Production and decay of top quark via FCNC couplings beyond leading order

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Nov. 14 2008, UCST, Hefei

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1. Introduction

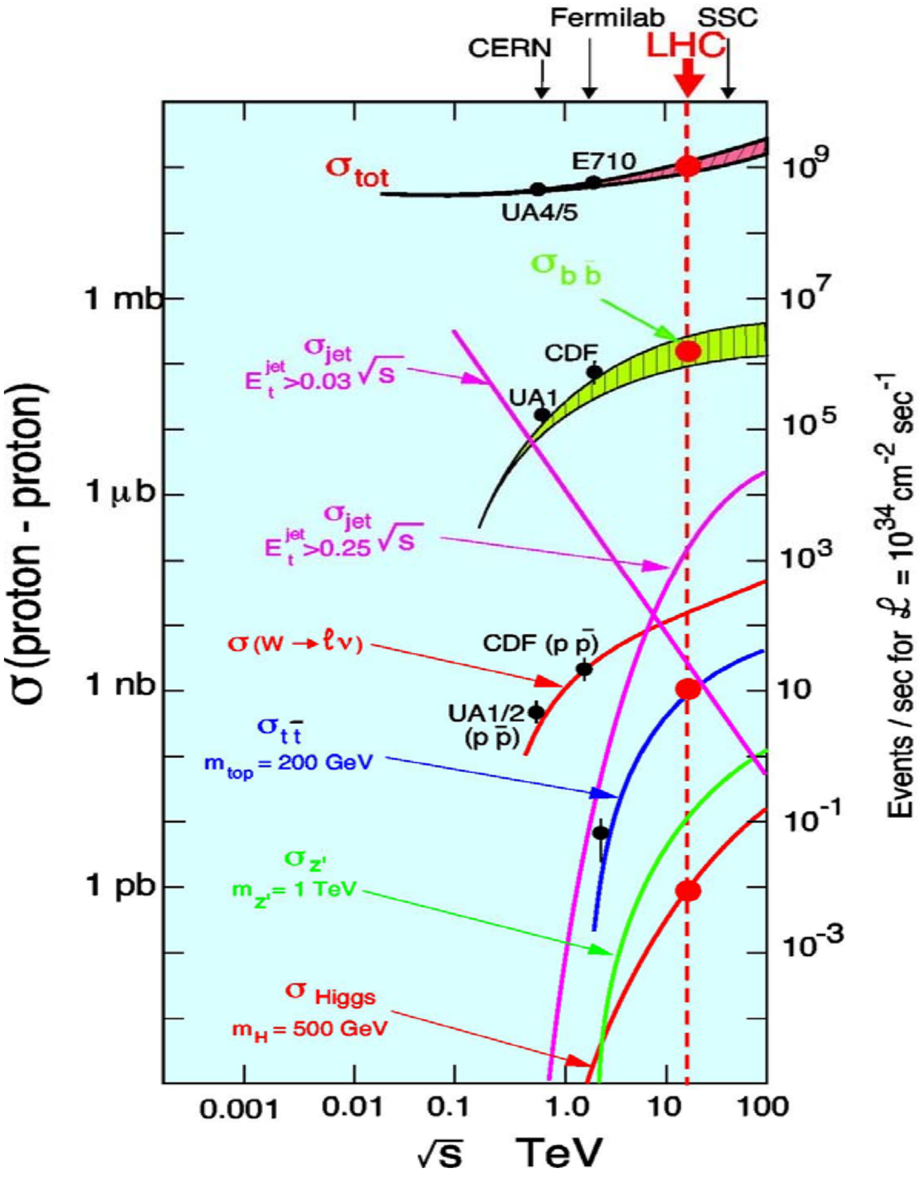
- LHC can produce abundant top events. Even in the initial low luminosity run (~ 10 fb^{-1} / year) 8 x 10^6 top quark pairs and 3 x 10^6 single top quark will be produced per year.

- With such large samples, precise measurements of its couplings will be available to test the SM predictions.

- Within the SM, FCNC couplings vanish at the tree level by the GIM mechanism and all FCNC processes are highly suppressed at the one –loop level according to the CKM matrix .

- Beyond the SM this GIM suppression can be relaxed, in some models involving new physics FCNC top quark couplings could appear at the tree level, and, therefore, lead to large FCNC effects.

● Cross Sections and Production Rates



Rates for L = 10^{34} cm^{-2} s^{-1}: (LHC)

• Inelastic proton-proton reactions:	10^9 / s
• bb pairs	5 10^6 / s
• tt pairs	8 / s
• W → e ν	150 / s
• Z → e e	15 / s
• Higgs (150 GeV)	0.2 / s
• Gluino, Squarks (1 TeV)	0.03 / s

LHC is a factory for:
top-quarks, b-quarks, W, Z, ……. Higgs, ……

The only problem: you have to detect them !

- Since we do not know which type of new physics will be responsible for a possible deviation from SM predictions, it is necessary to study the top quark FCNC production and decay in a model-independent way.

- Any new physics effect involved in top quark FCNC processes can be incorporated into an effective Lagrangian :

$$\begin{aligned}\mathcal{L}^{\rm eff} = & -\frac{g}{2\cos\theta_W}\sum_{q=u,c}\bar{t}\gamma^\mu(v^Z_{tq} - a^Z_{tq}\gamma_5)qZ_\mu - \frac{g}{2\cos\theta_W}\sum_{q=u,c}\frac{\kappa^Z_{tq}}{\Lambda}\bar{t}\sigma^{\mu\nu}(f^Z_{tq}+ih^Z_{tq}\gamma_5)qZ_{\mu\nu} \\ & -e\sum_{q=u,c}\frac{\kappa^\gamma_{tq}}{\Lambda}\bar{t}\sigma^{\mu\nu}(f^\gamma_{tq}+ih^\gamma_{tq}\gamma_5)qA_{\mu\nu} - g_s\sum_{q=u,c}\frac{\kappa^g_{tq}}{\Lambda}\bar{t}\sigma^{\mu\nu}T^a(f^g_{tq}+ih^g_{tq}\gamma_5)qG^a_{\mu\nu} + \text{h.c.}\,(1)\end{aligned}$$

where Λ is the new physics scale, κ is normalized to be real and positive and f, h to be complex numbers satisfying $|f|^2 + |h|^2 = 1$ for each term.

- Colliders such as the Tevatron, HERA and LHC have a nice opportunity to probe top quark FCNC couplings.

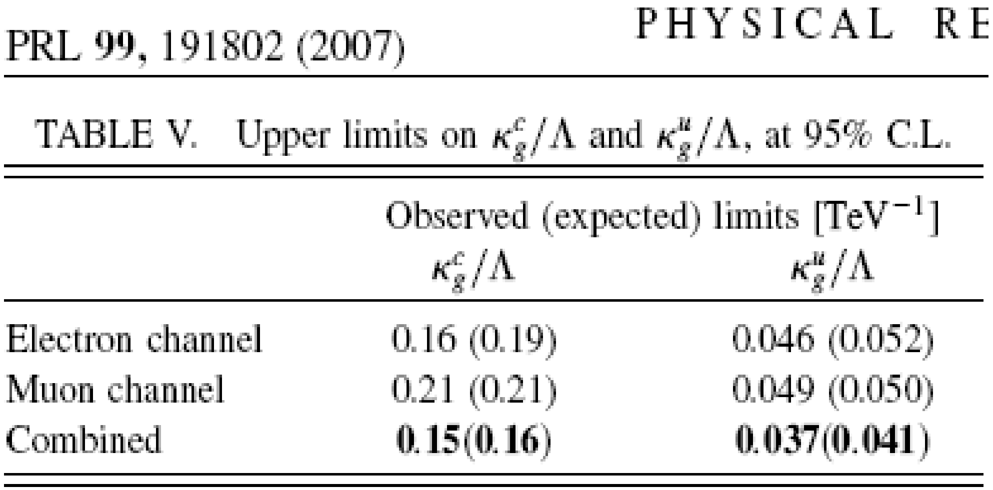
- In fact, very recent data from D0 collaboration has set upper limits on the top quark FCNC couplings.

  The upper limits on the anomalous coupling parameters at 95% C.L. are:

D0 Collaboration, Phys. Rev. Lett. 99,191802(2007)

$$\kappa^{c}{}_{g}/\Lambda < 0.15\mathrm{TeV}^{-1}$$

$$\kappa^{u}{}_{g}/\Lambda < 0.037\mathrm{TeV}^{-1}$$



PRL 99, 191802 (2007) PHYSICAL RE

TABLE V. Upper limits on κ_g^c/Λ and κ_g^u/Λ, at 95% C.L.

	Observed (expected) limits [TeV^{-1}]	
	κ_g^c/Λ	κ_g^u/Λ
Electron channel	0.16 (0.19)	0.046 (0.052)
Muon channel	0.21 (0.21)	0.049 (0.050)
Combined	**0.15(0.16)**	**0.037(0.041)**

2. Single top quark production via anomalous couplings

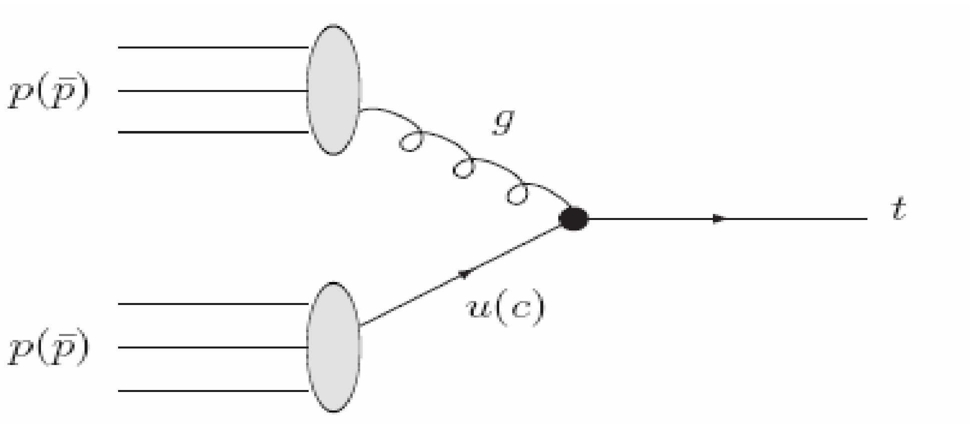
- The top quark FCNC processes induced by some new physics, such as SUSY, have been studied in detail[1,2,3]. In general, top quark decay processes provide the best place to discover top FCNC interactions involving anomalous t–q–γ and t–q–Z couplings. However, for t–q–g anomalous couplings, the direct top quark production processes are the most sensitive ones [4,5,6,7].

[1]. C.S.Li, R.J. Oakes, J.M.Yang, PRD, 49, 293(1994);
[2]. J.J.Liu, C.S.Li, L.L. Yang, and L.G. Jin PLB, 599,92(2004)
[3]. J.J.Liu, C.S.Li, L.L. Yang, and L.G. Jin Nucl, Phys. B705,3(2005)
[4] J.A. Aguilar-Saavedra, Acta Phys. Polon. B 35, 2695 (2004).
[5] T. Han, M. Hosch, K. Whisnant, B.-L. Young, and X. Zhang, PRD, 58, 073008 (1998); M. Hosch, K. Whisnant, and B.-L. Young, PRD 56, 5725 (1997).
[6] J.J. Liu, C.S.LI and L.L. Yang, PRD, 72,074018 (2005);
[7] L.L.Yang, C.S.Li, Y.Gao, and J.J. Liu, PRD, 73, 074017(2006)

- To probe smaller anomalous couplings, we must search for top quark FCNC processes directly. For κ^{g}_{tq} anomalous coupling, the most sensitive process is direct top quark production (Hosch, Whisnant and B.-L. Young, Phys. Rev. D 56, 5725; Tao Han, Hosch, Whisnant, B.-L. Young and X. Zhang, Phys. Rev. D 58, 073008).

Collider		Tevatron			LHC
$\sqrt{S}$ (TeV)		1.8	2		14
$\mathcal{L}$ (fb^{-1})		0.1	2	30	10
$\kappa^{g}_{tu}/\Lambda_N$	$2 \to 1$	0.058	0.019	0.0094	0.0033
	$2 \to 2$	0.082	0.026	0.013	0.0061
$\kappa^{g}_{tc}/\Lambda_N$	$2 \to 1$	0.22	0.062	0.030	0.0084
	$2 \to 2$	0.31	0.092	0.046	0.013

- Direct top quark production



- This is the most sensitive process to t-g-q anomalous couplings.

- The analysis based on the leading order cross sections suggests that the anomalous couplings can be detected down to 0.019/ TeV for q=u and 0.016/TeV for q=c at the Tevatron Run2, respectively.
  (M. Hosch et al., PRD56,5725(1997),T. Han et al., PRD58, 073008(1998))

- Studies with a fast detector simulation for ATLAS indicate a similar reach at the LHC (O.Cakir et al., J. Phys.G31,N1(2005))

Numerical results of leading order[5]

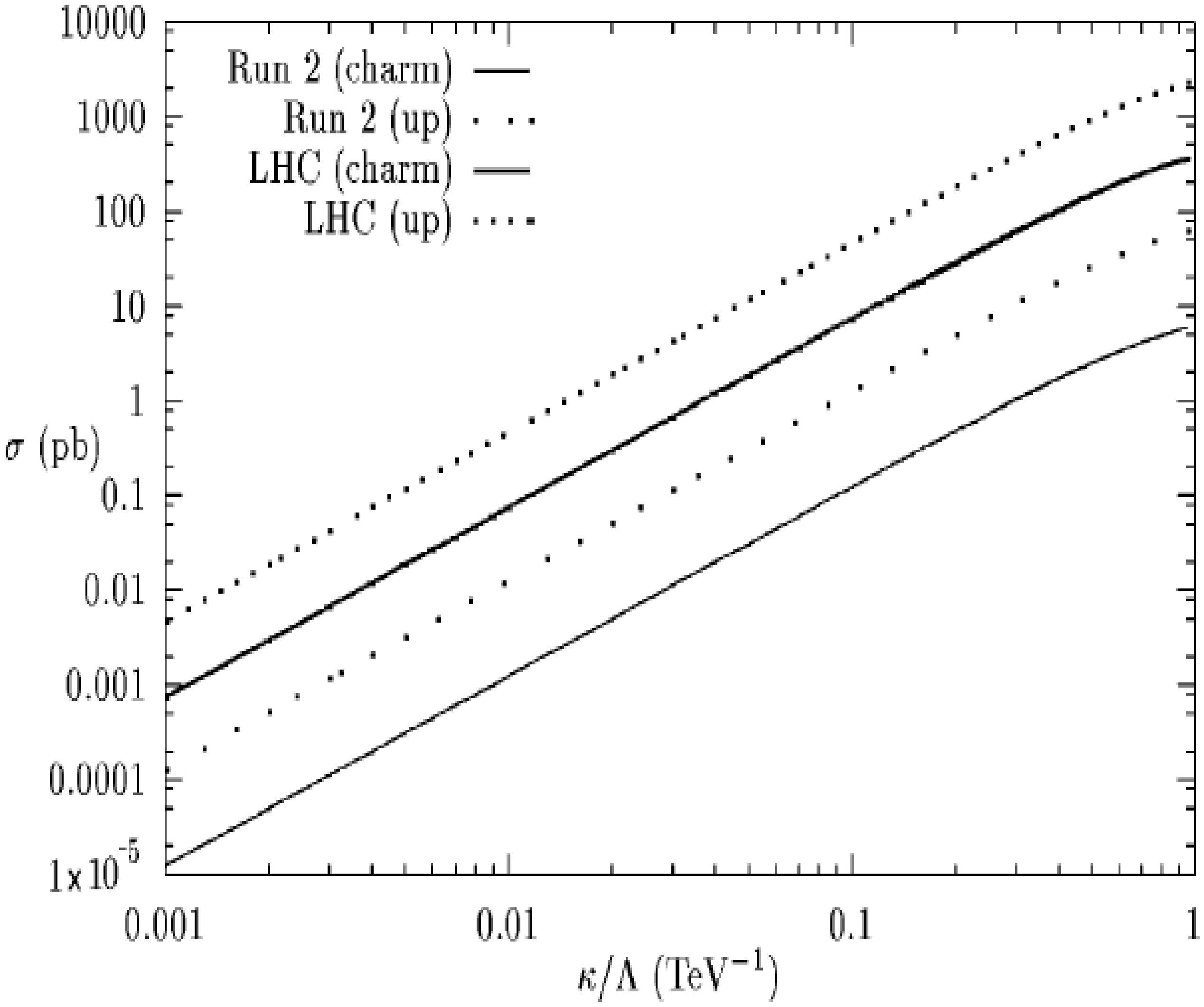
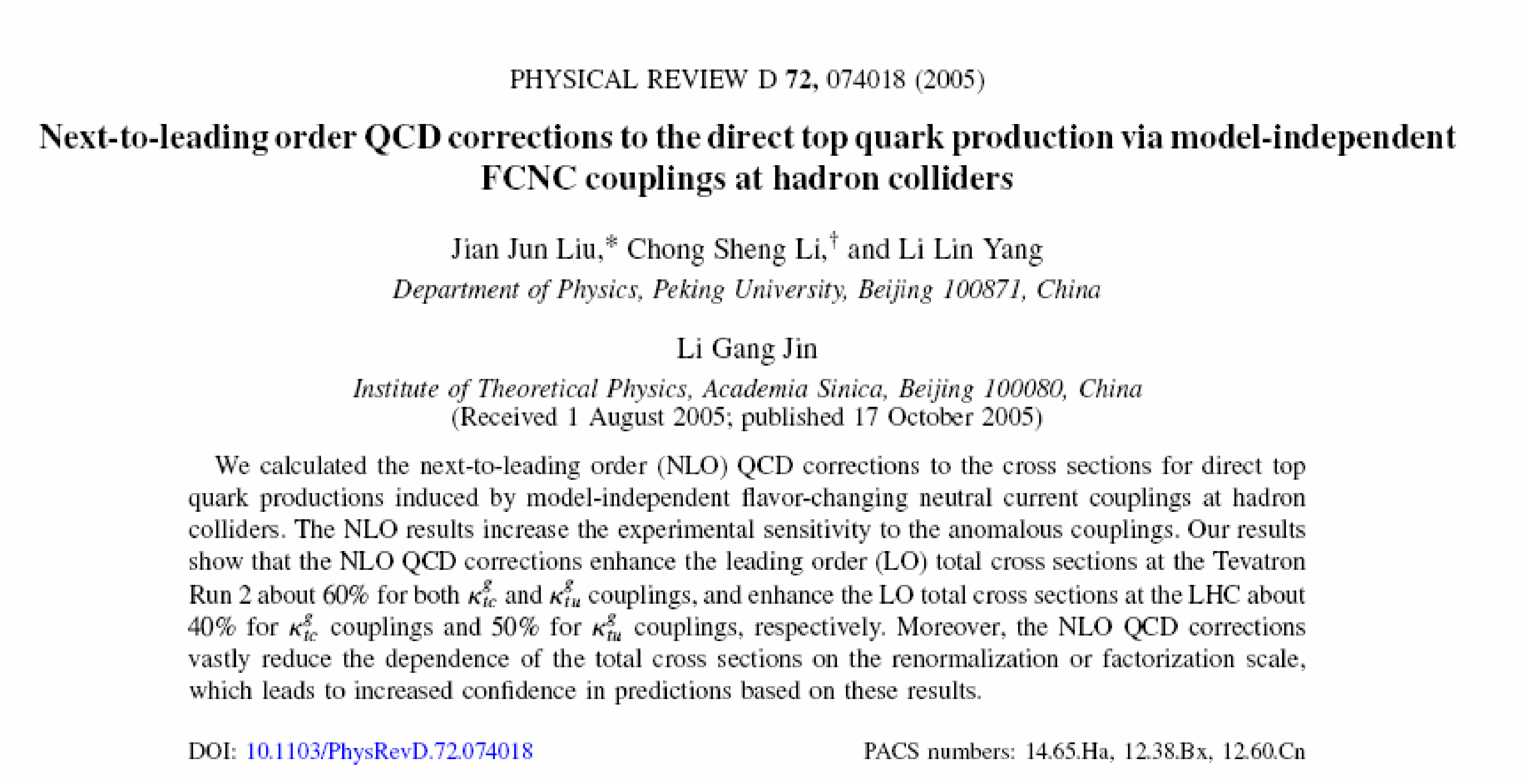


FIG. 2. Direct top quark cross section vs κ/Λ at run 2 of the Tevatron and the LHC. The cross sections for run 1 of the Tevatron are barely distinguishable from run 2, and are not shown here.

3. NLO QCD corrections[6]

As we know, LO cross sections at hadron colliders suffer from large uncertainties due to the arbitrary choices of the renormalization scale and factorization scale, and are not sufficient for the extraction of the anomalous couplings from experiments. In order to establish accurate limits on FCNC couplings, we need accurate predictions for both cross sections and decay branching ratios.



PHYSICAL REVIEW D **72,** 074018 (2005)

Next-to-leading order QCD corrections to the direct top quark production via model-independent FCNC couplings at hadron colliders

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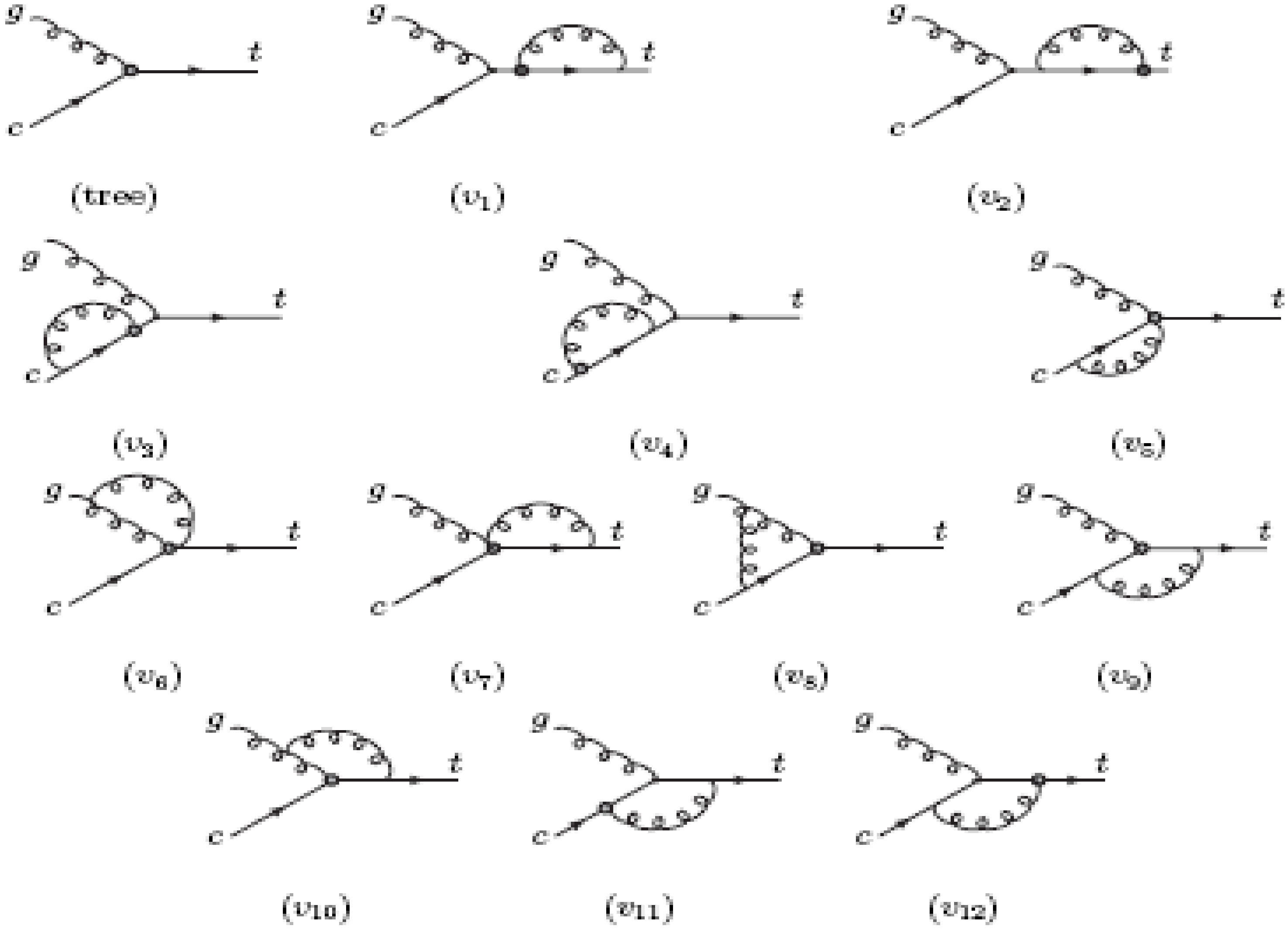
(Received 1 August 2005; published 17 October 2005)

We calculated the next-to-leading order (NLO) QCD corrections to the cross sections for direct top quark productions induced by model-independent flavor-changing neutral current couplings at hadron colliders. The NLO results increase the experimental sensitivity to the anomalous couplings. Our results show that the NLO QCD corrections enhance the leading order (LO) total cross sections at the Tevatron Run 2 about 60% for both κ_{tc}^{g} and κ_{tu}^{g} couplings, and enhance the LO total cross sections at the LHC about 40% for κ_{tc}^{g} couplings and 50% for κ_{tu}^{g} couplings, respectively. Moreover, the NLO QCD corrections vastly reduce the dependence of the total cross sections on the renormalization or factorization scale, which leads to increased confidence in predictions based on these results.

DOI: 10.1103/PhysRevD.72.074018 PACS numbers: 14.65.Ha, 12.38.Bx, 12.60.Cn



(tree) (v_1) (v_2)

(v_3) (v_4) (v_5)

(v_6) (v_7) (v_8) (v_9)

(v_{10}) (v_{11}) (v_{12})

FIG. 1. Tree-level and one-loop Feynman diagrams for the direct top quark production.

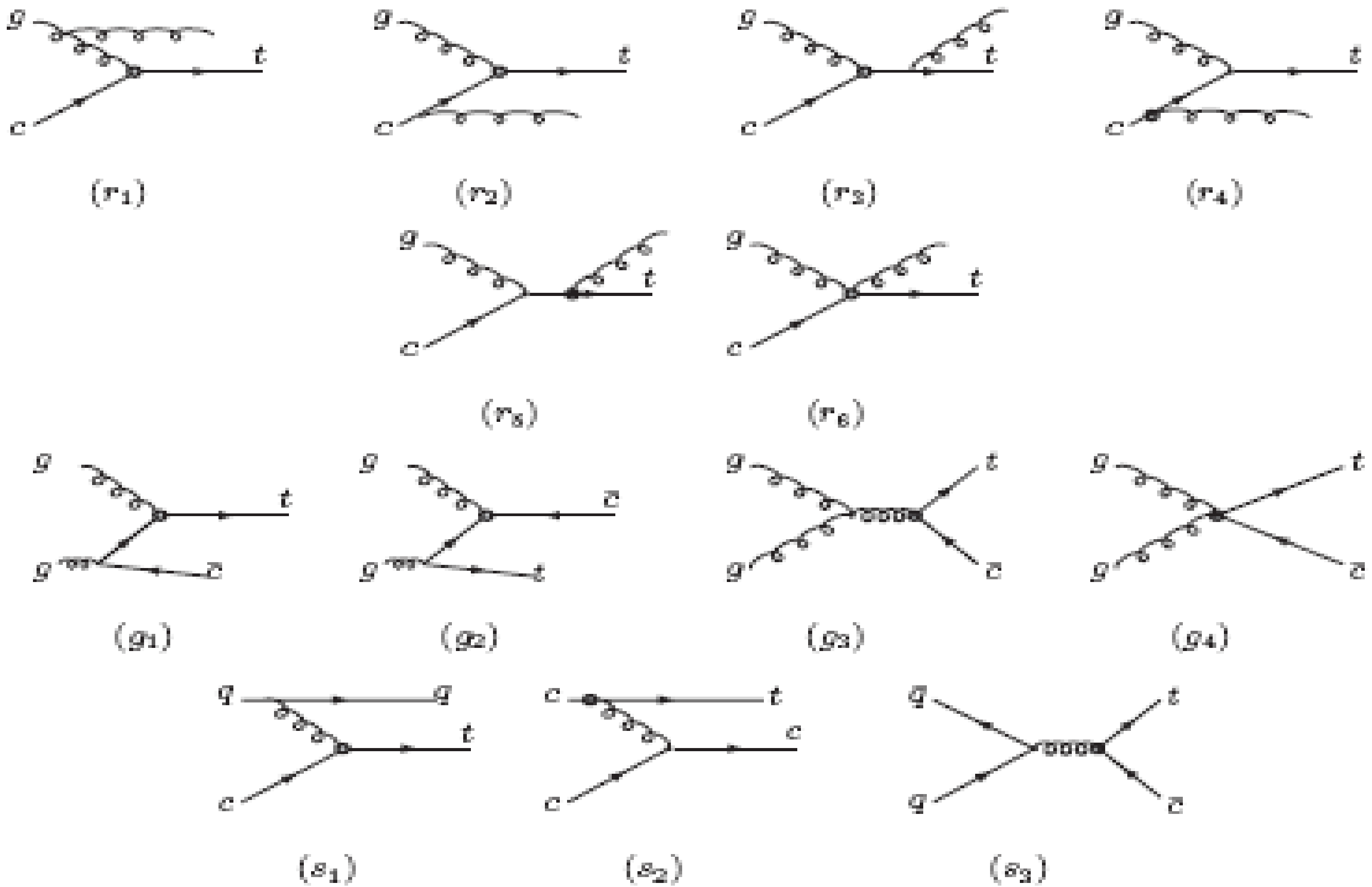
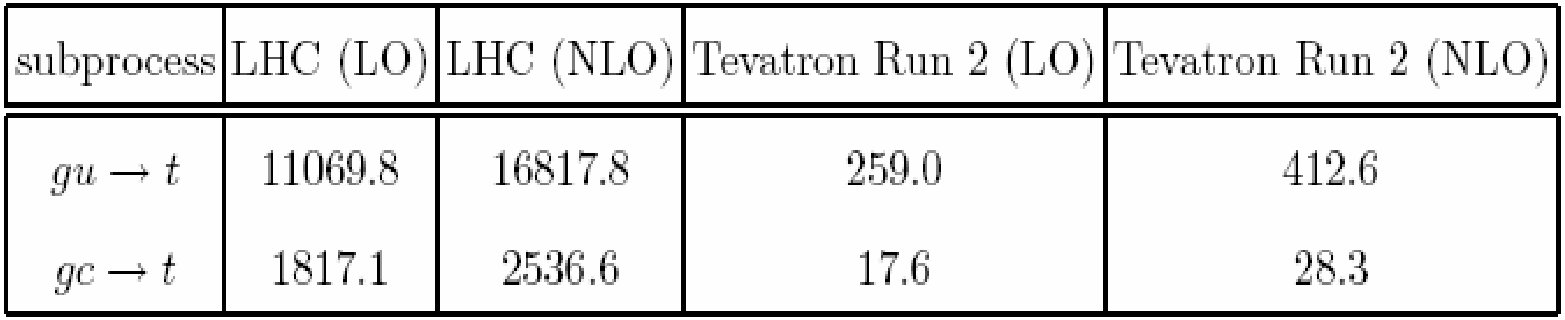


FIG. 2. Feynman diagrams of real gluon emission subprocesses [$(r_1) - (r_6)$], gluon initial state subprocesses [$(g_1) - (g_4)$], of which (g_1) and (g_2) have cross diagrams, and quark initial state subprocesses [$(s_1) - (s_3)$], of which (s_2) has a cross diagram.

• NLO Numerical Results at Tevatron and LHC

- In our numerical calculations, we take the top quark mass m_t = 178.0 GeV and the two–loop evolution of $\alpha_s(\mu_r)$ with $\alpha_s(M_Z)$ = 0.118. Moreover, CTEQ6L (CTEQ6M) PDFs are used in the calculation of the LO (NLO) cross sections. As for the anomalous couplings, which appear in the expressions as quadratic factors, we choose $\kappa_{tq}^{g}/\Lambda = 0.01 TeV^{-1}$.



subprocess	LHC (LO)	LHC (NLO)	Tevatron Run 2 (LO)	Tevatron Run 2 (NLO)
$gu \to t$	11069.8	16817.8	259.0	412.6
$gc \to t$	1817.1	2536.6	17.6	28.3

TABLE I: The LO and NLO cross sections of direct top quark production via anomalous FCNC couplings at the LHC and Tevatron Run 2 (fb). Here $\frac{\kappa_{tq}^{g}}{\Lambda} = 0.01$ TeV^{-1} and $\mu_F = \mu_r = m_t$.

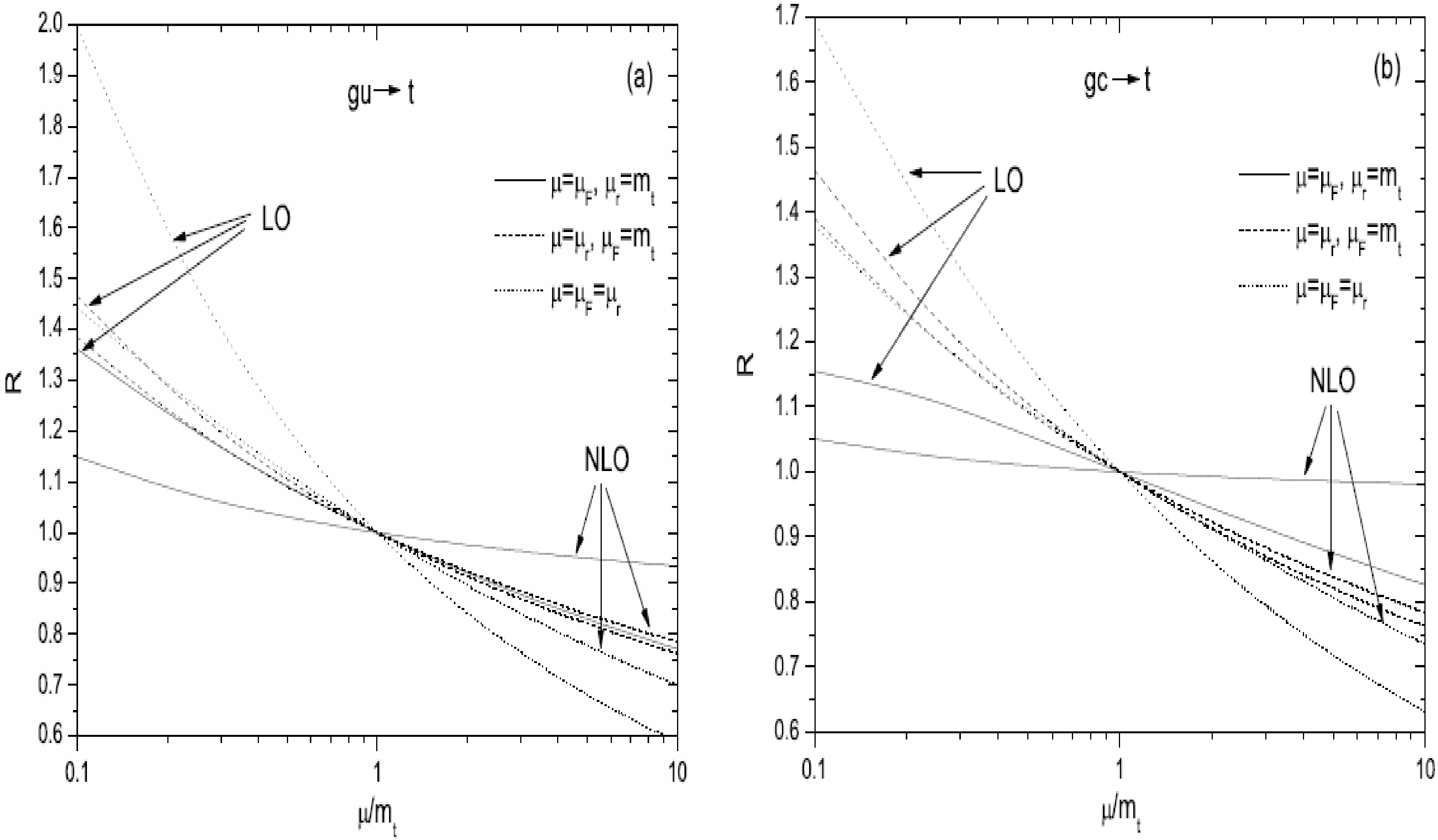


FIG. 3: The ratio R as functions of factorization (renormalization) scales for sub-processes $gc \to t$ and $gu \to t$ at the Tevatron Run 2: (a) up quark initial state and (b) charm quark initial state. Here $\frac{\kappa^g_{tc(u)}}{\Lambda} = 0.01\mathrm{TeV}^{-1}$.

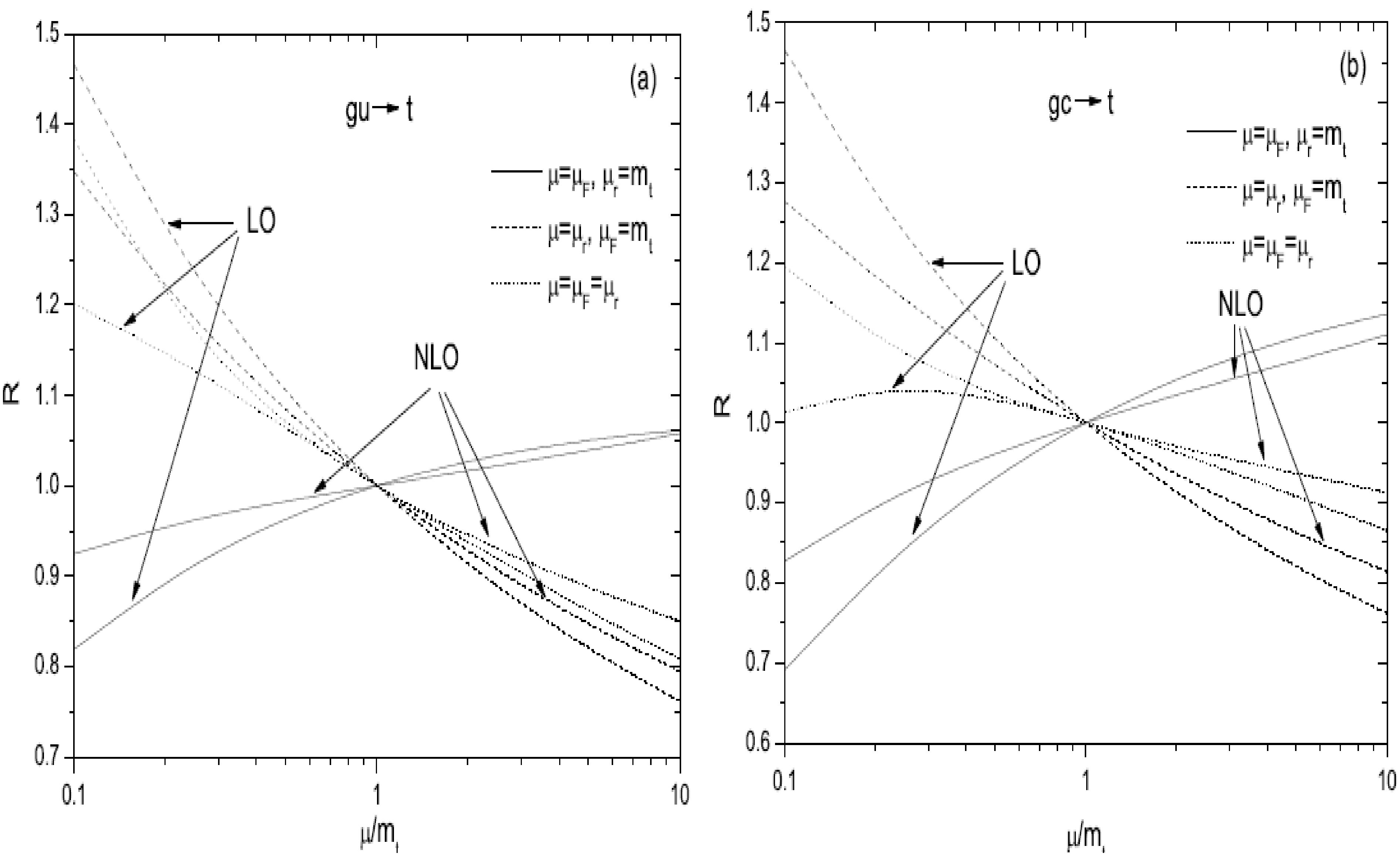


FIG. 4: The ratio R as functions of factorization (renormalization) scales for sub-processes $gc \to t$ and $gu \to t$ at the LHC: (a) up quark initial state and (b) charm quark initial state. Here $\frac{\kappa^g_{tc(u)}}{\Lambda} = 0.01\mathrm{TeV}^{-1}$.

[6]. J.J. Liu, C.S.LI and L.L. Yang, Phys.Rev. D72,074018 (2005)

- Conclusions of this part:

- The NLO QCD corrections results increase the experimental sensitivity to the anomalous couplings. Our results show that the NLO QCD corrections enhance the LO total cross sections at the Tevatron Run 2 by about 60% for both κ_{tc}^{g} and κ_{tu}^{g} couplings (K factor of 1.6), and enhance the LO total cross sections at the LHC by about 40% (K factor of 1.4), for κ_{tc}^{g} couplings and by 50% (K factor of 1.5), for κ_{tu}^{g} couplings, respectively.

- Moreover, the NLO QCD corrections vastly reduce the dependence of the total cross sections on the renormalization or factorization scale at the Tevatron, which leads to increased confidence in our predictions.

PRL **99,** 191802 (2007) PHYSICAL REVIEW LETTERS week ending
9 NOVEMBER 2007

Search for Production of Single Top Quarks Via tcg and tug Flavor-Changing-Neutral-Current Couplings

(D0 Collaboration)

We search for the production of single top quarks via flavor-changing-neutral-current couplings of a gluon to the top quark and a charm (c) or up (u) quark. We analyze 230 pb^{-1} of lepton + jets data from $p\bar{p}$ collisions at a center of mass energy of 1.96 TeV collected by the D0 detector at the Fermilab Tevatron Collider. We observe no significant deviation from standard model predictions, and hence set upper limits on the anomalous coupling parameters κ_g^c/Λ and κ_g^u/Λ, where κ_g define the strength of tcg and tug couplings, and Λ defines the scale of new physics. The limits at 95% C.L. are $\kappa_g^c/\Lambda < 0.15$ TeV^{-1} and $\kappa_g^u/\Lambda < 0.037$ TeV^{-1}.

DOI: 10.1103/PhysRevLett.99.191802 PACS numbers: 14.65.Ha, 11.30.Hv, 13.85.Rm, 14.70.Dj

The effects of FCNC couplings are parametrized in a model-independent way via an effective Lagrangian [12] that is a linear function of the factor κ_g/Λ. The production cross section of single top quarks thus depends quadratically on κ_g/Λ, and for certain values of κ_g/Λ can be significantly larger than that in the SM, as shown in Table I. The cross sections are evaluated at a top quark mass of $m_t = 175$ GeV, with the factorization and renormalization scales set to $Q^2 = m_t^2$. The LO cross sections are scaled to next-to-leading (NLO) order by a K factor (NLO/LO cross section ratio) of 1.6 [17].

[17] J. J. Liu *et al.*, Phys. Rev. D **72**, 074018 (2005).

PRL **99,** 191802 (2007) PHYSICAL REV

TABLE I. The production cross sections of single top quarks through a gluon exchange in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV for different values of κ_g/Λ, as obtained from COMPHEP and scaled to NLO by a K factor of 1.6.

κ_g/Λ [TeV^{-1}]	$\sigma(t)$ [pb]	
	tcg ($\kappa_g^u = 0$)	tug ($\kappa_g^c = 0$)
0.01	0.05	0.88
0.03	0.45	7.92
0.07	2.40	42.61
0.11	5.86	104.78

NLO results

$$
\begin{aligned}
\frac{\hat{\sigma}_{gq}}{\hat{\sigma}_0} &= \delta(1-z) \\
&+ \frac{\alpha_s}{6\pi}\left\{\delta(1-z)\left[\left(\frac{45}{2}-n_f\right)\ln\frac{Q^2}{\mu_f^2}+\left(\frac{29}{2}-n_f\right)\ln\frac{\mu_r^2}{Q^2}+\frac{4}{3}\pi^2-15\right]\right. \\
&+ \frac{1}{(1-z)_+}\left[26\ln\frac{Q^2}{\mu_f^2}-\frac{77z+27}{4}\ln z+\frac{1}{8}\left(27z^2-57z-23-\frac{11}{z}\right)\right] \\
&\qquad\qquad\qquad\qquad + \frac{77z+27}{2}\left(\frac{\ln(1-z)}{1-z}\right)_+ + \cdots
\end{aligned}
$$

Behavior near threshold

The NLO partonic cross section contains singular terms like $\left(\frac{\ln(1-z)}{1-z}\right)_+$ and $\frac{1}{(1-z)_+}$. Under Mellin transformation

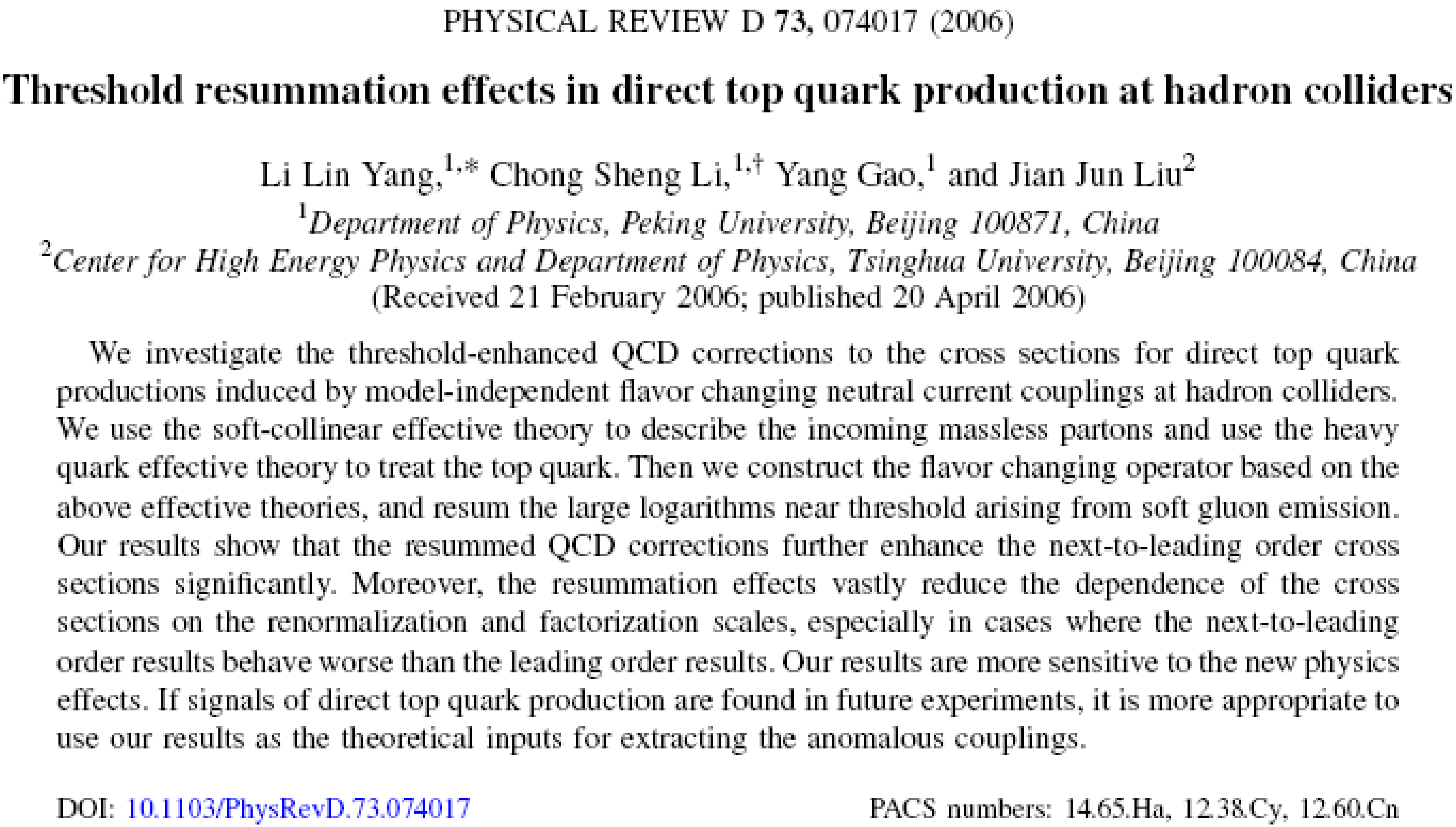
$$f(z) \to \tilde{f}(N) = \int_0^1 z^{N-1} f(z),$$

$$\left(\frac{\ln(1-z)}{1-z}\right)_+ \to \frac{1}{2}\ln^2 \bar{N} + \frac{\pi^2}{12} + \mathcal{O}\left(\frac{1}{N}\right),$$

$$\frac{1}{(1-z)_+} \to -\ln \bar{N} + \mathcal{O}\left(\frac{1}{N}\right),$$

where $\bar{N} = N e^{\gamma_E}$ and γ_E is Euler's constant. When $z \to 1$ or $N \to \infty$ (near threshold), the above terms will be large and it is essential to resum them to all orders in α_s.

4.Threshold resummation effects [7]



PHYSICAL REVIEW D **73,** 074017 (2006)

Threshold resummation effects in direct top quark production at hadron colliders

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(Received 21 February 2006; published 20 April 2006)

We investigate the threshold-enhanced QCD corrections to the cross sections for direct top quark productions induced by model-independent flavor changing neutral current couplings at hadron colliders. We use the soft-collinear effective theory to describe the incoming massless partons and use the heavy quark effective theory to treat the top quark. Then we construct the flavor changing operator based on the above effective theories, and resum the large logarithms near threshold arising from soft gluon emission. Our results show that the resummed QCD corrections further enhance the next-to-leading order cross sections significantly. Moreover, the resummation effects vastly reduce the dependence of the cross sections on the renormalization and factorization scales, especially in cases where the next-to-leading order results behave worse than the leading order results. Our results are more sensitive to the new physics effects. If signals of direct top quark production are found in future experiments, it is more appropriate to use our results as the theoretical inputs for extracting the anomalous couplings.

DOI: 10.1103/PhysRevD.73.074017 PACS numbers: 14.65.Ha, 12.38.Cy, 12.60.Cn

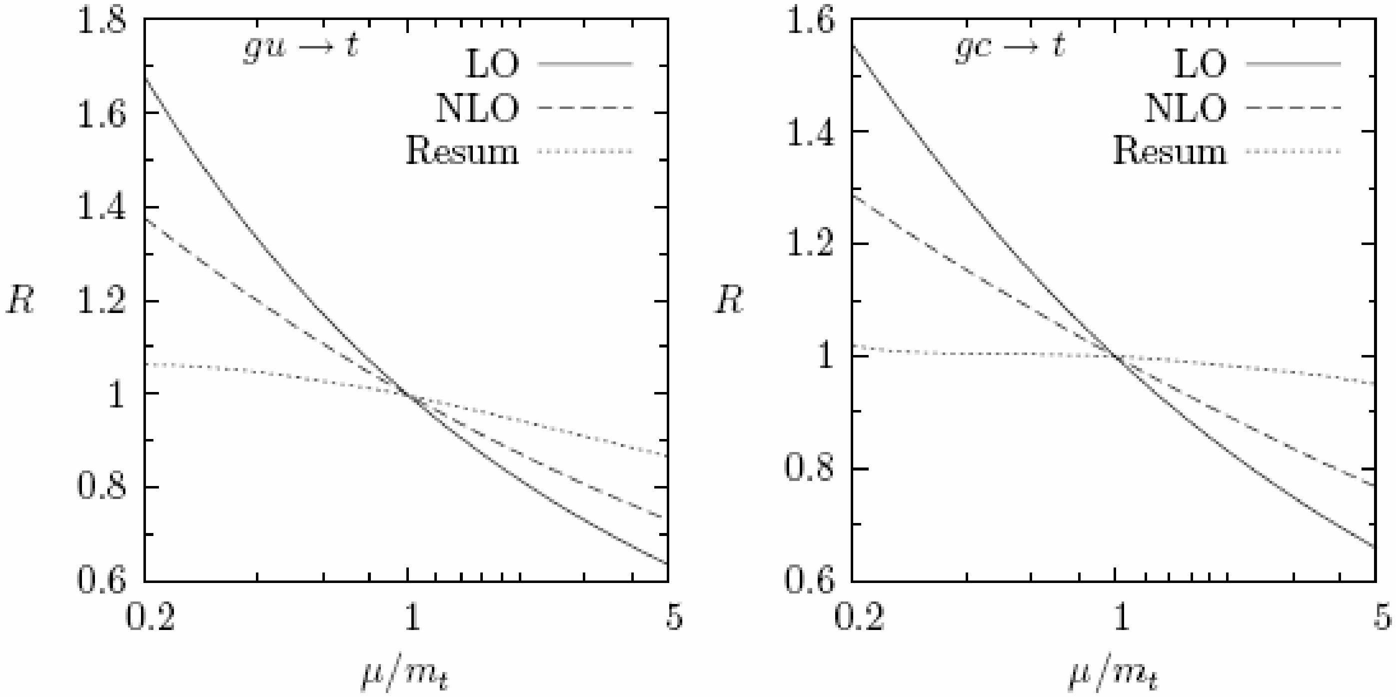
Numerical results

subprocess	PDF	LHC $\left(\frac{\kappa/\Lambda}{0.01\mathrm{TeV}^{-1}}\right)^2$ pb			Tevatron $\left(\frac{\kappa/\Lambda}{0.01\mathrm{TeV}^{-1}}\right)^2$ fb		
		LO	NLO	Resum	LO	NLO	Resum
$gu \to t$	CTEQ	12.9	17.0	23.7	268	425	547
	MRST	12.2	16.3	19.5	262	426	520
$gc \to t$	CTEQ	1.71	2.53	3.71	13.1	28.1	38.2
	MRST	1.68	2.38	2.92	17.0	30.3	38.6

Here $\mu_r = \mu_f = m_t$.

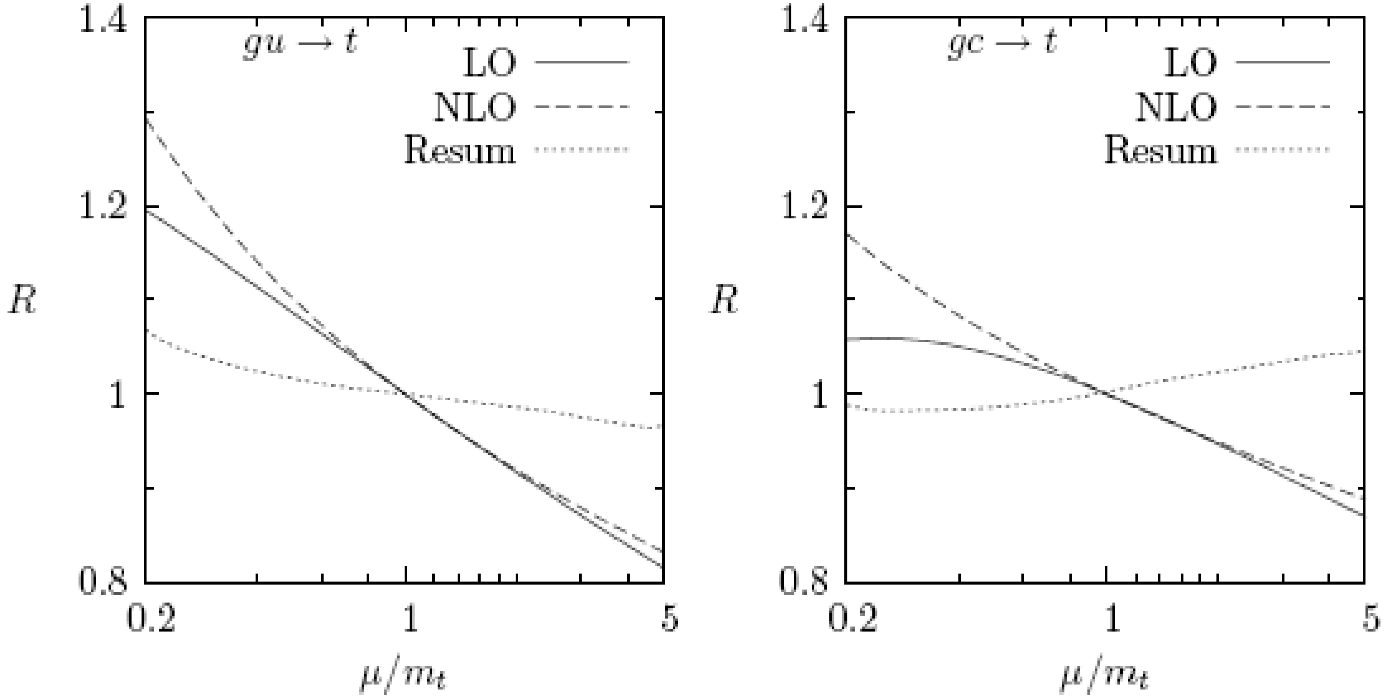
- The resummation effects further increase the NLO cross sections.
- The discrepancies between the different PDF sets are still large. These have to be improved by the fitting groups.

Scale dependence: Tevatron Run II



- NLO QCD corrections reduce the scale dependence of the cross sections.
- Threshold resummation effects further reduce such dependence, and make the theoretical predictions more reliable.

Scale dependence: LHC



- NLO corrections can not reduce the scale dependence of the cross sections. In the region $\mu < m_t$, the behavior of NLO results are even worse than that of the LO ones.
- Threshold resummation effects significantly reduce the scale dependence and improve the precision of the predictions.

- The newly presented results on the search of FCNC direct top production by CDF Collaboration [8]:

Using resummation predictions for $\sigma(u(c)+g\rightarrow t)$ [6, 7] , they convert the upper limit on the cross section into upper limits on the FCNC coupling constants at the 95% C.L. and find $\frac{\kappa_{tu}^{g}}{\Lambda} < 0.018\ \mathrm{TeV}^{-1}$, assuming $\frac{\kappa_{tc}^{g}}{\Lambda} = 0$ and $\frac{\kappa_{tc}^{g}}{\Lambda} < 0.069\ \mathrm{TeV}^{-1}$, assuming $\frac{\kappa_{tu}^{g}}{\Lambda} = 0$.

[6] L.L. Yang, C.S. Li, Y. Gao, J.J. Liu, Phys. Rev. D 73, 074017 (2006).
[7] J.J. Liu, C.S. Li, L.L. Yang, and L.G. Jin, Phys. Rev. D 72, 074018 (2005).

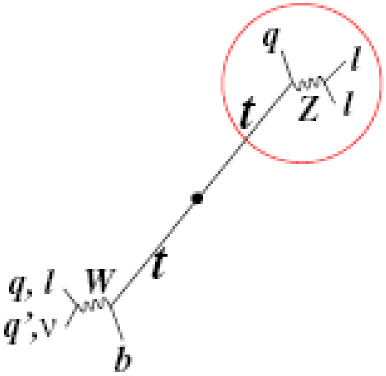
[8] see the paper draft at, http://www-cdf.fnal.gov/cdfnotes/cdf9440_fcnc_anotop_v02.pdf

5. Top quark decay via anomalous couplings at the NLO in QCD

(Based on recent collaboration work with J.J. Zhang, J. Gao, H. Zhang, Z. Li, C.P. Yuan and T.-C.Yuan, aiXiv:0810.3889 [hep-ph])

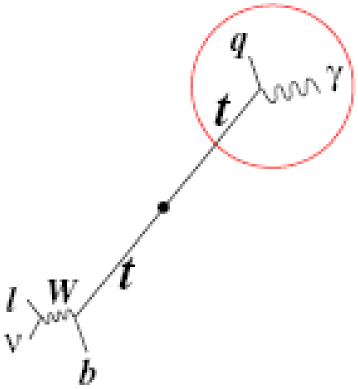
- To be consistent, besides obtaining limits on the coupling constants, we should deduce limits on the BRs as well. Moreover, experimentalists are more interest in measuring BRs.
- So we need to have NLO predictions for the branching ratios.

$t \to qZ$



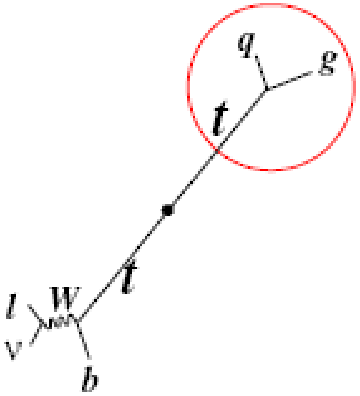
$t \to q\gamma$

(2jets+1l+1γ+missing)



$t \to qg$

(3jets+1l+1+missing)

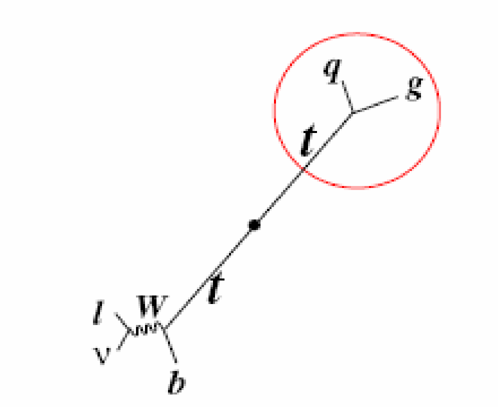


- Top QCD FCNC decay at the leading order

Here, we are mainly concerned with the decay mode: $t \to qg$

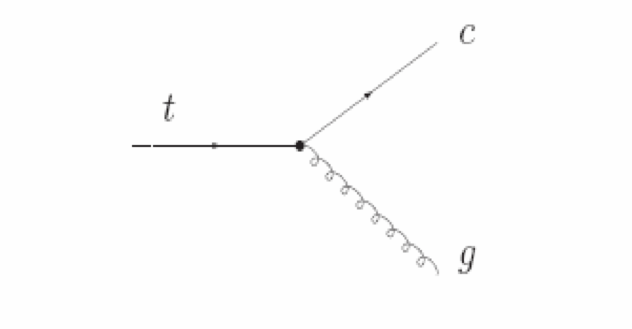
- Signal at the LHC

3 jets + 1 l + missing energy



- **Leading order Feynman diagram and decay width for top QCD FCNC decay**

$$\Gamma_0(t \to c + g) = \frac{8 m_t^3 \alpha_S}{3} \left(\frac{\kappa^g}{\Lambda}\right)^2$$



- **NLO Feynman diagrams :** the real corrections include both cgg and $cq\bar{q}$ (q=u, d, c, s, b) final states contributions, the last Feynman diagram exists only if q=c.

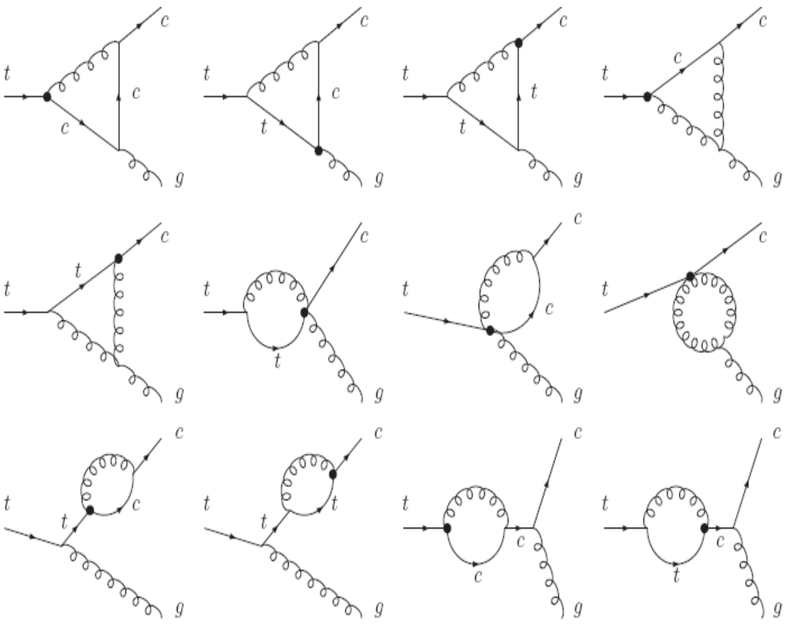


FIG. 2: One-loop Feynman diagrams for $t \to c + g$.

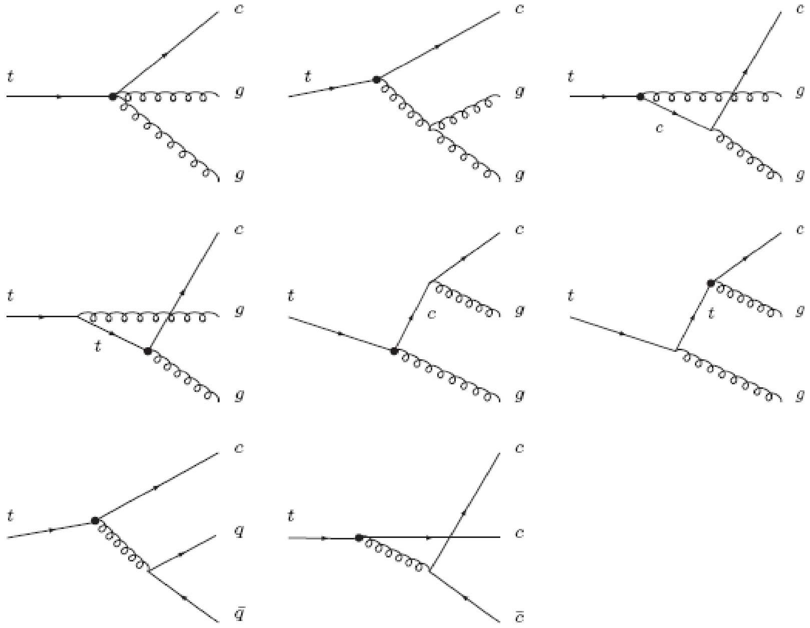


FIG. 3: Feynman diagrams of real gluon emission and gluon split.

- **Analytical results**: using dimensional regularization scheme in dimension d=4-2ε

tree level:

$$\Gamma_0(t\to c+g)=\frac{8m_t^3\alpha_S}{3}(\frac{\kappa^g}{\Lambda})^2\frac{\Gamma(2-\varepsilon)}{\Gamma(2-2\varepsilon)}(\frac{4\pi\mu^2}{m_t^2})^\varepsilon$$

virtual corrections:

$$\Gamma_{\text{virtual}}=\frac{\alpha_S}{6\pi}\Gamma_0\{-\frac{13}{\varepsilon_{IR}^2}+\frac{1}{\varepsilon_{IR}}[-13\ln\frac{4\pi\mu^2}{m_t^2}+13\gamma_E+N_f-\frac{53}{2}]+[-\frac{13}{2}(\ln\frac{4\pi\mu^2}{m_t^2}-\gamma_E)^2$$

$$-12\ln\frac{\mu^2}{m_t^2}+(N_f-\frac{53}{2})(\ln4\pi-\gamma_E)+\frac{55\pi^2}{12}-23]\}$$

real corrections:

$$\Gamma_{\text{real}}=\frac{\alpha_S}{6\pi}\Gamma_0\{\frac{13}{\varepsilon_{IR}^2}-\frac{1}{\varepsilon_{IR}}[-13\ln\frac{4\pi\mu^2}{m_t^2}+13\gamma_E+N_f-\frac{53}{2}]+[\frac{13}{2}(\ln\frac{4\pi\mu^2}{m_t^2}-\gamma_E)^2$$

$$+\frac{53}{2}(\ln\frac{4\pi\mu^2}{m_t^2}-\gamma_E)-N_f(\ln\frac{4\pi\mu^2}{m_t^2}+3-\gamma_E)-\frac{31\pi^2}{4}+\frac{1025}{12}]\}$$

total results:

$$\boxed{\begin{aligned}&\Gamma_{\text{NLO}}(t\to c+g)=\Gamma_0+\Gamma_{\text{real}}+\Gamma_{\text{virtual}}\\&=\Gamma_0\{1+\frac{\alpha_S}{72\pi}[(174-12N_f)\ln(\frac{\mu^2}{m_t^2})-36N_f-38\pi^2+749]\}\end{aligned}}$$

- Branching ratio: we take the results of the SM dominate top quark decay mode in Ref.[8],

$$\Gamma_0(t\to W+b)=\frac{G_F m_t^3}{8\sqrt{2}\pi}|V_{tb}|^2\beta_W^4(3-2\beta_W^2),$$

$$\boxed{\begin{aligned}\Gamma_{\rm NLO}(t\to W+b)=\Gamma_0(t\to Wb)\{1+\frac{C_F\alpha_S}{2\pi}[2(\frac{(1-\beta_W^2)(2\beta_W^2-1)(\beta_W^2-2)}{\beta_W^4(3-2\beta_W^2)})\ln(1-\beta_W^2)\\ -\frac{9-4\beta_W^2}{3-2\beta_W^2}\ln\beta_W^2+2Li_2(\beta_W^2)-2Li_2(1-\beta_W^2)-\frac{6\beta_W^4-3\beta_W^2-8}{2\beta_W^2(3-2\beta_W^2)}-\pi^2]\},\end{aligned}}$$

where $\boxed{\beta_W=(1-\frac{m_W^2}{m_t^2})^{\frac{1}{2}}}$

and define

$$\mathrm{BR}_{\rm LO}(t\to c+g)\equiv\frac{\Gamma_0(t\to c+g)}{\Gamma_0(t\to W+b)},\qquad \mathrm{BR}_{\rm NLO}(t\to c+g)\equiv\frac{\Gamma_{\rm NLO}(t\to c+g)}{\Gamma_{\rm NLO}(t\to W+b)},$$

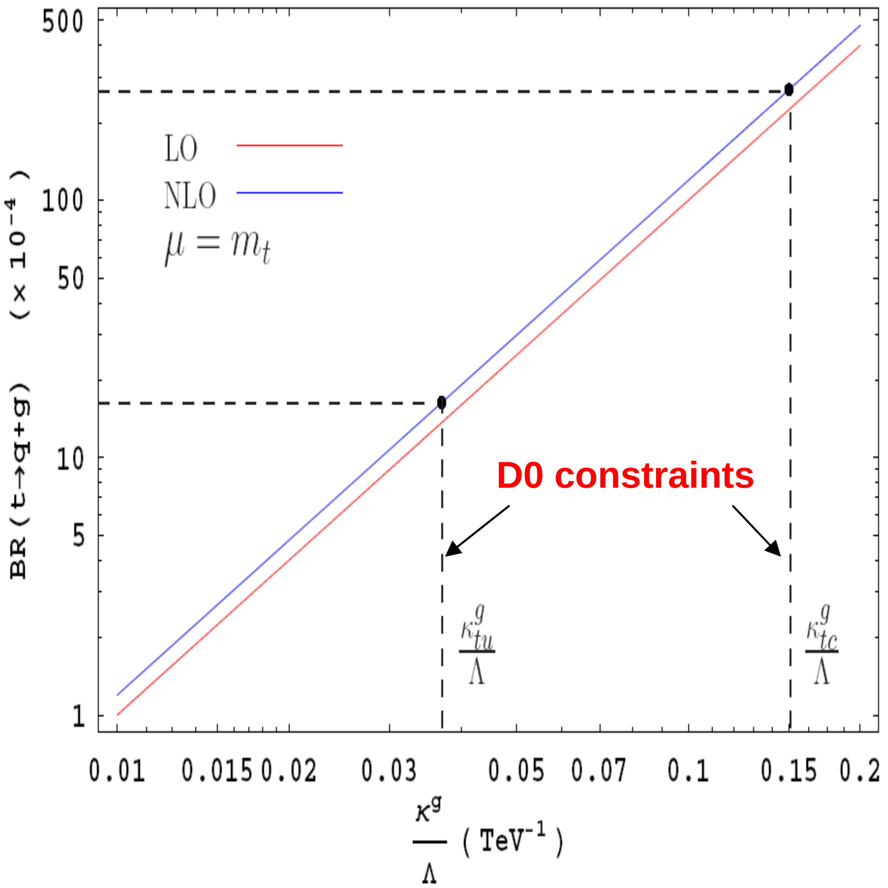
then we get

$$\mathrm{BR}_{\rm LO}(t\to c+g)=0.125(\frac{\kappa^g}{\Lambda}TeV)^2,\qquad \boxed{\begin{aligned}\mathrm{BR}_{\rm NLO}(t\to c+g)&=0.150(\frac{\kappa^g}{\Lambda}TeV)^2\\ &=1.2\mathrm{BR}_{\rm LO}(t\to c+g)\end{aligned}}$$

$$\mu=m_t=171.2\mathrm{GeV},\quad m_W=80.398\mathrm{GeV},\quad V_{tb}=1,\quad G_F=1.166\times10^{-5}\mathrm{GeV}^{-2}.$$

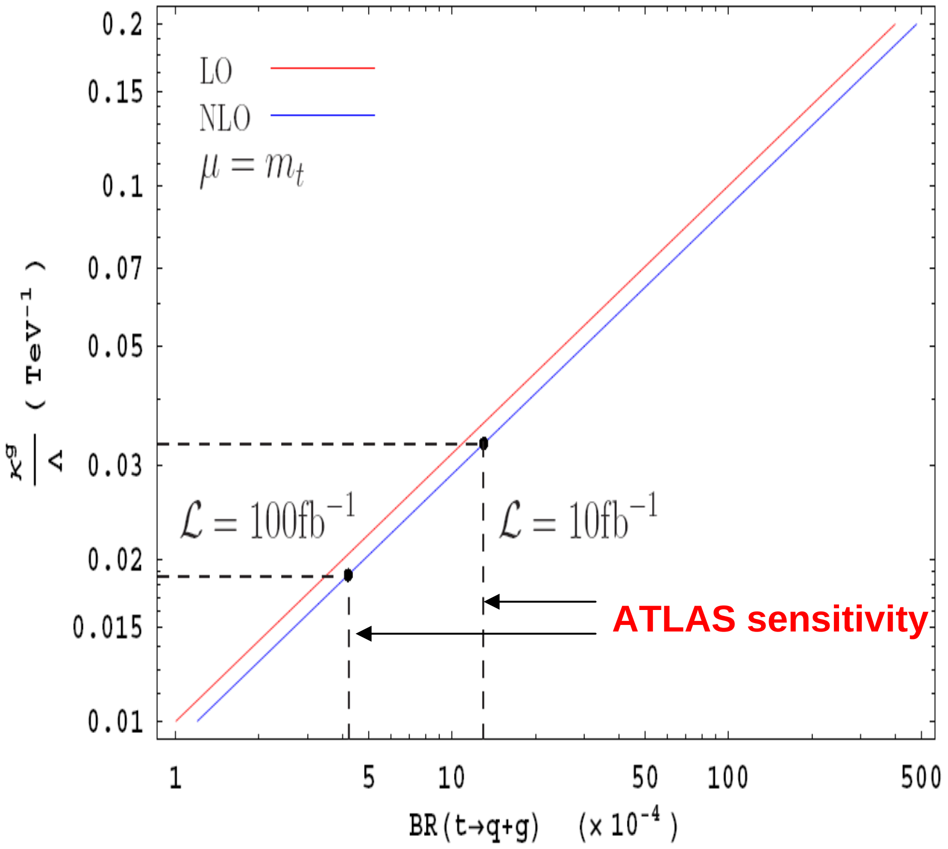
[8] C. S. Li, R. J. Oakes and T. C. Yuan, Phys. Rev. D 43, 3759 (1991).

- Relations between branch ratio and FCNC couplings



D0 constraints

Fig4. Branching ratio as function of $\frac{\kappa^g}{\Lambda}$.



ATLAS sensitivity

Fig.5 $\frac{\kappa^g}{\Lambda}$ as functions of Branching ratio

- In Fig4, using D0 upper bounds $\frac{\kappa^g_{tu}}{\Lambda}$ <0.037 TeV^{-1} and $\frac{\kappa^g_{tc}}{\Lambda}$ <0.15 TeV^{-1}, we get NLO level predictions for the upper limits for FCNC decay branching ratio, 1.6×10^{-3} and 2.7×10^{-2} for t → u g and t → c g , respectively.

- In Fig 5, considering the ATLAS sensitivity of the FCNC decay branching ratios at the LHC , **1.3×10^{-3} and 4.2×10^{-4}** [9], with an integrated luminosity of 10 fb^{-1} and 100 fb^{-1}, respectively, we get the corresponding upper limits of the couplings $\frac{\kappa^g_{tq}}{\Lambda}$ at NLO level, 0.033 TeV^{-1} and 0.019 TeV^{-1}, respectively.

Tevatron D0:

$$\frac{\kappa^g_{tu}}{\Lambda} < 0.037\,TeV^{-1} \Rightarrow BR < 1.6 \times 10^{-3}$$

$$\frac{\kappa^g_{tc}}{\Lambda} < 0.15\,TeV^{-1} \Rightarrow BR < 2.7 \times 10^{-2}$$

LHC ATLAS:

$$BR \geq 4.2 \times 10^{-4} \Rightarrow \frac{\kappa^g_{tq}}{\Lambda} \geq 0.019\,TeV^{-1}$$

$$BR \geq 1.3 \times 10^{-3} \Rightarrow \frac{\kappa^g_{tq}}{\Lambda} \geq 0.033\,TeV^{-1}$$

[9] J. Carvalho et al. (ATLAS collaboration), EPJC 52,999 (2007)

- Scale dependence of the branching ratios

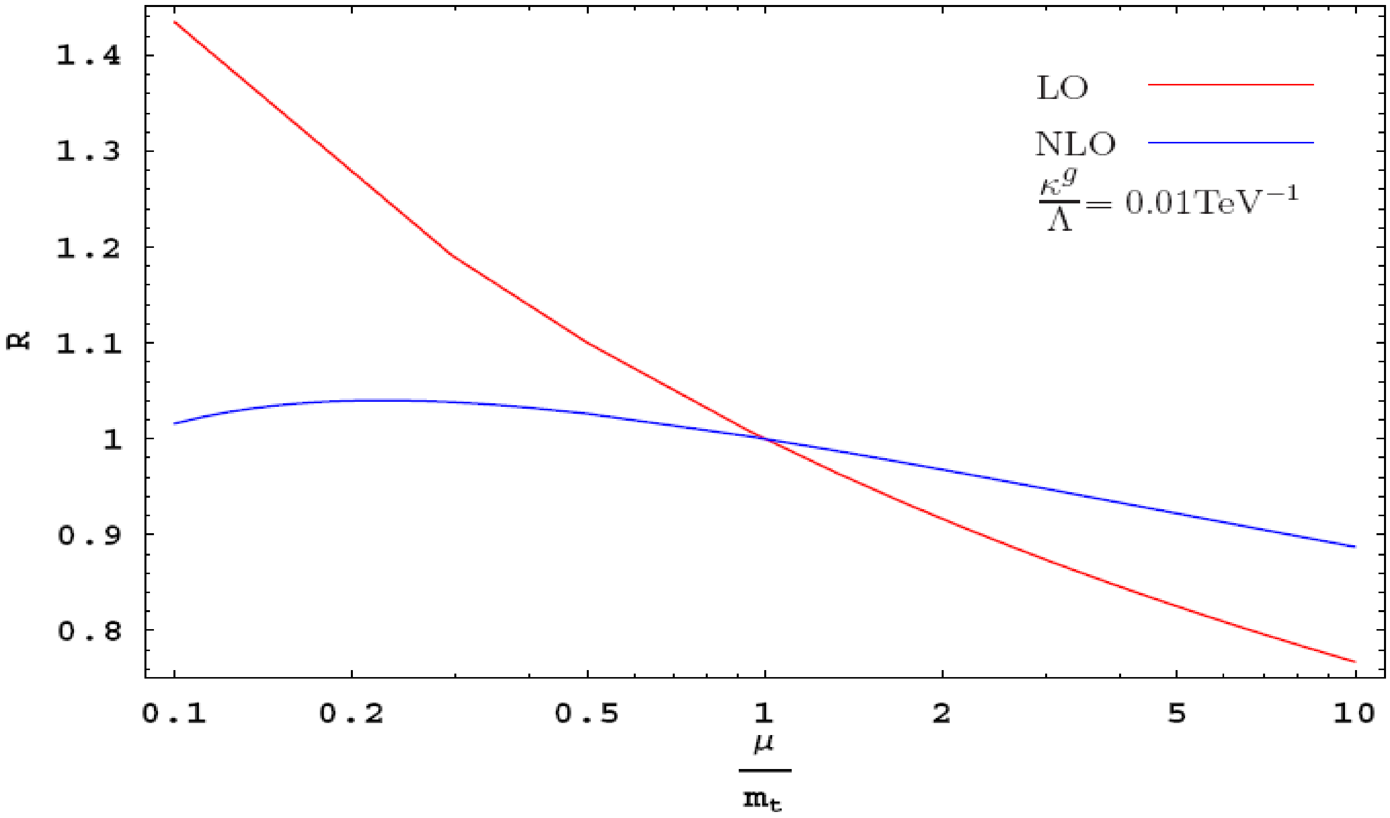


FIG. 5: The ratio R as function of renormalization scale. Here $\frac{\kappa^g}{\Lambda} = 0.01\mathrm{TeV}^{-1}$.

- We also calculated the NLO corrections to the top FCNC decay, $t \to c\gamma$ and $t \to cZ$.

$$\Gamma_0(t \to c+\gamma) = 2\alpha m_t^3 \left(\frac{\kappa^\gamma}{\Lambda}\right)^2$$

$$\boxed{\begin{aligned}\Gamma_{\rm NLO}(t \to c+\gamma) &= \Gamma_0 + \Gamma_{\rm real} + \Gamma_{\rm virtual}\\ &= \Gamma_0\left\{1 + \frac{4\alpha_S}{9\pi}(-\pi^2+4)\right\}\end{aligned}}$$

$$\Gamma_0(t \to c+Z) = \frac{\alpha m_t^3 \beta_Z^4}{\sin^2 2\theta_W}\left(\frac{\kappa^Z}{\Lambda}\right)^2 (3-\beta_Z^2)$$

$$\boxed{\begin{aligned}\Gamma_{\rm NLO}(t \to c+Z) &= \Gamma_0 + \Gamma_{\rm real} + \Gamma_{\rm virtual}\\ &= \Gamma_0\left\{1 + \frac{\alpha_S}{3\pi}\left[-\frac{4(9-\beta_z^2)}{3-\beta_z^2}\ln\beta_z - \frac{(1-\beta_z^2)(1+6\beta_z^2-3\beta_z^4)}{\beta_z^4(3-\beta_z^2)}\ln(1-\beta_z^2)\right.\right.\\ &\left.\left.+ 4\,\mathrm{Li}_2\left(-\frac{1-\beta_z^2}{\beta_z^2}\right) + \frac{1+3\beta_z^2}{\beta_z^2(3-\beta_z^2)} - \frac{4\pi^2}{3} + \frac{10}{3}\right]\right\}, \quad \text{where } \beta_Z \equiv \left(1-\frac{m_Z^2}{m_t^2}\right)^{\frac{1}{2}}\end{aligned}}$$

- the branching ratio

$$\mathrm{BR}_{\rm LO}(t \to c+\gamma) = 0.054\left(\frac{\kappa^\gamma}{\Lambda}TeV\right)^2, \qquad \mathrm{BR}_{\rm LO}(t \to c+Z) = 0.045\left(\frac{\kappa^Z}{\Lambda}TeV\right)^2,$$

$$\boxed{\mathrm{BR}_{\rm NLO}(t \to c+\gamma) = 0.996\,\mathrm{BR}_{\rm LO}(t \to c+\gamma)} \qquad \boxed{\mathrm{BR}_{\rm NLO}(t \to c+Z) = 1.022\,\mathrm{BR}_{\rm LO}(t \to c+Z)}$$

6.Summary

- NLO QCD corrections increase the total cross sections and reduce the scale dependence at the Tevatron, but can not reduce the scale dependence at the LHC in some region.

- Threshold resummation effects further enhance the cross sections and significantly reduce the theoretical uncertainties at both Tevatron and LHC.

- Search for single top production via tcg and tug FCNC couplings by D0 collaboration at the Tevatron has set upper limits on these couplings. Our previous NLO QCD results was quoted by them and our new QCD threshold resummation effects was quoted by CDF collaboration recently.

- At LHC, when the single top production is measured with more accuracy, high order QCD corrections will be very important, and the anomalous couplings can be investigated with more details. These can help us to understand further where is the new physics beyond SM.

- Since the resummation effects increase the cross sections of single top quark production and significantly reduce the theoretical uncertainties, our results are more sensitive to the new physics effects and it is important to use our results as the theoretical inputs.

- NLO QCD corrections enhance the leading order branching ratios for $t \to gq$ about 20%, but our results of NLO QCD corrections to the branching ratios for $t \to (z,\gamma)q$ are very small, although they can decrease the LO widths by about 9% and 7%, respectively.

- Especially, NLO QCD corrections increase the reliability of theoretical predictions for the branching ratios of top QCD FCNC decay mode and also lead to the most consistent treatment of the top FCNC couplings, which may be very useful for the experimentalists.

Thank you