Single top-quark production by Strong and Electroweak supersymmetric flavor-changing interactions in the LHC

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Outline

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2. $pp \longrightarrow t\bar{c} + \bar{t}c$: phenomenological context
   - A brief motivation
   - Supersymmetry basics
   - the Minimal Supersymmetric Standard Model
   - SUSY in particle phenomenology
3. $pp \longrightarrow t\bar{c} + \bar{t}c$: Computational Setup
4. $pp \longrightarrow t\bar{c} + \bar{t}c$: Numerical Results
   - Standard Model contribution
   - SUSY-QCD contribution
   - SUSY-EW contribution
5. Conclusions

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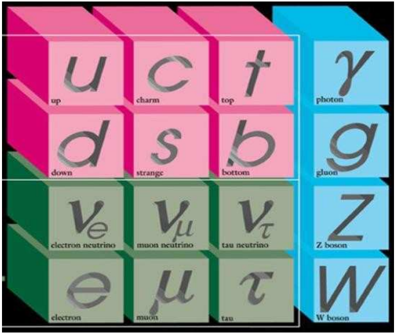

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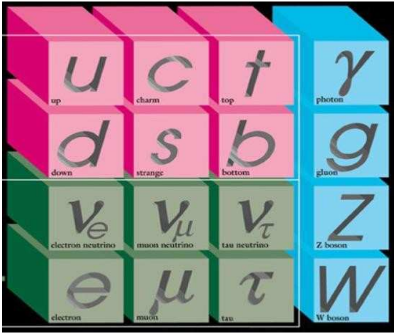
- What can we actually see ?
  - Old problems: mass generation, quadratic divergences, GUT unification



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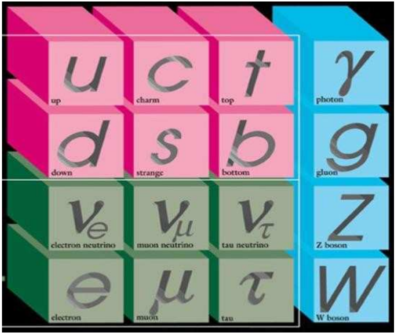

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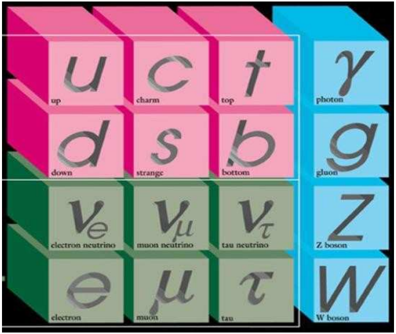
  - Old problems: mass generation, quadratic divergences, GUT unification
  - Current ideas: 2HDM's, technicolor, low-energy SUSY
  - Future tools: the LHC ! ⇒ New Physics unveiled at the TeV scale ?



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Theorem (Haag-Sohnius-Lopuszanski, 1975)

The largest symmetry which an interacting, unitary field theory can have is the direct product of (several) gauge symmetries, Poincaré invariance (P^μ), and Supersymmetry (Q), in such a way that:

$$\{Q^A_\alpha, \bar{Q}_{\dot{\beta}B}\} = 2\sigma^\mu_{\alpha\dot{\beta}} P_\mu \delta^A_B$$
$$\{Q^A_\alpha, Q^B_\beta\} = \{\bar{Q}_{\dot{\alpha}A}, \bar{Q}_{\dot{\beta}B}\} = 0$$
$$[P_\mu, Q^A_\alpha] = [P_\mu, \bar{Q}_{\dot{\alpha}A}] = 0$$
$$[P_\mu, P_\nu] = 0$$

the MSSM

How can we build up a supersymmetrized version of the SM ?

- $SU_C(3) \otimes SU_L(2) \otimes U_Y(1)$ gauge invariance
- Renormalizability
- A set of Soft SUSY-breaking parameters
- A minimal matter content
- A Minimal number of Yukawa couplings

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Minimal **S**upersymmetric **S**tandard **M**odel

MSSM: particle content

	fields			gauge group		
	superfield	fermion	boson	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Matter sector						
Quarks	$\tilde{Q}_i$	$\begin{pmatrix} u_i \\ d_i \end{pmatrix}_L$	$\begin{pmatrix} \tilde{u}_i \\ \tilde{d}_i \end{pmatrix}_L$	**3**	**2**	$\frac{1}{3}$
	$\hat{U}_i$	$u^c_{i\,R}$	$\tilde{u}^*_{i\,R}$	$\bar{\mathbf{3}}$	**1**	$-\frac{4}{3}$
	$\hat{D}_i$	$d^c_{i\,R}$	$\tilde{d}^*_{i\,R}$	$\bar{\mathbf{3}}$	**1**	$-\frac{4}{3}$
Leptons	$\hat{L}_i$	$\begin{pmatrix} \nu_i \\ e_i \end{pmatrix}_L$	$\begin{pmatrix} \tilde{\nu}_i \\ \tilde{e}_i \end{pmatrix}_L$	**1**	**2**	-1
	$\hat{E}_i$	$e^c_{i\,R}$	$\tilde{e}^*_{i\,R}$	**1**	**1**	2
Gauge sector						
$SU(3)_C$	$\hat{G}^a$	$\tilde{\lambda}^a_g$	g^a_μ	**8**	**1**	0
$SU(2)_L$	$\hat{W}^i$	$\tilde{\lambda}^i_W$	W^i_μ	**1**	**3**	0
$U(1)_Y$	$\hat{B}$	$\tilde{\lambda}_B$	B_μ	**1**	**1**	0

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	fields			gauge group		
	superfield	fermion	scalar	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Higgs Sector						
	$\hat{H}_1$	$\begin{pmatrix} \tilde{H}_1^1 \\ \tilde{H}_1^2 \end{pmatrix}$	$\begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix}$	**1**	**2**	-1
	$\hat{H}_2$	$\begin{pmatrix} \tilde{H}_2^1 \\ \tilde{H}_2^2 \end{pmatrix}$	$\begin{pmatrix} H_2^1 \\ \tilde{H}_2^2 \end{pmatrix}$	**1**	**2**	1

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	mass eigenstates	gauge eigenstates
(physical) **Higgses**	$h^0, H^0, A^0, H^\pm$	$H_1^0, H_2^0, H_1^-, H_2^+$
squarks	$\tilde{u}_\alpha, \tilde{d}_\alpha, \alpha = 1, \ldots, 6$	$\tilde{u}_L, \tilde{u}_R, \tilde{d}_L, \tilde{d}_R$
sleptons	$\tilde{l}_1, \tilde{l}_2, \tilde{\nu}_l$	$\tilde{l}_L, \tilde{l}_R, \tilde{\nu}_l$
neutralinos	$\tilde{\chi}_1, \tilde{\chi}_2, \tilde{\chi}_3, \tilde{\chi}_3$	$\tilde{B}^0, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0$
charginos	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	$\tilde{W}^\pm, \tilde{H}_1^-, \tilde{H}_2^+$

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♠ Direct production ⇒ tagging through the decay products

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$$\widetilde{t} \longrightarrow \widetilde{\chi}^+ b \longrightarrow \widetilde{\chi}^0_1 b W^+$$

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$$\tilde{t} \to \tilde{\chi}^+ b \to \tilde{\chi}_1^0 b W^{+*} \Rightarrow \begin{cases} \tilde{\chi}_1^0 b \, \ell \, \nu \\ \tilde{\chi}_1^0 b + 2jets \end{cases}$$

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$$\mathcal{B}(t \to c\, g) \begin{cases} \sim 10^{-11} \text{ (SM)} \\ \leq 10^{-5} \text{ (MSSM)} \end{cases}$$

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Flavor Changing Neutral Current

$$\mathcal{B}(t \longrightarrow c\, g) \begin{cases} \sim 10^{-11}\ (\text{SM}) \Rightarrow \text{GIM-supressed !} \\ \lesssim 10^{-5}\ (\text{MSSM})\ \text{enhanced !} \end{cases}$$

Guasch, Solà ['99]

Outline

Previous studies

- Liu, Li, Yang, Jin (2004)
- Guasch, Hollik, Peñaranda, Solà (2005)
- Eilam, Frank, Turan (2006).

General Features

- The 1-loop order is the leading order for a process such as pp $\rightarrow t\bar{c} + \bar{t}c$ (the GIM mechanism forbidds any tree-level contribution.)
  - We do not have to renormalize any bare parameter nor field-strenght term.
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Setting up the parameters

- We fix the Renormalization and Factorization scales at a common value, $\mu_R = \mu_F = \frac{1}{2}(m_c + m_t)$
- We take the RG running SM parameters at μ_R:
  - for the masses
  - For the coupling constants

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$m_c(\mu_R)$ (GeV)	$m_b(\mu_R)$ (GeV)	$m_t(\mu_R)$ (GeV)
0.877	3.024	183.365

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$\alpha_s(\mu_R)$	$\alpha_{em}(\mu_R)$	$\sin^2\theta_W(\mu_R)$
0.1177	1/128.89	0.23

Hadronic Cross Sections

- The process pp $\rightarrow$ t$\bar{c}$ + $\bar{t}$c can be **factorized** into two pieces:

- We get the total hadronic cross section by convoluting $\frac{d\mathcal{L}}{d\tau}$ with the partonic cross section $\sigma_{gg\rightarrow t\bar{c}}$:

$$\sigma_{pp\rightarrow t\bar{c}} = \int_{\tau_0}^{1} d\tau\, \frac{d\mathcal{L}}{d\tau} \hat{\sigma}_{gg\rightarrow t\bar{c}}(\hat{S}, \alpha_s(\mu_R))$$

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  - The short-distance (perturbative) partonic subprocess, gg → tc̄
  - The long-distance (non-perturbative) dynamics of the gluons, encoded in the *gluon luminosity*

$$\frac{d\mathcal{L}}{d\tau} = \int_{\tau}^{1} \frac{dx}{x}\, f_{pg}(x,\mu_F)\, f_{pg}(\frac{\tau}{x},\mu_F)$$

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Phenomenological Constraints

- B-meson radiative decay

$$\mathcal{B}(\mathrm{b} \to \mathrm{s}\,\gamma) = (2.1 - 4.5) \times 10^{-4}$$

at the 3σ level CLEO, ALEPH, BELLE, BABAR

PDG 2006

- Mass bounds

$$m_{\tilde{\chi}^0_1} > 46\text{GeV} \qquad m_{\tilde{\chi}^\pm_1} > 94\text{GeV}$$

$$m_{\tilde{\mathrm{b}}} > 89\text{GeV} \qquad m_{\tilde{\mathrm{t}}} > 95.7\text{GeV}$$

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- We have made use of the standard computational packages:
    - **FeynArts:** for the generation of the Feynman diagrams
    - **FormCalc:** for the analytical computation and simplification of the scattering amplitude
    - **LoopTools:** for the computation of the loop integrals
- We also need to adress the computation of the hadronic cross section:
    - **HadCalc:** for the convolution of the partonic cross section with the gluon luminosity M.Rauch [06]
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T. Hahn www.feynarts.de

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  - **FormCalc:** for the analytical computation and simplification of the scattering amplitude
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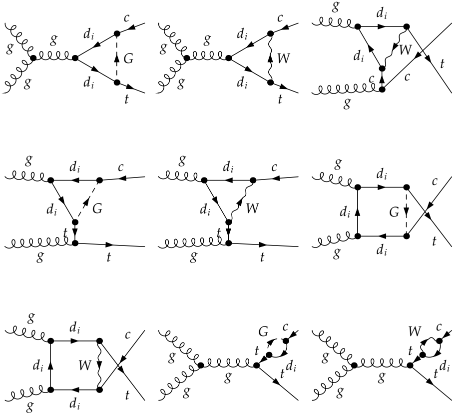
Outline

SM results



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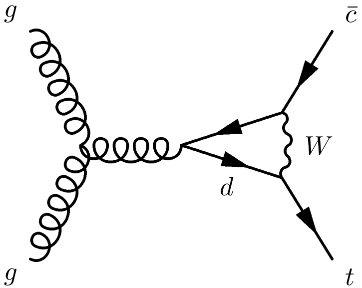

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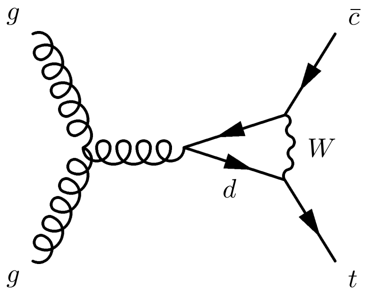

Let us compute the corresponding form factor

$$f \sim \frac{g^2}{16\pi^2} \sum_{i=d,s,b} (K^*_{ti}\, K_{ic}) \left(\frac{m_i}{M_W}\right)^2$$

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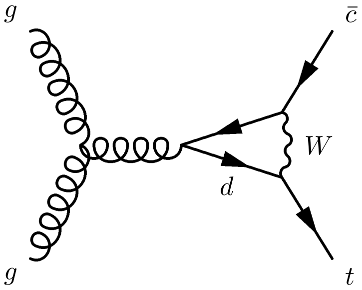

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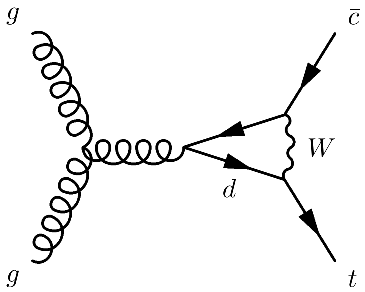

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LL-block only: based on RG arguments Duncan ['83]

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Therefore ...

Non-standard flavor-changing effects in the t$\bar{c}$ sector also become constrained by $\mathcal{B}(b \longrightarrow s\gamma)$

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The above flavor-changing terms participate through the gaugino-quark-squark couplings of the guise:

$$\mathcal{L}_{\tilde{\lambda}\psi\tilde{\psi}} \quad = \quad i\sqrt{2}\, g_s \tilde{\psi}_k^* \tilde{\lambda}^a (T^a)_{kl} \psi_l + h.c.$$

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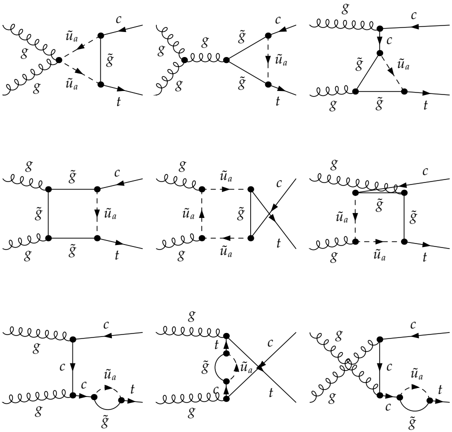
Such couplings are free of GIM supressions

SUSY-QCD contribution



$b \longrightarrow s\gamma$ constraints

The MSSM parameter space gets restricted by the SUSY contributions to the B-meson radiative decay Bobeth, Misiak, Urban ['99]

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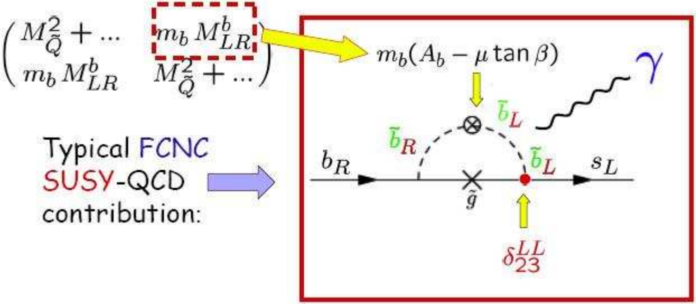

$$A(b \to s\gamma) \sim \delta_{23}^{(d)LL} \times \frac{m_b(A_b - \mu \tan\beta)}{M_{SUSY}^2} \times \frac{1}{m_{\tilde{g}}}$$

SUSY-QCD contribution

$\tan\beta$	5
A_t(GeV)	2238.25
A_b(GeV)	2000
$m_{\tilde{g}}$(GeV)	200
M_{SUSY}(GeV)	746
μ(GeV)	400
$\delta_{23}^{LL}(u)$	0.7

Table 1: Set (I) of MSSM parameters (favoring SUSY-QCD) Guasch, Hollik, Peñaranda, Solà ['06]

SUSY-QCD contribution

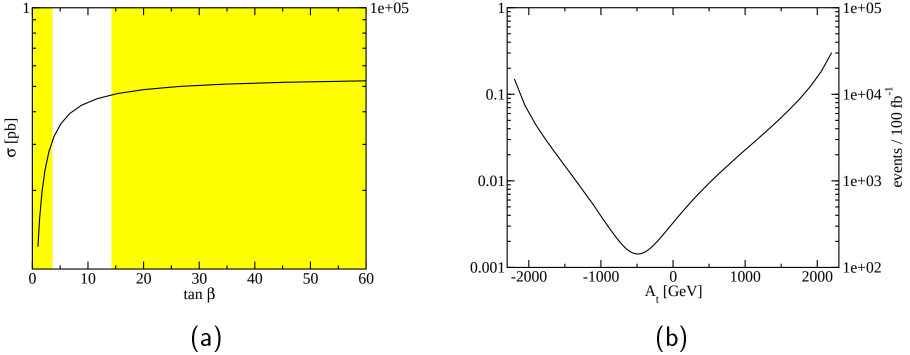

Figure 1: SUSY-QCD contribution to the total cross section $\sigma_{t\bar{c}}$ (in pb) and the corresponding number of events per 100 fb^{-1} of integrated luminosity at the LHC, as a function of **a)** $\tan\beta$ and **b)** A_t for the set I of MSSM parameters. The shaded region in **a)** is excluded by $B_{exp}(\mathrm{b} \longrightarrow \mathrm{s}\gamma)$.

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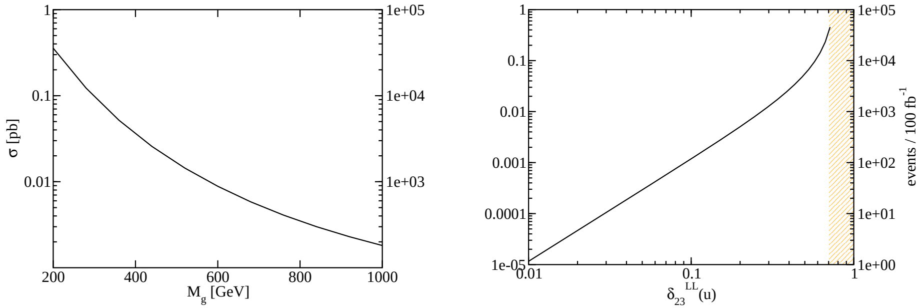

(a) (b)

Figure 2: SUSY-QCD contribution to the total cross section $\sigma_{t\bar{c}}$ (in pb) and the corresponding number of events per 100 fb^{-1} of integrated luminosity at the LHC, as a function of **a)** $m_{\tilde{g}}$ and **b)** $\delta_{23}^{LL}(u)$ for the set (I) of MSSM parameters.

SUSY-QCD contribution

- In the most favorable scenarios, those triggered by light gluino masses and large intergenerational mixing, we get production rates of $2\sigma_{t\bar{c}} \sim 10^5$ events per 100 fb^{-1} of integrated luminosity at the LHC
- Notice thus that

$$\frac{\sigma(gg \to t\bar{c})_{\mathrm{SUSY-QCD}}}{\sigma(gg \to t\bar{c})_{\mathrm{SM}}} \sim 10^7$$

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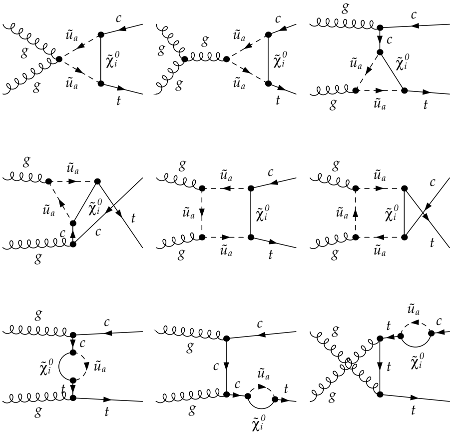
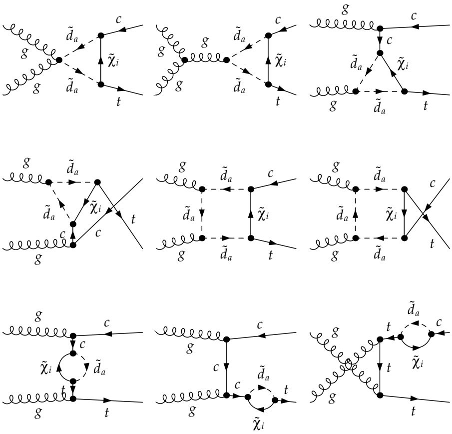


SUSY-EW

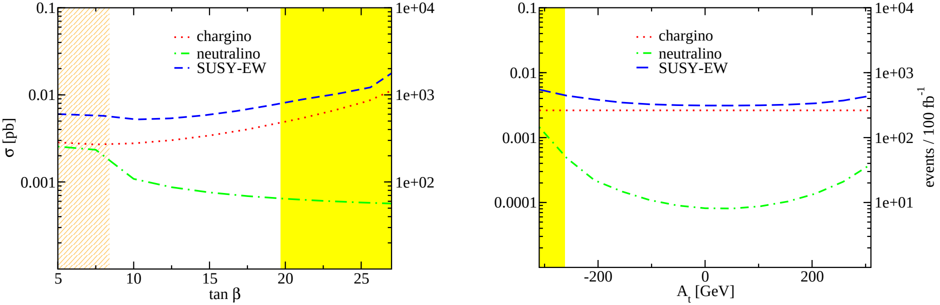


SUSY-EW

$\tan\beta$	10
A_t(GeV)	-300
A_b(GeV)	-300
A_τ(GeV)	-300
$m_{\tilde{g}}$(GeV)	2000
M_{SUSY}(GeV)	250
μ(GeV)	400
M_1(GeV)	48
M_2(GeV)	102
M_{A^0}(GeV)	150
$\delta_{23}^{LL}(u)$	0.7

Table 2: Set (II) of MSSM parameters (favoring SUSY-EW)

SUSY-EW



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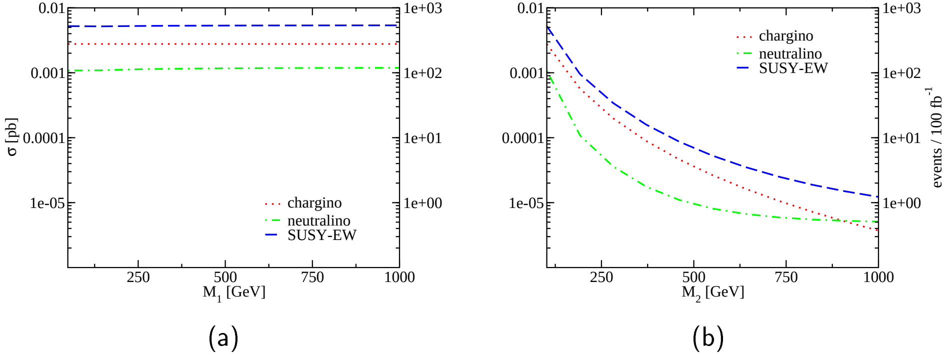
SUSY-EW



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Comparison

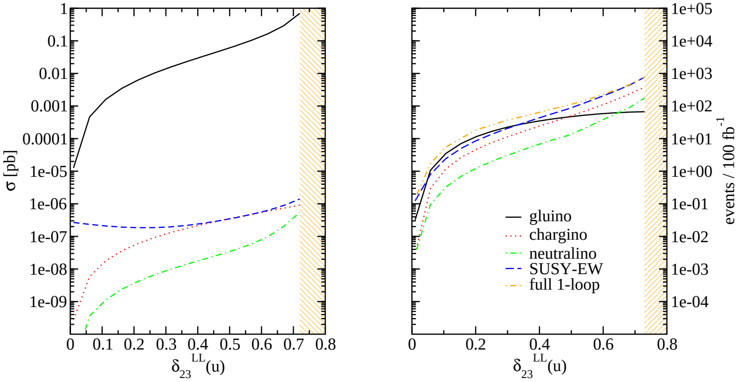

Figure 5: SUSY-QCD and SUSY-EW contributions to the total cross section $\sigma_{t\bar{c}}$ (pb) as a function of $\delta_{23}^{LL}(u)$ for the choices of parameters that optimize the SUSY-QCD part (left) and the SUSY-EW one (right).

On the whole ...

basic features

- The SUSY-EW contribution to $\sigma(\mathrm{pp} \longrightarrow \mathrm{t}\bar{\mathrm{c}} + \bar{\mathrm{t}}\mathrm{c})$ is particularly sensitive to the wino mass (M_2) and the SUSY-breaking scale (M_{SUSY}), as well as to δ_{23}.
- There are regions in the MSSM parameter space where the SUSY-EW contribution becomes of the order, and even higher, than that of SUSY-QCD.
- Such scenarios bring us lower (but still sizeable) production rates of 10^3 events per 100 fb^{-1} of integrated luminosity.
- Therein the t$\bar{c}$ quark pair production turns out to be sensitive to both the SUSY-EW and the SUSY-QCD effects .

Outline

Conclusions

- The aim of the present work was to study the direct SUSY single top-quark production through gluon fusion in pp collisions at the LHC, in correspondence with the $\mathcal{B}(b \rightarrow s\gamma)$ constraints.
- In the most favorable scenarios, the SUSY-QCD contribution can lead to $\sigma(pp \rightarrow t\bar{c} + \bar{t}c) \sim 10^5$ events per 100 fb^{-1}.
- Such scenarios entail light gluino masses ($m_{\tilde{g}}$) and large intergenerational mixings (δ_{LL}^{23}).
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