TC corrections to the single-top-quark production at the Fermilab Tevatron

Gongru Lu, Yigang Cao, Jinshu Huang, Junde Zhang

Physics Department, Henan Normal University, Xinxiang, Henan, 453002, P. R. China

Zhenjun Xiao

Rutherford Appleton Laboratory, Chilton, DIDCOT, OX11 0QX, U.K.

Physics Department, Henan Normal University, Xinxiang, Henan, 453002, P. R. China

Abstract

We calculate one-loop corrections to the single-top-quark production via $qq' \rightarrow t\bar{b}$ at the Fermilab Tevatron from the Pseudo-Goldstone bosons (PGBs) in the framework of one generation technicolor model. The maximum correction to the total cross section for the single-top-quark production is found to reach -2.4% relative to the tree-level cross section, which may be observable at a high-luminosity Tevatron.

PACS numbers: 12.15.LK,12.60.Nz,13.30.Eg

*E-mail: Lugr@sun.ihep.ac.cn
†E-mail: xiaozj@v2.rl.ac.uk
‡Current mailing address
I. Introduction

Recently, the top quark was discovered at the Tevatron with the mass $m_t = 174.4 \pm 8.3GeV$ [1], which is of the order of the electroweak symmetry breaking (EWSB) scale $\mu = (\sqrt{2}G_F)^{-1/2} = 246GeV$. This means that the top quark couples rather strongly to the EWSB sector so that the effects from new physics would be more apparent in the processes with the top quark than with other light quarks [2]. Experimentally, it is possible to measure all of the production and decay form factors of the top quark at the level of a few percent separately [3]. Therefore, theoretical calculations of the radiative corrections to the production and decay of the top quark is of much interest. In this paper, we will address the production of top quark.

At the Tevatron top quark are produced primarily via two independent mechanisms: The dominant production mechanism is the QCD pair production process $q\bar{q} \rightarrow t\bar{t}$ [4]. W-gluon fusion process $g + W \rightarrow t\bar{b}$ [5, 6] and Drell-Yan type process $q\bar{q} \rightarrow t\bar{b}$ [7] are important too. These latter processes produce a single top quark, rather than a $t\bar{t}$ pair.

Both involve the weak interaction, so they are suppressed relative to the strong production of $t\bar{t}$; however, this suppression is partially compensated by the presence of only one heavy particle (such as the top quark) in the final state. Both processes probe the charged-current weak interaction of the top quark. And it was shown in Ref.[8] that the signal for single top production in $q\bar{q} \rightarrow t\bar{b}$ via a timelike W boson $q^2 > (m_t + m_b)^2$ is potentially observable at the Tevatron. The signal for this process is unobservable at LHC due to the large background from $t\bar{t}$ production and single top production via W-gluon fusion [6]. Compared to the single top production via W-gluon fusion the process $q\bar{q} \rightarrow t\bar{b}$ has the advantage that the cross section can be calculated reliably because the quark and antiquark structure functions at the relevant value of $x$ are better known than the gluon structure functions that enter the calculation for the W-gluon cross section.

In this paper we will concentrate on the single top production process via $q\bar{q} \rightarrow t\bar{b}$ at the Fermilab Tevatron. In the standard model (SM), this process can be reliably predicted and the theoretical uncertainty in the cross section is only about a few percent because of the QCD corrections [9]. Although the statistical error in the measured cross section for this process at the Tevatron will be about $\pm 30\%$ [8], a high-luminosity would allow a measurement of the cross section with a statistical uncertainty of about $1\%$ [9]. At this level of experimental accuracy a calculation of the radiative corrections is necessary. In Ref.[9], the QCD and Yukawa corrections to single-top-quark production via $q\bar{q} \rightarrow t\bar{b}$
have been calculated in the SM. But the QCD corrections were found to be quite large, the Yukawa corrections were found to be negligible. The SM electroweak corrections are also negligible since which are expected to be comparable to the Yukawa corrections. The corrections to the single top cross section in the extensions of the standard model, such as the two-Higgs-doublet model ( 2HDM ) [10] and the minimal supersymmetric model ( MSSM ) [11] have been calculated [12]. In this paper we will address the single top production at Tevatron via $q\bar{q}' \rightarrow t\bar{b}$ in the one generation technicolor model ( OGTM ) [13, 14]. We will find that the maximum one-loop correction to the total cross section for the single-top-production from PGBs in the OGTM may reach -2.4% relative to the tree-level cross section, which may be observable at a high-luminosity Tevatron.

The paper is organized as follows: In section II, we give a brief review of the OGTM and then calculate the corrections to the cross section for the single top production via $q\bar{q}' \rightarrow t\bar{b}$ at the Fermilab Tevatron. Numerical results and discussions are presented in section III.

**II. One-loop corrections from PGBs**

In detail, we consider the OGTM [13, 14], in which the global flavor symmetry will break as follows:

$$SU(8)_L \times SU(8)_R \rightarrow SU(8)_{L+R},$$

(1)

when the technifermion condensate $<\bar{T}T>\neq 0$ is formed. Consequently 63 ( pseudo ) Goldstone bosons would be produced from this breaking. When all other interactions but the technicolor are turned off, these 63 Goldstone bosons are exactly massless. Three of them are eaten by gauge bosons and the others acquire masses ranging from a few to above 300 GeV when the gauge interactions are turned on.

It was known [15] that only the color-singlet $p$ and color-octet $p_8$ contribute to the $W\bar{t}b$ vertex. As for the mass ranges of $p$ and $p_8$, the electroweak contribution to their masses is theoretically well understood and can be reliably computed ( with some dependence on the technicolor model ) [16]:

$$m_p|_{EW} = 5 - 14 GeV.$$  

(2)

The ETC interactions also contribute to $m_p$, but this kind of contribution is very model dependent [16], so that it is very difficult to make precise predictions for the light
PGB masses. For the $p_8$, the dominant source of its mass derives from the strong color interactions. Under the approximation of single-gluon exchange the mass of $p_8$, $m_{p_8}$, was estimated [16] according to the relation:

$$
\frac{m_{p_8}^2}{m^2(\pi^\pm) - m^2(\pi^0)} = 3\left(\frac{\Lambda_{TC}}{\Lambda_{QCD}}\right)^2\alpha_s(\Lambda_{TC})\alpha_{em},
$$

(3)
e.g.

$$
m_{p_8} \approx 246 \times \sqrt{4/N_{TC}} \text{GeV},
$$

(4)

where the $N_{TC}$ is the number of technicolor.

Because the LEP limit on the Higgs bosons $H^\pm$, $m_{H^\pm} > 50 \text{ GeV}$ [17], also applies to the charged color-singlet $p$, we here assume that $m_p = 60 \text{GeV}$. For the mass of the color-octets $p_8$, we will consider the range of

$$
m_{p_8} = 200 - 400 \text{GeV}.
$$

(5)

Ellis et al. [15] estimated the Yukawa couplings to the ordinary fermions of the PGBs in the OGTM under some simplifying assumptions. The Feynman rules needed in the calculation of the effects of the virtual PGBs on the $Wt\bar{b}$ vertex at one-loop level come from Ref.[15]. One should bear in mind that the technipion decay constant $F_\pi = 250 \text{GeV}$ in the first paper of Ref.[15] is substituted for $F_\pi = 123 \text{GeV}$ for the OGTM.

Because of the lightness of the $b$ quark when compared with the large top quark mass, we will partially neglect the mass of the $b$ quark in the calculation for the sake of simplicity. We will use dimensional regularization to regulate all the ultraviolet divergences in the virtual loop corrections and we adopt the on-mass-shell renormalization scheme.

Fig.1(a) is the tree-level Feynman diagram for single-top-quark production via $q\bar{q}' \rightarrow t\bar{b}$. The PGBs’ corrections of order $O(m_t^2/F_\pi^2)$ to the process $q\bar{q}' \rightarrow t\bar{b}$ arise from the Feynman diagrams shown in Fig.1(b, c, d, e).

Including the $O(m_t^2/F_\pi^2)$ PGBs’ corrections, the renormalized amplitude for $q\bar{q}' \rightarrow t\bar{b}$ can be written as

$$
M_{ren} = i \frac{g^2}{2} \frac{1}{\tilde{s} - m_W^2}\mathcal{M}_t(p_3)\Gamma_{\mu}Lv(p_4)\overline{\nu}(p_2)\gamma^\mu Lu(p_1),
$$

(6)

where $p_1$ and $p_2$ denote the momentum of the incoming quarks $q$ and $\bar{q}'$, while $p_3$ and $p_4$ are the momentum of the outgoing $t$ and $\bar{b}$ quarks, $\tilde{s}$ is the center-of-mass energy of the
subprocess, and we denote the left and right-handed projectors by
\[ L, R = \frac{1}{2} (1 \mp \gamma_5), \] (7)
and \( \Gamma_\mu \) is given by
\[ \Gamma_\mu = -i \frac{g}{\sqrt{2}} [\gamma_\mu L(1 + \frac{1}{2} \delta Z_b^L + \frac{1}{2} \delta Z_t^L + F_L + \frac{1}{4} m_t H_L)], \] (8)
where the form factors \( F_L, H_L \) originate from the vertex corrections [ Fig.1(d) ]; \( \delta Z_b^L \) and \( \delta Z_t^L \) are the left-handed field renormalization constants for the b and t quarks respectively, and \( \delta Z_b^R, \delta Z_t^R \) have the form of
\[ \delta Z_f^R = -\Sigma_f(k^2) - m_f^2 \Sigma_f^R(k^2) + \Sigma_f^L(k^2) + 2\Sigma_f^s(k^2) \] (9)
and the self-energy (real part) has been decomposed according to
\[ \Sigma_f(k) = \Sigma_f^L(k) \cdot L + \Sigma_f^R(k) \cdot R + m_f \Sigma_f^s(k). \] (10)

The renormalized differential cross section of the subprocess is
\[ \frac{d\hat{\sigma}}{d\cos \theta} = \frac{\tilde{s} - m_t^2}{32\pi \tilde{s}^2} \sum |M_{ren}|^2, \] (11)
where \( \theta \) is the angle between the top quark and incoming quark. Integrating this subprocess differential cross section over \( \cos \theta \) we get
\[ \hat{\sigma} = \hat{\sigma}_0 + \delta \hat{\sigma} \] (12)
with
\[ \hat{\sigma}_0 = \frac{g^4}{128\pi} \frac{\tilde{s} - m_t^2}{\tilde{s}^2(\tilde{s} - m_W^2)^2} \left[ \frac{1}{3} (2\tilde{s}^2 - m_t \tilde{s} - m_W^4) \right] \] (13)
being the tree-level result, and
\[ \delta \hat{\sigma} = (\delta Z_b^L + \delta Z_t^L + 2F_L + \frac{1}{2} m_t H_L) \hat{\sigma}_0 \]
\[ = \delta \hat{\sigma}_p + \delta \hat{\sigma}_{ps}, \] (14)
where \( \delta \hat{\sigma}_p \) and \( \delta \hat{\sigma}_{ps} \) stand for the contributions of color-singlet PGBs and color-octet PGBs, respectively. The explicit forms of \( \delta \hat{\sigma}_p \) and \( \delta \hat{\sigma}_{ps} \) are
\[ \delta \hat{\sigma}_p = \frac{m_t^2 \hat{\sigma}_0}{24 F_0^2 \pi^2} \text{Re}[B_1(m_b, m_t, m_p) + B_1(m_t, m_t, m_p) + 2m_t^2 B_1(m_t, m_t, m_p) \]
\[ + m_t^2 B_1'(m_t, m_t, m_p) + 2m_t^2 B_0'(m_t, m_t, m_p) + 4C_{24} + m_t(C_{22} - C_{23} - C_{11} + C_{12})], \] (15)
with $C_{ij} = C_{ij}(m_b, m_t, \sqrt{s}, m_p, m_t, m_p)$ and $B'_i = \frac{\partial}{\partial \sigma^2} B_i$, where functions $B_1$, $B_0$ and $C_{ij}$ can be found in Ref.[18], and

$$\delta \hat{\sigma}_{ps} = 18\delta \hat{\sigma}_p|_{m_p \rightarrow m_{p8}}.$$  \hspace{1cm} (16)

It can be easily found from eqs.(15, 16) that all the ultraviolet divergences are canceled for $p$, $p_8$ respectively and therefore the results are finite.

The hadronic cross section is obtained by convoluting the subprocess cross section $\hat{\sigma}_{ij}$ of partons $i$ and $j$ with parton distribution functions $f^A_i(x_1, Q)$ and $f^B_j(x_2, Q)$, which is given by

$$\sigma(s) = \sum_{i,j} \int dx_1 dx_2 [f^A_i(x_1, Q)f^B_j(x_2, Q) + (A \leftrightarrow B)] \hat{\sigma}_{ij}(\hat{s}, \alpha_s(\mu))$$

$$= \sum_{i,j} \int_{\tau_0}^{1} d\tau \left( \frac{1}{s} \frac{dL_{ij}}{d\tau} \right) (\hat{s}\hat{\sigma}_{ij})$$  \hspace{1cm} (17)

with

$$\frac{dL_{ij}}{d\tau} = \int_{\tau}^{1} \frac{dx_1}{x_1} [f^A_i(x_1, Q)f^B_j(\tau/x_1, Q) + (A \leftrightarrow B)].$$  \hspace{1cm} (18)

In the above the sum runs over all incoming partons carrying a fraction of the proton and antiproton momenta ($p_{1,2} = x_{1,2}p_{1,2}$), $\sqrt{s} = 2TeV$ is the center-of-mass energy of the Tevatron, $\tau = x_1 x_2$, and $\tau_0 = 4m_t^2/s$. As in Ref. [19], we do not distinguish the factorization scale $Q$ and the renormalization scale $\mu$ and take both as $\sqrt{s}$. In our numerical calculations, we have used the CTEQ3L parton distribution functions [20].

### III. Numerical results and discussions

In the following, we present the numerical results for the PGBs’ corrections to the total cross section for single-top-quark production via $q\bar{q} \rightarrow t\bar{b}$ at the Fermilab Tevatron with $\sqrt{s} = 2TeV$. In our numerical calculations we use $m_Z = 91.188GeV$, $m_W = 80.33GeV$, $G_F = 1.166372 \times 10^{-5}GeV^{-2}$, $V_{tb} = 1$, $\mu = \sqrt{s}$, $m_t = 176GeV$, $m_b = 4.7GeV$, $m_p = 60GeV$ and $m_{p8} = 200 - 400GeV$ as input parameters.

In Fig.2 we plot $\delta \sigma/\sigma_0$ as a function of $m_{p8}$. From Fig.2 one can find that the maximum correction to the total cross section may reach -2.4%, which is expected to be observable at a high-luminosity Tevatron.
To summarize, we calculated the one-loop corrections to the single top production via $q\bar{q}' \rightarrow t\bar{b}$ at the Fermilab Tevatron from the PGBs in the one-generation technicolor model. We found that the maximum correction to the total cross section could reach -2.4%, which may be observable at a high-luminosity Tevatron.

Acknowledgment

We would like to thank Professor Xinmin Zhang for suggestion of this topic. One of the authors Yigang Cao would like to thank Professor Xuelei Wang for helpful discussions. This work is supported by the National Natural Science Foundation of China and the Natural Science Foundation of Henan Scientific Committee.
Reference

1. F. Abe et al., The CDF Collaboration, Phys. Rev. Lett. 74 (1995) 2626; S. Abachi et al., The D0 Collaboration, Phys. Rev. Lett. 74 (1995) 2632; S. Willenbrock, hep-ph/9608418.

2. R. D. Peccei and X. Zhang, Nucl. Phys. B 337, (1990) 269; R. D. Peccei, S. Peris and X. Zhang, Nucl. Phys. B 349, (1991) 305; C. T. Hill and S. Parke, Phys. Rev. D 49, (1994) 4454; D. Atwood, A. Kagan and T. Rizzo, Phys. Rev. D 52, (1995) 6264; D. O. Carlson, E. Malkawi and C.-P. Yuan, Phys. Lett. B 337, (1994) 145; S. Dawson and G. Valencia, Phys. Rev. D 53, (1996) 1721; T. Han, R. D. Peccei and X. Zhang, Nucl. Phys. B 454, (1995) 527; X. Zhang and B.-L. Young, Phys. Rev. D 51, (1995) 6584; G. Gounaris, D. Papadamou and F. Renard, hep-ph/9611224; A. Heinson et al., hep-ph/9612424.

3. For example, see M. E. Peskin, in Physics and Experiments with Linear Collider, Proceedings of the Workshop, Saarilka, Finland, 1991, edited by R. Orava and M. Nordberg (World Scientific, Singapore, 1992) P. 1.

4. F. Berends, J. Tausk and W. Giele, Phys. Rev. D 47 (1993) 2746.

5. S. Willenbrock and D. Dicus, Phys. Rev. D 34 (1986) 155; R. K. Ellis and S. Parke, Phys. Rev. D 46 (1992) 3785; G. Bordes and B. Van Eijk, Nucl. Phys. B 435, (1995) 23.

6. C. P. Yuan, Phys. Rev. D 41 (1990) 42.

7. S. Cortese and R. Petronzio, Phys. Lett. B 306 (1993) 386.

8. T. Stelzer and S. Willenbrock, Phys. Lett. B 357 (1995) 125.

9. M. Smith and S. Willenbrock, Phys. Rev. D54(1996) 6696.

10. J.F. Gunion, H.E. Haber, G.Kane and S.Dawson, The Higgs Hunters' Guide (Addison-Wesley, Reading, MA, 1990).

11. H. E. Haber and G. L. Kane, Phys. Rep. 117 (1985) 75; J. F. Gunion and H. E. Haber, Nucl. Phys. B 272 (1986) 1.
12. Chongsheng Li, Robert J. Oakes and Jinmin Yang, Phys. Rev D55 (1997)1672, hep-ph/9611455.

13. S. Weinberg, Phys. Rev. D 13 (1976) 974; D 19 (1979) 1277; L. Suskind, Phys. Rev. 20 (1979) 2619.

14. E. Farhi and L. Suskind, Phys. Rev. D 20 (1979) 3404; S. Dimopoulos, Nucl. Phys. B 168 (1980) 69; S. Dimopoulos et al., ibid. B 176 (1980) 449.

15. J. Ellis, M.K. Jaillard, D.V. Nanopoulos, and P. Sikivie, Nucl. Phys. B182 (1981) 529; E. Eichten et al., Phys. Rev. D 344 (1986) 1547; S. Dimopoulos, S. Raby and G. L. Kane, Nucl. Phys. B 182 (1981) 77; F. Hayot, Nucl. Phys. B 191 (1981) 82; W. C. Kuo and Bing-lin Young, Phys. Rev. D 42 (1990) 2274; D. Slaven, Bing-lin Young and X. Zhang, ibid. 45 (1992) 4349.

16. M. E. Peskin, Nucl. Phys. B 175 (1980) 197; J. Preskill Nucl.Phys. B 177 (1981) 21; P. Binetruy et al., Phys. Lett. B 107 (1981) 425.

17. W. de Boer et al., hep-ph/9609209.

18. M. Clements et al., Phys. Rev. D 27 (1983) 570; A. Axelrod, Nucl. Phys. B 209, (1994) 349; W. Hollik, Fortschr. Phys. 38 (1990)165.

19. W. Beenakker et al., Nucl. Phys. B 411 (1994) 343.

20. H. L. Lai et al., Phys. Rev. D 51 (1995) 4763.
Figure captions

Fig.1(a): The Feynman diagram of tree-level $q\bar{q} \rightarrow t\bar{b}$ process.

Fig.1(b, c, d, e): The Feynman diagrams of one-loop corrections to the $Wt\bar{b}$ vertex from PGBs in the OGTM.

Fig.2: The plot of $\delta\sigma/\sigma_0$ versus $m_{ps}$ in the OGTM (assuming $m_p = 60 GeV$).
Fig. 1