Single top/bottom quark production by direct Supersymmetric FCNC interactions at the LHC

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Related works and collaborators

The present work has been done in collaboration with Jaume Guasch, Wolfgang Hollik and Siannah Peñaranda.

Previous related works:

- S. Béjar, J. Guasch, JS ,Production and FCNC decay of supersymmetric Higgs bosons into heavy quarks in the LHC, hep-ph/0508043
- S. Béjar, J. Guasch, JS , Higgs boson flavor changing neutral decays into bottom quarks in Supersymmetry, JHEP 0408:018,2004.
- S. Béjar, J. Guasch, JS ,Higgs boson flavor changing neutral decays into top quark in a general 2HDM, Nucl.Phys.B675:270-288,2003.
- S. Béjar, J. Guasch, JS ,Loop induced flavor changing neutral decays of the top quark in a general 2HDM, Nucl.Phys.B600:21-38,2001.
- J. Guasch, JS ,FCNC top quark decays: a door to SUSY physics in high luminosity colliders?, Nucl.Phys.B562:3-28,1999

GUIDELINES

- **Introduction** and **motivation**: **rare** **FCNC** processes in the SM;
- Higgs boson **FCNC** processes in the **MSSM** and the **2HDM**;
- Production of heavy quarks by **SUSY**-**FCNC** interactions in the **LHC**;
- Comparison of direct and indirect **FCNC** production of heavy quarks at the **LHC**;
- **Conclusions.**

FCNC processes in the SM

• At tree-level there are no **FCNC** processes in the SM, and at one-loop they are induced by charged current (W) interactions, which are GIM-suppressed

• Common examples at low-energy:
$K^0 - \bar{K^0}$ $(d \leftrightarrow s)$, $B - \bar{B}$ mixing $(d \leftrightarrow b)$, radiative B-decays: $\boxed{B(b \to s\gamma) \sim 10^{-4}}$.

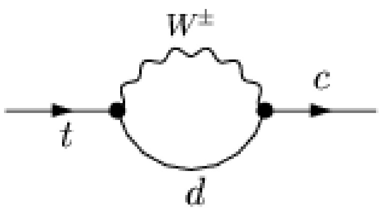
• More interesting for some purposes are the **rare** **FCNC** processes:

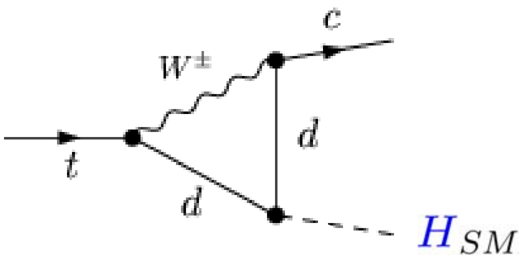
$$B(t \to g\,c) \sim 4 \times 10^{-11}$$

$$B(t \to \gamma\,c) \sim 4 \times 10^{-13}\,, \quad B(t \to Z\,c) \sim 1 \times 10^{-13}$$

• Even more interesting are some of the **rarest FCNC** processes in the SM:

i) $t \to H_{SM}\, c$ ii) $H_{SM} \to t\, c$





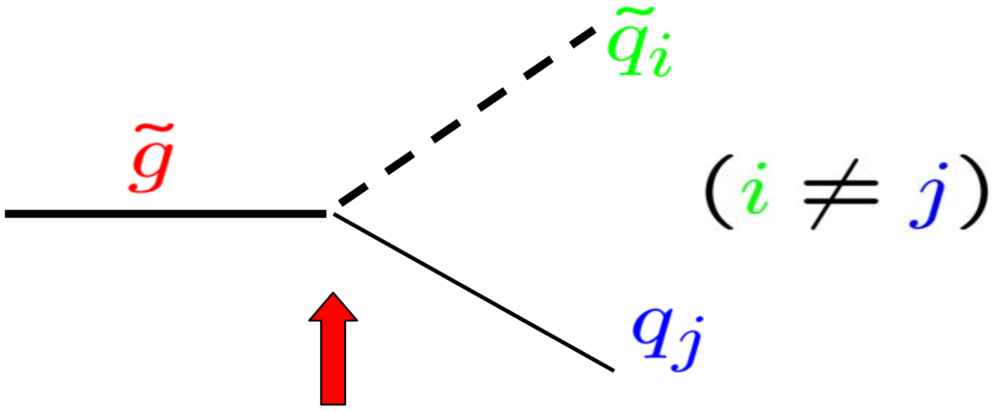
$$B(t \to H_{SM}\, c) \sim (5 \to 3) \times 10^{-14}\,, \quad m_H = (115 \to 130)\, GeV$$

Similarly for the crossed channel:

$$B(H_{SM} \to t\, c) \sim 10^{-13} - 10^{-16}\,, \quad m_H = (200-500)\, GeV$$

FCNC- SUSY Interactions

- **SUSY** interactions in the MSSM can also trigger **FCNC** processes:
  - Loop induced **FCNC** processes from SUSY-QCD tree-level **gluino** couplings

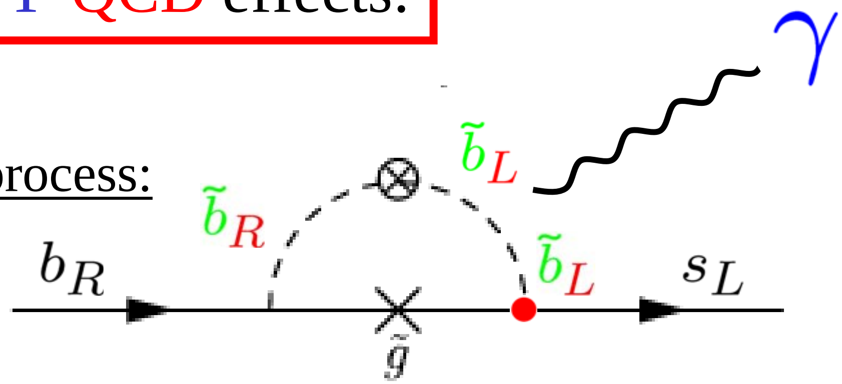


strong FCNC interaction !

Examples of SUSY-QCD effects:

Relatively well-measured process:

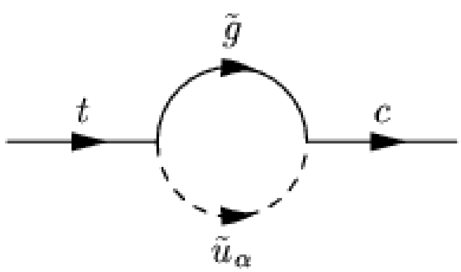
$$b \longrightarrow s\,\gamma$$

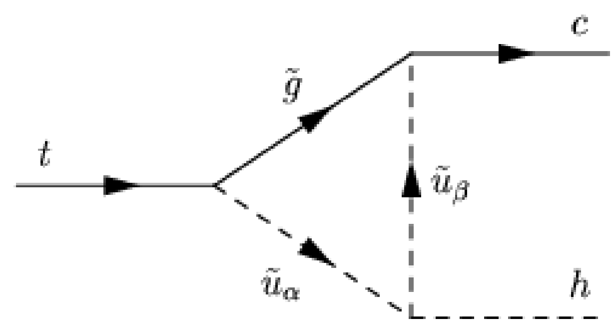


$$B^{\mathrm{exp}}(b \to s\gamma) = (3.3 \pm 0.4) \times 10^{-4}$$

(CLEO,ALEPH,BELLE,BABAR)

Undetected processes, yet:





$B(t \to h\,c) \sim 10^{-5} - 10^{-4}$ $\quad$ $(\mathbf{h = h^0,\ H^0\ \ A^0})$

Can be **enhanced** 10 orders of magnitude above the SM result!!

J. Guasch, J.S., *Nucl. Phys. B 562 (1999) 3*

Another undetected process, which could be highly enhanced in the MSSM and could be a sign of SUSY:

$$h \to t\,c \qquad (\mathrm{h} = \mathrm{h}^0,\ \mathrm{H}^0\ \ \mathrm{A}^0)$$

$$B(h \to b\,s) \lesssim 10^{-3} \qquad B(h \to t\,c) \sim 10^{-3}$$

4 10 orders of magnitude larger than in the SM!!

Comparable to $B(h \to \gamma\gamma) \sim 10^{-3}$!

A few thousand events could be produced at the LHC -- see details in the talk by J. Guasch.

Several calculations in the literature, with different assumptions:

A.M. Curiel et al, *Phys.Rev.D67:075008,2003*

S. Bejar, J. Guasch, J.S., *Nucl.Phys.B675:270-288,2003*

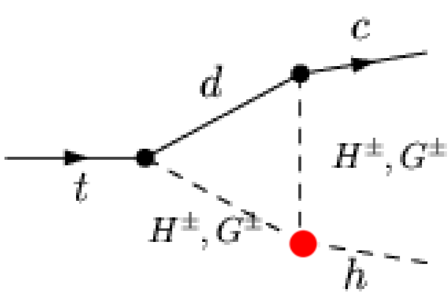
S. Bejar, J. Guasch, J.S., *JHEP 0408:018,2004*

A.M. Curiel et al, *Phys.Rev.D69:075009,2004*

S.Bejar, J. Guasch, J.S., hep-ph/0508043

Let us remark that non-SUSY physics can also give enhanced FCNC contributions, e.g. generic 2HDM effects !!

$$B(t \to h\, c) \sim 10^{-4}\ , \quad B(h \to t\, c) \sim 10^{-5}$$



$H^\pm H^\mp h^0$	$(-ig)\left[(m^2_{H^\pm} - m^2_{A^0} + \frac{1}{2}m^2_{h^0})\sin(2\beta)\sin(\beta-\alpha) + (m^2_{h^0} - m^2_{A^0})\cos(2\beta)\cos(\beta-\alpha)\right]\frac{1}{M_W\sin(2\beta)}$

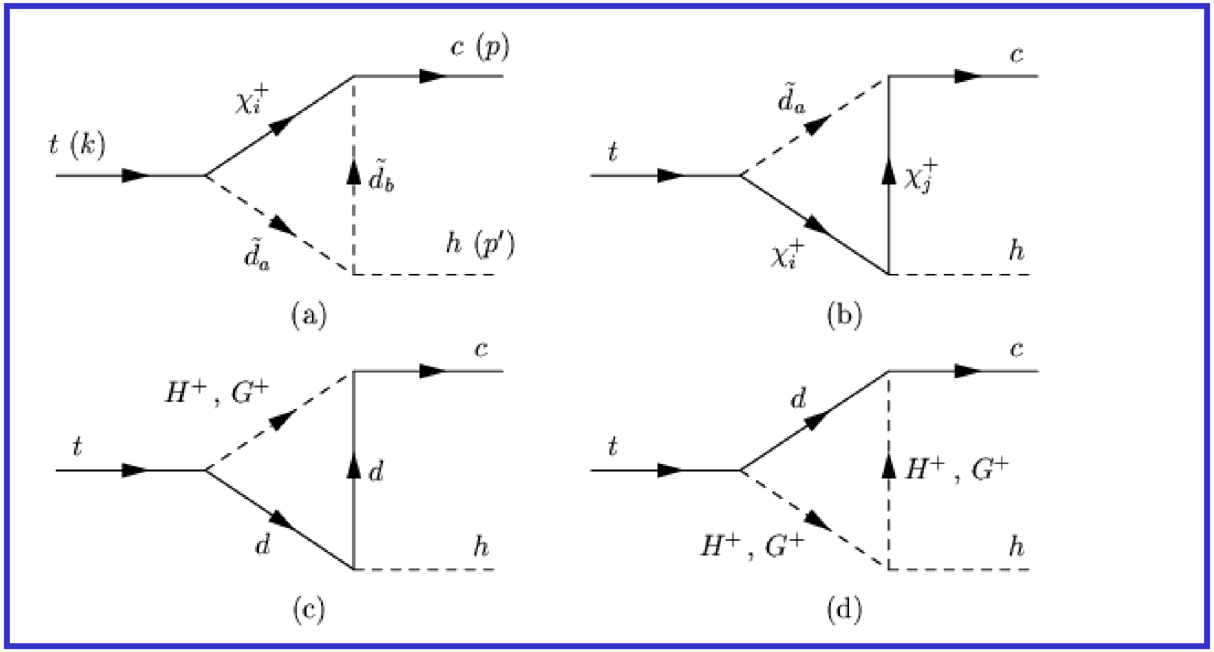
S. Bejar, J. Guasch, J.S., *Nucl. Phys. B 675 (2003) 270*; ibid. *Nucl. Phys. B 600 (2001) 21*

The dynamical origin of the 2HDM contributions (enhanced trilinear HHH couplings) is very different as compared to SUSY case (FCNC gluino/neutralino-mediated couplings)

Very important to compare SUSY and non-SUSY effects !

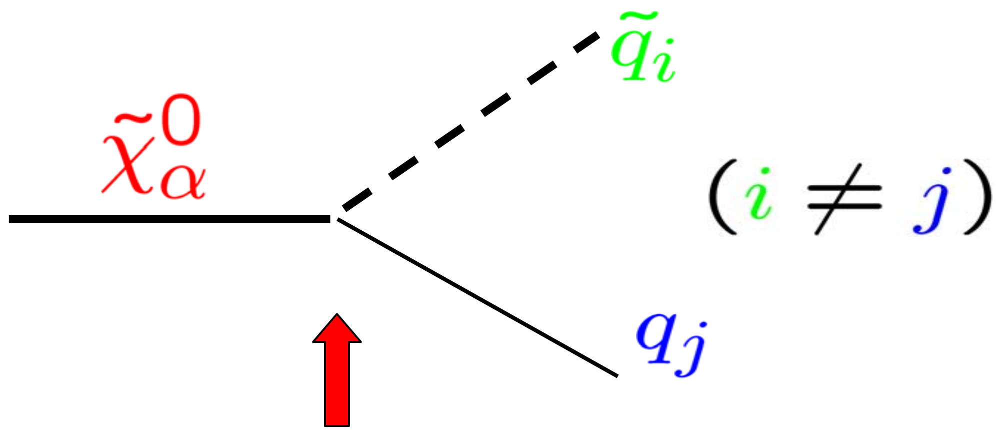
– Loop induced FCNC processes from SUSY-EW effects (charged currents)

SUSY-EW computed in the Super-CKM basis $\Rightarrow$ FCNC processes appear at one loop through normal MSSM contributions from the charged sector (charged Higgs and charginos).



J. Guasch, J.S., *Nucl. Phys. B 562 (1999) 3*

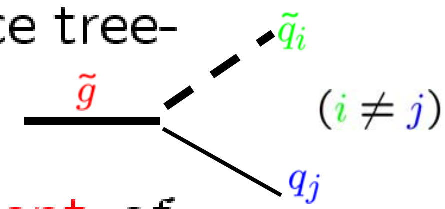
- SUSY-EW effects can also appear through (neutral currents) tree-level $\Rightarrow$ **FCNC neutralino** couplings. These effects will not be considered here (they are under study)



weak (enhanced!) FCNC interaction !

SUSY-QCD Lagrangian with FCNC interactions

- SUSY-QCD interactions may induce tree-level gluino-mediated FCNC



- This is because of the misalignment of quark/squark mass matrices $\Rightarrow$ the squark mass matrix in general need not to diagonalize with the same matrices as the quark mass matrix.

- From RG-arguments one can show (see e.g. Duncan, 1983) that starting from an aligned configuration at a high scale one ends up with a misaligned one at low energies in the LL-sector.

$\diamond$ The gluino interactions lead to FCNC because the 6×6 (flavour)×(chiral) space squark mass-matrix contains intergenerational coefficients, which we restrict within the **LL** block:

$$\begin{pmatrix} \boxed{M^2_{LL}} & M^2_{LR} \\ M^2_{RL} & M^2_{RR} \end{pmatrix} \qquad \boxed{(M^2_{LL})_{ij} = m^2_{ij} \equiv \delta_{ij}\, m_i\, m_j \ ,} \qquad (i \neq j)$$

essential parameters for our analysis !!

$\diamond$ The δ_{ij} are restricted by low-energy data on FCNC processes involving the d-quark sector (e.g. from $b \to s\,\gamma$ etc.).

$\diamond$ $SU(2)$ gauge invariance $(M^2_{\widetilde{U}})_{LL} = K\ (M^2_{\widetilde{D}})_{LL}\ K^\dagger$ is used to transfer these bounds to the up-quark sector ($\Rightarrow$ previous talk)

• As a result the SUSY-QCD Lagrangian in the mass-eigenstate basis has the following structure:

$$\boxed{\begin{aligned}\mathcal{L}_{\text{SQCD}} = &-\frac{g_s}{\sqrt{2}}\bar{\psi}_c^{\tilde{g}}\left[R^*_{1\alpha}P_L - R^*_{2\alpha}P_R\right]\tilde{q}^*_{\alpha,i}\,\lambda^c_{ij}\,u_j \\ &-\frac{g_s}{\sqrt{2}}\bar{\psi}_c^{\tilde{g}}\left[R^*_{3\alpha}P_L - R^*_{4\alpha}P_R\right]\tilde{q}^*_{\alpha,i}\,\lambda^c_{ij}\,c_j \\ &-\frac{g_s}{\sqrt{2}}\bar{\psi}_c^{\tilde{g}}\left[R^*_{5\alpha}P_L - R^*_{6\alpha}P_R\right]\tilde{q}^*_{\alpha,i}\,\lambda^c_{ij}\,t_j\end{aligned}}$$

where the R are rotation matrices which diagonalize the 6×6 squark mass-matrix $\Rightarrow$

weak eig. mass eig.

$$\tilde{q}'_\alpha = \sum_\beta R^{(q)}_{\alpha\beta}\tilde{q}_\beta$$

$$R^{(q)\dagger}\mathcal{M}^2_{\tilde{q}}R = \mathcal{M}^2_{\tilde{q}D} = \text{diag}\{m^2_{\tilde{q}_1},\ldots,m^2_{\tilde{q}_6}\}\ ,\ q \equiv u,\ d$$

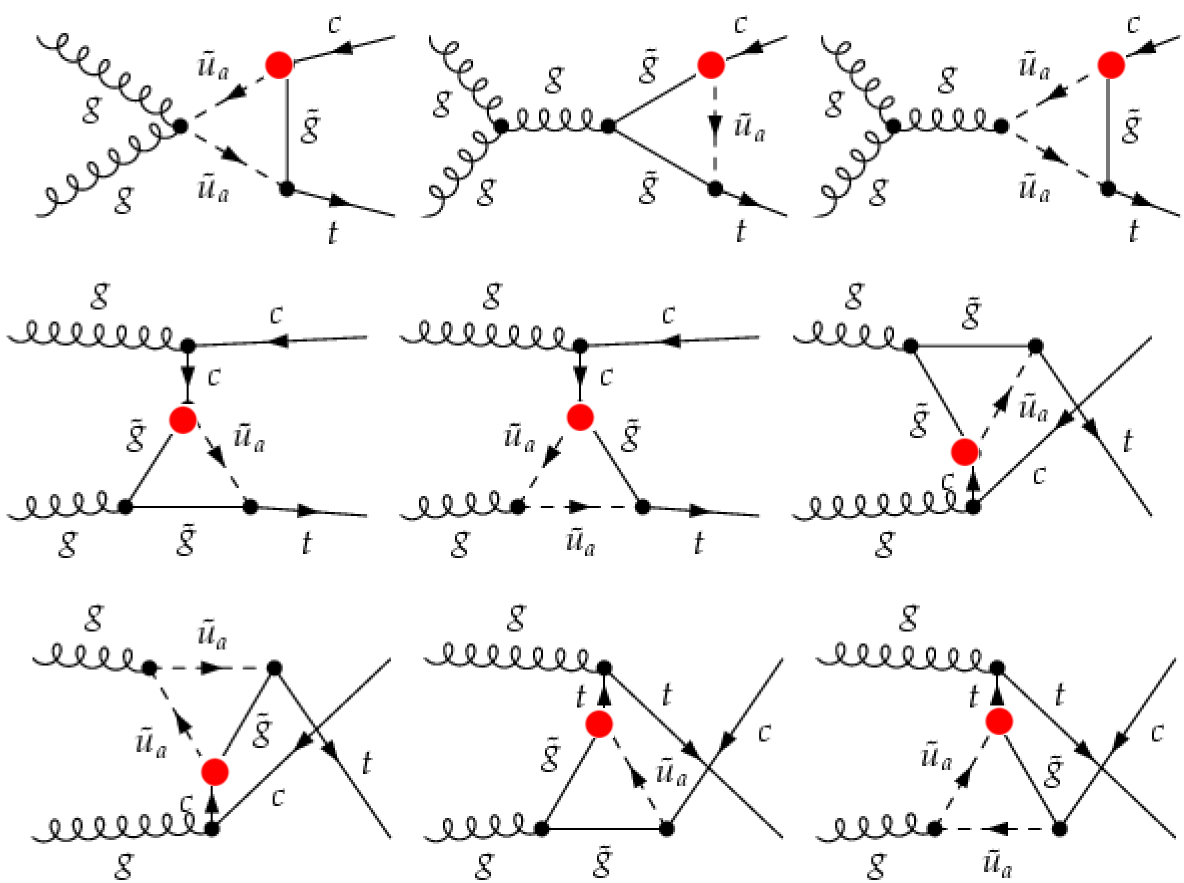
with indices $\alpha = 1,2,3,\ldots,6 \equiv \tilde{u}_L,\tilde{u}_R,\tilde{c}_L,\ldots,\tilde{t}_R$ for up-type squarks, and a similar assignment for down-type squarks.

SUSY-QCD direct FCNC Diagrams

At the **LHC** the main SUSY production mechanisms for **t c** is the following *

$$g\ g \longrightarrow t\ c$$

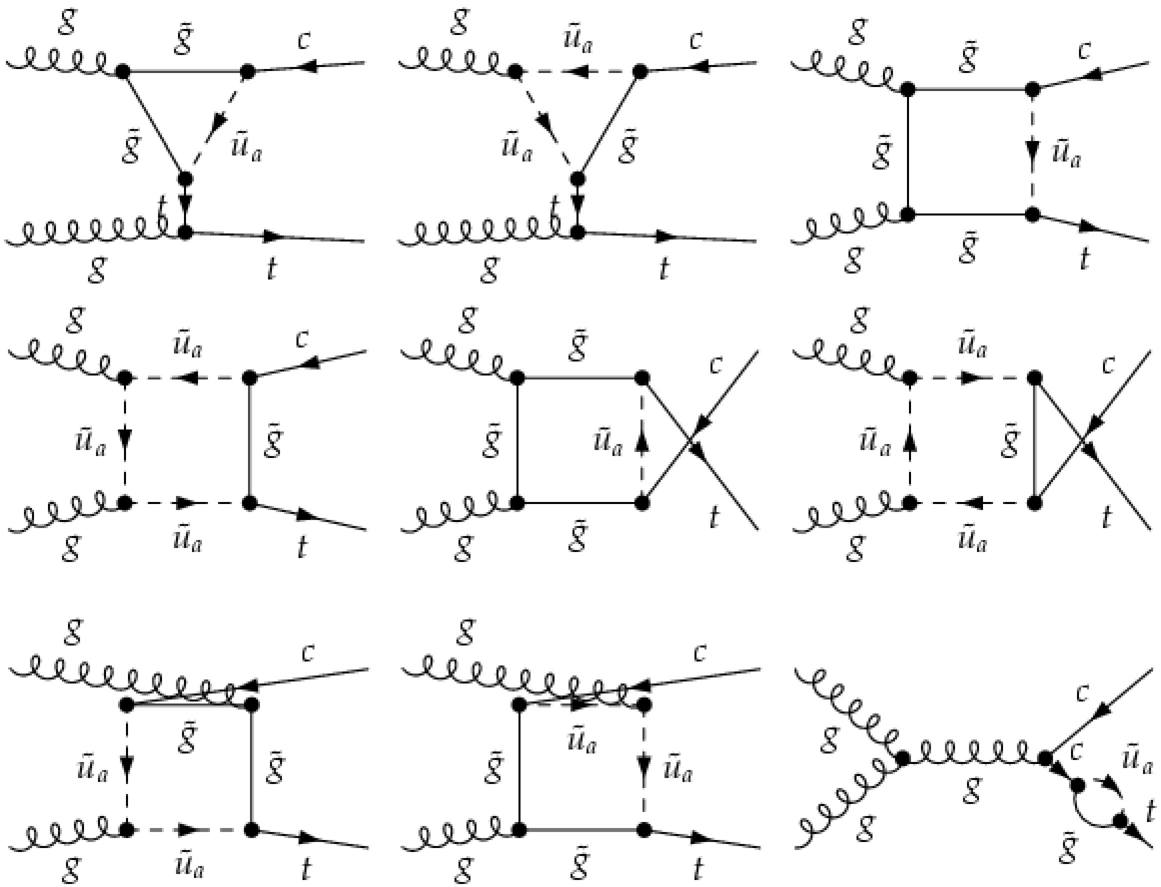
SUSY-QCD effects:



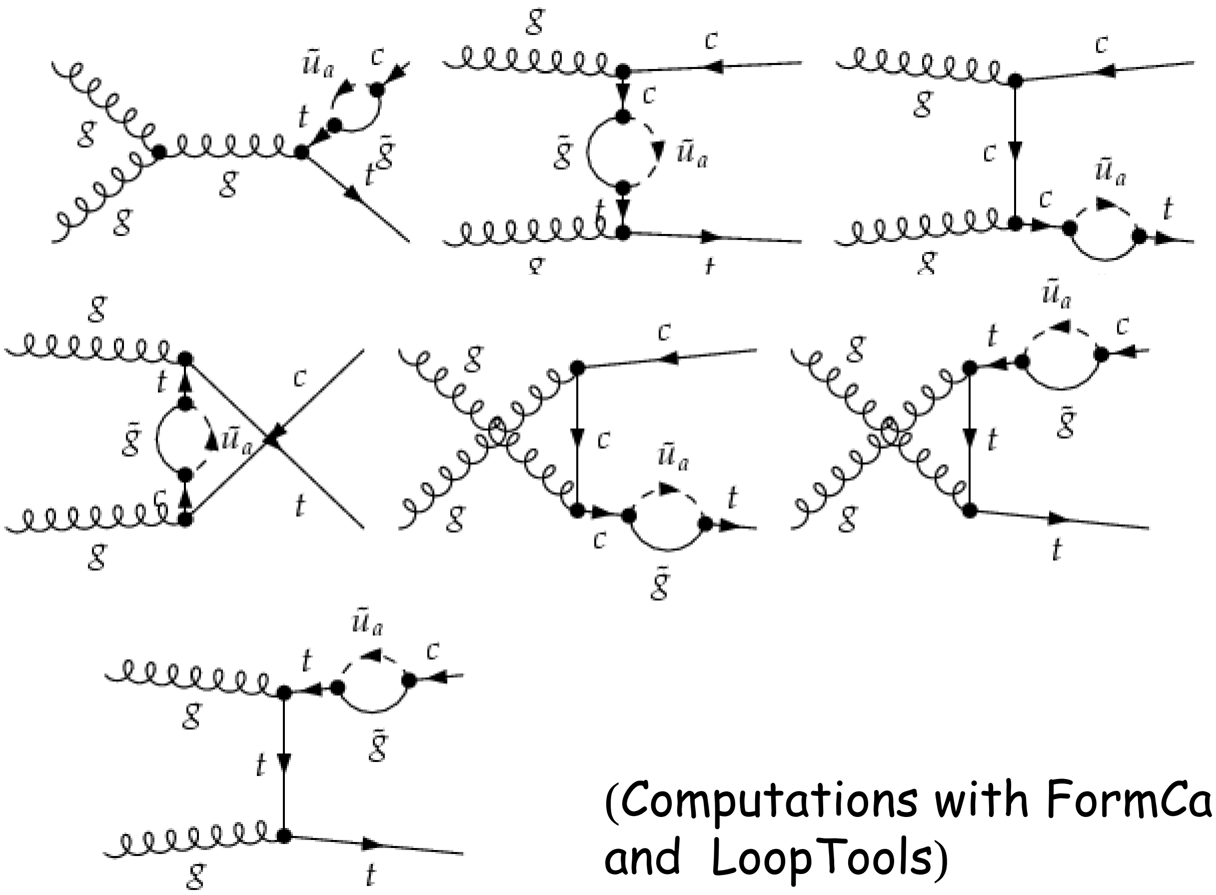
*SM contribution

negligible!

…more SUSY-QCD effects:



…more SUSY-QCD effects:

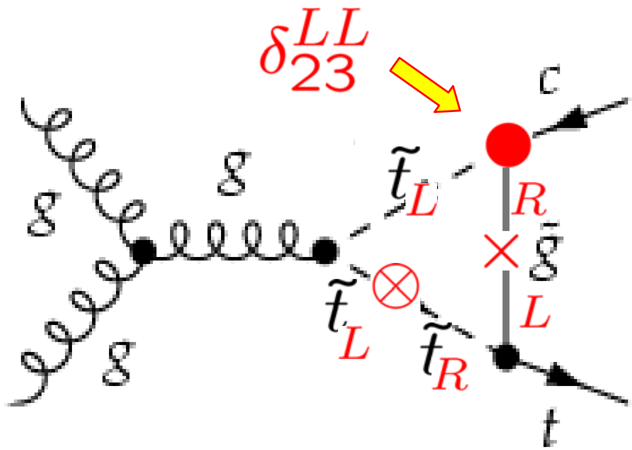


(Computations with FormCalc
and LoopTools)

Tools

T. Hahn, M. Pérez Victoria, Comput. Phys. Commun. 118 (1999) 153;
T. Hahn, http://www.feynarts.de/looptools.

Typical behavior of the cross-section



``stop'' mass matrix:

$$\begin{pmatrix} M_{\tilde{Q}}^2 + \mathcal{O}(M_Z^2) & \boxed{m_t\, M_{LR}^t} \\ \boxed{m_t\, M_{LR}^t} & M_{\tilde{Q}}^2 + \mathcal{O}(M_Z^2) \end{pmatrix}$$

Amplitude:

$$(M_{LR}^t = A_t - \mu/\tan\beta)$$

$$\boxed{A(pp[gg] \to t\bar{c}) \sim \delta_{23}^{LL} \times \frac{m_t(A_t - \mu/\tan\beta)}{M_{SUSY}^2} \times \frac{1}{m_{\tilde{g}}}}$$

$$(\sigma \sim |A(pp[gg] \to t\bar{c})|^2)$$

NUMERICAL ANALISIS

- Our numerical analysis aims to find $\Rightarrow$ maximum contributions preserving the current bounds on sparticle masses;

- A full-fledged numerical exploration of the MSSM parameter space (even under some restrictions) is highly demanding in this case, due to the production of the final states via direct **FCNC-SUSY** interactions;

- We used approximate analytical methods based on the general form of the cross-section;

$\longrightarrow$ Appendix

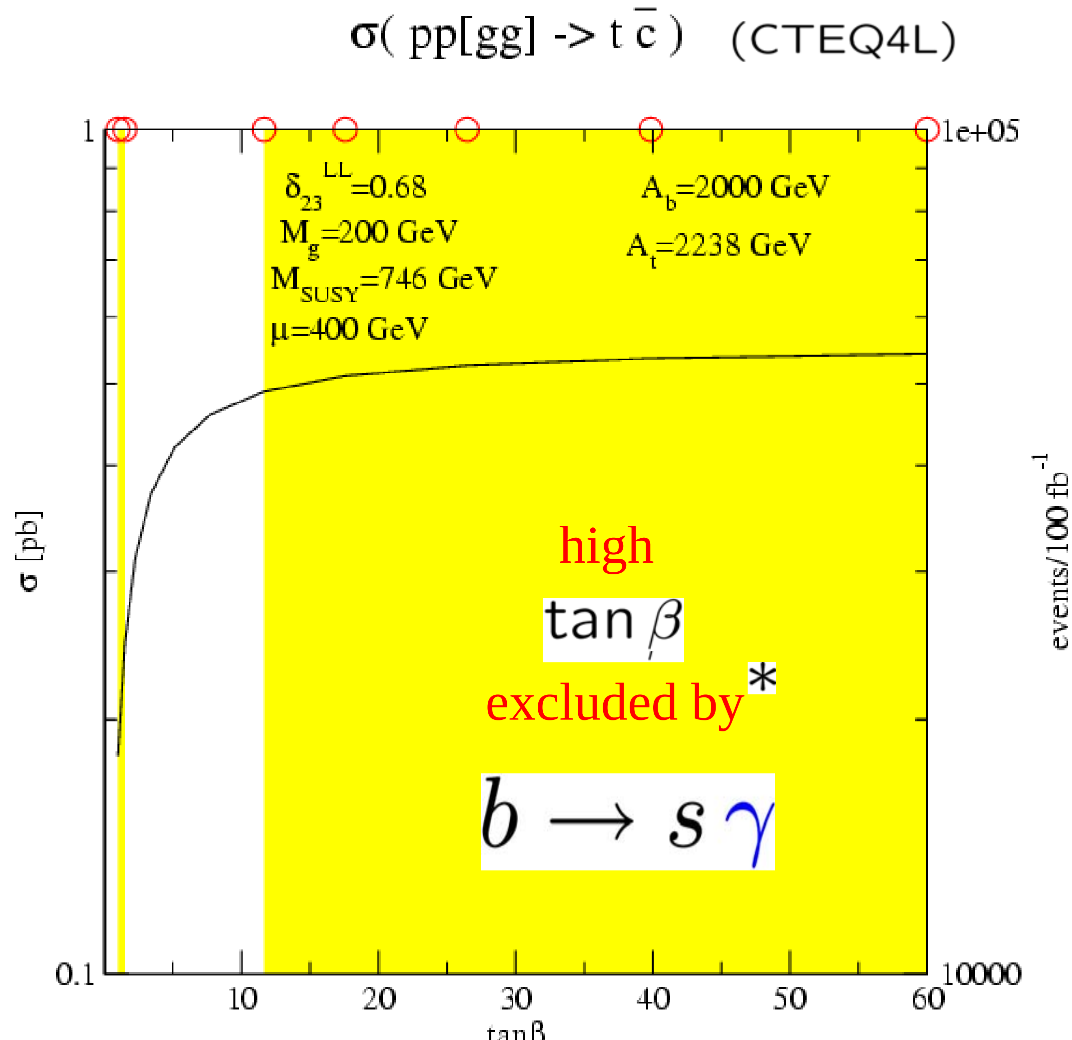
- Previous analysis by J.J. Liu *et al.* hep-ph/0404099 (NPB B705:3-32,2005) did not carry out a systematic study of the parameter space ($\Rightarrow$ only particular choice of the parameters); did not take into account the important restrictions imposed by $b \to s\gamma$ at high $\tan\beta$. Analysis missed the bulk of the contribution and tended to emphasize that the origin of the main effects come from LR sector.

NUMERICAL RESULTS: Maximum contributions

Obtained under

$b \to s\gamma$

restrictions *



Notice that $\delta_{23}^{LL} \lesssim 0.7$

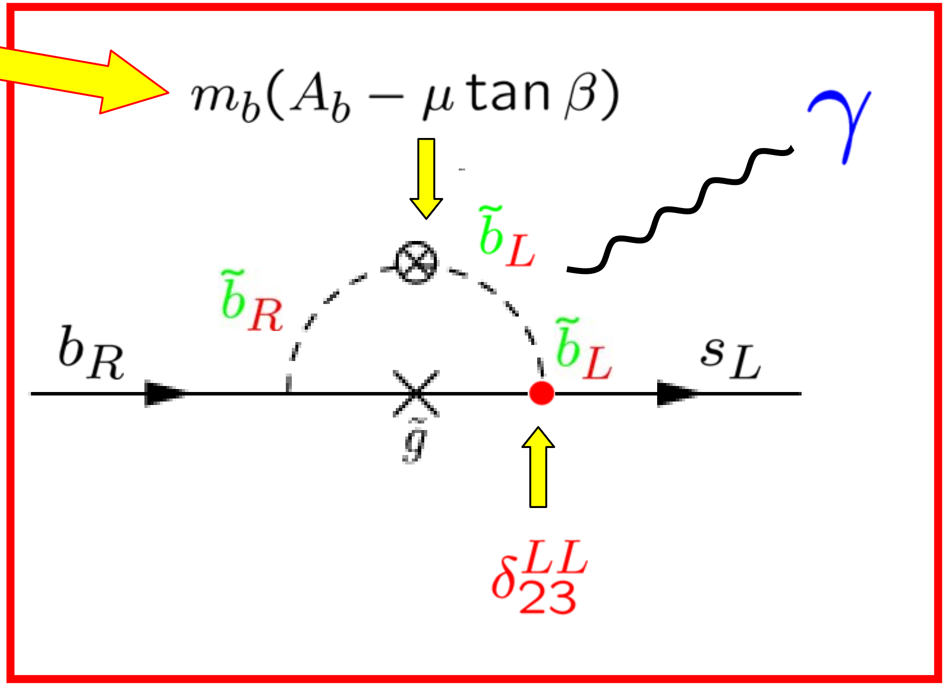
and $M_{SUSY} \lesssim 1\, TeV$

$*$ $B^{\exp}(b \to s\gamma) \sim (2.1 - 4.5) \times 10^{-4}$ (within $3\,\sigma$)

Origin of the restrictions from $b \to s\,\gamma$

$$\begin{pmatrix} M^2_{\tilde{Q}} + \ldots & \boxed{m_b\, M^b_{LR}} \\ m_b\, M^b_{LR} & M^2_{\tilde{Q}} + \ldots \end{pmatrix}$$

Typical FCNC SUSY-QCD contribution:



$$A(b \to s\gamma) \sim \delta^{(d)LL}_{23} \times \frac{m_b(A_b - \mu \tan\beta)}{M^2_{SUSY}} \times \frac{1}{m_{\tilde{g}}}$$

$$A(pp[gg] \to t\bar{c}) \sim \delta_{23}^{(u)LL} \times \frac{m_t(A_t - \mu/\tan\beta)}{M_{SUSY}^2} \times \frac{1}{M_{\tilde{g}}}$$

$\Updownarrow$ ($\tan\beta$ interplay)

$$A(b \to s\gamma) \sim \delta_{23}^{(d)LL} \times \frac{m_b(A_b - \mu\tan\beta)}{M_{SUSY}^2} \times \frac{1}{M_{\tilde{g}}}$$

Recall that

$$\boxed{\sigma(pp[gg] \to t\bar{c}) \sim \left(\delta_{23}^{LL}\right)^2 \frac{m_t^2(A_t - \mu/\tan\beta)^2}{M_{SUSY}^4} \frac{1}{M_{\tilde{g}}^2}}$$

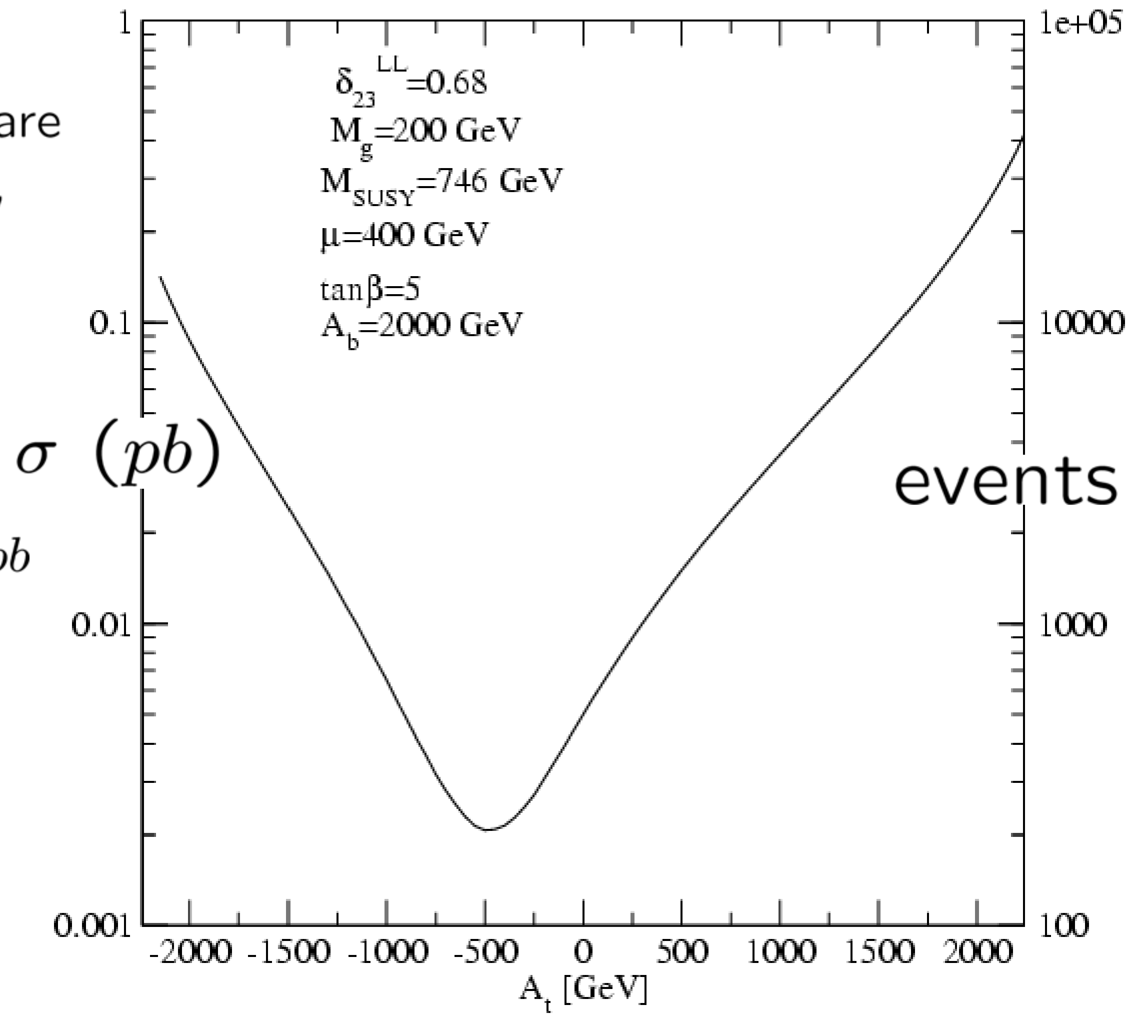
For small $\tan\beta \lesssim 10$ there are no restrictions from $b \to s\gamma$, and σ increases as $\sim A_t^2$

$$\Downarrow$$

$$\sigma^{max}(pp[gg] \to t\bar{c} + \bar{t}c) \simeq 1\,pb$$

$$\Downarrow$$

10^5events
for $\int \mathcal{L}dt = 100\,fb^{-1}$



$$\sigma(pp[gg] \to t\bar{c}) \sim \left(\delta_{23}^{LL}\right)^2 \frac{m_t^2 (A_t - \mu/\tan\beta)^2}{M_{SUSY}^4} \frac{1}{M_{\tilde{g}}{}^2}$$

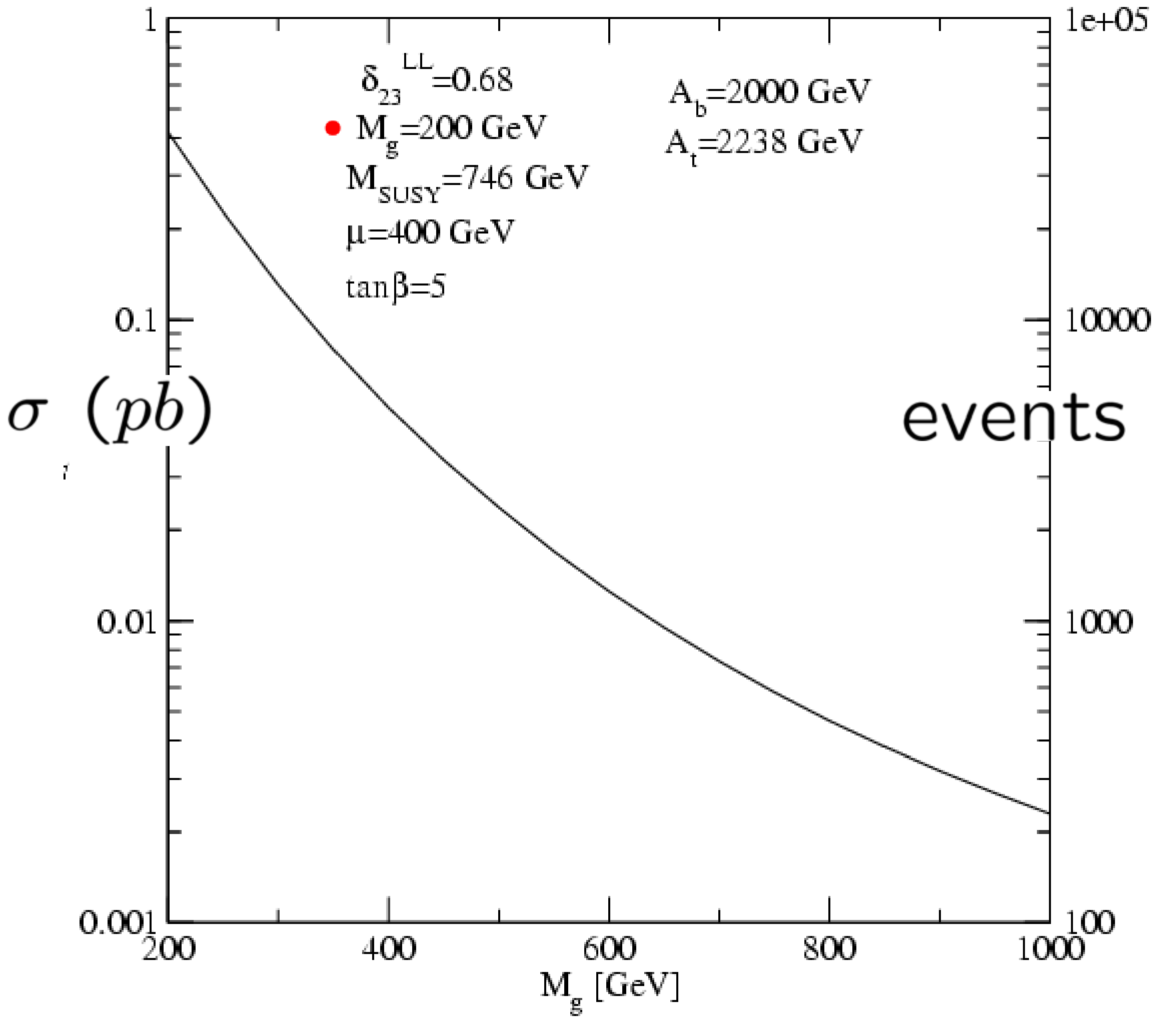
As expected there is a fast decay of σ as a function of the gluino mass $M_{\tilde{g}}$

For $M_{\tilde{g}} \simeq 500\, GeV$

$$\sigma(pp[gg] \to t\bar{c} + \bar{t}c) \simeq 0.04\, pb$$

4×10^3events

for $\int \mathcal{L} dt = 100\, fb^{-1}$

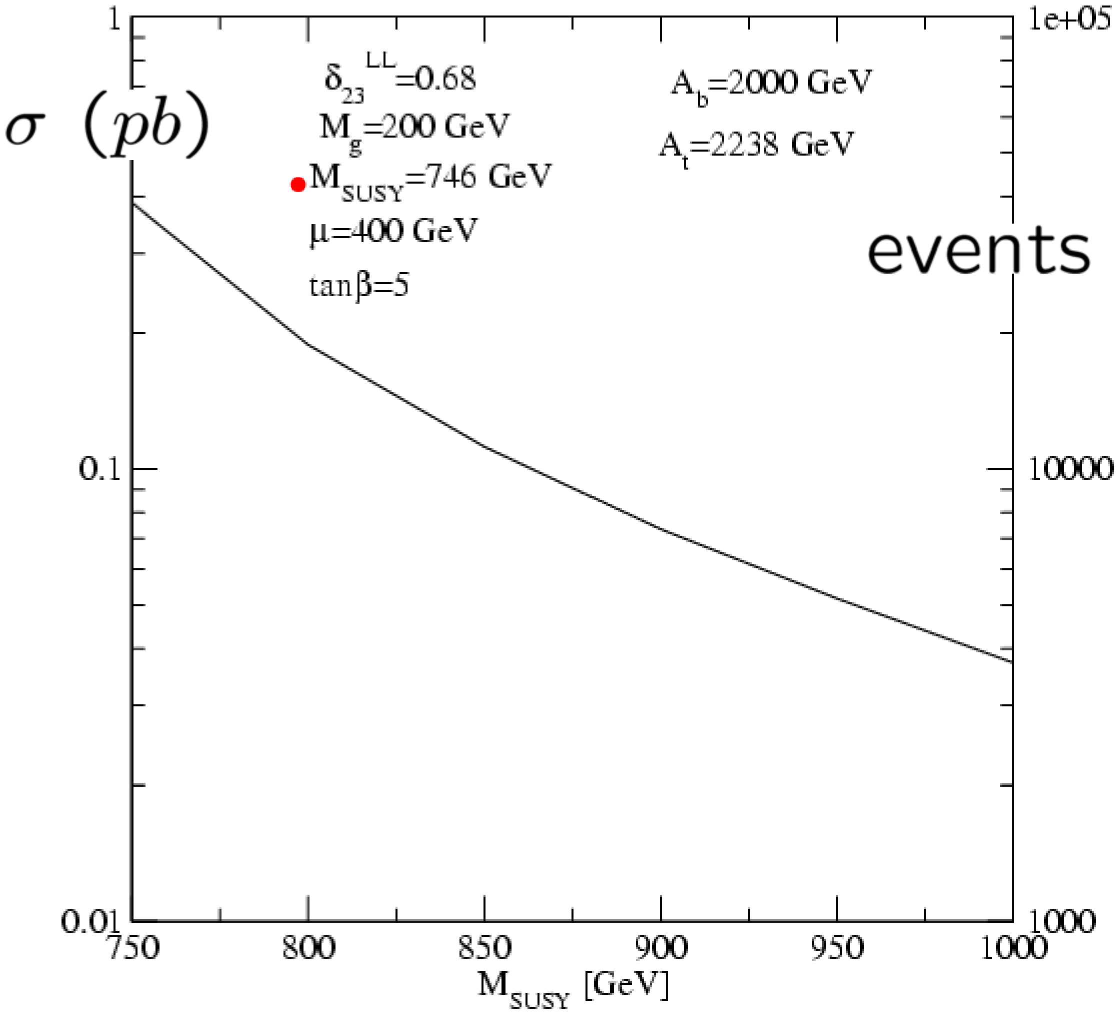


$$\boxed{\sigma(pp[gg] \to t\bar{c}) \sim \left(\delta_{23}^{LL}\right)^2 \frac{m_t^2 (A_t - \mu/\tan\beta)^2}{M_{SUSY}^4} \frac{1}{M_{\tilde{g}}^2}}$$

The cross section also decays significantly with M_{SUSY}

We plot for $M_{SUSY} > 750\, GeV$ because with the values of the parameters this insures that the physical squark masses satisfy

$$\boxed{M_{\tilde{q}} \gtrsim 150\, GeV}$$

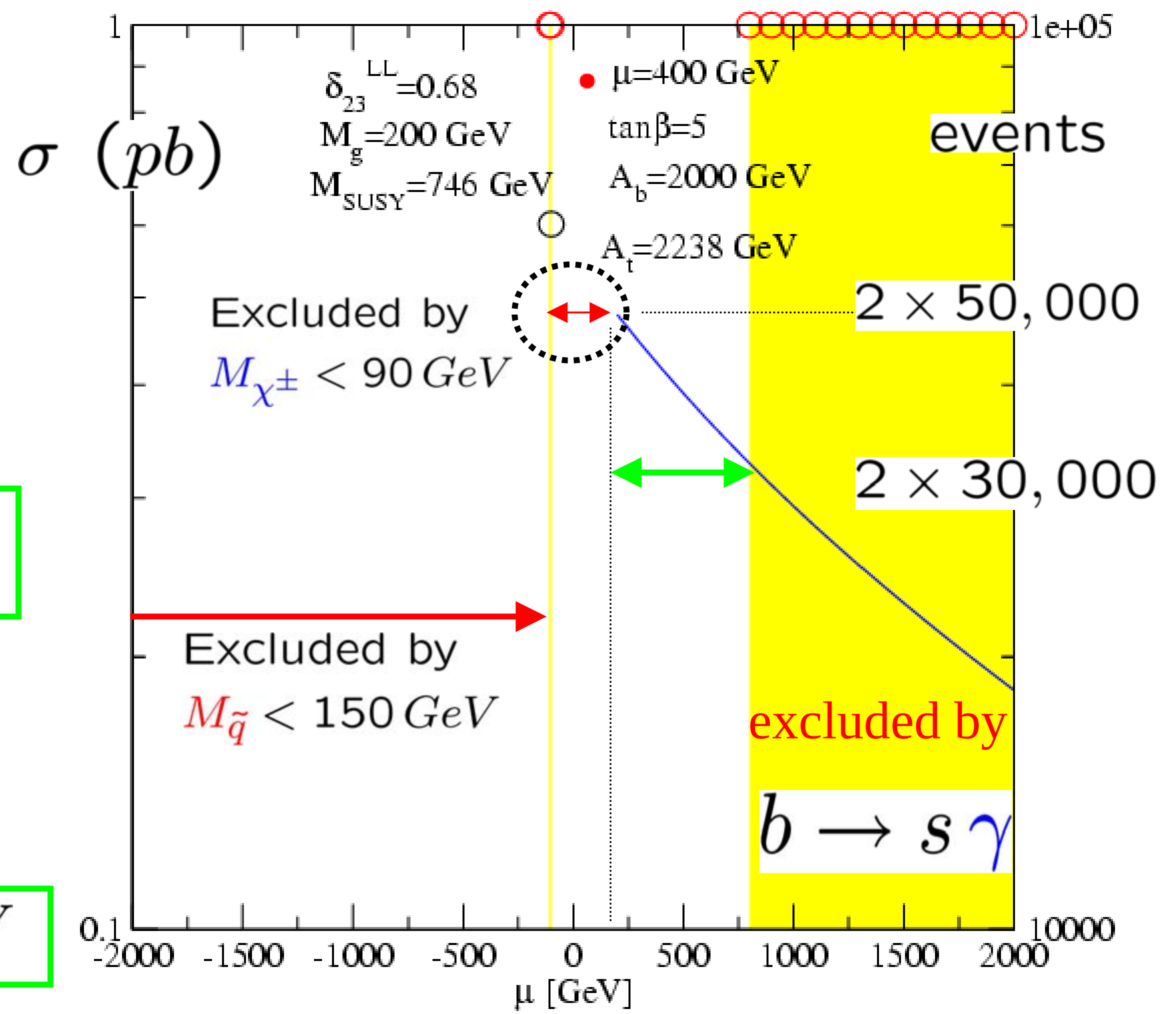


$$\boxed{\sigma(pp[gg] \to t\bar{c}) \sim \left(\delta_{23}^{LL}\right)^2 \frac{m_t^2 (A_t - \mu/\tan\beta)^2}{M_{SUSY}^4} \frac{1}{M_{\tilde{g}}^2}}$$

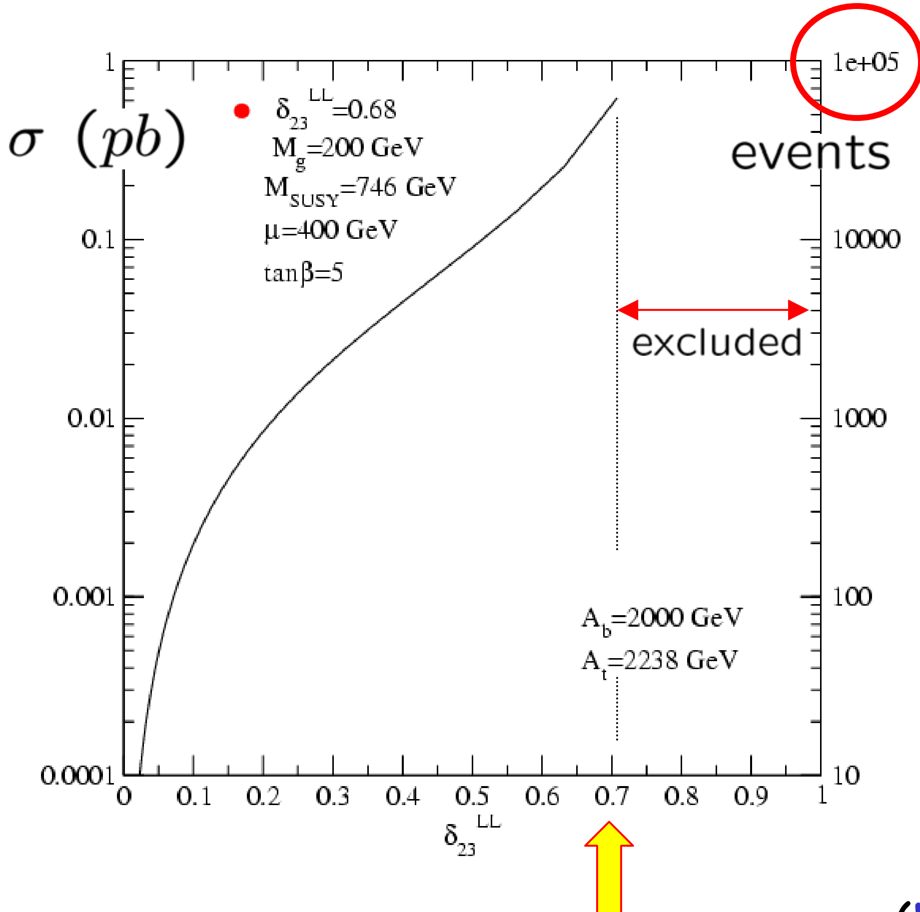
Allowed region:

$$\boxed{\mu \simeq (200 - 800)\, GeV}$$

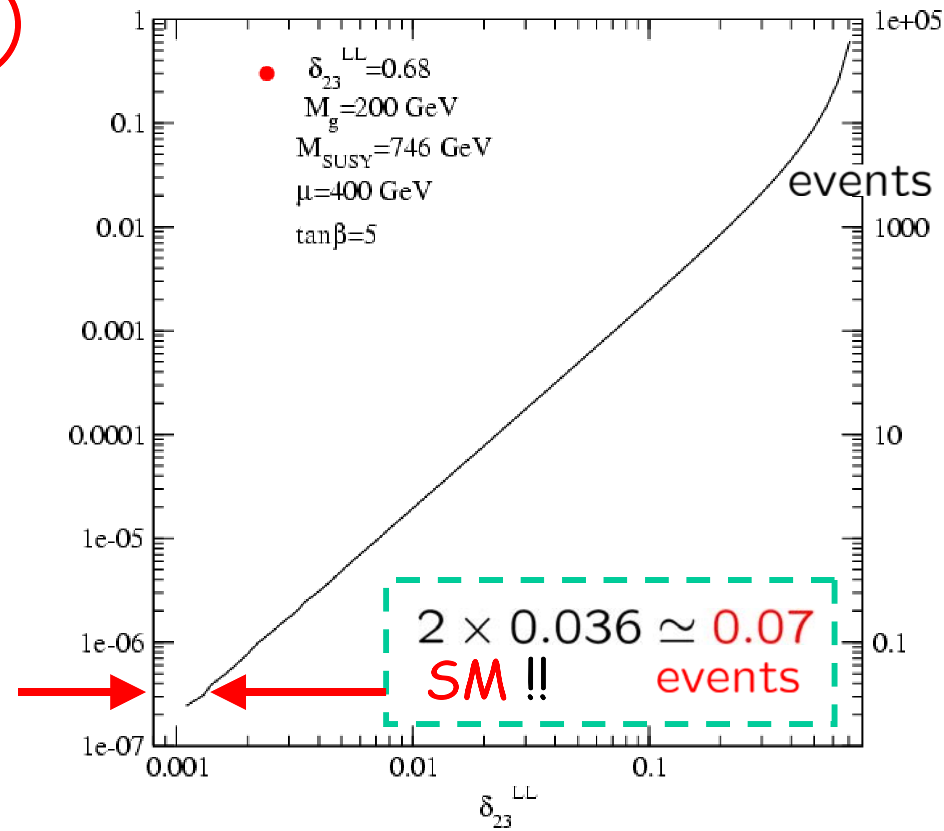
$$\boxed{M_{\chi_1^\pm} \simeq (90 - 300)\, GeV}$$



$$\sigma(pp[gg] \to t\bar{c}) \sim \left(\delta_{23}^{LL}\right)^2 \frac{m_t^2 (A_t - \mu/\tan\beta)^2}{M_{SUSY}^4} \frac{1}{M_{\tilde{g}}^2}$$



$$\delta_{23}^{LL} \simeq 0.7$$



(Not even a single event in the SM for the entire lifetime of the LHC !!)

$$(\sigma_{SM} = 3.6 \times 10^{-7}\, pb)$$

Appendix: Approximate strategy to find the maximum

$$\sigma(pp[gg] \to t\bar{c}) \sim \left(\delta_{23}^{LL}\right)^2 \frac{m_t^2 (A_t - \mu/\tan\beta)^2}{M_{SUSY}^4} \frac{1}{M_{\tilde{g}}^2} \equiv \left(\delta_{23}^{LL}\right)^2 \times \left(\delta_{33}^{LL}\right)^2 \times \frac{1}{M_{\tilde{g}}^2}$$

$\Downarrow$

Isolines $\sigma \equiv \sigma_0 \Rightarrow$ hyperbolas $\boxed{\delta_{23}^{LL} \times \delta_{33}^{LR} = const.}$

Lightest squark masses *

$$m_{\tilde{q}_1}^2 = M_{SUSY}^2 \left(1 - \sqrt{(\delta_{23}^{LL})^2 + (\delta_{33}^{LR})^2}\right) > M_l^2$$

exp. limit

Circle of allowed squark masses:

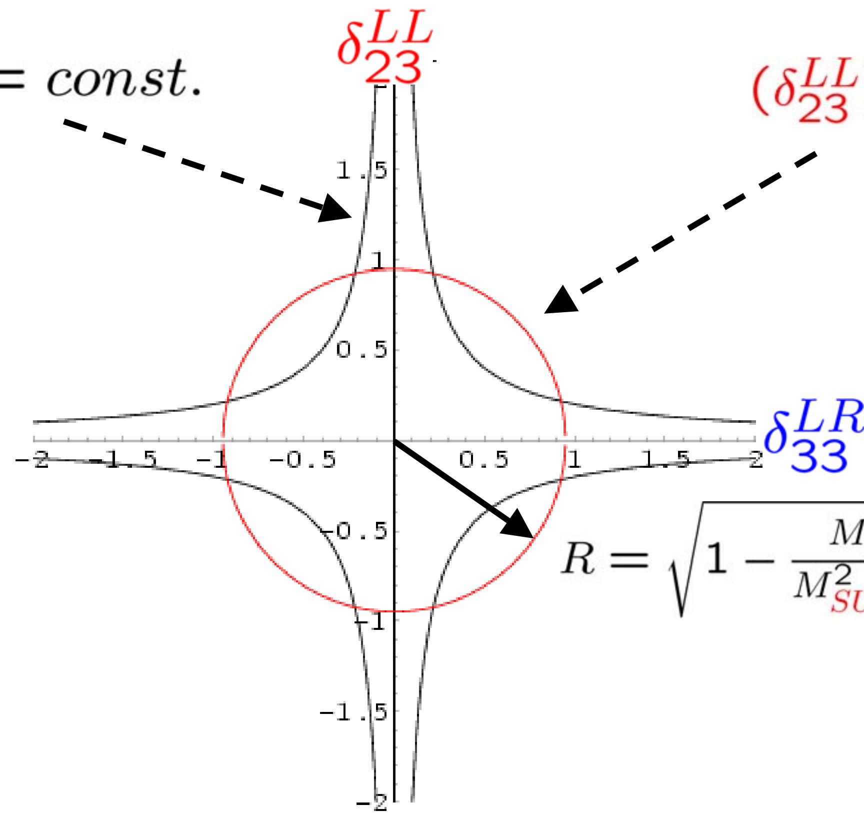
$$\boxed{(\delta_{23}^{LL})^2 + (\delta_{33}^{LR})^2 < \left(1 - \frac{M_l^2}{M_{SUSY}^2}\right)^2 \equiv R^2}$$

* in the approximation

$$M_{\tilde{q}}^2 = M_{SUSY}^2 \left(\begin{array}{c|ccc} & c_L & t_L & t_R \\ \hline c_L & 1 & \delta_{23}^{LL} & 0 \\ t_L & \delta_{23}^{LL} & 1 & \delta_{33}^{LR} \\ t_R & 0 & \delta_{33}^{LR} & 1 \end{array}\right)$$

$\delta^{LL}_{23} \times \delta^{LR}_{33} = const.$

$(\delta^{LL}_{23})^2 + (\delta^{LR}_{33})^2 \equiv R^2$

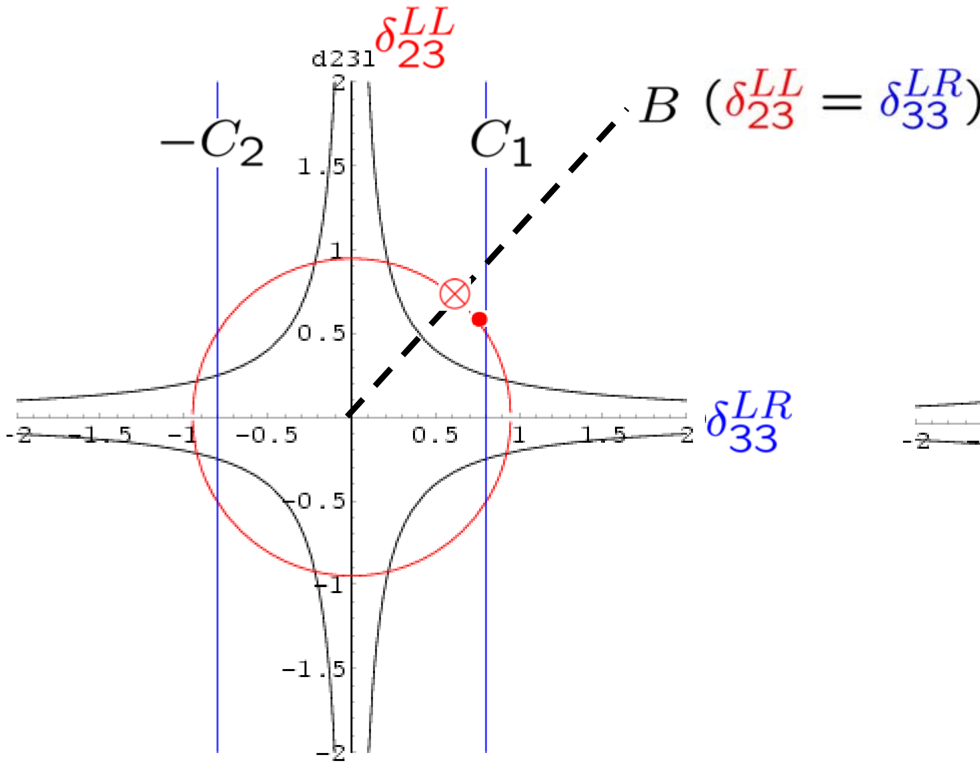


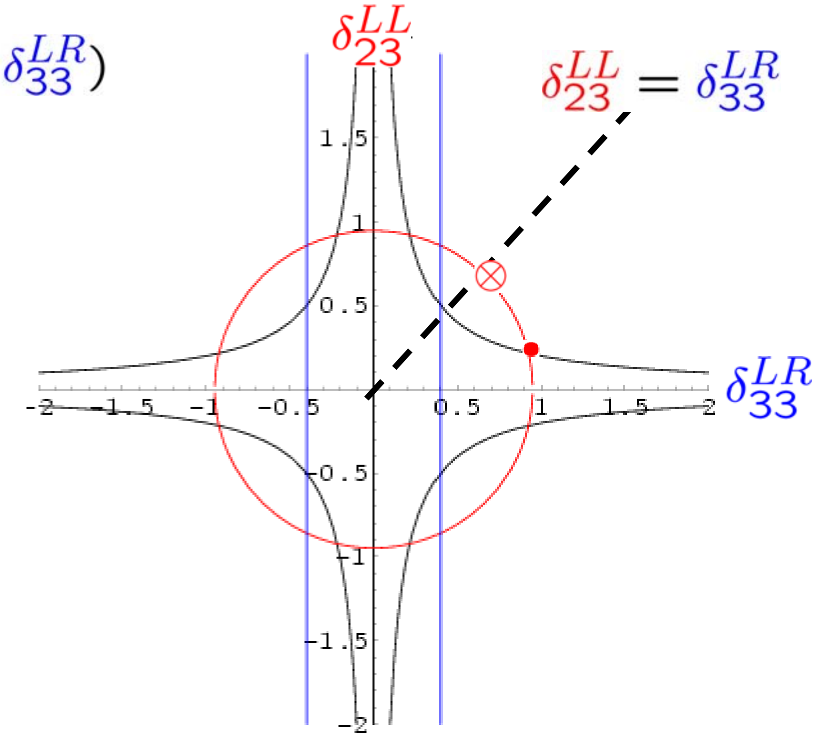
$R = \sqrt{1 - \frac{M_l^2}{M_{SUSY}^2}}$

Radius of allowed circle grows with M_{SUSY},
but then we would reach

$$A_t \equiv \frac{M_{SUSY}^2}{m_t}\delta^{LR}_{33} + \mu/\tan\beta \gg 3M_{SUSY}$$ (color-breaking condition !!)

Must require $|A_t| < 3M_{SUSY}$ $\Rightarrow$ $-C_2 < \delta^{LR}_{33} < C_1$





Putting all conditions together and in the approximation $C_1 = C_2 \Rightarrow$ maximum of σ occurs when the crossing point $\bullet$ lies also in the bisector line $B \Rightarrow \otimes$

$$\delta_{33}^{LR} = \delta_{23}^{LL} = \frac{\sqrt{2}}{1+\sqrt{1+\frac{2}{9}\frac{M_l^2}{m_t^2}}}$$

$$M_{SUSY} = \frac{3m_t}{\sqrt{2}}\left(1+\sqrt{1+\frac{2}{9}\frac{M_l^2}{m_t^2}}\right)$$

$$\Rightarrow A_t = \frac{M_{SUSY}^2}{m_t}\delta_{33}^{LR} + \mu \tan\beta$$

With $M_l = 150\,GeV$ (exp. limit)

$(\mu = -700\,GeV\,,\quad \tan\beta = 5)$

$\delta_{23}^{LL} = \delta_{33}^{LR}$	$\simeq 0.68$
A_t	$\simeq 2174$ GeV
M_{SUSY}	$\simeq 771$ GeV

What are the restrictions on this maximum from $b \longrightarrow s\,\gamma$?

$\delta_{33}^{(b)LR}$

$$\boxed{A(b \to s\gamma) \sim \delta_{23}^{(b)LL} \times \frac{m_b(A_b - \mu \tan\beta)}{M_{SUSY}^2} \times \frac{1}{M_{\tilde{g}}}}$$

$(\delta_{23}^{(b)LL}, \delta_{33}^{(b)LR})$ - plane (similar arguments as before)

We must impose $|\mu| < \frac{A_b}{\tan\beta} < \frac{3M_{SUSY}}{\tan\beta}$

(easy to satisfy because $\tan\beta$ is preferred small, $\tan\beta = \mathcal{O}(1)$, by our σ(FCNC))

In these conditions the position of the previously found maximum should essentially stay unmodified

Conclusions

- FCNC rare processes can be a complementary **clue** to disentangle hints of physics **beyond** the SM at the LHC, most particularly of **SUSY**;

- There are various sources of enhanced FCNC processes of this kind, but the most important ones are: **i)** FCNC Higgs boson decays, and **ii)** direct production by **SUSY**-FCNC couplings.

- Both kinds of processes can be comparable. For the favorable $\boxed{t\,c}$ final state one may collect up to 10^5 **events** in the LHC versus **zero** in the SM;

FCNC processes can be a **helpful signature** of **SUSY** physics in the forthcoming LHC collider