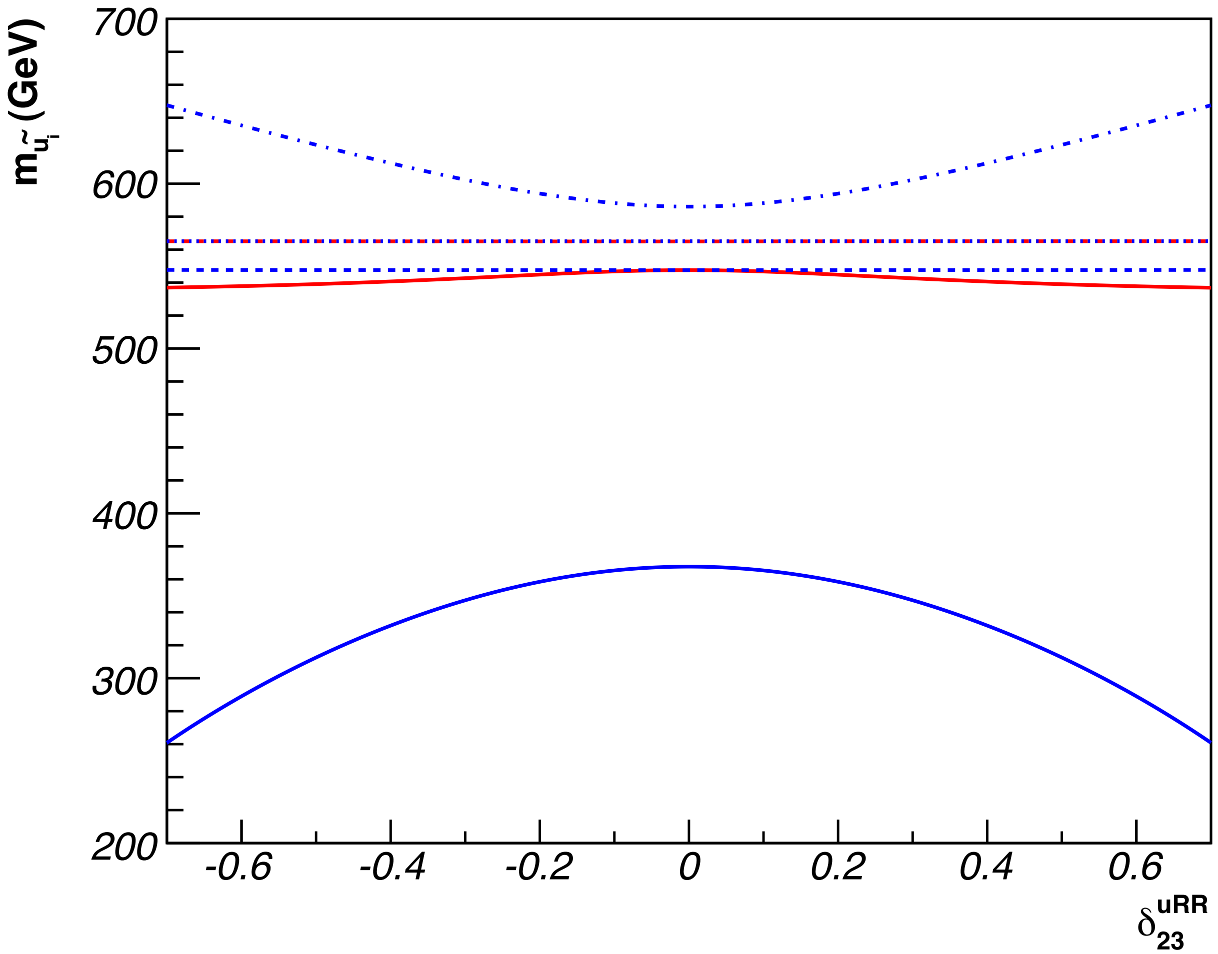


Rather wide regions for QFV elements remain allowed w.r.t. precision measurements, in particular no stringent constraints on flavour mixing in right-right sector

Squark masses and flavour contents

Non-diagonal elements directly affect mass eigenvalues and flavour contents of squarks



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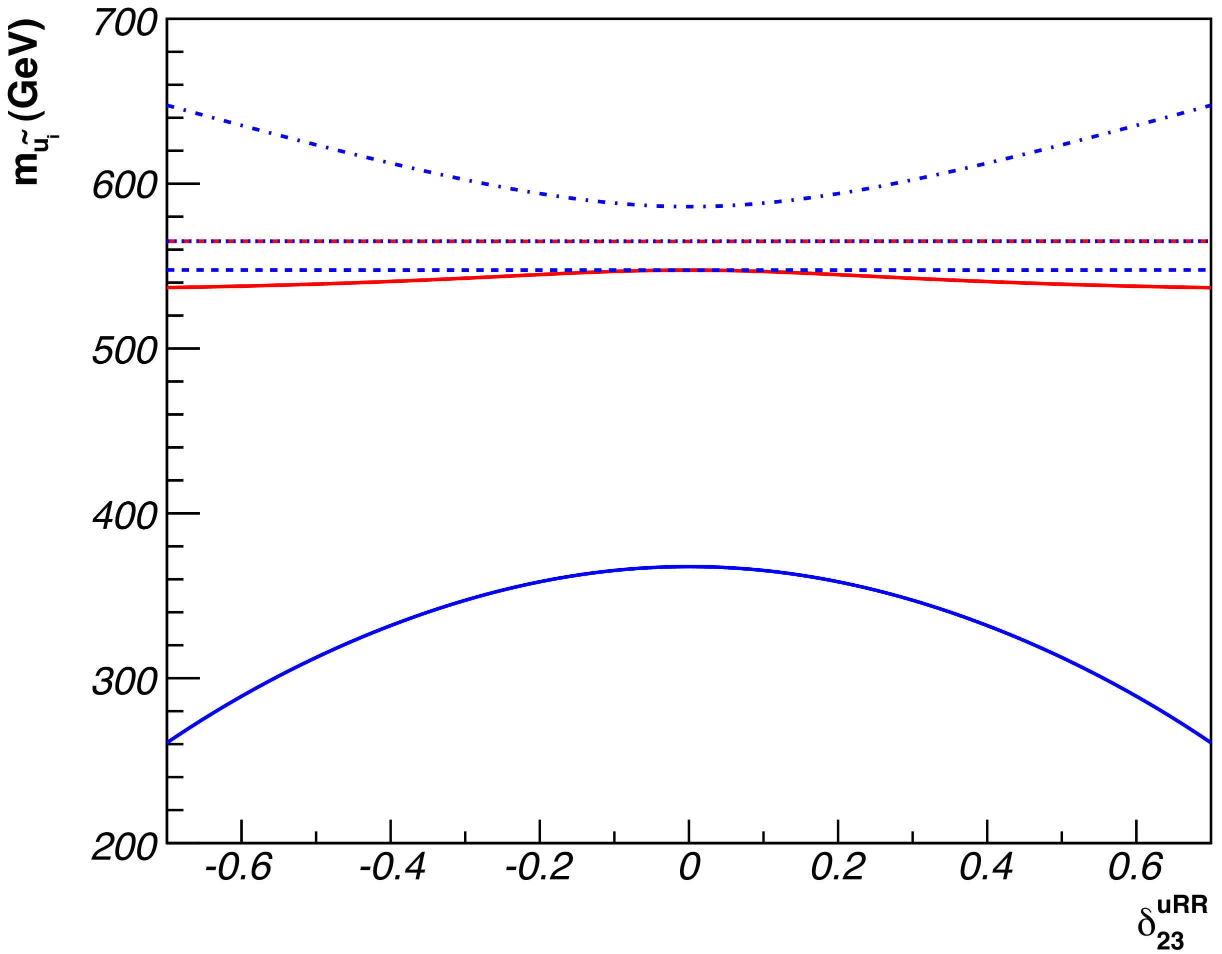

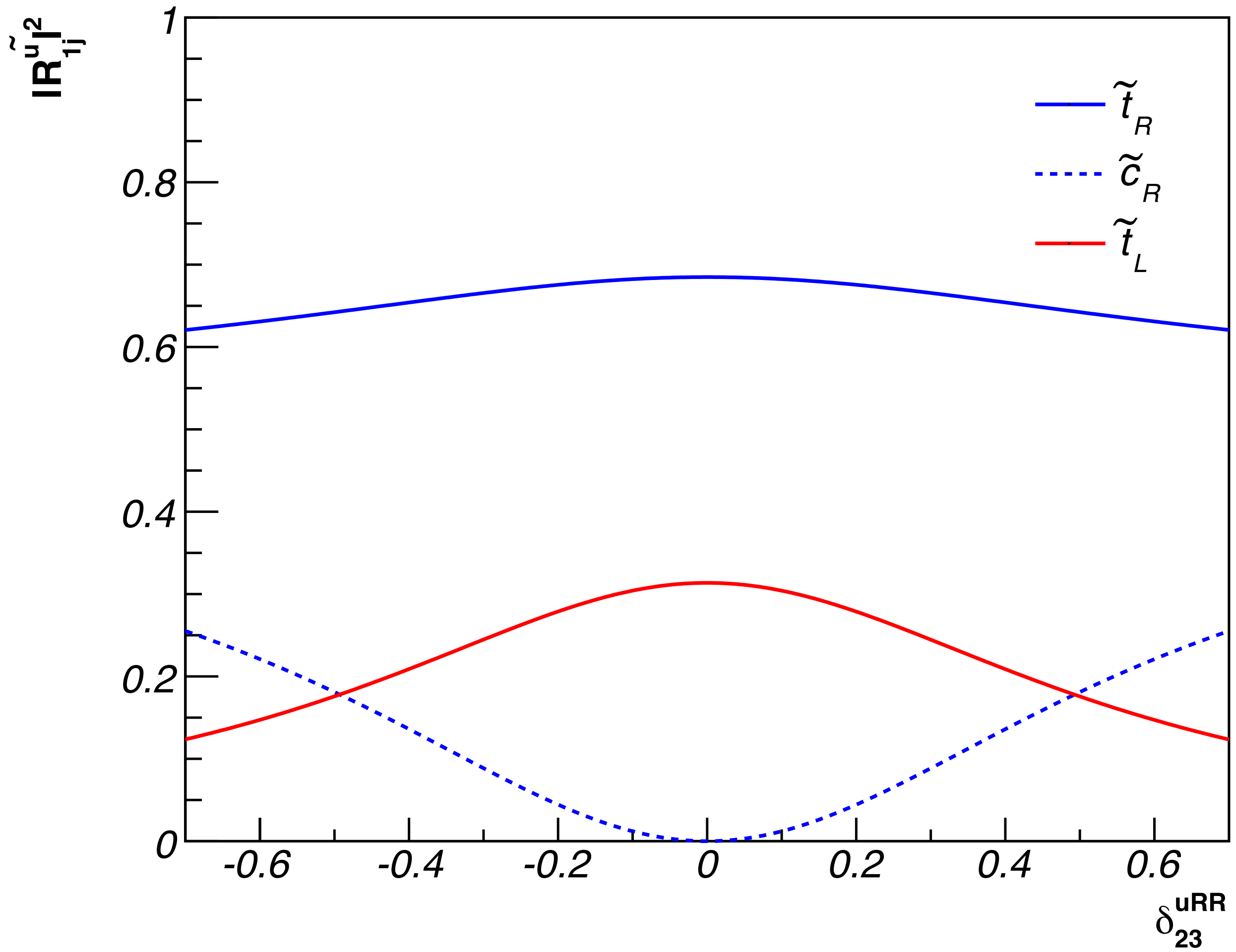

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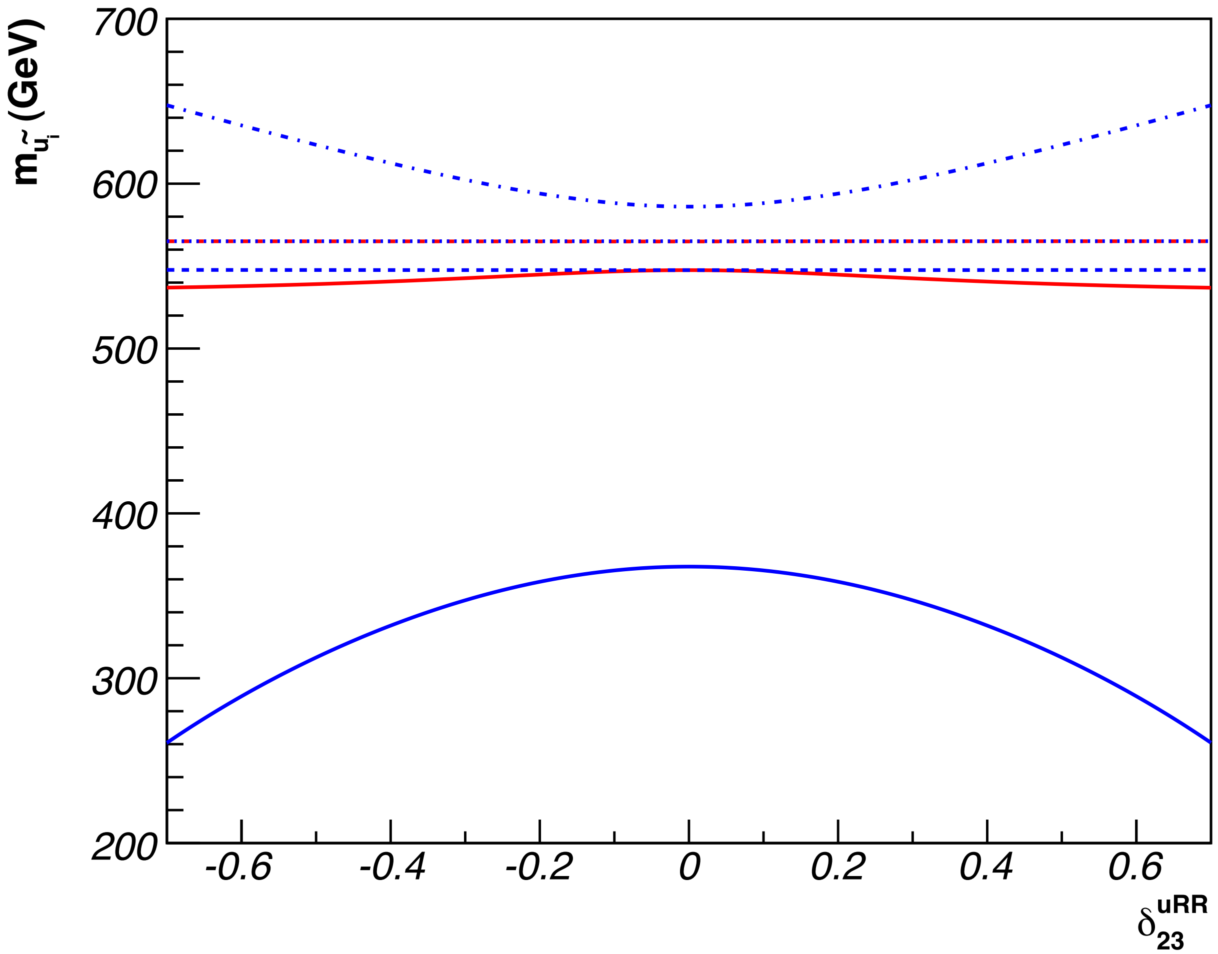

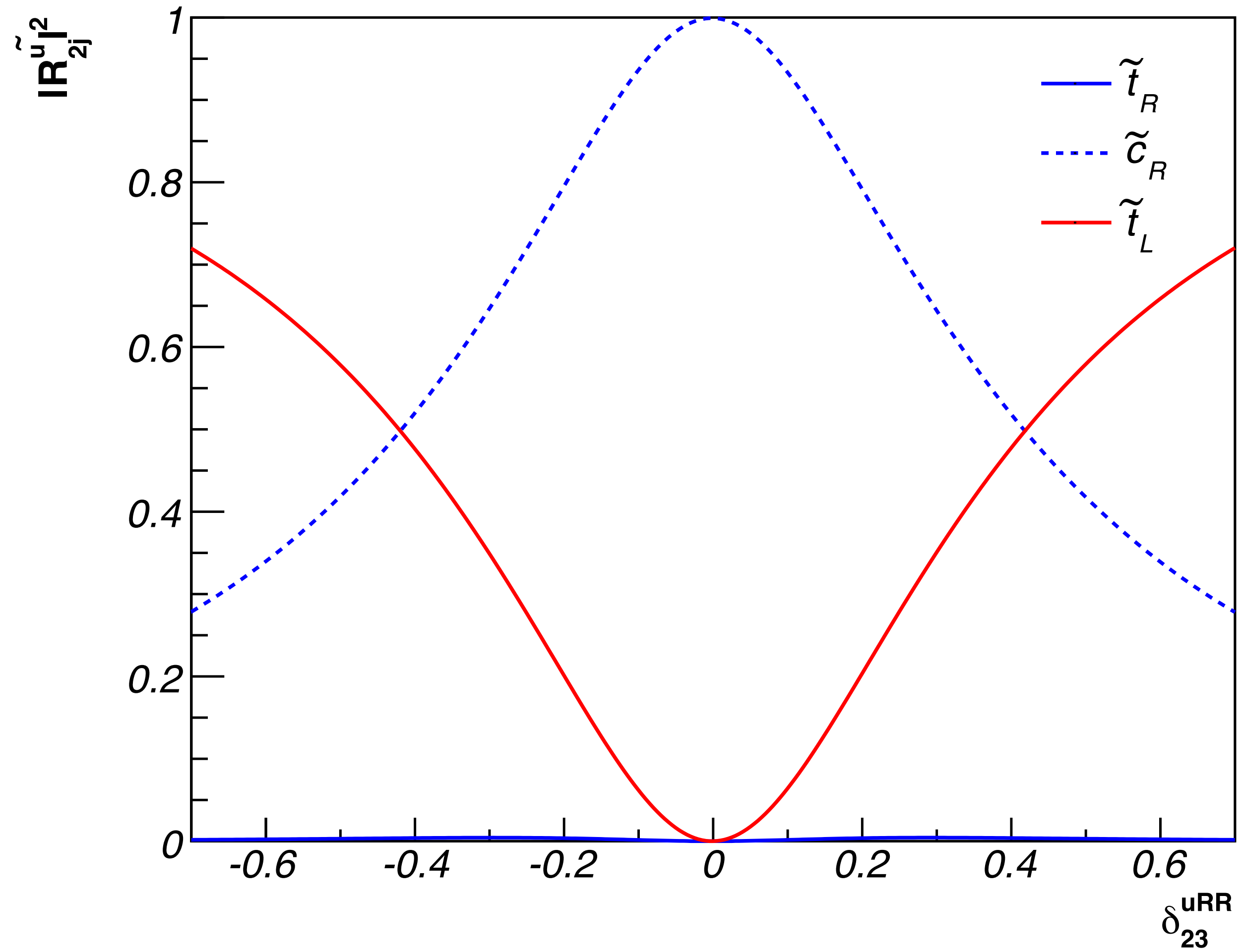

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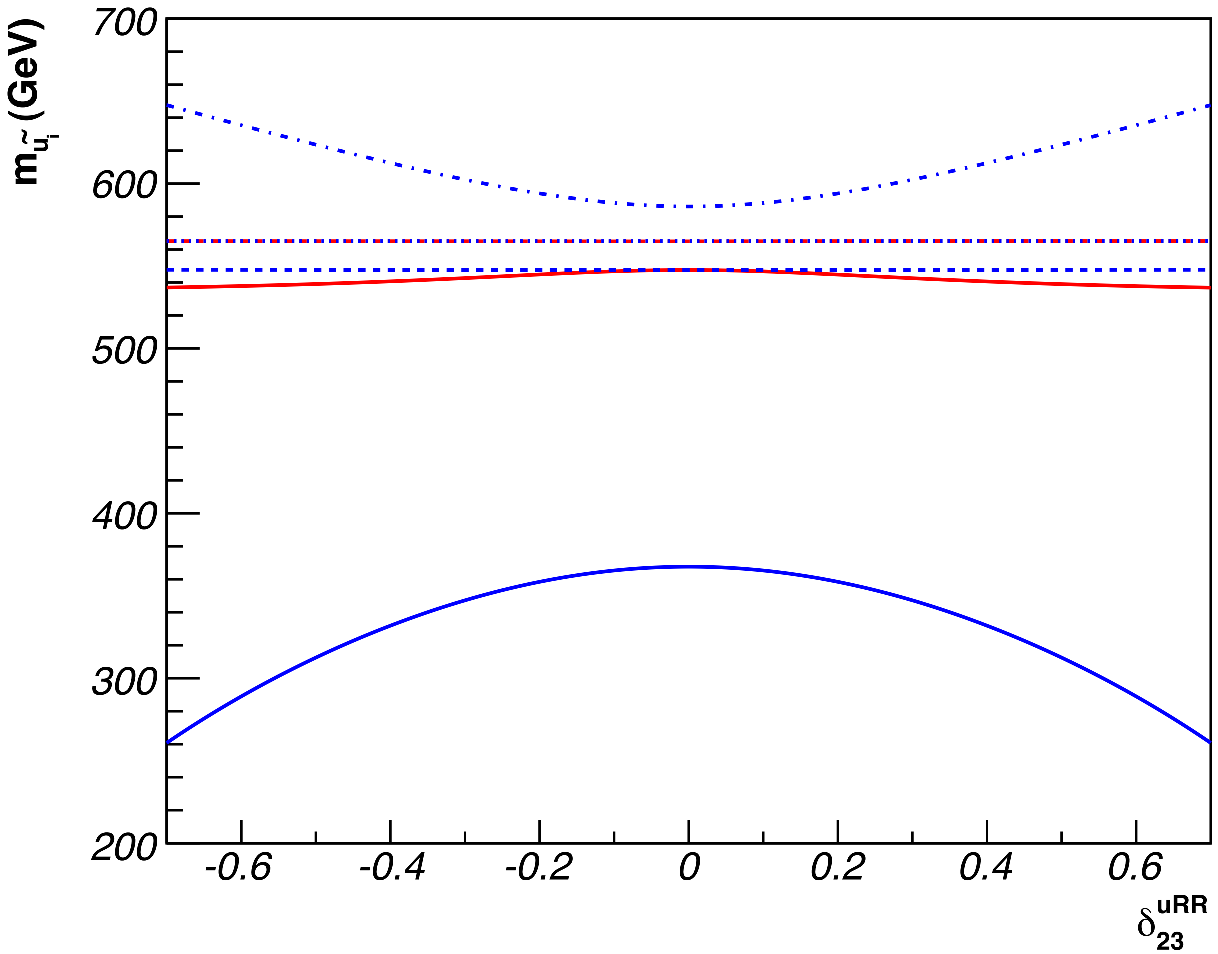
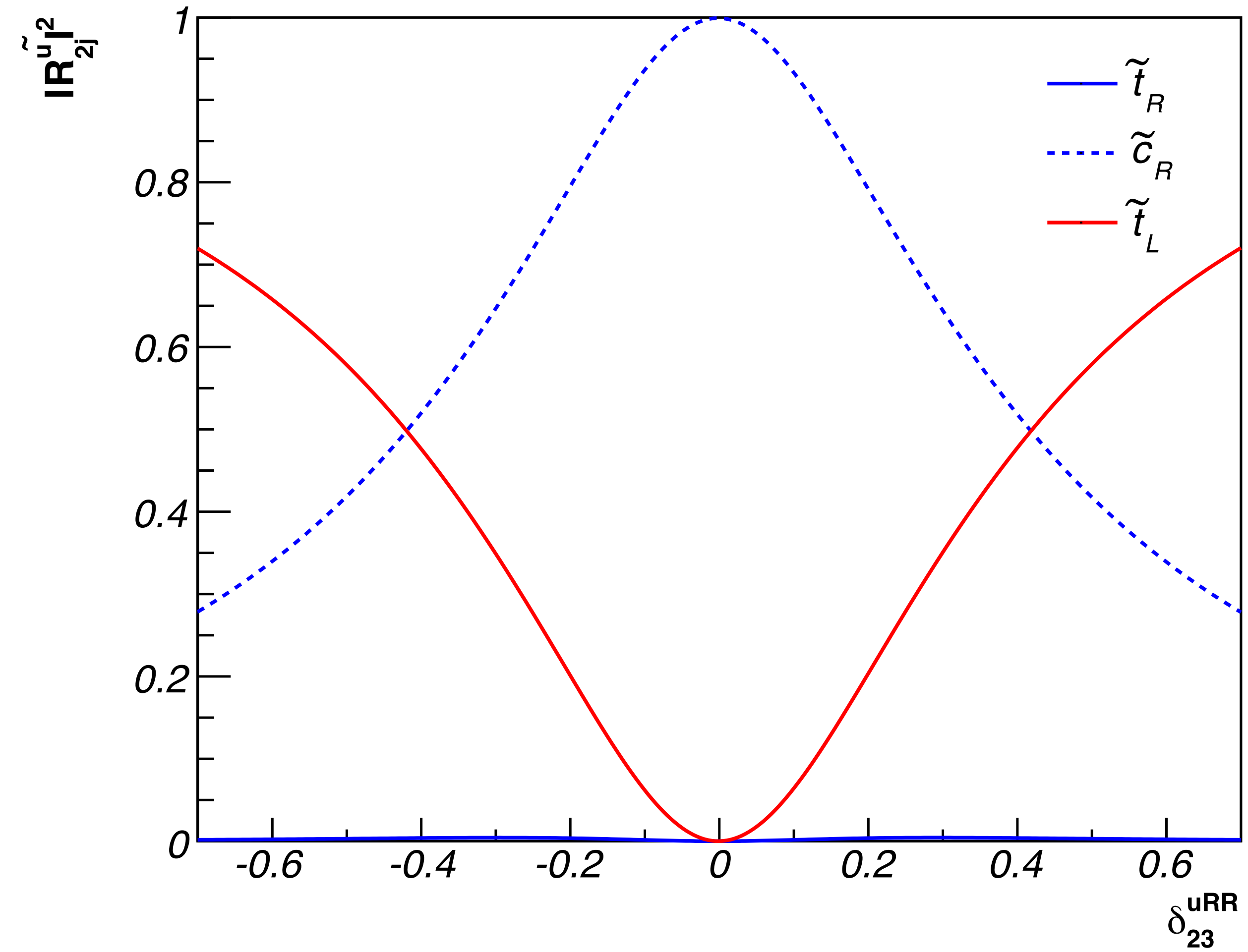




Couplings of squarks to scalars and fermions governed by flavour contents (i.e. rotation matrices)

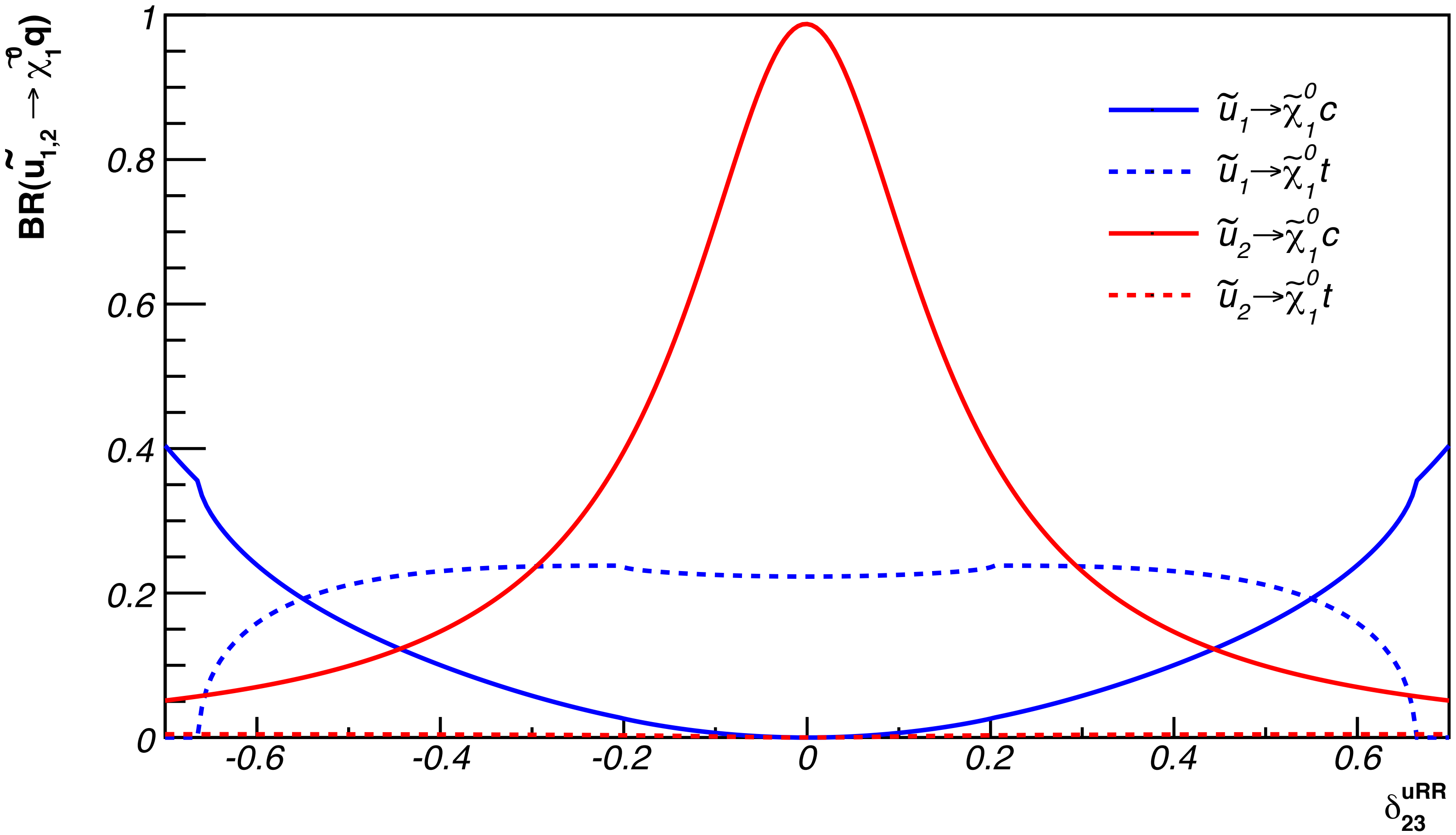
$$\Gamma_{\tilde{u}_i \tilde{u}_j A^0} = \frac{g_2}{2 m_W} \left[\mu^* \big(\mathcal{R}_{\tilde{u}}\big)_{i(k+3)} m_{u_i} \big(\mathcal{R}^\dagger_{\tilde{u}}\big)_{kj} + \frac{v_u}{\sqrt{2}\tan\beta} \big(\mathcal{R}_{\tilde{u}}\big)_{i(k+3)} \big(T_U\big)_{kl} \big(\mathcal{R}^\dagger_{\tilde{u}}\big)_{lj} \right] + \text{h.c.}$$

[see e.g. Bozzi, Fuks, Herrmann, Klasen (2007); Fuks, Herrmann, Klasen (2008); Bruhnke, Herrmann, Porod (2010)]

Fermionic squark decays

[Bartl, Eberl, Herrmann, Hidaka, Majerotto, Porod (2010)]

New squarks decay channels into fermions can be opened for non-minimal flavour violation



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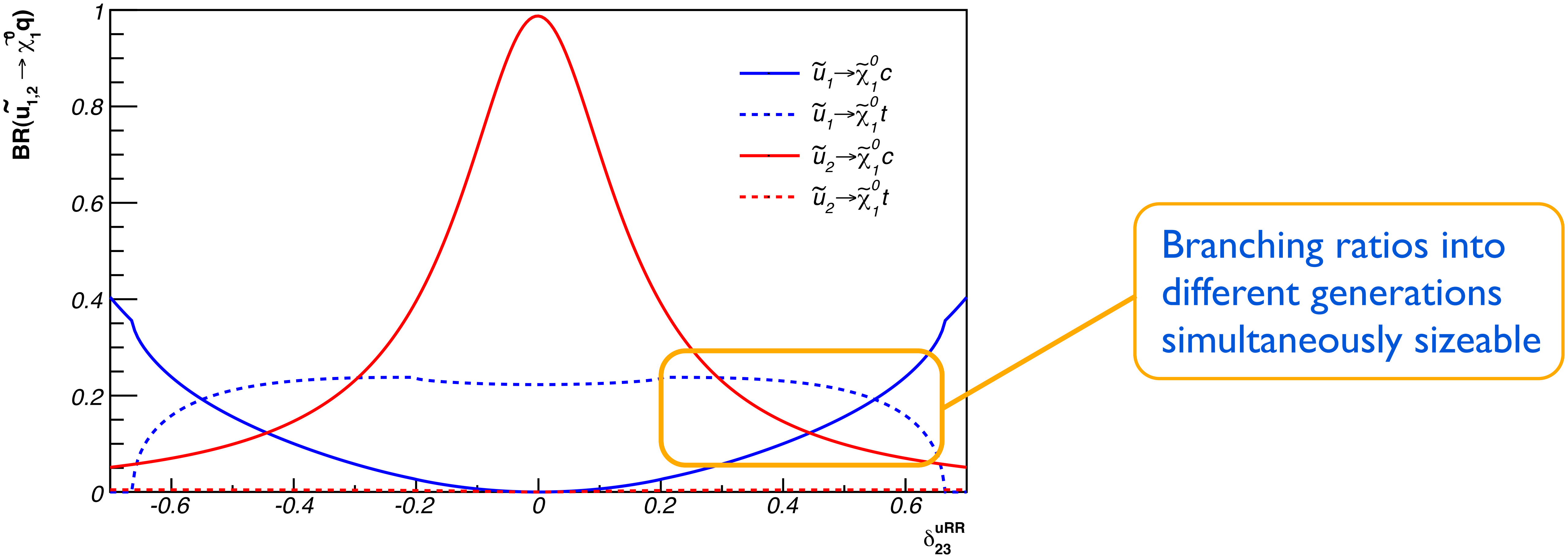

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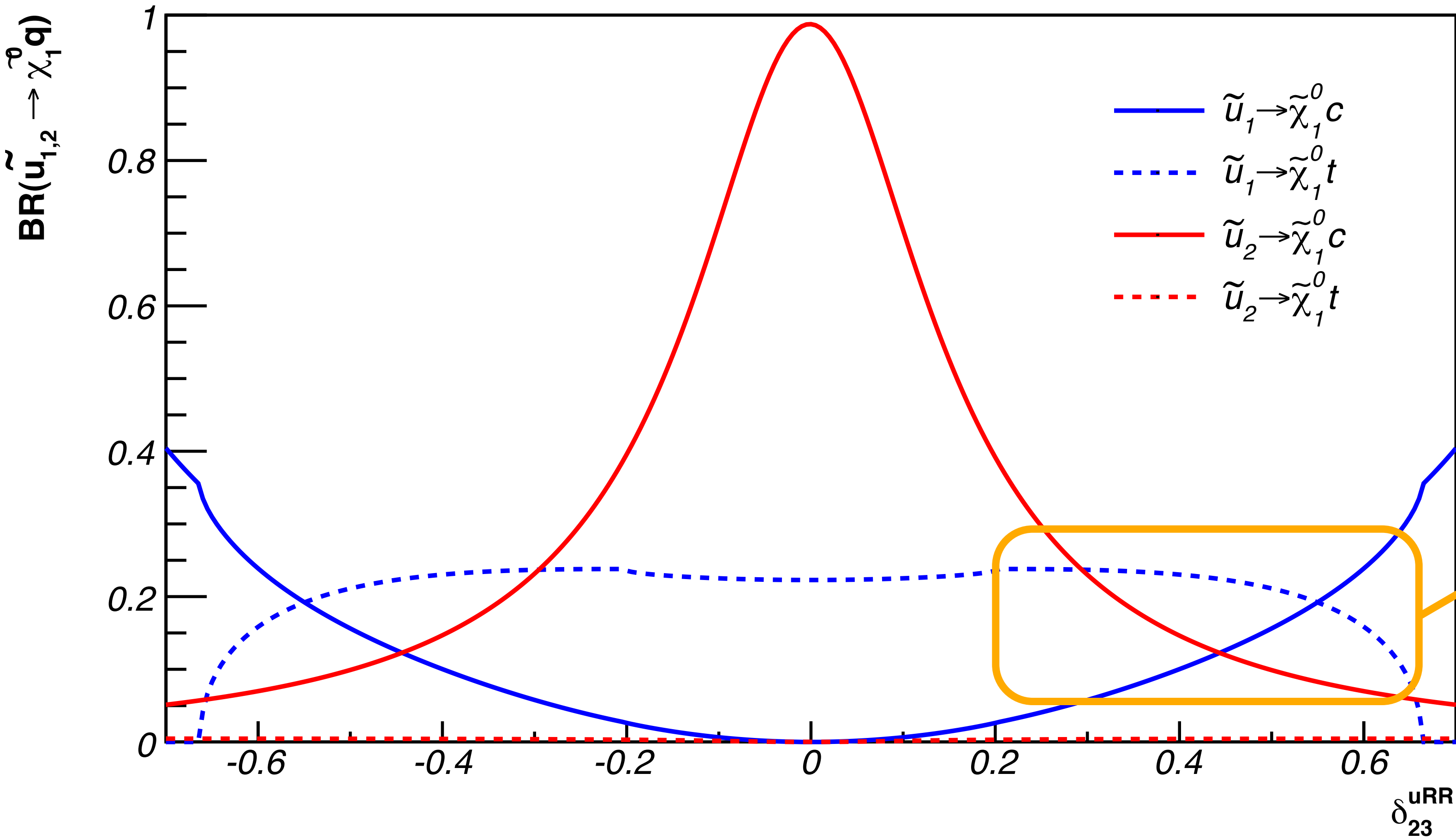

Branching ratios into different generations simultaneously sizeable

Potentially large branching ratios lead to interesting production signatures at colliders

$$
\boxed{\begin{aligned} p\,p &\;\to\; \tilde{u}_{1,2}\,\tilde{u}^*_{1,2} \;\to\; c\,\bar{t}\;\tilde{\chi}^0_1\,\tilde{\chi}^0_1 \\ p\,p &\;\to\; \tilde{u}_{1,2}\,\tilde{u}_{1,2} \;\to\; t\,t\;\tilde{\chi}^0_1\,\tilde{\chi}^0_1 \end{aligned}}
$$

Numerical evaluation of cross-sections using Whizard/O'Mega 1.93 [Kilian, Reuter, Ohl 2001-2010], FeynArts/FormCalc [Hahn 2000-2010] and CTEQ6L parton density functions [Pumplin *et al.* 2002]

Production cross-sections and LHC signatures

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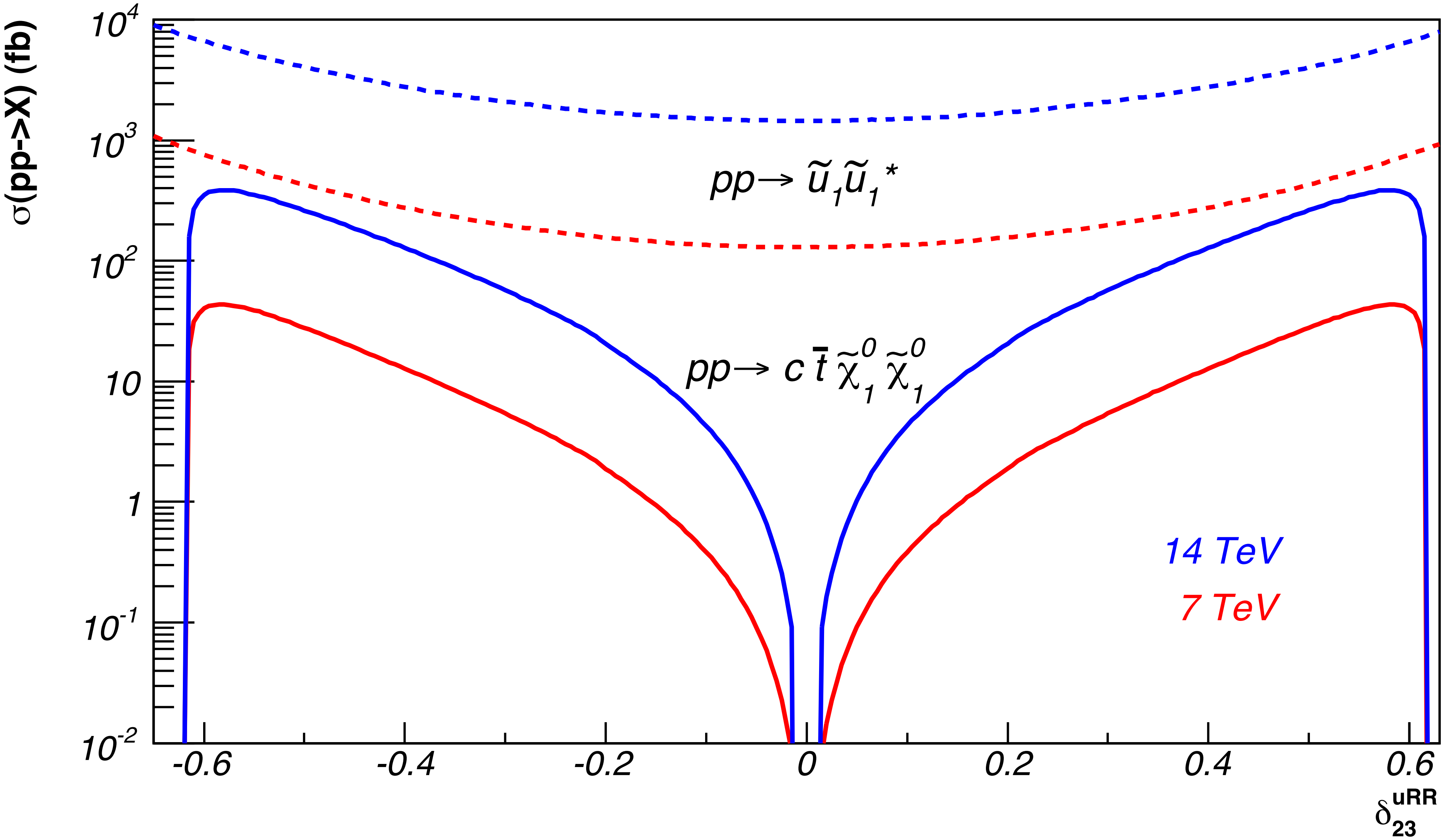
Associated production of charm and top (plus missing energy) provides interesting signature



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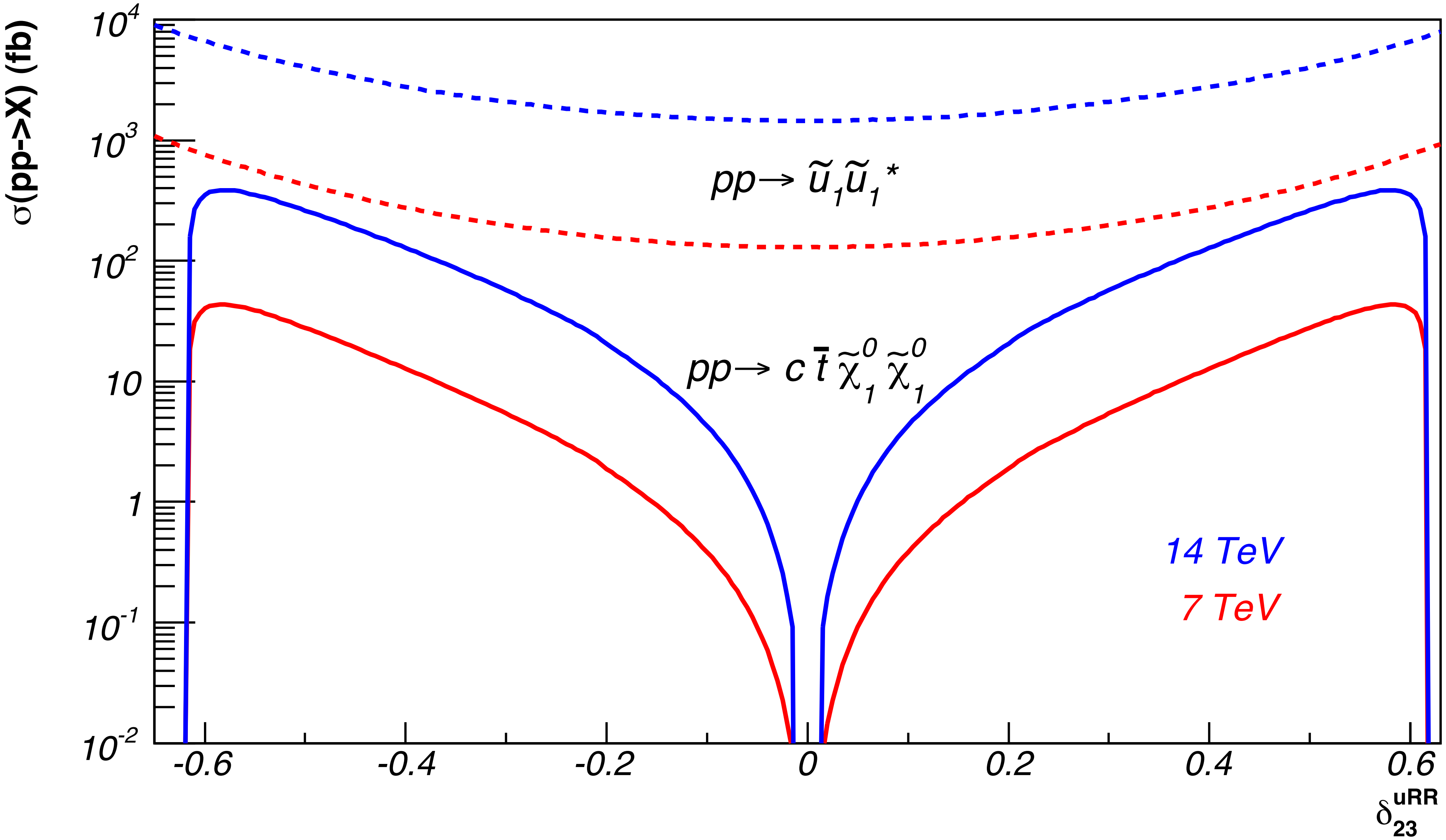

Expect up to 10^4 events for "jet + top + E_T^{miss}" production at E_{cm}=14 TeV and L_{int}=100 fb^{-1}

Event rate for top-top production found to be rather small ($\sigma \leq 0.1$ fb at E_{cm}=14 TeV)

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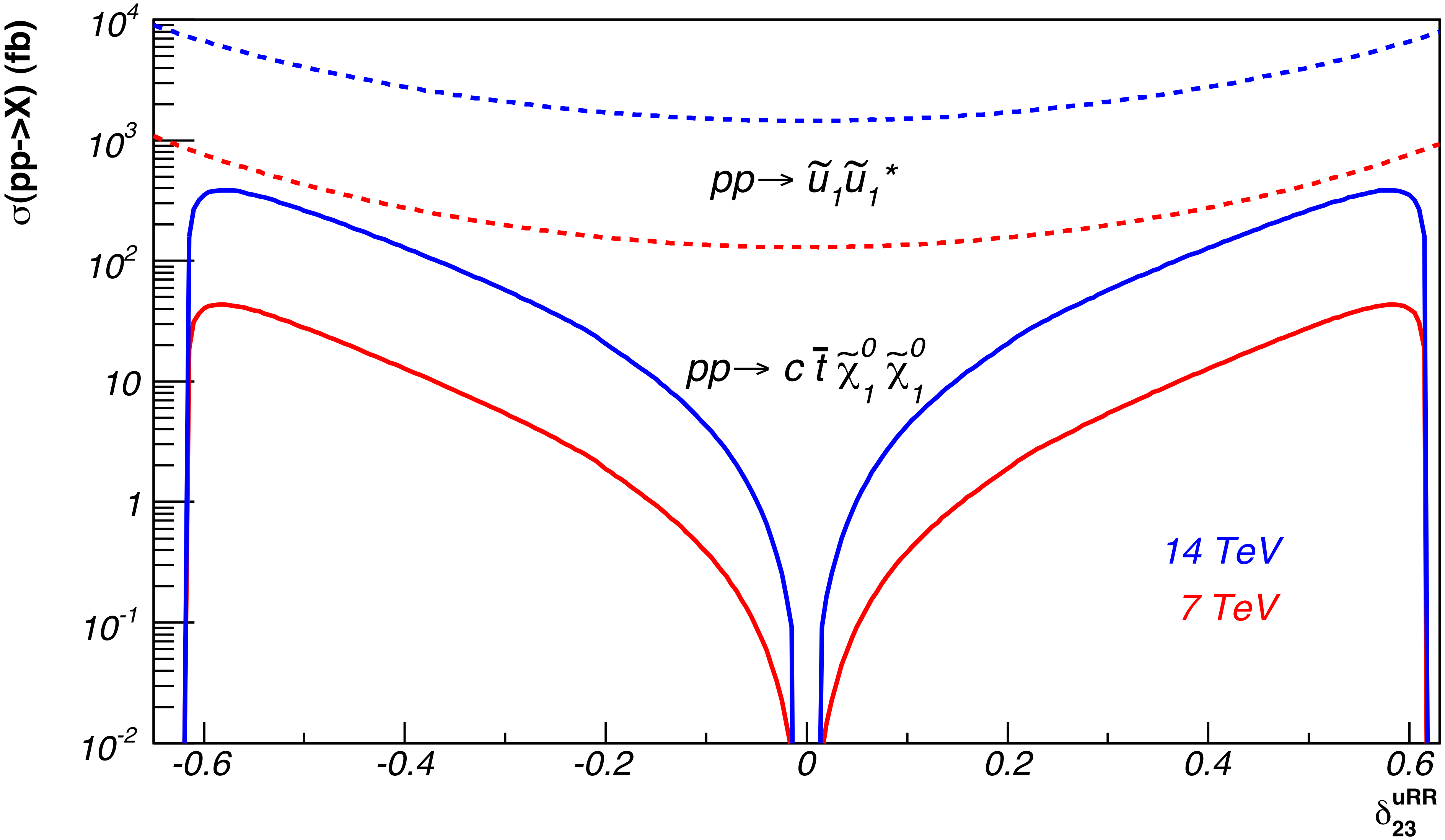

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Loop corrections for dominant (flavour-conserving) channels increase cross-section by about 30%

[Beenakker, Höpker, Spira, Zerwas 1997]

Discrimination and background

[Bartl, Eberl, Herrmann, Hidaka, Majerotto, Porod (2010)]

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Identification of top-quarks crucial: $t \to bW^+ \to b\ q\bar{q}$ [Hisano *et al.* (2002+2003)]

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Gluino production channel found to be numerically small in scenarios under consideration

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Standard Model top quark production can be distinguished through jets and/or missing energy

Bosonic squark decays

[Bruhnke, Herrmann, Porod (2010)]

Within MFV, only one (two) squark(s) can decay into a given squark plus a neutral (charged) boson

$$\tilde{u}_1 = \tilde{t}_1 \qquad \tilde{u}_6 = \tilde{t}_2$$
$$\tilde{d}_1 = \tilde{b}_1 \qquad \tilde{d}_2 = \tilde{b}_2$$

$$\boxed{\begin{array}{ccc} \tilde{u}_6 & \longrightarrow & \tilde{u}_1 Z^0/h^0 \\ \tilde{d}_1 & \longrightarrow & \tilde{u}_1 W^- \\ \tilde{d}_2 & \longrightarrow & \tilde{u}_1 W^- \end{array}}$$

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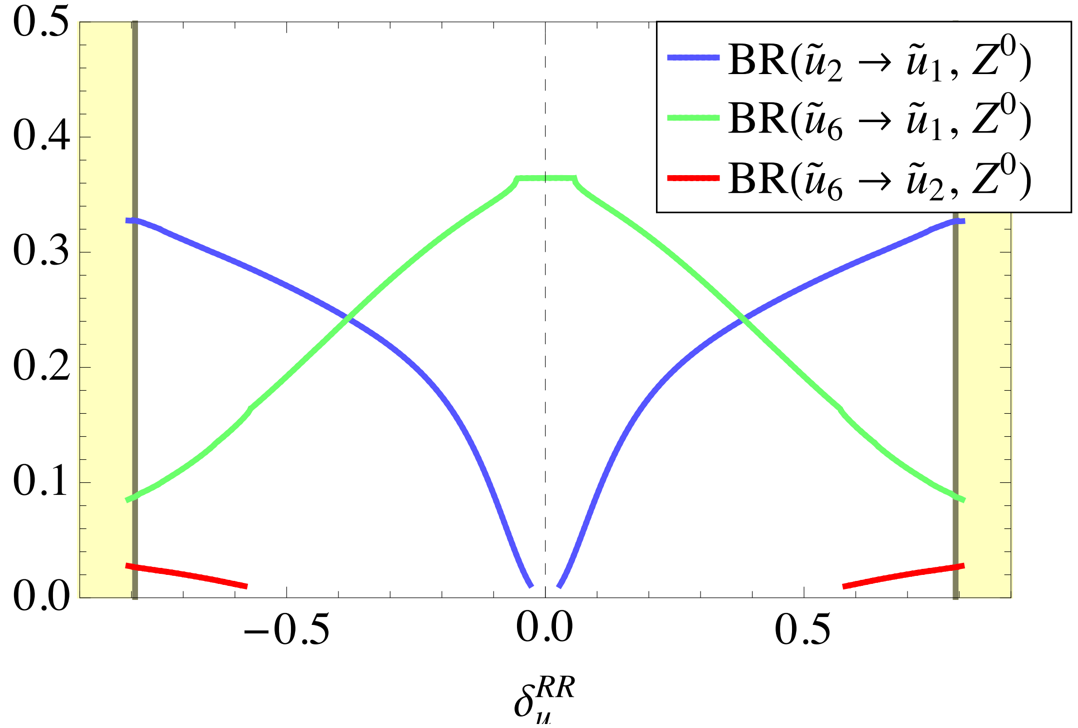
Considering NMFV, additional decay channels with the same final state can be opened
due to the modified phase space and squark flavour contents



Bosonic squark decays

[Bruhnke, Herrmann, Porod (2010)]

Within MFV, only one (two) squark(s) can decay into a given squark plus a neutral (charged) boson

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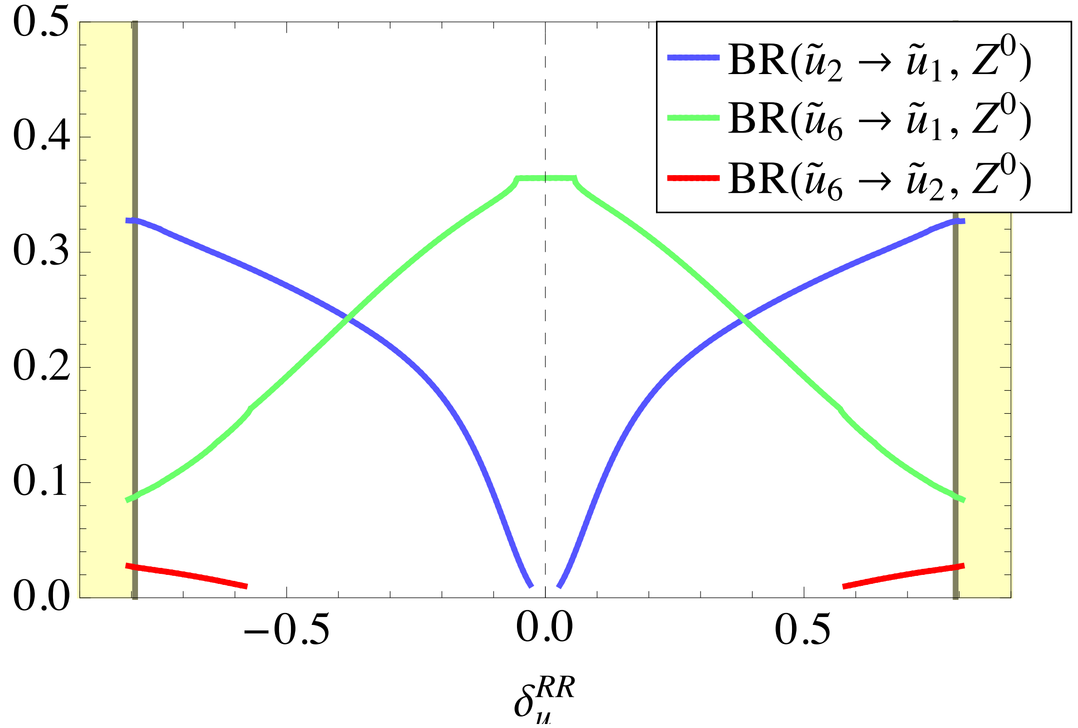

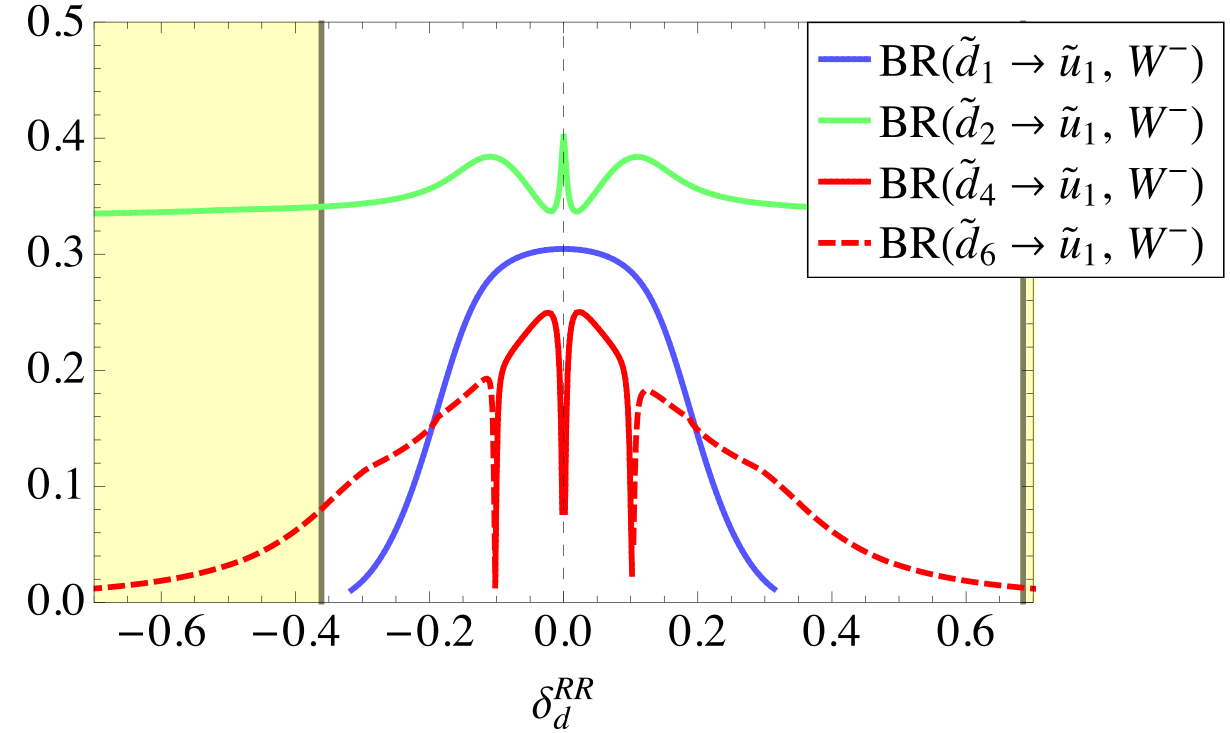

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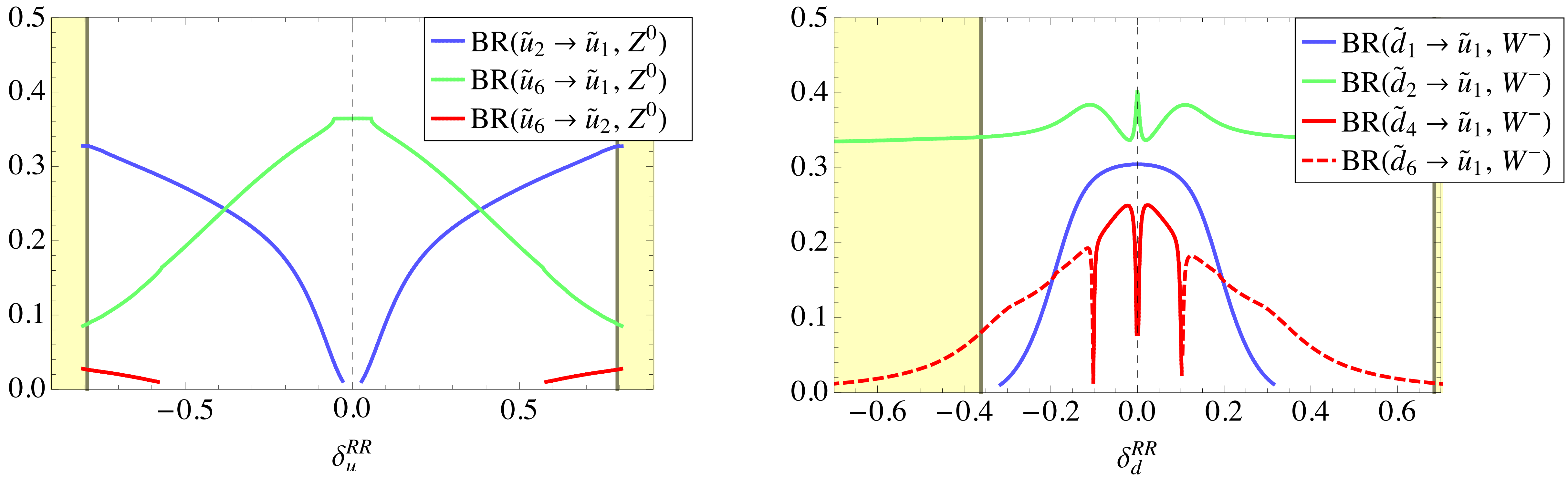

Characteristical signatures found in wide ranges of NMFV-MSSM parameter space

$\tilde{q}_i \longrightarrow \tilde{q}_j Z^0/H^0$ for given i and (at least) two different values of j (or vice-versa)

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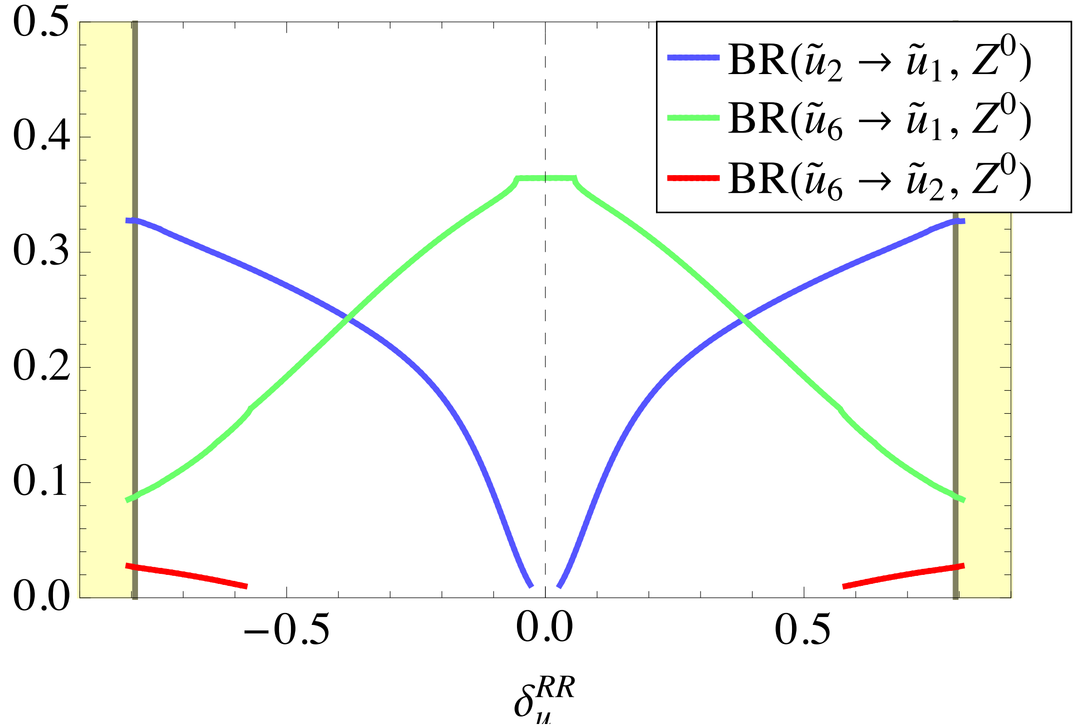

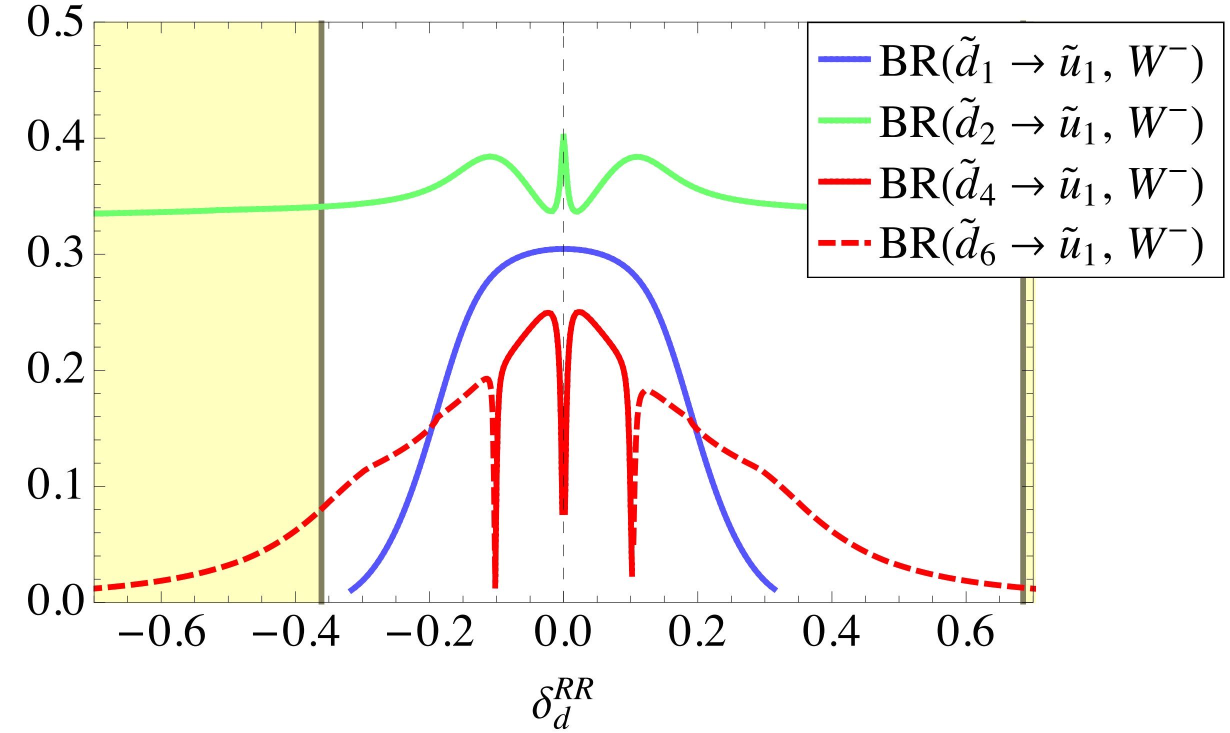

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If squarks are observed at LHC, bosonic modes can provide complementary information w.r.t. fermionic decays (which will be helpful for reconstruction of couplings and mass parameters)

Variation of two QFV parameters

[Bruhnke, Herrmann, Porod (2010)]

Simultaneous variation of more than one QFV-parameters extends or amplifies signal patterns

Each of the seven QFV-parameters has specific impact on squark generation mixing
Simultaneous variation superimposes the corresponding effects

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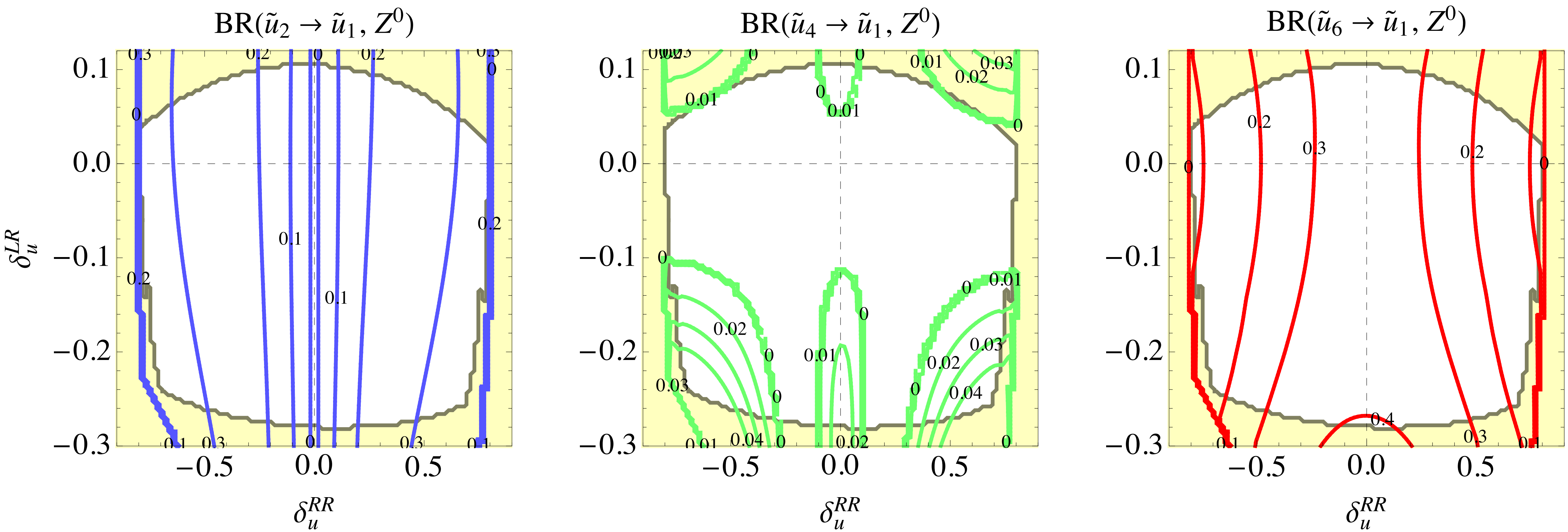

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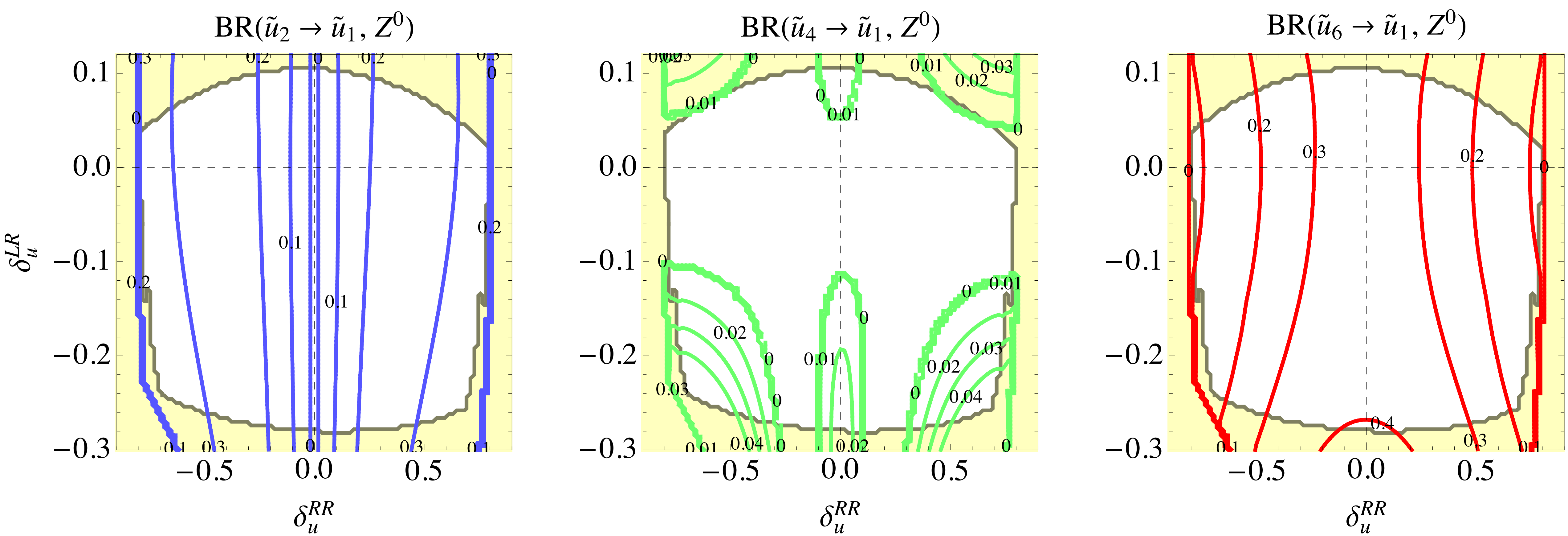

Studies of other scenarios (e.g. SPS1b, ...) show qualitatively similar signatures
However, differences in the mass spectrum lead to quantitatively different results

Conclusion and Outlook

Flavour-violating terms can *a priori* be present in soft-breaking terms at the weak scale

Possibly not related to CKM-matrix (non-minimal flavour violation)

Important impact on phenomenology (e.g. masses, flavour contents, ...)

Observation of characteristic signatures at colliders might rule out hypothesis of MFV

New decay channels of squarks are possible in NMFV

Fermionic decays may lead to sizeable event rates at the LHC [Bruhnke, Herrmann, Porod (2010)]

$$\boxed{p\,p \;\rightarrow\; \tilde{u}_{1,2}\,\tilde{u}^*_{1,2} \;\rightarrow\; c\,\bar{t}\;\tilde{\chi}^0_1\,\tilde{\chi}^0_1}$$

Bosonic decays may give additional information (once squarks are observed)
[Bartl, Eberl, Herrmann, Hidaka, Majerotto, Porod (2010)]

$$\boxed{\tilde{q}_i \rightarrow \tilde{q}_j Z^0/H^0 \qquad\qquad \tilde{q}_i \rightarrow \tilde{q}'_j W^\pm/H^\pm}$$

The obtained results are a clear call for a detailed Monte Carlo study

Explore feasibility in current collider experiments

Determine regions of parameter space where signals would be observable
("5-sigma-discovery-region")