Flavour violating gluino decays at the LHC

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in collaboration with
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Quark Flavour Violation in the MSSM

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Minimal flavour violation

- 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

- new sources of flavour violation can appear within SUSY-GUTs
- e.g. gravity-mediation, messenger-matter mixing, ...
- corresponding flavour-violating entries not related to CKM-matrix
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Experimental distinction between MFV and NMFV possible...?

Interesting because of direct connection to the Supersymmetry breaking mechanism!

Quark Flavour Violation in the MSSM

The flavour-violating terms are incorporated in the mass matrices at the electroweak scale and can lead to intesting effects at colliders (and also in dark matter annihilation, see Quentin's talk)

$$\mathcal{M}^2_{\tilde{u}} = \begin{pmatrix} \mathcal{M}^2_{uLL} & \left(\mathcal{M}^2_{uRL}\right)^\dagger \\ \mathcal{M}^2_{uRL} & \mathcal{M}^2_{uRR} \end{pmatrix}$$

$$\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_2}{\sqrt{2}}A_{U,\alpha\beta} - m_{u,\alpha}\frac{\mu^*}{\tan\beta}\delta_{\alpha\beta}
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Dimensionless (and scenario-independent) parametrization of flavour violating entries

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Rotation matrices reflect flavour decomposition and influence couplings of squarks

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Focus in this talk on additional mixing between $\tilde{c}_R$ and $\tilde{t}_R$ induced by the parameter δ^{uRR}_{23}

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Constraints on the MSSM parameter space

Mass limits from collider searches [PDG 2008-2010]

Consider only additional flavour-mixing between second and third generation squarks due to strong constraints on mixing involving the first generation from precision measurements related to B- and K-mesons [Hagelin *et al.* 1994; Gabbiani *et al.* 1996; Ciuchini *et al.* 2007]

Electroweak precision and low-energy measurements [PDG 2008-2010; HFAG 2008-2010]

$$\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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Cosmological implications from cold dark matter (neutralino) relic density [WMAP 2010]

$$0.1018 < \Omega_{\mathrm{CDM}} h^2 < 0.1228$$

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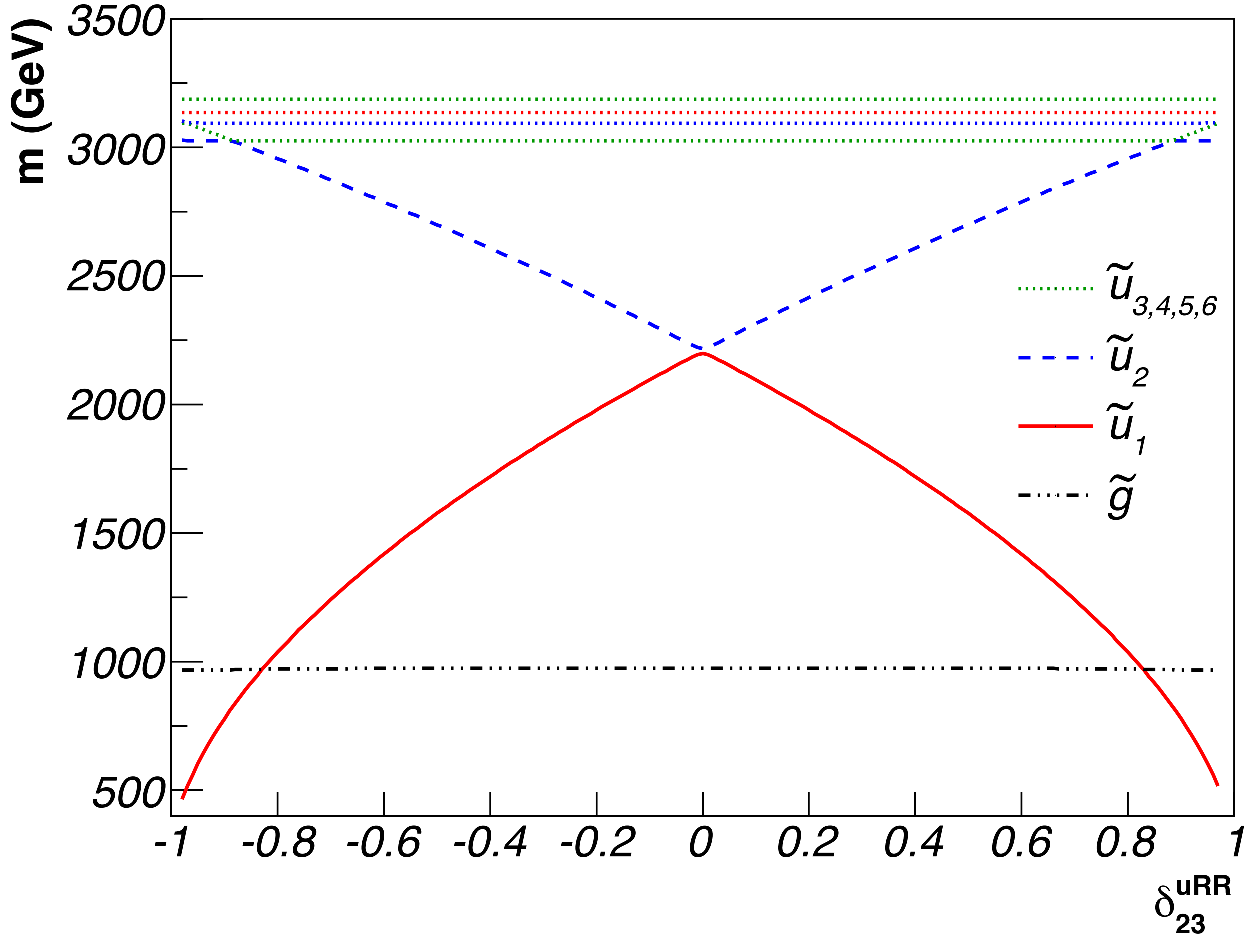
All scenarios discussed in the following are in agreement with these constraints

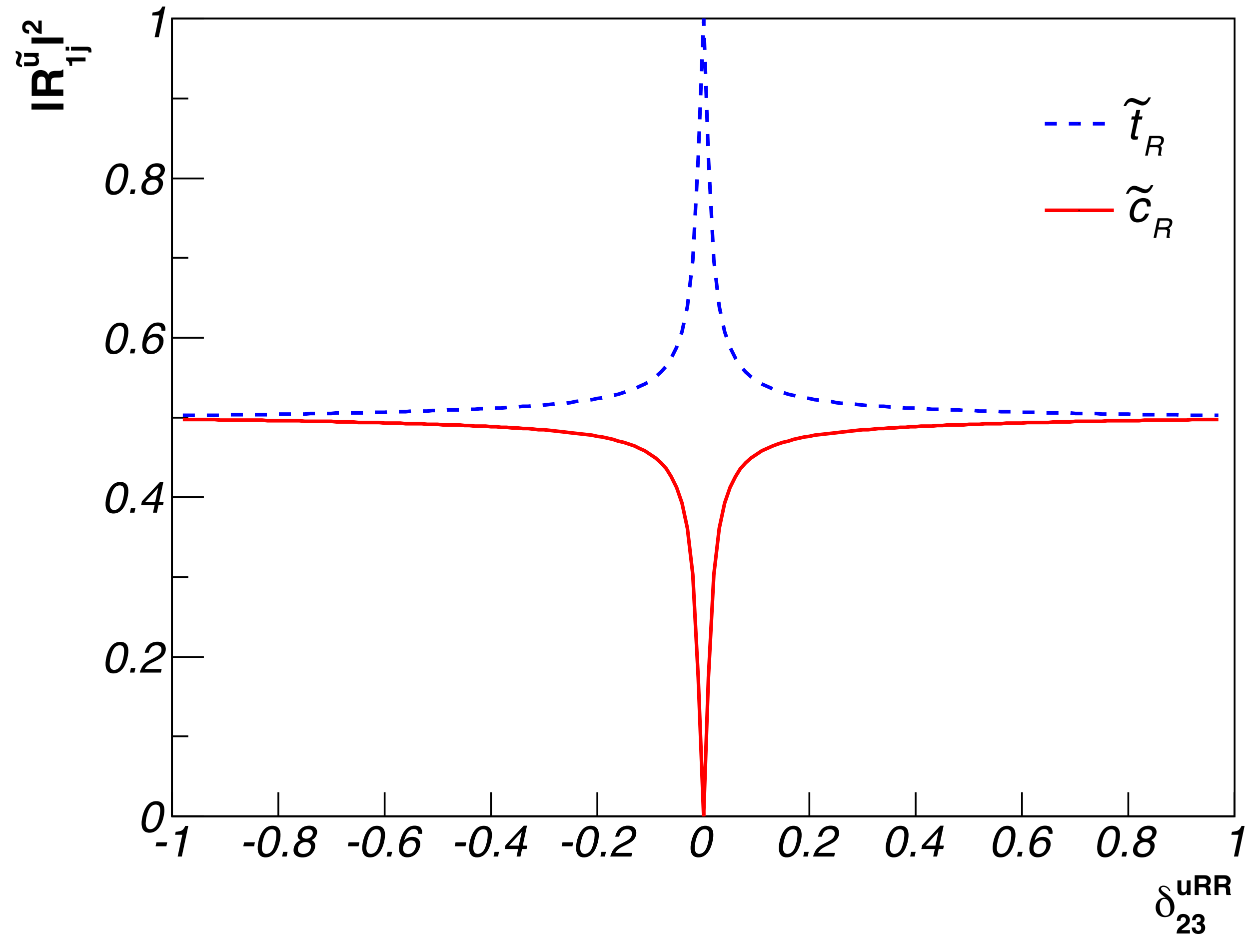
Squark masses and flavour decomposition

Introduce non-diagonal elements in squark mass matrix at the electro-weak scale (Q=1 TeV)

Spectrum calculation and evaluation of constraints using SPheno 3.0 [Porod 2003-2011]

Increased mass splitting and altered flavour decomposition w.r.t. minimal flavour violation





$$M^2_{\tilde{Q}} = \mathrm{diag}\left(3150^2, 3100^2, 3050^2\right)\ \mathrm{GeV}^2 \qquad M_1 = 139\ \mathrm{GeV}, M_2 = 264\ \mathrm{GeV}$$

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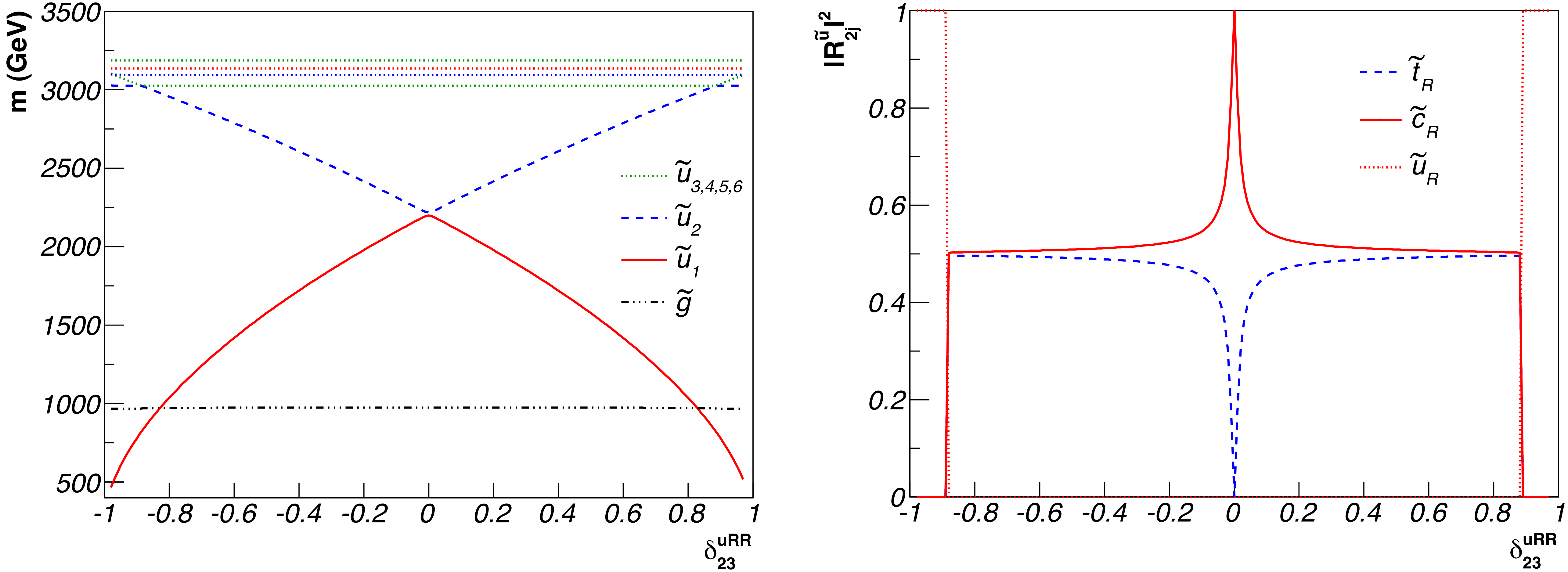

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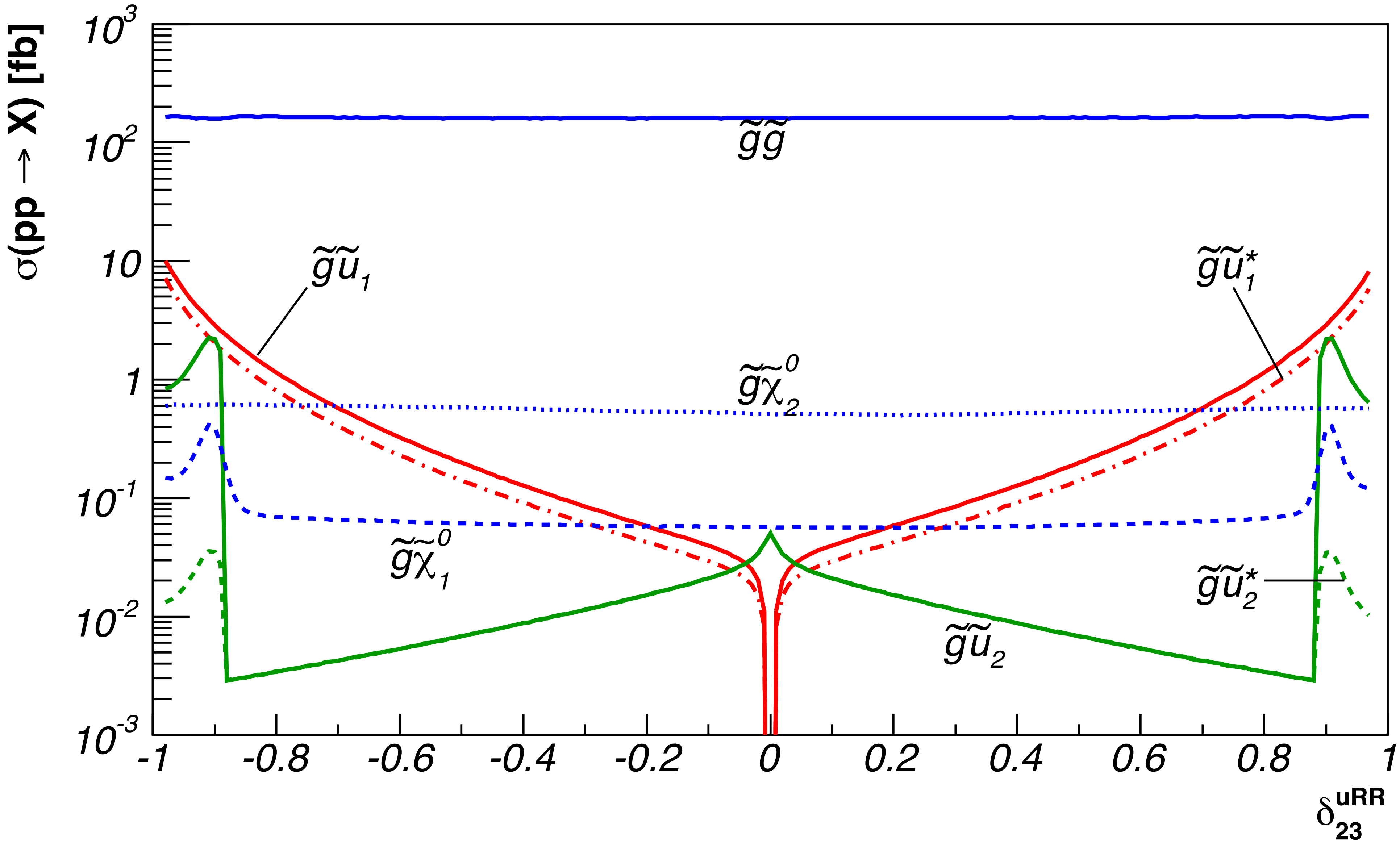
Gluino production at the LHC

Fuks, Herrmann, Klasen (2011); Bartl, Eberl, Ginina, Herrmann, Hidaka, Majerotto, Porod (2011)

Dominant production mode (gluon exchange) is flavour conserving

Subdominant channels (squark exchange) and decay modes depend on flavour violating elements



$$m_{\tilde{g}} = 972 \text{ GeV}$$
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$$\sqrt{s} = 14 \text{ TeV}$$

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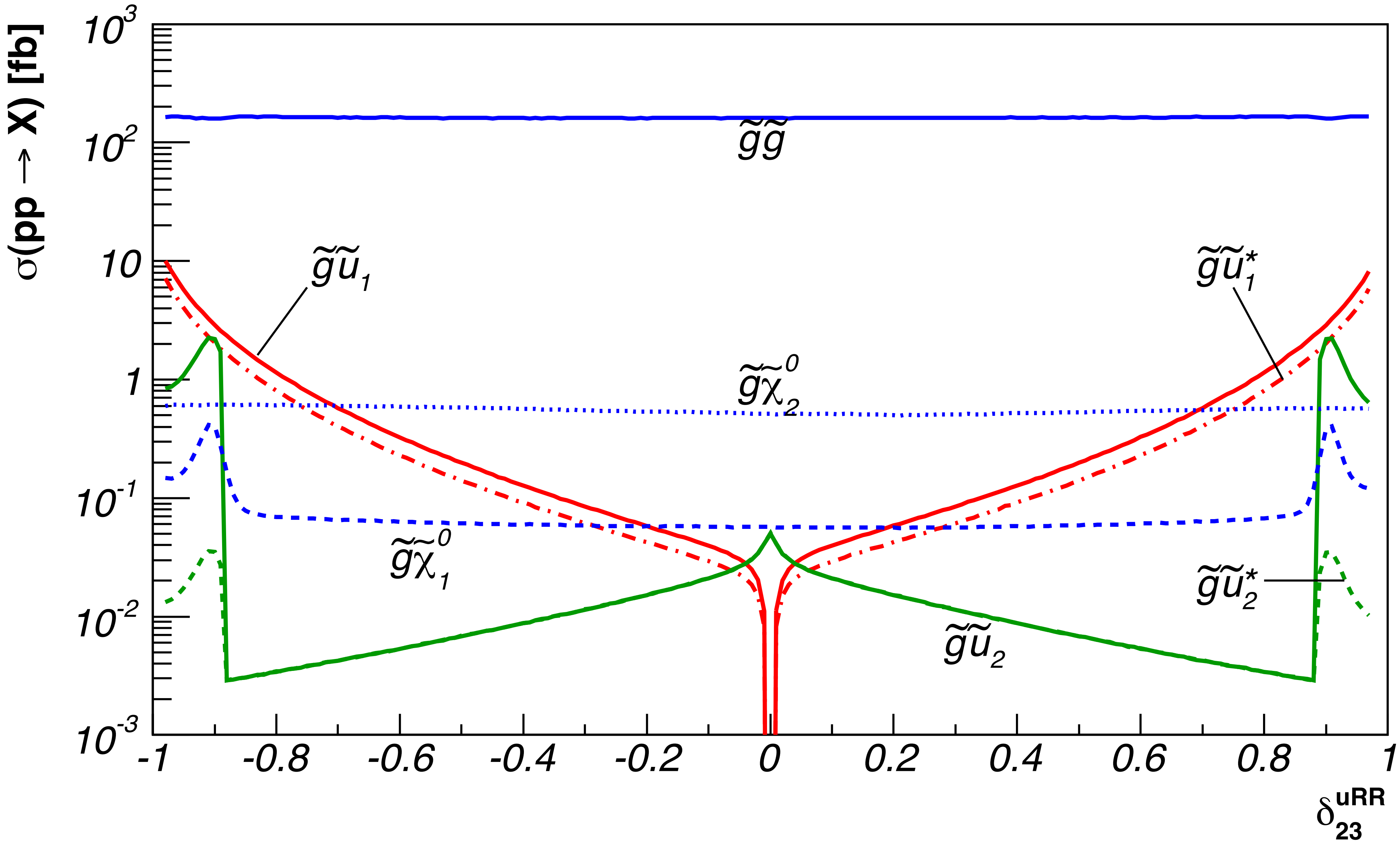

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$m_{\tilde{g}} > m_{\tilde{q}_i}$

Gluino two-body decays...

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Gluino three-body decays...

Gluino two-body decays (including subsequent squark decays)

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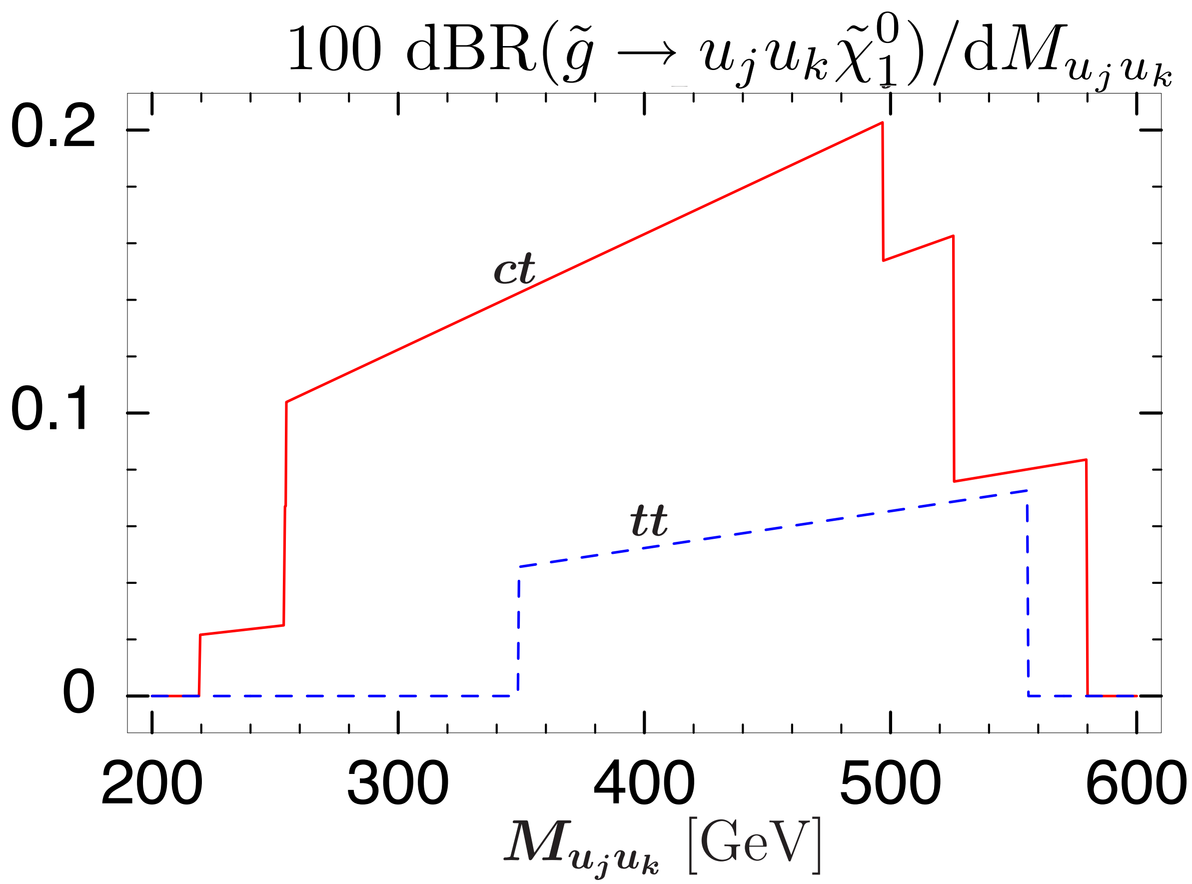

$$m_{\tilde{g}} = 800\ \mathrm{GeV}, \quad \delta^{uRR}_{23} = 0.144$$
$$m_{\tilde{u}_1} = 558\ \mathrm{GeV}, \quad m_{\tilde{u}_2} = 642\ \mathrm{GeV}$$

$$\mathrm{BR}(\tilde{g} \to q\tilde{q}' \to c\bar{t}\tilde{\chi}^0_1) = 46\%$$
$$\mathrm{BR}(\tilde{g} \to q\tilde{q}' \to c\bar{c}\tilde{\chi}^0_1) = 38\%$$
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Invariant mass distribution of produced quark pairs from gluino (and subsequent squark) decay

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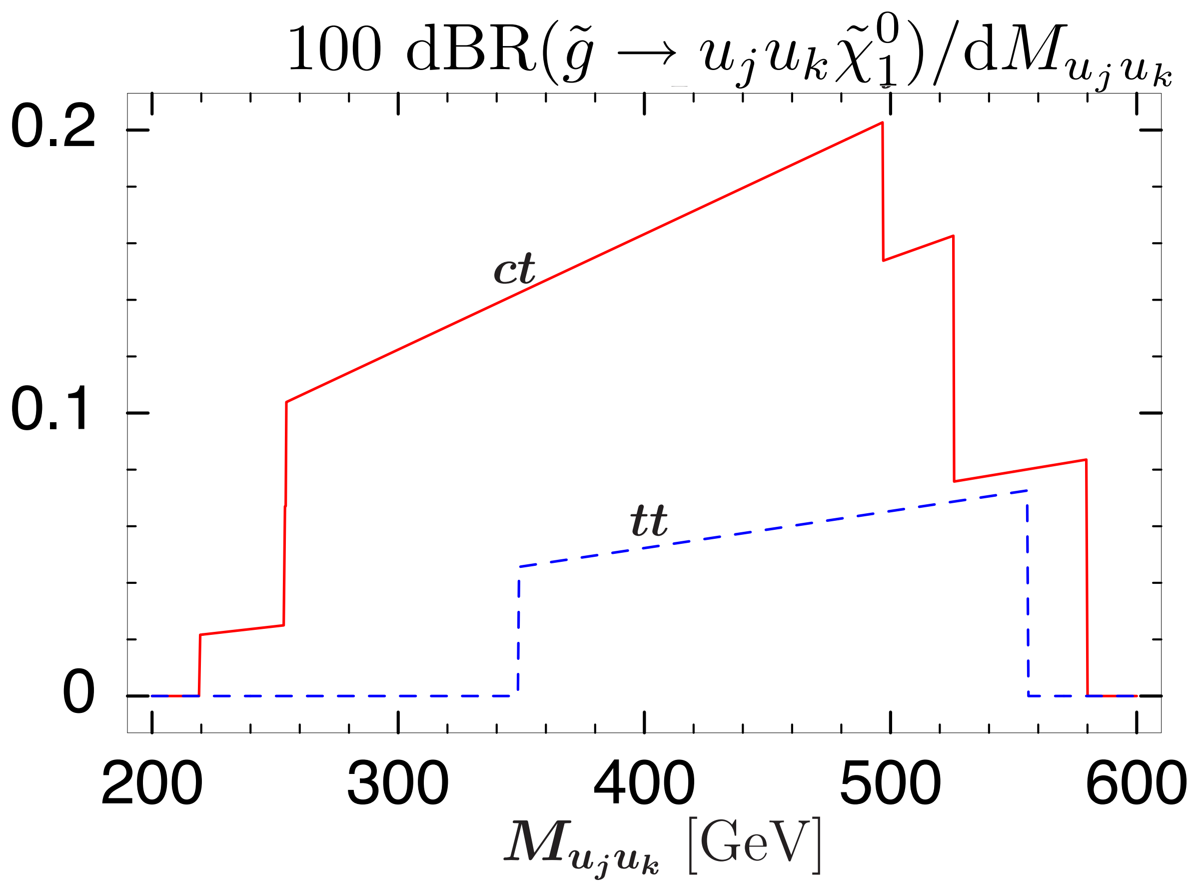

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Invariant mass distribution of produced quark pairs from gluino (and subsequent squark) decay

No additional edge structure for top-top final state (only $\tilde{u}_1$ can mediate this channel)

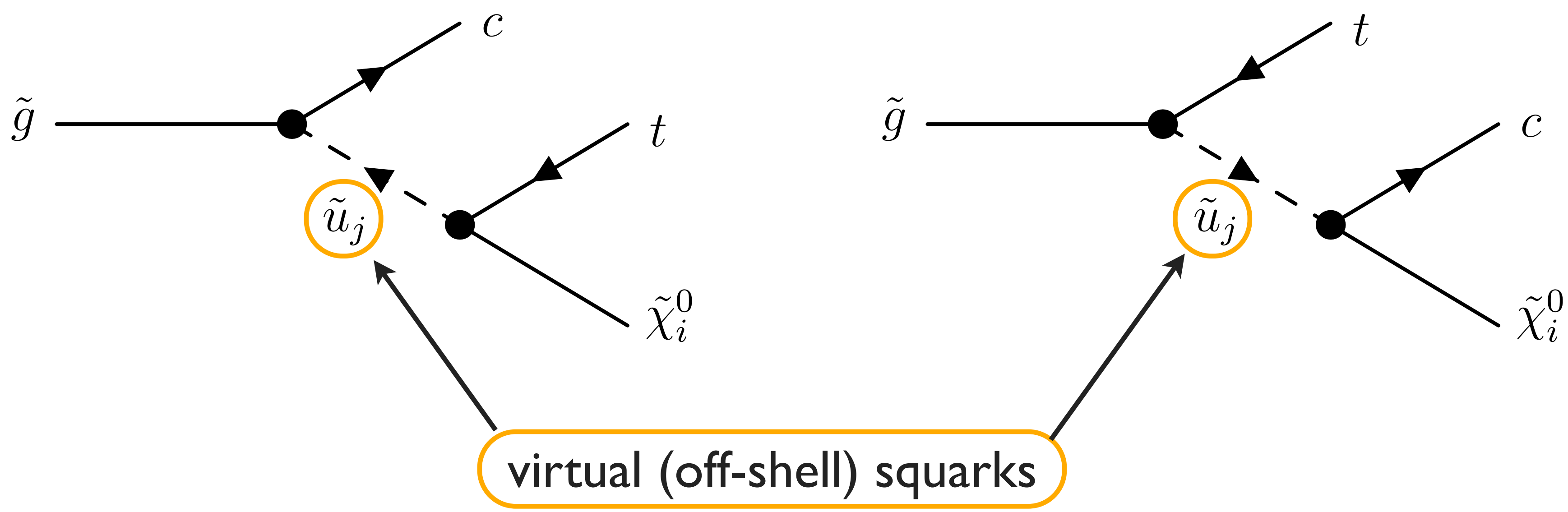
Additional (well seperated) edge structure for top-charm corresponding to kinematical endpoints

$$\tilde{g} \to t\tilde{u}_1^* \to c\bar{t}\tilde{\chi}_1^0 \qquad M_{tc} = [253, 526] \text{ GeV}$$
$$\tilde{g} \to c\tilde{u}_1^* \to c\bar{t}\tilde{\chi}_1^0 \qquad M_{tc} = [254, 580] \text{ GeV}$$
$$\tilde{g} \to c\tilde{u}_2^* \to c\bar{t}\tilde{\chi}_1^0 \qquad M_{tc} = [219, 497] \text{ GeV}$$

Gluino three-body decays

Bartl, Eberl, Ginina, Herrmann, Hidaka, Majerotto, Porod (2011)

If the gluino is heavier than all squarks, three-body decays may lead to flavour-violating signatures



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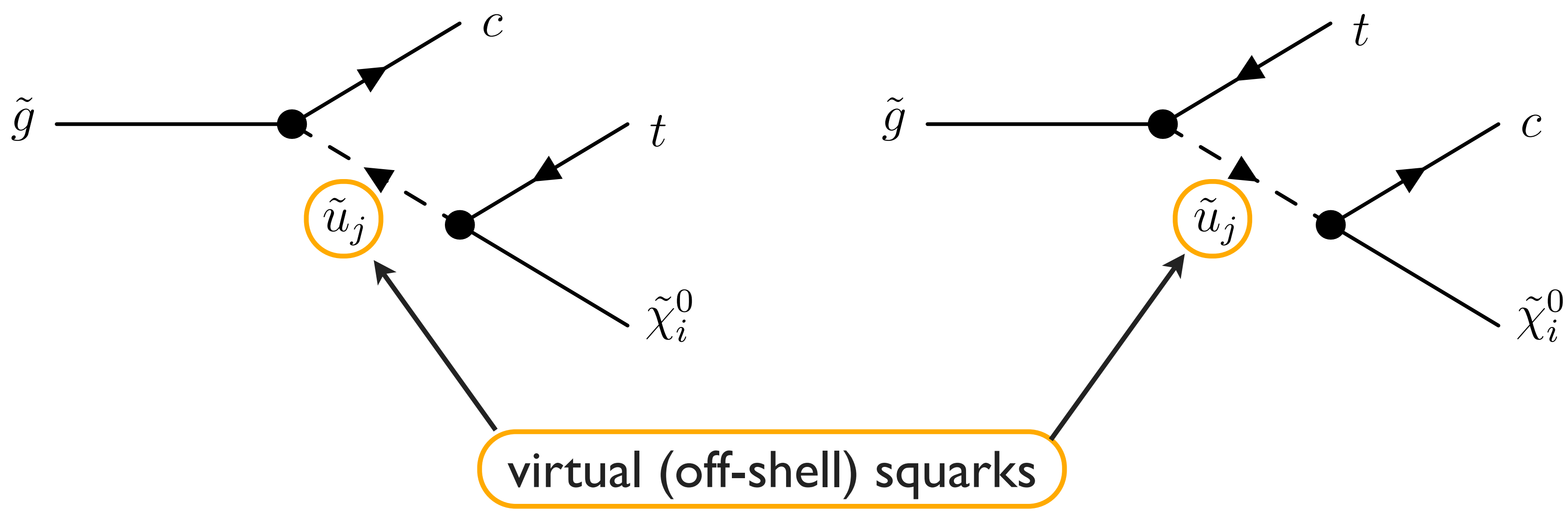

However, strong destructive interference between ũ₁ and ũ₂ contributions if masses are similar

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

$$\Gamma_{\tilde{g}\to c\bar{t}\tilde{\chi}_1^0} \;\sim\; \underbrace{(\cos\theta\sin\theta)}_{\tilde{u}_1} + \underbrace{(-\cos\theta\sin\theta)}_{\tilde{u}_2} \;\sim\; 0$$

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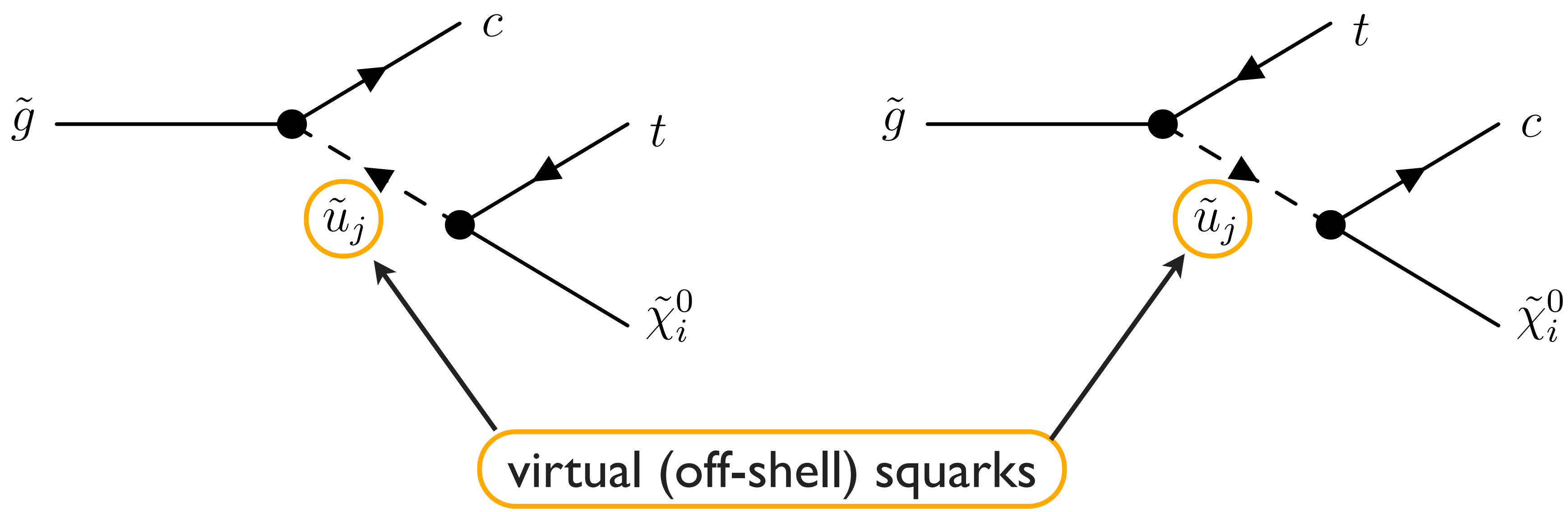

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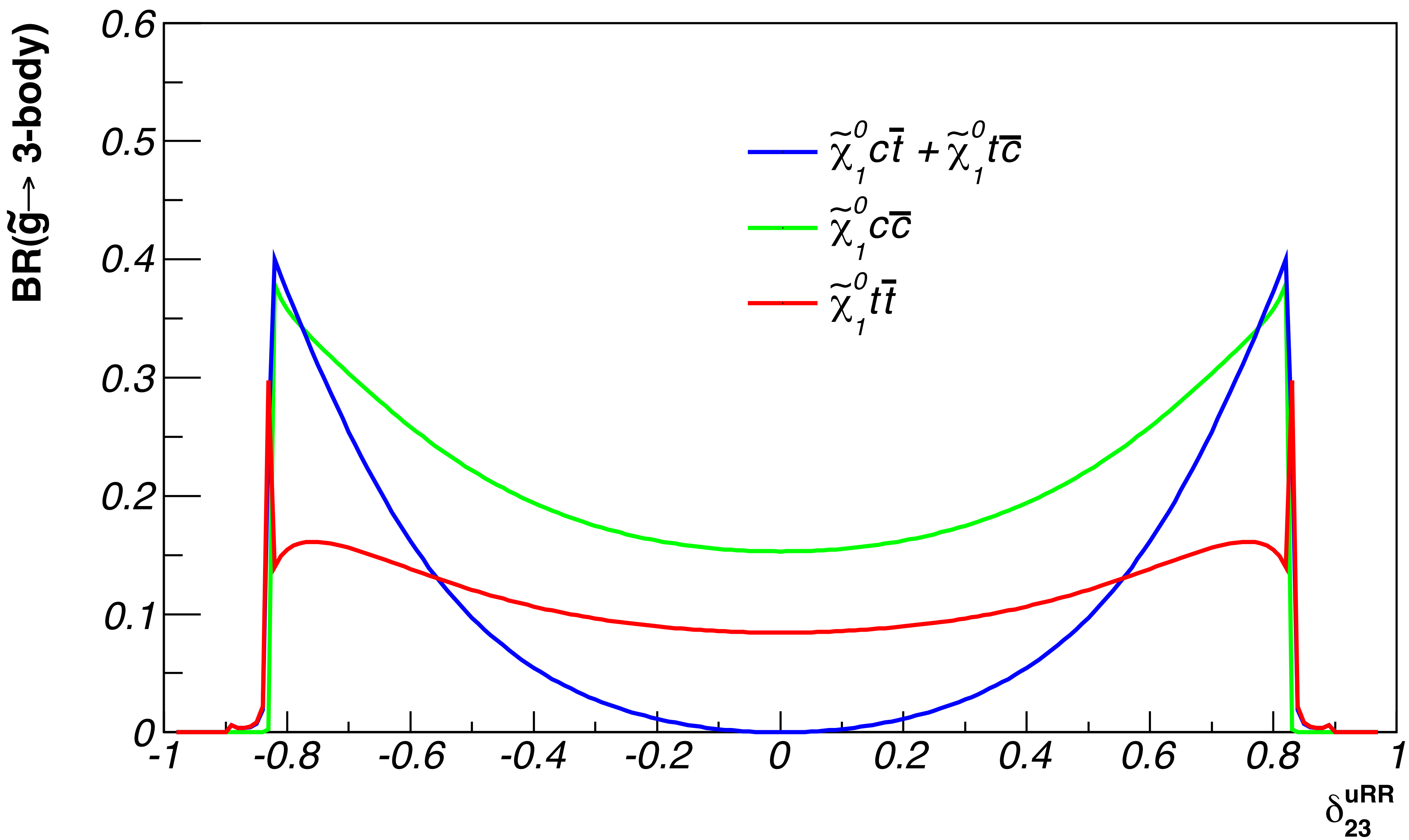
Sizeable flavour violation effects only for large mass splitting, i.e. large off-diagonal elements

However, such configurations are close to exclusion limits or two-body decay regime

Gluino three-body decays: Branching ratios

Bartl, Eberl, Ginina, Herrmann, Hidaka, Majerotto, Porod (2011)

Sizeable flavour violation effects only for large mass splitting (where $m_{\tilde{g}} \lesssim m_{\tilde{u}_1}$)



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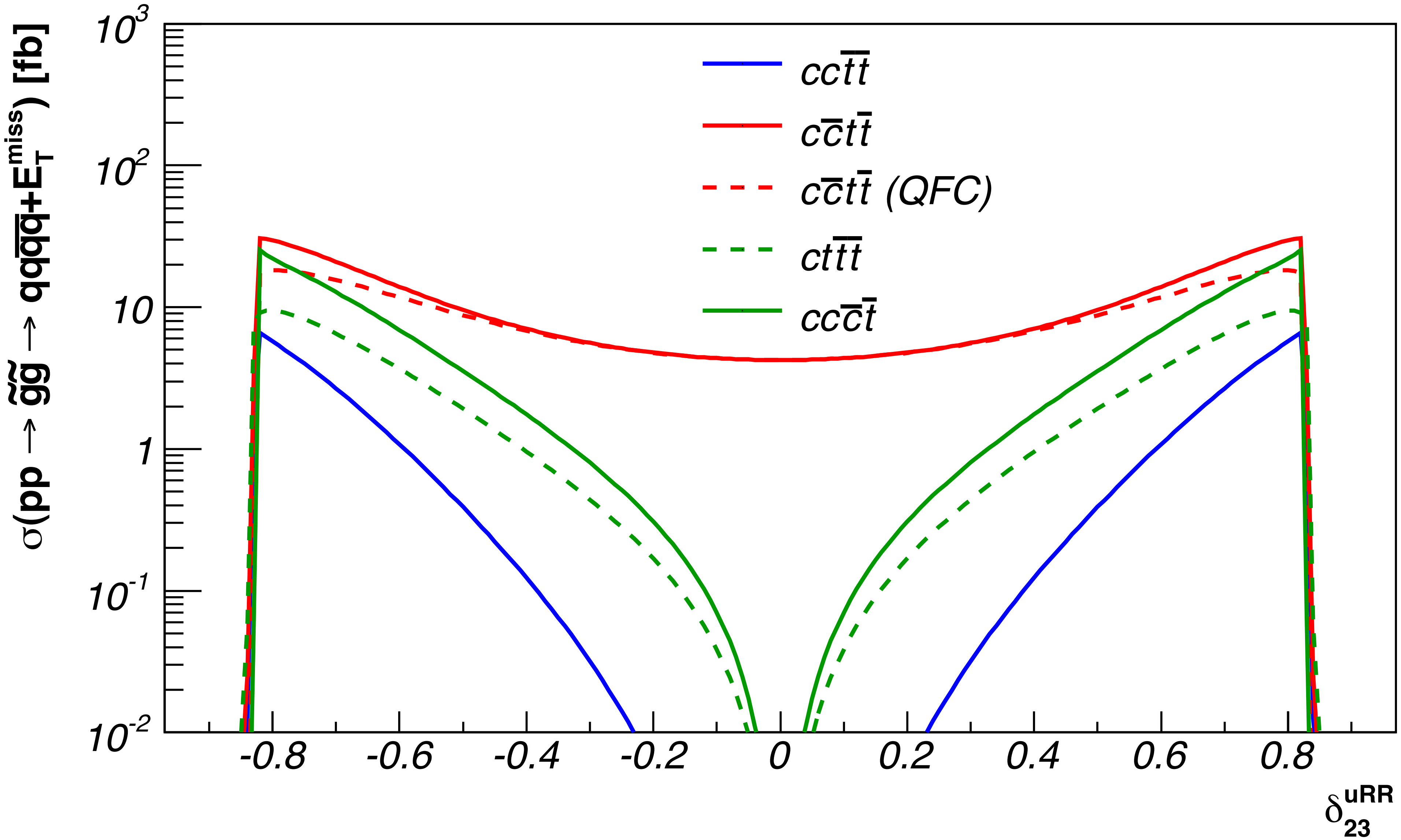
For $m_{\tilde{u}_1} < m_{\tilde{g}}$, two-body decays become dominant ($\delta_{23}^{uRR} \gtrsim 0.8$, not shown)

Scenarios with $\mathrm{BR}(\tilde{g} \to c\bar{t}\tilde{\chi}_1^0) \gtrsim 50\%$ (or also $\mathrm{BR}(\tilde{g} \to s\bar{b}\tilde{\chi}_1^0) \gtrsim 50\%$) can be found in the MSSM

Gluino three-body decays: Signal estimation

Bartl, Eberl, Ginina, Herrmann, Hidaka, Majerotto, Porod (2011)

Estimate up to around 1000 events at LHC for E_{cm}=14 TeV and L_{int}=100 fb^{-1}



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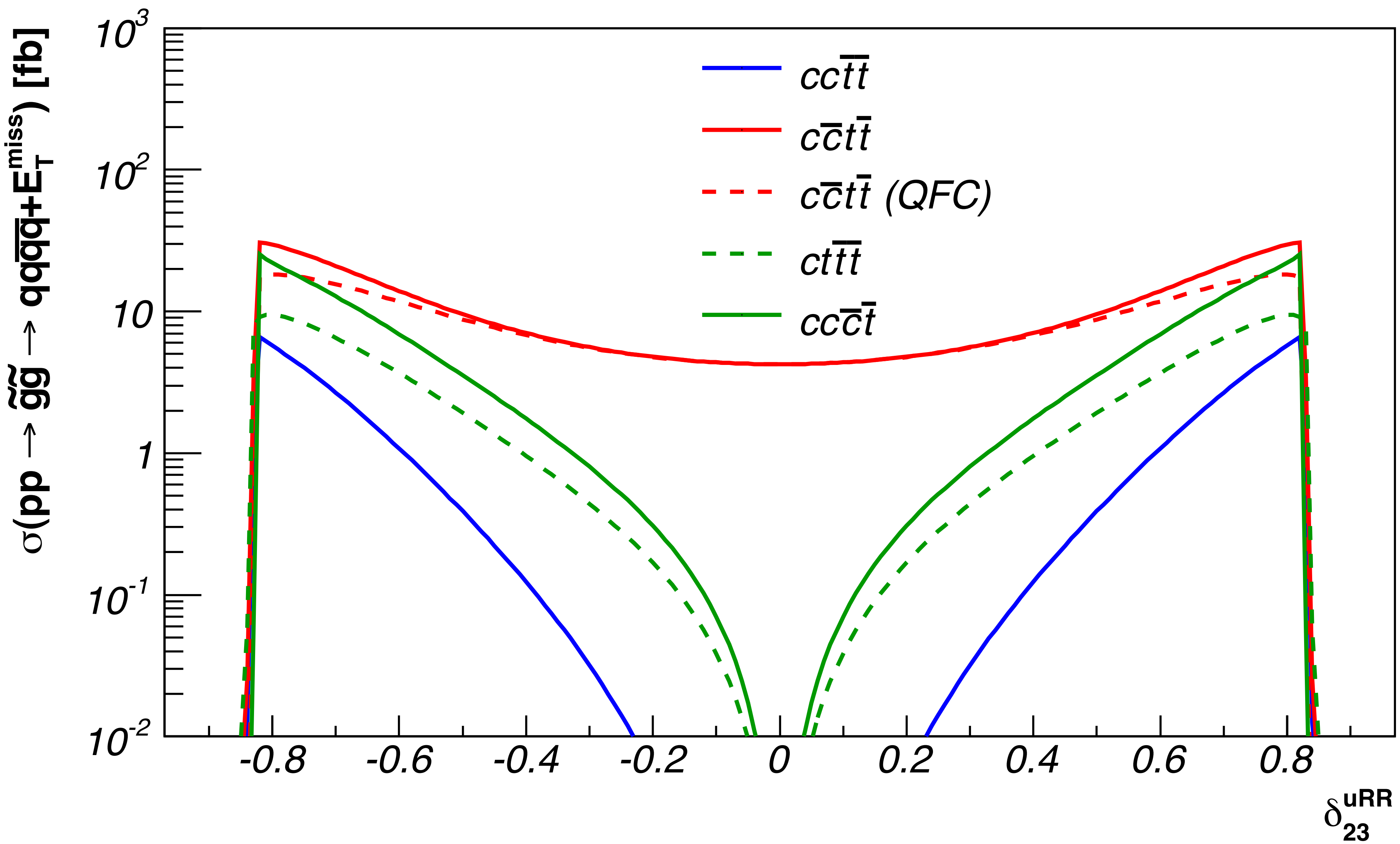

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Higher-order contributions to gluino-pair production increase signal by almost 100 percent

[Beenakker, Höpker, Spira, Zerwas 1996]

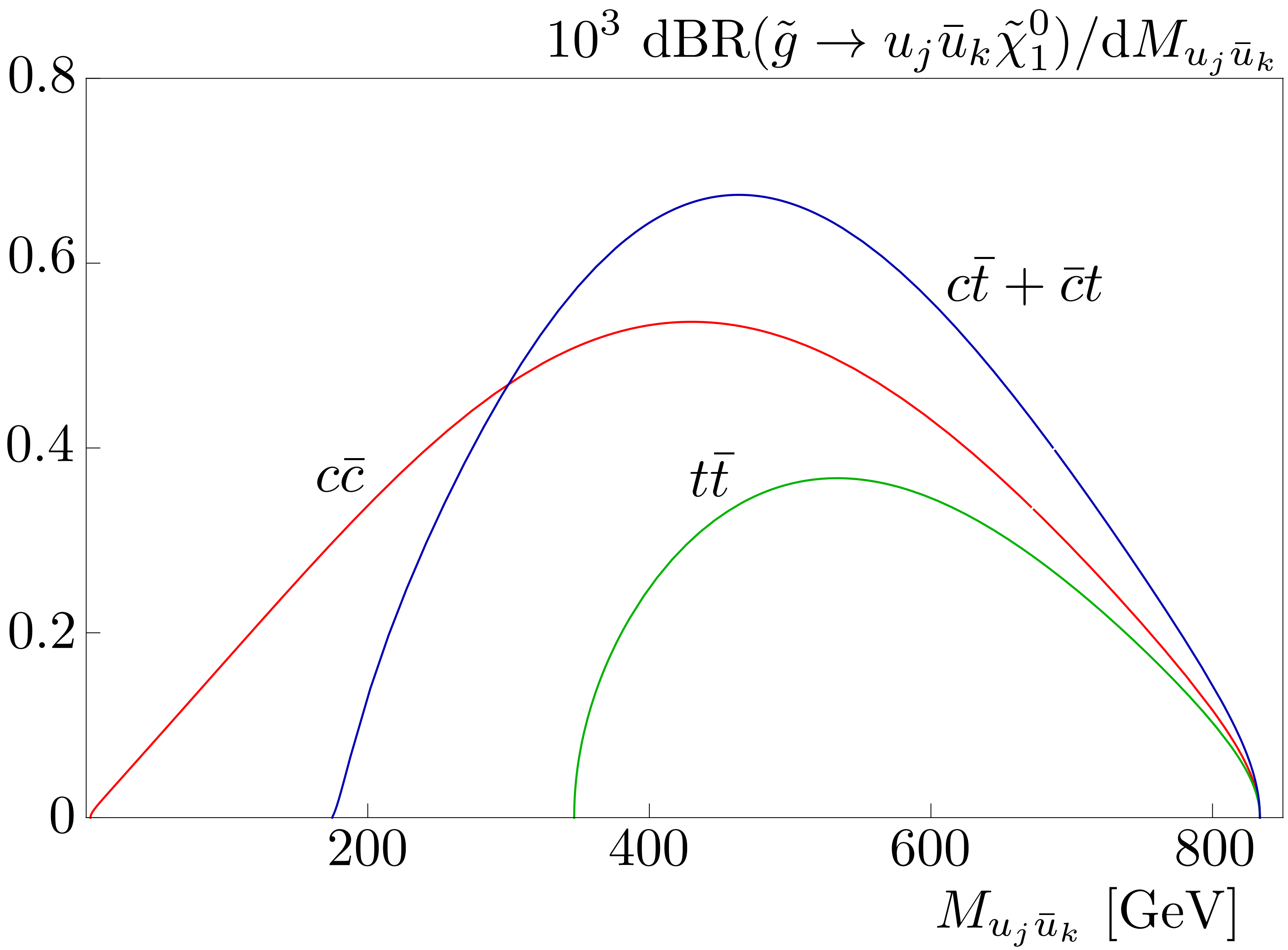
Top-identification necessary and efficient charm-tagging useful

Otherwise search for $\tilde{g} \to q\bar{t}\ (\bar{q}t)\ \tilde{\chi}_1^0$ with $q \neq b, t$

Gluino three-body decays: Invariant mass distribution

Bartl, Eberl, Ginina, Herrmann, Hidaka, Majerotto, Porod (2011)

Smooth invariant mass distribution (no edge structure) due to off-shell squark in the propagator



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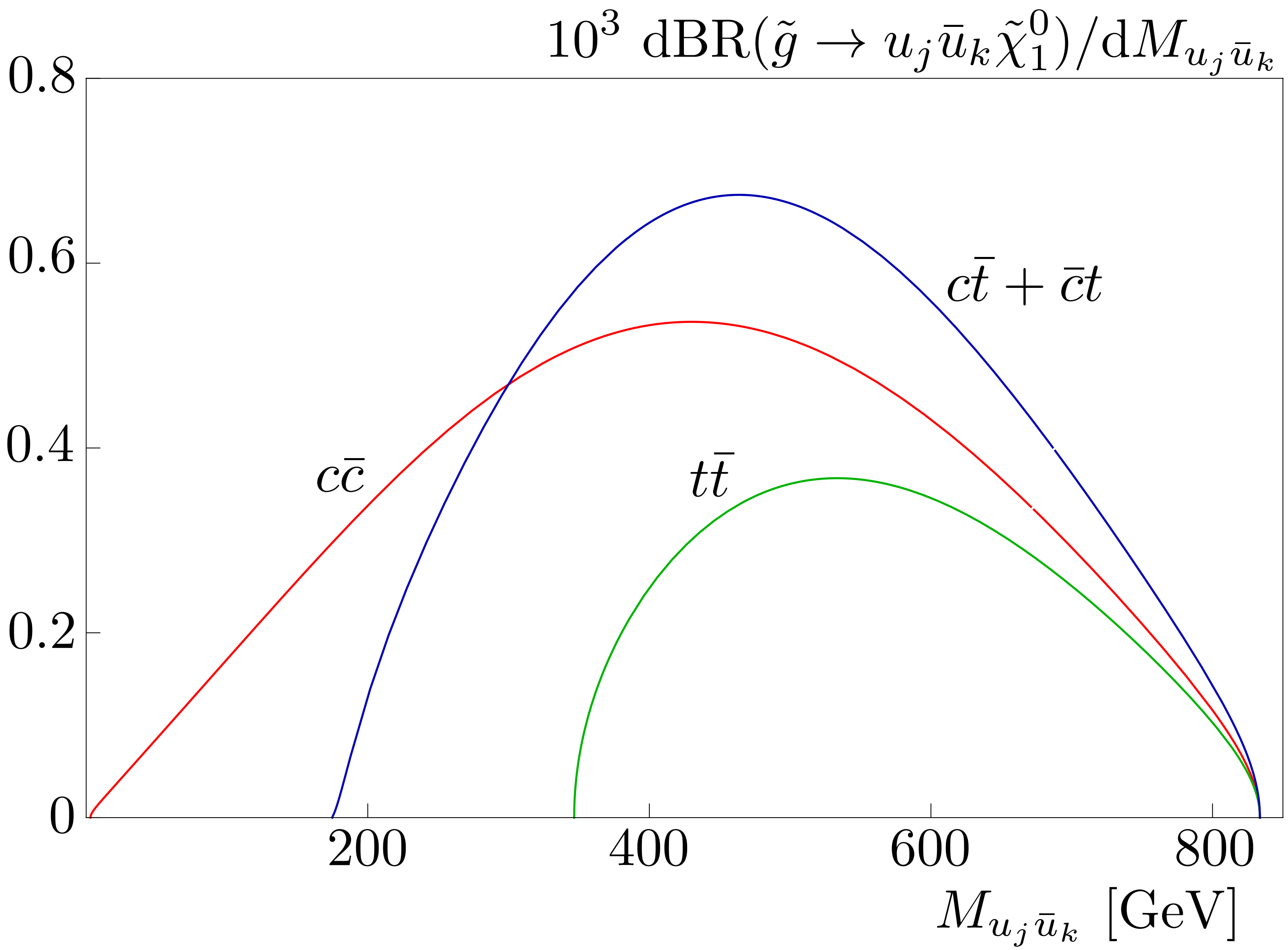

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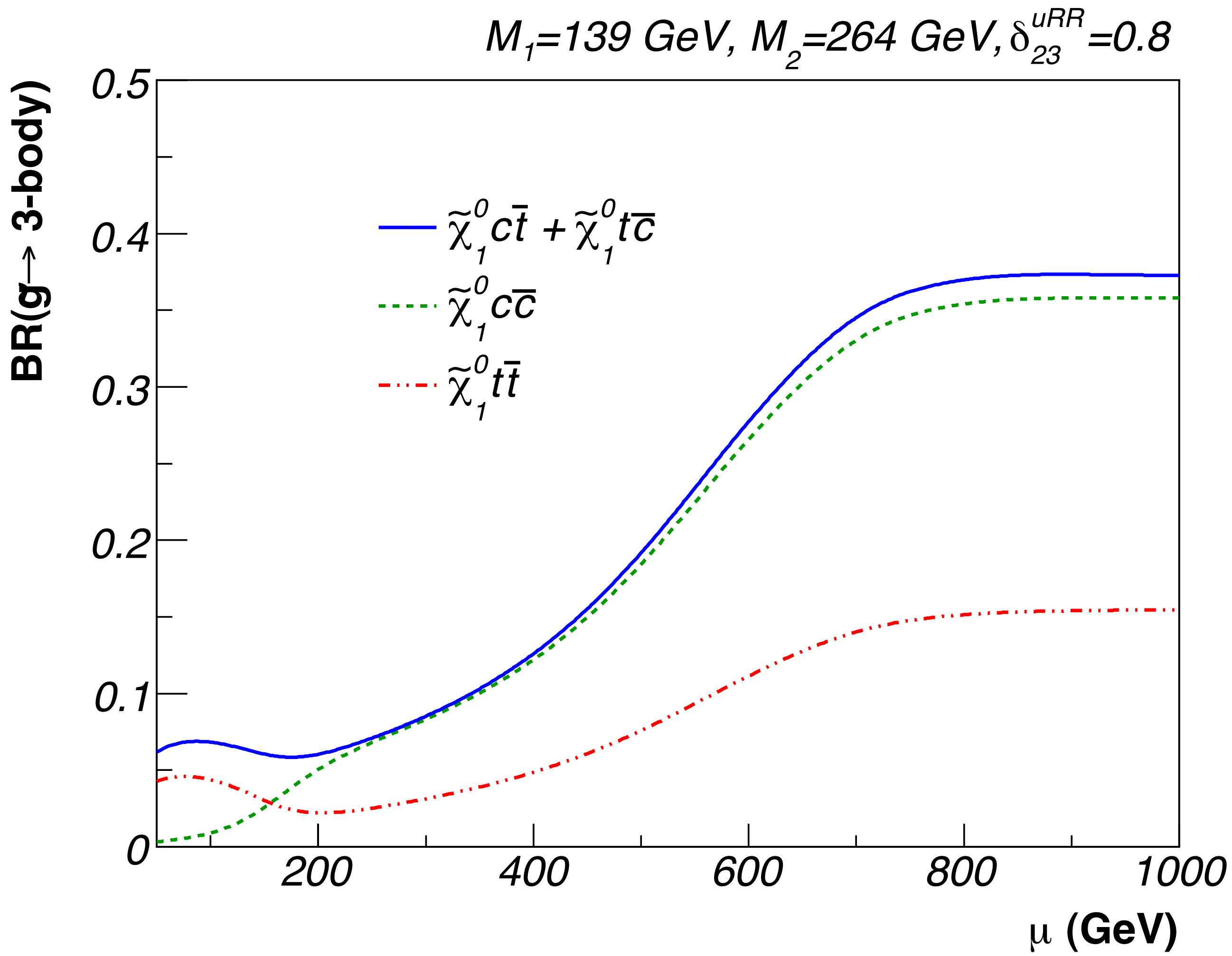
$$\mathrm{BR}(\tilde{g} \to c\bar{c}\tilde{\chi}_1^0) = 36\%$$
$$\mathrm{BR}(\tilde{g} \to t\bar{t}\tilde{\chi}_1^0) = 15\%$$

However, thresholds ($2m_c$, m_c+m_t, $2m_t$) and shapes of distributions rather different,
which could be helpful for seperating the QFV decays from the QFC decays with same final state

Gluino three-body decays: Dependence on nature of neutralino

Bartl, Eberl, Ginina, Herrmann, Hidaka, Majerotto, Porod (2011)

QFV branching ratios do not only depend on squark mixing, but also on neutralino mixing



For $\mu > M_1$, the QFV branching ratio increases with the bino-component of lightest neutralino

For $\mu < M_1$, the lighter neutralinos are higgsino-like leading to a lower QFV branching ratio

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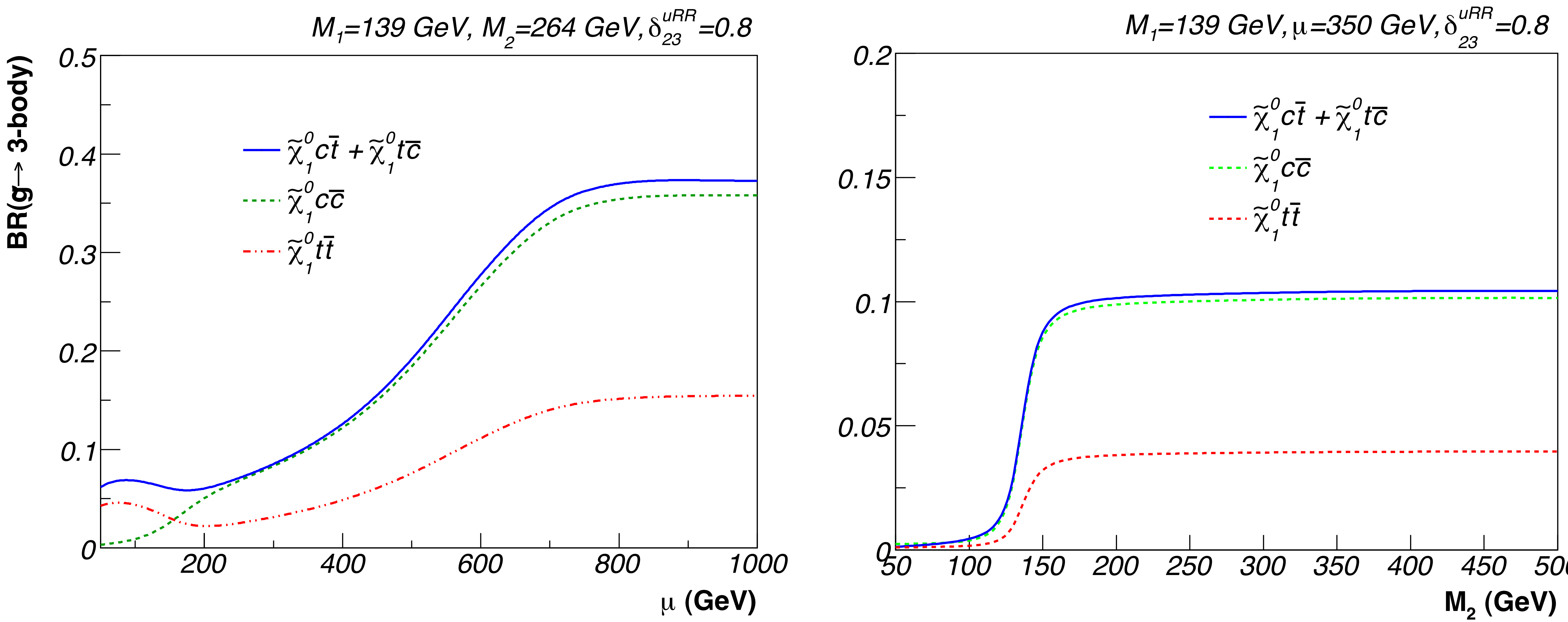

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For $\mu < M_1$, the lighter neutralinos are higgsino-like leading to a lower QFV branching ratio

For $M_2 < M_1 < \mu$, the wino-like neutralino does not couple to c_R or t_R, leading to low QFV signals

However, large branching ratios for bino-like neutralinos (i.e. $M_1 < M_2 < \mu$)

Conclusion

Flavour non-diagonal entries might be present in the squark mass matrices
and lead to an interesting phenomenology at colliders (despite the strong experimental constraints)

Production and decay of squarks and gluinos can then lead to rather clean signatures

$$pp \to \tilde{u}_i \tilde{u}_j^* \to c\,\bar{t} + E_T^{\rm miss}$$
$$pp \to \tilde{u}_i \tilde{u}_j \to t\,t + E_T^{\rm miss}$$

Hurth, Porod (2009);
Bruhnke, Herrmann, Porod (2010);
Bartl, Eberl, Herrmann, Hidaka, Majerotto, Porod (2010)

$$pp \to \tilde{g}\tilde{g} \to c\,\bar{c}\,c\,\bar{t} + E_T^{\rm miss}$$
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Hurth, Porod (2009);
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Efficient charm-tagging necessary to identify final state (but most likely only 10-20%)

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→ **This clearly calls for detailed Monte-Carlo studies**

Explore feasibility in current collider experiments
Determine regions of parameter space where signals would be observable

Herrmann, Porod *(in preparation)*