Eur. Phys. J. C 48, 243–249 (2006)
Digital Object Identifier (DOI) 10.1140/epjc/s2006-02624-5

THE EUROPEAN
PHYSICAL JOURNAL C

Little Higgs models and single top production at the LHC

C.-X. Yue[a], L. Zhou, S. Yang

Department of Physics, Liaoning Normal University, Dalian 116029, China

Received: 11 March 2006 / Revised version: 16 June 2006 /
Published online: 26 July 2006 – © Springer-Verlag / Società Italiana di Fisica 2006

Abstract. We investigate the corrections of the "littlest" Higgs (LH) model and the $SU(3)$ simple group model to single top production at the CERN Large Hadron Collider (LHC). We find that the new gauge bosons $W_H^{\pm}$ predicted by the LH model can generate significant contributions to single top production via the s-channel process. The correction terms for the tree-level Wqq' couplings coming from the $SU(3)$ simple group model can give large contributions to the cross sections of the t-channel single top production process. We expect that the effects of the LH model and the $SU(3)$ simple group model on single top production can be detected at the LHC experiments.

1 Introduction

The top quark, with a mass of the order of the electroweak scale $m_t = 172.7 \pm 2.9\,\text{GeV}$ [1] is the heaviest particle yet discovered and might be the first place in which new physics effects could appear. The properties of the top quark could reveal information regarding flavor physics, the electroweak symmetry breaking (EWSB) mechanism, as well as new physics beyond the standard model (SM) [2]. Hadron colliders, such as the Tevatron and the CERN Large Hadron Collider (LHC), can be seen as top quark factories. One of the primary goals for the Tevatron and the LHC is to determine the top quark properties and see whether any hint of non-SM effects may be visible. Thus, studying the top quark production at hadron colliders is of great interest. It can help the collider experiments to probe the EWSB mechanism and test the new physics beyond the SM.

In the context of the SM, the top quark can be produced singly via electroweak interactions involving the Wtb vertex. There are three production processes which are distinguished by the virtuality Q^2 of the electroweak gauge boson W ($Q^2 = -p^2$, where p is the four-momentum of the gauge boson W) [2]. The first process is the so-called W-gluon fusion, or t-channel process, which is the dominant process involving a space-like W boson ($p^2 < 0$) both at the Tevatron and the LHC. If a b quark distribution function is introduced into the calculation, the leading order process for the W-gluon fusion channel is the t-channel process $q + b \to q' + t$ including $\overline{q}' + b \to \overline{q} + t$ [3]. The second process is the s-channel process $q + \overline{q}' \to t + \overline{b}$ mediated by a time-like W boson ($p^2 > (m_t + m_b)^2$). A single top quark can also be produced in association with a real W boson ($p^2 \approx M_W^2$). The cross section for the tW associated production process is negligible at the Tevatron, but of considerable size at the LHC, where the production cross section is larger than that of the s-channel process.

At the leading order, the production cross sections for all three processes are proportional to the Cabibbo–Kobayashi–Maskawa (CKM) matrix element $|V_{tb}|^2$. Thus, measuring the cross section of single top production generally provides a direct probe of $|V_{tb}|$, the effective Wtb vertex, and furthermore the strength and handedness of the top charged-current couplings. This fact has already motivated a large number of dedicated experimental and theoretical studies. Since the cross section of single top production is smaller than that of the $t\bar{t}$ production and the final state signals suffer from large background, the observation of the single top events is even more challenging than $t\bar{t}$. It is expected that increased luminosity and improved methods of analysis will eventually achieve detection of single top events. So far, there are not single top events to be observed. The cross sections of single top production for the s- and t-channels might be observed at the Tevatron Run II with a small data sample of only a few fb^{-1}. However, the LHC can precisely measure single top production, and the CKM matrix element V_{tb} could be measured down to less than one percent error at the ATLAS detector [4].

The three processes for single top production can be affected by new physics beyond the SM in two ways. One way proceeds via the modification of the SM couplings between the known particles, such as Wtb and Wqq' ($q, q' = u, d, c, s$) couplings, and the other way involves the effects of new particles that couple to the top quark. Certainly, these two classifications can be seen to overlap in the limit in which the extra particles are heavy and decouple from the low energy description. The SM couplings between the ordinary particles take well defined and calculable values in the SM; any deviation from these values would indicate the presence of new physics. Thus, single top production

[a] e-mail: cxyue@lnnu.edu.cn

at hadron colliders might be sensitive to certain effects of new physics and studying the non-SM effects on single top production is very interesting and needed.

To address EWSB and the hierarchy problem in the SM, many alternative new physics models, such as supersymmetry, extra dimensions, topcolor, and the recent little Higgs models, have been proposed over the past three decades. Of particular interest to us are the little Higgs models [5]. In this kind of models, the Higgs particle is a pseudo-Goldstone boson of a global symmetry which is spontaneously broken at some high scales. EWSB is induced by radiative corrections leading to a Coleman–Weinberg type of potential. Quadratic divergence cancellations of radiative corrections to the Higgs boson mass are due to contributions from new particles with the same spin as the SM particles. Some of these new particles can generate characteristic signatures at the present and future collider experiments [6, 7]. The aim of this paper is to study the effects of the little Higgs models on single top production and to see whether the corrections of the little Higgs models to the cross section of single top production can be detected at the LHC.

The rest of this paper is organized as follows. In the next section, we shall briefly summarize some coupling expressions in the little Higgs models, which are related to single top production. The contributions of the correction terms for the tree-level Wtb and Wqq' couplings to single top production at the LHC are calculated in Sect. 3. In Sect. 4, we discuss the corrections of the new charged gauge bosons, such as $W_H^{\pm}$ and X^-, predicted by the little Higgs models, to single top production at the LHC. Our conclusions and discussions are given in Sect. 5.

2 The relevant couplings

There are several variations of the little Higgs models, which differ in the assumed higher symmetry and in the representations of the scalar multiplets. According to the structure of the extended electroweak gauge group, the little Higgs models can be generally divided into two classes [6, 8]: product group models, in which the SM $SU(2)_{\mathrm{L}}$ is embedded in a product gauge group, and simple group models, in which it is embedded in a larger simple group. The "littlest" Higgs model (LH) [9] and the $SU(3)$ simple group model [8, 10] are the simplest examples of the product group models and the simple group models, respectively. To predigest our calculation, we will discuss single top production at the LHC in the context of these two simplest models.

The LH model [9] consists of a nonlinear σ model with a global $SU(5)$ symmetry and a locally gauged symmetry $[SU(2)\times U(1)]^2$. The global $SU(5)$ symmetry is broken down to its subgroup $SO(5)$ at a scale $f \sim \Lambda_s/4\pi \sim$ TeV, which results in 14 Goldstone bosons (GBs). Four of these GBs are eaten by the gauge bosons $(W_H^{\pm}, Z_H, B_H)$, resulting from the breaking of $[SU(2)\times U(1)]^2$, giving them mass. The Higgs boson remains as a light pseudo-Goldstone boson, and other GBs give mass to the SM gauge bosons and form a Higgs field triplet. The gauge and Yukawa couplings radiative generate a Higgs potential and trigger EWSB. In the LH model, the couplings constants of the SM gauge boson W and the new gauge boson W_H to ordinary particles, which are related to our calculation, can be written as [11]

$$g_{\mathrm{L}}^{Wtb} = \frac{\mathrm{i}e}{\sqrt{2}S_{\mathrm{W}}}\left[1-\frac{v^2}{2f^2}\left(x_{\mathrm{L}}^2+c^2(c^2-s^2)\right)\right], \quad g_{\mathrm{R}}^{Wtb}=0\,; \tag{1}$$

$$g_{\mathrm{L}}^{Wqq'} = \frac{\mathrm{i}e}{\sqrt{2}S_{\mathrm{W}}}\left[1-\frac{v^2}{2f^2}c^2(c^2-s^2)\right], \quad g_{\mathrm{R}}^{Wqq'}=0\,; \tag{2}$$

$$g_{\mathrm{L}}^{W_H tb} = g_{\mathrm{L}}^{W_H qq'} = \frac{\mathrm{i}e}{\sqrt{2}S_{\mathrm{W}}}\frac{c}{s}, \quad g_{\mathrm{R}}^{W_H tb} = g_{\mathrm{R}}^{W_H qq'} = 0\,, \tag{3}$$

where $\nu \approx 246\,\mathrm{GeV}$ is the electroweak scale, and $S_{\mathrm{W}} = \sin\theta_{\mathrm{W}}$; θ_{W} is the Weinberg angle. c $(s=\sqrt{1-c^2})$ is the mixing parameter between the $SU(2)_1$ and $SU(2)_2$ gauge bosons and the mixing parameter $x_{\mathrm{L}} = \lambda_1^2/(\lambda_1^2+\lambda_2^2)$ comes from the mixing between the SM top quark t and the vector-like top quark T, in which λ_1 and λ_2 are the Yukawa coupling parameters. The $SU(2)$ doublet quarks (q, q') represent (u, d) or (c, s). In the above equations, we have assumed $V_{tb} \approx V_{ud} \approx V_{cs} \approx 1$.

The $SU(3)$ simple group model [8, 10] consists of two σ model with a global symmetry $[SU(3)\times U(1)]^2$ and a gauge symmetry $SU(3)\times U(1)_X$. The global symmetry is spontaneously broken down to its subgroup $[SU(2)\times U(1)]^2$ by two vacuum condensates $\langle\Phi_{1,2}\rangle = (0,0,f_{1,2})$, where $f_1 \sim f_2 \sim 1$ TeV. At the same time, the gauge symmetry is broken down to the SM gauge group $SU(2)\times U(1)$, and the global symmetry is broken explicitly down to its diagonal subgroup $SU(3)\times U(1)$ by the gauge interactions. This breaking scenario gives rise to an $SU(2)_{\mathrm{L}}$ doublet of gauge bosons (Y^0, X^-) and a new neutral gauge boson Z'. Due to the gauged $SU(3)$ symmetry in the $SU(3)$ simple group model, all of the SM fermion representations have to be extended to transform as fundamental (or antifundamental) representations of $SU(3)$, which demands the existence of new heavy fermions in all three generations. The fermion sector of the $SU(3)$ simple group model can be constructed in two ways: universal and anomaly free, which might induce different signatures at the high energy collider experiments. However, the coupling forms of the gauge bosons W and X to the SM quarks can be written in a unified manner as [6]

$$g_{\mathrm{L}}^{Wtb} = \frac{\mathrm{i}e}{\sqrt{2}S_{\mathrm{W}}}\left(1-\frac{1}{2}\delta_t^2\right), \qquad g_{\mathrm{R}}^{Wtb}=0\,; \tag{4}$$

$$g_{\mathrm{L}}^{Wqq'} = \frac{\mathrm{i}e}{\sqrt{2}S_{\mathrm{W}}}\left(1-\frac{1}{2}\delta_\nu^2\right), \qquad g_{\mathrm{R}}^{Wqq'}=0\,; \tag{5}$$

$$g_{\mathrm{L}}^{Xtb} = \frac{\mathrm{i}e}{\sqrt{2}S_{\mathrm{W}}}\delta_t\,, \qquad g_{\mathrm{R}}^{Xtb}=0\,; \tag{6}$$

$$g_{\mathrm{L}}^{Xqq'} = \frac{\mathrm{i}e}{\sqrt{2}S_{\mathrm{W}}}\delta_\nu\,, \qquad g_{\mathrm{R}}^{Xqq'}=0\,, \tag{7}$$

with

$$\delta_t = \frac{\nu}{\sqrt{2}f} t_\beta \frac{x_\lambda^2 - 1}{x_\lambda^2 + t_\beta^2}\,, \qquad \delta_\nu = -\frac{\nu}{2 f t_\beta}\,, \tag{8}$$

where $f = \sqrt{f_1^2 + f_2^2}$, $t_\beta = \tan\beta = f_2/f_1$, and $x_\lambda = \lambda_1/\lambda_2$.

Using these Feynman rules, we will estimate the contributions of the LH model and the $SU(3)$ simple group model to single top production at the LHC in the following sections.

3 The contributions of the correction terms to single top production

For the t-channel process $q + b \to q' + t$, at the leading order, there is only one diagram with W exchange in the t-channel. In the context of the little Higgs models, the corresponding scattering amplitude can be written as

$$M_i^t = \frac{2\pi\alpha_e \left(1 + \delta g_{\mathrm{L}i}^{Wtb}\right)\left(1 + \delta g_{\mathrm{L}i}^{Wqq'}\right)}{S_{\mathrm{W}}^2 \left(\hat{t} - m_W^2\right)} \times \left[\overline{u}(q')\gamma^\mu P_{\mathrm{L}} u(q)\right]\left[\overline{u}(t)\gamma_\mu P_{\mathrm{L}} u(b)\right]\,, \tag{9}$$

where $\hat{t} = (P_b - P_t)^2$, $P_{\mathrm{L}} = (1 - \gamma^5)/2$ is the left-handed projection operator. $i = 1$ and 2 represent the LH model and the $SU(3)$ simple group model, respectively. $\delta g_{\mathrm{L}i}^{Wtb}$ and $\delta g_{\mathrm{L}i}^{Wqq'}$ are the correction terms for the Wtb and Wqq' couplings induced by these two little Higgs models, which have been given in (1), (2), (4), and (5).

In the context of the little Higgs models, the scattering amplitude of the s-channel process $q + \overline{q}' \to t + \overline{b}$ can be written as

$$M_i^s = \frac{2\pi\alpha_e \left(1 + \delta g_{\mathrm{L}i}^{Wtb}\right)\left(1 + \delta g_{\mathrm{L}i}^{Wqq'}\right)}{S_{\mathrm{W}}^2 \left(\hat{s} - m_W^2\right)} \times \left[\overline{\nu}(\overline{q}')\gamma^\mu P_{\mathrm{L}} u(q)\right]\left[\overline{u}(t)\gamma_\mu P_{\mathrm{L}} \nu(\overline{b})\right]\,, \tag{10}$$

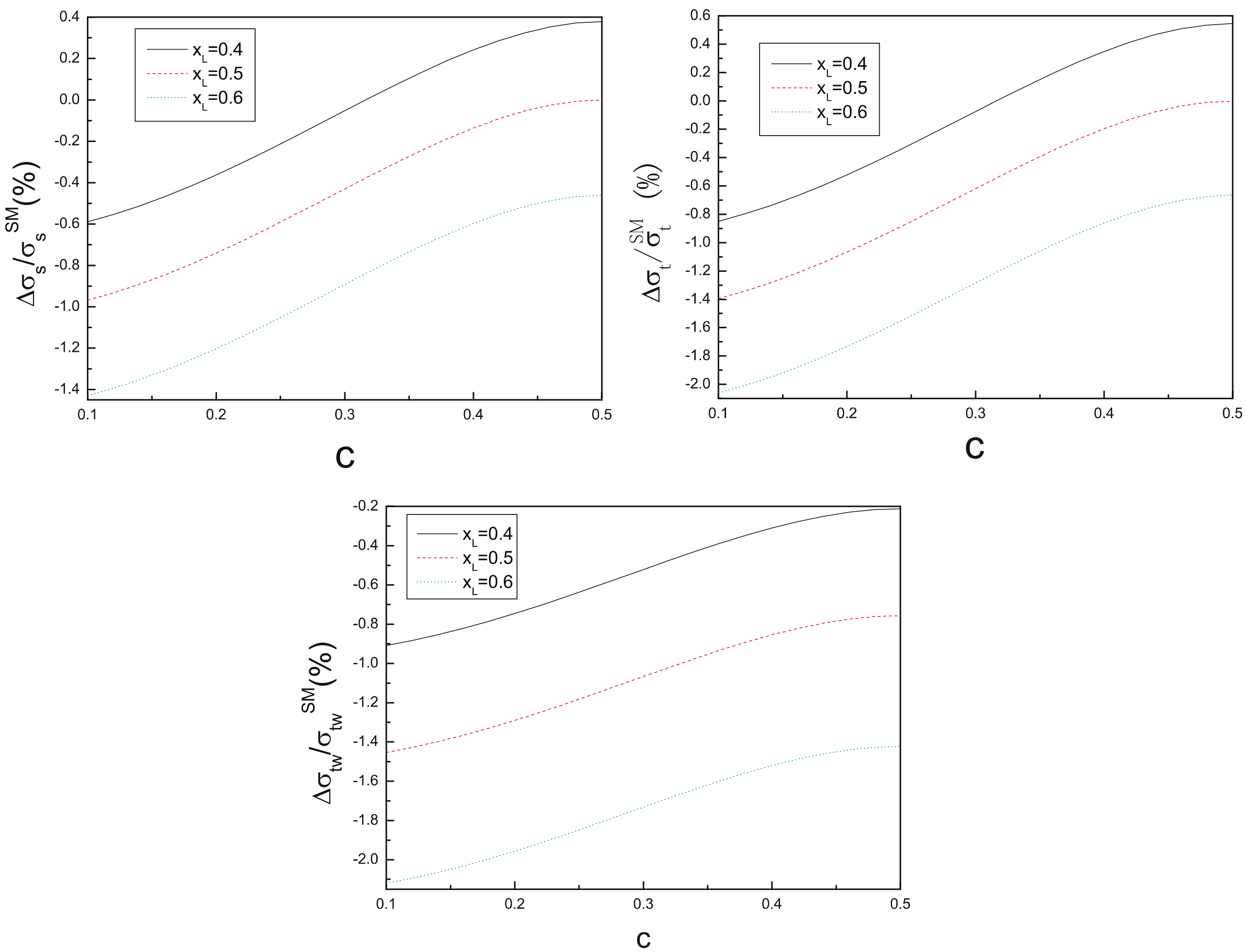

Fig. 1. The relative correction $\Delta\sigma_i/\sigma_i^{\mathrm{SM}}$ as a function of the mixing parameter c for $f = 1.0$ TeV and different values of the mixing parameter x_{L}

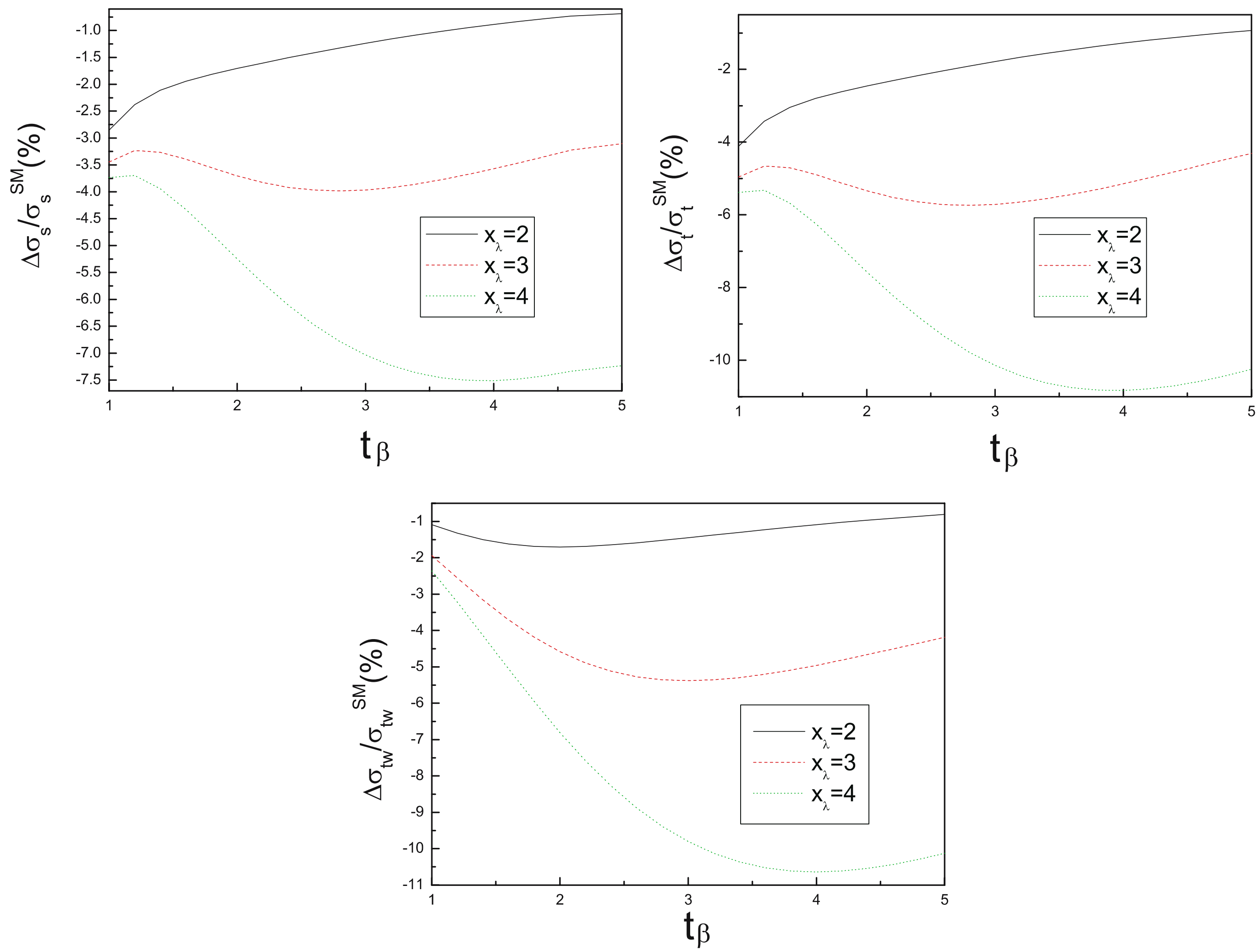

Fig. 2. The relative correction $\Delta\sigma_i/\sigma_i^{\rm SM}$ as a function of the free parameter t_β for $f = 1.0$ TeV and different values of the mixing parameter x_λ

where $\hat{s} = (P_q + P_{\overline{q}'})^2$ and $\sqrt{\hat{s}}$ is the center-of-mass energy of the subprocess $q + \overline{q}' \to t + \overline{b}$.

At the leading order, the production of a single top quark in association with a W boson is given via the processes mediated by the s-channel b quark exchange and the u-channel top quark exchange. In the little Higgs models, the tree-level coupling of the gluon to a pair of fermions is the same as that in the SM; thus, the scattering amplitude of this process can be written as

$$M_i^{tW} = \frac{e g_s \left(1 + \delta g_{{\rm L}i}^{Wtb}\right)}{\sqrt{2} S_{\rm W}} \times \overline{u}(t) \left[\frac{\not{\epsilon}_2 P_{\rm L} \left(\not{P}_g + \not{P}_b + m_b\right) \not{\epsilon}_1}{\hat{s}' - m_b^2} + \frac{\not{\epsilon}_1 \left(\not{P}_t - \not{P}_g + m_t\right) \not{\epsilon}_2 P_{\rm L}}{\hat{u} - m_t^2} \right] u(b) , \qquad (11)$$

where $\hat{s}' = (P_g + P_b)^2 = (P_W + P_t)^2$, $\hat{u} = (P_t - P_g)^2 = (P_b - P_W)^2$.

After calculating the cross sections $\hat{\sigma}_i(\hat{s})$ for the t-channel, s-channel, and tW associated production processes, the total cross section $\sigma_i(S)$ for each process of single top production at the LHC can be obtained by convoluting $\hat{\sigma}_{ijl}(\hat{s})$ $[\hat{\sigma}_i(\hat{s}) = \sum_{j,l} \hat{\sigma_{ijl}}(\hat{s})]$ with the parton distribution functions (PDFs):

$$\sigma_i(S) = \sum_{j,l} \int_0^1 {\rm d}x_1 \int_0^1 {\rm d}x_2 f_j\left(x_j, \mu_f^2\right) f_l\left(x_l, \mu_{\rm f}^2\right) \hat{\sigma_{jl}}(\hat{s}) , \qquad (12)$$

where j and l are the possible combination of incoming gluon, quark and antiquark. $f(x, \mu_{\rm f}^2)$ is the PDF evaluated at the factorization scale $\mu_{\rm f}$. Throughout this paper, we neglect all quark masses with the exception of m_t, use the CTEQ6L PDF with $\mu_{\rm f} = m_t$ [12], and take the center-of-mass energy $\sqrt{S} = 14$ TeV for the process $pp \to t + X$ at the LHC.

To obtain numerical results, we need to specify the relevant SM parameters. These parameters are $m_t =$

172.7 GeV [1], $\alpha(m_Z) = 1/128.8$, $\alpha_s = 0.118$, $S_W^2 = 0.2315$, and $m_W = 80.425$ GeV [13]. Except for these SM input parameters, the contributions of the LH model and the $SU(3)$ simple group model to single top quark production are dependent on the free parameters (f, x_L, c) and (f, x_λ, t_β), respectively. Considering the constraints of the electroweak precision data on these free parameters, we will assume $f \geq 1$ TeV, $0.4 \leq x_L \leq 0.6$ and $0 < c \leq 0.5$ for the LH model [14] and $f \geq 1$ TeV, $x_\lambda > 1$, and $t_\beta > 1$ for the $SU(3)$ simple group model [6, 8, 10], in our numerical estimation.

The relative corrections of the LH model and the $SU(3)$ simple group model to the cross section σ_i of single top production at the LHC are shown in Figs. 1 and 2, respectively. In these figures, we have taken $\Delta\sigma_i = \sigma_i - \sigma_i^{SM}$, $f = 1.0$ TeV and three values of the mixing parameters x_L and x_λ. From these figures, we can see that the contributions of the $SU(3)$ simple group model to single top production are larger than those of the LH model. For the LH model, the absolute values of the relative correction $\Delta\sigma_i/\sigma_i^{SM}$ are smaller than 2% in most of the parameter space preferred by the electroweak precision data. The $SU(3)$ simple group model has negative contributions to single top production at the LHC. For $f = 1$ TeV, $x_\lambda \geq 3$, and $1 \leq t_\beta \leq 5$, the absolute values of the relative correction $\Delta\sigma_i/\sigma_i^{SM}$ for the t-channel, s-channel, and tW associated production processes are in the ranges of $4.3\% \sim 10.8\%$, $3.1\% \sim 7.5\%$, and $2\% \sim 10.6\%$, respectively.

In the context of the SM, the production cross sections at hadron colliders for the t-channel and s-channel single top production processes have been calculated at the next to leading order (NLO) [2, 15]. The values of $\sigma_t^{SM}(t)$ [$\sigma_t^{SM}(\bar{t})$] and $\sigma_s^{SM}(t)$ [$\sigma_s^{SM}(\bar{t})$] at the LHC are given as (156 ± 8) pb [(91 ± 5) pb] and (6.6 ± 0.6) pb [(4.1 ± 0.4) pb], respectively. A NLO calculation of the tW associated production cross section at the LHC has recently been given in [16]. The large backgrounds of the signature from single top production come from $W +$ jets and $t\bar{t}$ production. Despite the relatively large expected rate and the fact that $D0$ has developed several advanced multivariate techniques to discriminate single top production from backgrounds [17], single top production has not been discovered yet. For all three processes for single top production, the production cross section of the t-channel process can be most precisely measured at the LHC, which is expected to be measured to 2% accuracy [4]. Thus, at least we can say that, in most of the parameter space, the effects of the $SU(3)$ simple group model on the t-channel single top production process might be detected at the LHC.

In general, the contributions of the little Higgs models to the observables are proportional to the factor $1/f^2$. To see the f dependence of the corrections of the $SU(3)$ simple group model to single top production, we plot the relative correction $\Delta\sigma_i/\sigma_i^{SM}$ as a function of the scale parameter f for $t_\beta = 3$ and $x_\lambda = 3$ in Fig. 3, in which the solid line, dotted line, and dashed line represent the s-channel, t-channel, and tW associated production processes, respectively. One can see from Fig. 3 that the value of the relative correction $\Delta\sigma_i/\sigma_i^{SM}$ gets close to zero as f increasing. Thus, the contributions of the $SU(3)$ simple group model to single top production decouple for large value of the scale parameter f. However, for $t_\beta > 3$, $x_\lambda > 3$, and $1\text{ TeV} < f \leq 2.5$ TeV, the absolute value of the relative correction $\Delta\sigma_t/\sigma_t^{SM}$ is larger than 2%, which might be detected at the LHC.

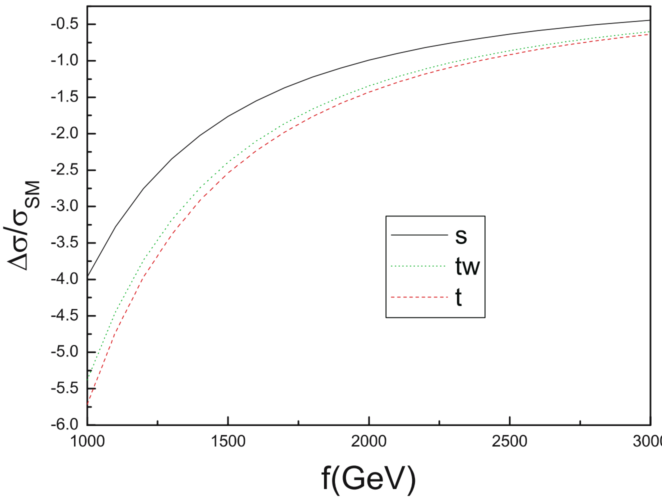

Fig. 3. The relative correction $\Delta\sigma_i/\sigma_i^{SM}$ as a function of the scale parameter f for $t_\beta = 3$ and $x_\lambda = 3$

4 The contributions of the new gauge bosons W_H and X to single top production

Some of the new particles, such as the new charged gauge boson W' and the scalar boson Φ, can couple the top quark to one of the lighter SM particles and thus can generate contributions to single top production at tree level or at one loop. The one-loop contributions are generally too small to be observed at hadron colliders [18]. From (3), (6), and (7), we can see that the new charged gauge bosons $W_H^\pm$ and X^- have contributions to the t-channel and s-channel processes for single top production. However, since these new gauge bosons must have space-like momentum in the t-channel process $q + b \to q' + t$, their contributions to the production cross section of the t-channel process are suppressed by the factor $1/M_{W_H}^2 (M_X^2)$ [19]. The masses M_{W_H} and M_X are at the order of TeV. Thus, the contributions of these heavy gauge bosons to the t-channel process are very small, which can be neglected. For the s-channel process $q + \bar{q}' \to t + \bar{b}$, the new charged gauge boson W' might generate significant contributions to its production cross section because of the possibility of W' resonant production [19, 20]. So, in this section, we will only consider that the contributions of the new gauge bosons W_H^- and X^- to the s-channel process $\bar{q} + q' \to \bar{t} + b$. Certainly, our numerical results are easily transferred to those of the new charged gauge boson W_H^+ for the process $q + \bar{q}' \to t + \bar{b}$ by replacing $\bar{b}$ by b and t by $\bar{t}$.

The center-of-mass energy $\sqrt{S}$ of the LHC is large enough to produce the heavy gauge bosons W_H^- or X^- on shell; thus, these heavy gauge bosons might produce significant contributions to the s-channel process $\overline{q}+q' \to \overline{t}+b$. The corresponding scattering amplitude including the SM gauge boson W can be written as

$$M_i = \frac{2\pi\alpha_e}{S_W^2}\left[\frac{1}{\hat{s}-m_W^2}+\frac{AB}{\hat{s}-M_i^2+\mathrm{i}M_i\Gamma_i}\right] \times \left[\overline{u}(\overline{q})\gamma^\mu P_L \nu(q')\right]\left[\overline{u}(b)\gamma_\mu P_L \nu(\overline{t})\right] , \qquad (13)$$

where i represents the gauge boson W_H^- or X^-. For the gauge boson W_H^-, $A=B=c/s$, and for the gauge boson X^-, $A=\delta_t$ and $B=\delta_\nu$. The expression of the total decay width Γ_{W_H} has been given in [21]. If the decay of the gauge boson X^- to one SM fermion and one TeV-scale fermion partner is kinematically forbidden, then it can decay to pairs of SM fermions through their mixing with the TeV-scale fermion partners, which is independent of the fermion embedding [6]. For the gauge boson X^-, the possible decay modes are $\overline{t}b$, $\overline{u}d$, $\overline{c}s$, and $l\nu_l$, in which l presents all three generation leptons e, μ, and τ. The total decay width Γ_{X^-} can be written as [6]

$$\Gamma_{X^-} = \frac{\alpha M_X}{4S_W^2}\left(\delta_t^2+5\delta_\nu^2\right) . \qquad (14)$$

The new gauge bosons predicted by the little Higgs models get their masses from the f condensate, which breaks the extended gauge symmetry. At the leading order, the masses of the new charged gauge bosons $W_H^\pm$ and X^- can be written as [5–7]

$$M_{W_H} = \frac{gf}{2sc} \approx 0.65 f \cdot \frac{c}{s} , \qquad (15)$$

$$M_X = \frac{gf}{\sqrt{2}} \approx 0.46 f . \qquad (16)$$

For the LH model, if we assume that the free parameters f and c are in the ranges of $1 \sim 3$ TeV and $0 \sim 0.5$, then we have $M_{W_H} \geq 1.12$ TeV, while the mass of the gauge boson X^- predicted by the $SU(3)$ simple group model is larger than 920 GeV even for $f \geq 2$ TeV. As a numerical estimation, we will simply assume 1 TeV $\leq M_{W_H} \leq$ 3 TeV and 1 TeV $\leq M_X \leq$ 3 TeV.

In Figs. 4 and 5, we plot the relative correction parameters $R_W = \Delta\sigma_s^W/\sigma_s^{SM}$ and $R_X = \Delta\sigma_s^X/\sigma_s^{SM}$ as functions of the gauge boson masses M_{W_H} and M_X for $t_\beta = 3$ and three values of the mixing parameters c and x_λ, respectively. In these figures, we have assumed $\Delta\sigma_s^W = \sigma_s(W+W_H) - \sigma_s(W)$ and $\Delta\sigma_s^X = \sigma_s(W+X) - \sigma_s(W)$. From these figures, we can see that the value of R_W is significantly larger than that of R_X. This is because, compared to the gauge boson W_H^-, the contributions of the gauge boson X^- to the s-channel process $\overline{q}+q' \to \overline{t}+b$ are suppressed by the factor ν^2/f^2. For $0.3 \leq c \leq 0.6$ and 1 TeV $\leq M_{W_H} \leq$ 2 TeV, the value of the relative correction parameter R_W is in the range of $1.5\% \leq R_W \leq 90\%$. Even for $M_{W_H} \geq 2.0$ TeV ($f \sim 2$ TeV), the value of the relative correction parameter R_W can reach 6.3%. Thus, the effects of the new gauge boson W_H to the s-channel process for single top production might be detected at the LHC.

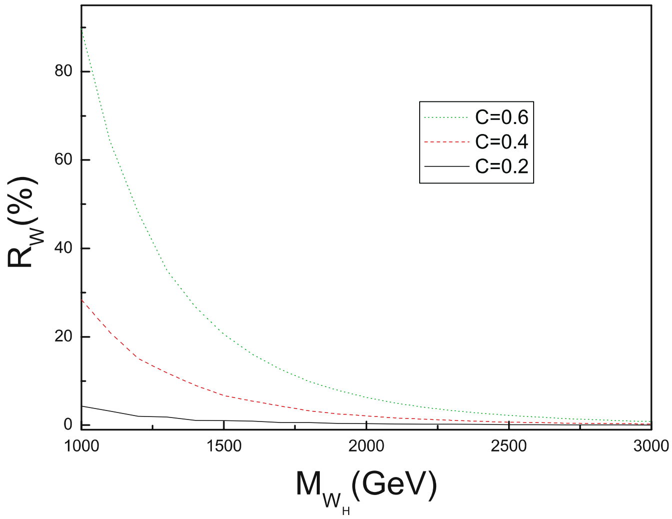

Fig. 4. The relative correction parameter R_W as a function of M_{W_H} for three values of the mixing parameter c

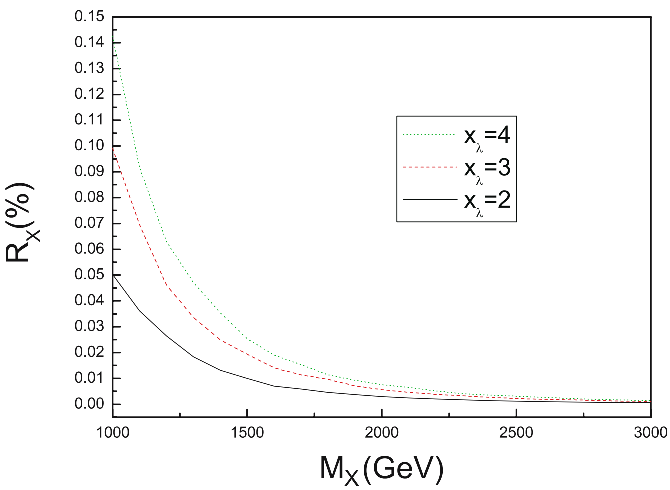

Fig. 5. The relative correction parameter R_X as a function of M_X for $t_\beta = 3$ and three values of the mixing parameter x_λ

5 Conclusions and discussion

The electroweak production of a single top quark at hadron colliders is an important prediction of the SM which proceeds through three distinct subprocesses. These subprocesses are classified by the virtuality of the electroweak gauge boson W involved: t-channel ($p^2 < 0$), s-channel ($p^2 > 0$), and associated tW ($p^2 = m_W^2$) production. Each process has rather distinct event kinematics, and thus they are potentially observable separately from each other [2]. All of these processes are sensitive to modification of the Wtb coupling, and the s-channel process is rather sensitive to some heavy charged particles. Thus, studying single top production at the LHC can help to test the SM and further to probe new physics beyond the SM.

To solve the so-called hierarchy or fine-tuning problem of the SM, the little Higgs theory was proposed as a kind of model for EWSB accomplished by a naturally light Higgs boson. All of the little Higgs models predict the existence of the new heavy gauge bosons and generate corrections to the SM tree-level Wqq' couplings. Thus, the little Higgs models have effects on single top production at hadron colliders.

Little Higgs models can be generally divided in two classes: product group models and simple group models. The LH model and the $SU(3)$ simple group model are the simplest examples of the two class models, respectively. In this paper, we have investigated single top production at the LHC in the context of the LH model and the $SU(3)$ simple group model. We find that these two simplest little Higgs models generate contributions to single top production at hadron colliders via two ways: correcting the SM tree-level Wqq' couplings and new charged gauge boson exchange. For the LH model, the contributions mainly come from the s-channel W_H exchange. For $0.3 \leq c \leq 0.6$ and $1\,\text{TeV} \leq M_{W_H} \leq 2\,\text{TeV}$, the relative correction of the new gauge boson W_H to the production cross section of the s-channel process at the LHC with $\sqrt{S} = 14\,\text{TeV}$ is in the range of $1.5\% \leq R_W \leq 90\%$. For the $SU(3)$ simple group model, the contributions of the new gauge boson X to the s-channel single top production process is very small. However, in most of the parameter space, the correction terms to the tree-level Wtb and Wqq' couplings can generate significant corrections to all production cross sections of the three processes for single top production at the LHC.

It is well known that precise electroweak data provide strong constraints on any extensions of the SM. Most of the little Higgs models are severely constrained by the precise electroweak data, with the exception of the littlest Higgs model with T parity, in which a low scale parameter f is allowed. However variations in the model can give rise to very different constraints. For example, for the LH model, if the SM fermions are charged under $U(1)_1 \times U(1)_2$, the constraints become relaxed. The scale parameter $f = 1 \sim 2\,\text{TeV}$ is allowed for the mixing parameter c, c', and x_L in the ranges of $0 \sim 0.5$, $0.62 \sim 0.73$, and $0.3 \sim 0.6$, respectively [6, 14]. In this case, the mass of the new charged gauge boson W_H is allowed in the range of $1\,\text{TeV} \sim 3\,\text{TeV}$. Thus, as a numerical estimation, we have simply assumed the scale parameter $f \geq 1\,\text{TeV}$. Certainly, the effects of the little Higgs models on single top production decrease as f is increasing, as shown in Fig. 3. However, our numerical results shown that, even for $f \geq 2\,\text{TeV}$, the relative correction of the $SU(3)$ simple group model to the cross section for the t-channel single top production process can reach -9%. Even, if we assume that the mass of the new charged gauge boson W_H predicted by the LH model is larger than 2 TeV, it can also make the cross section of the s-channel single top production process enhance about 6%. So we expect that the effects of the $SU(3)$ simple group model on the t-channel process for single top production and the contributions of the new charged gauge bosons $W_H^{\pm}$ predicted by the LH model to the s-channel process can be detected at the LHC experiments.

Acknowledgements. This work was supported in part by Program for New Century Excellent Talents in University (NCET-04-0290), the National Natural Science Foundation of China under Grant No.10475037.

References

1. CDF Collaboration, D0 Collaboration, Tevatron Electroweak Working Group, hep-ex/0507091
2. M. Beneke et al., hep-ph/0003033; D. Chakraborty, J. Konigsberg, D. Rainwater, Ann. Rev. Nucl. Part. Sci. **53**, 301 (2003); W. Wagner, Rep. Prog. Phys. **68**, 2409 (2005)
3. Z. Sullivan, Phys. Rev. D **70**, 114012 (2004); J. Campbell, R.K. Ellis, F. Tramontano, Phys. Rev. D **70**, 094012 (2004); C.-R. Chen, F. Larios, C.-P. Yuan, Phys. Lett. B **631**, 126 (2005)
4. J. Parsons, Top Quark Physics at the LHC I, talk presented at the Top Quark Symposium, April 7–8, 2005, Michigan Centor for Theoretical Physics, University of Michiyan, Ann Arbor
5. For recent review see: M. Schmaltz, D. Tucker-Smith, Ann. Rev. Nucl. Part. Sci. **55**, 229 (2005)
6. T. Han, H.E. Logan, L.T. Wang, JHEP **0601**, 099 (2006)
7. M. Perelstein, hep-ph/0512128
8. D.E. Kaplan, M. Schmaltz, JHEP **0310**, 039 (2003)
9. N. Arkani-Hamed, A.G. Cohen, E. Katz, A.E. Nelson, JHEP **0207**, 034 (2002)
10. M. Schmaltz, JHEP **0408**, 056 (2004)
11. T. Han, H.E. Logan, B. McElrath, L.T. Wang, Phys. Rev. D **67**, 095004 (2003)
12. J. Pumplin et al., JHEP **0207**, 012 (2002); D. Stump et al., JHEP **0310**, 046 (2003)
13. Particle Data Gruop, S. Eidelman et al., Phys. Lett. B **592**, 1 (2004)
14. R. Casalbuoni, A. Deandrea, M. Oertel, JHEP **0402**, 032 (2004); M.-C. Chen, S. Dawson, Phys. Rev. D **70**, 015003 (2004); C.-X. Yue, W. Wang, Nucl. Phys. B **683**, 48 (2004); W. Kilian, J. Reuter, Phys. Rev. D **70**, 015004 (2004); A. Deandrea, hep-ph/0405120; J.L. Hewett, F.J. Petriello, T.G. Rizzo, JHEP **0310**, 062 (2003); C. Csaki, J. Hubisz, G.D. Kribs, P. Meade, J. Terning, Phys. Rev. D **67**, 115002 (2003); C. Csaki et al., Phys. Rev. D **68**, 035009 (2003); T. Gregoire, D.R. Smith, J.G. Wacker, Phys. Rev. D **69**, 115008 (2004); M.-C. Chen, Mod. Phys. Lett. A **21**, 621 (2006)
15. B.W. Harris et al., Phys. Rev. D **66**, 054024 (2002)
16. J. Campbell, F. Tramontano, Nucl. Phys. B **726**, 109 (2005); M. Beccaria, F.M. Renard, C. Verzegnassi, Phys. Rev. D **71**, 033005 (2005); M. Beccaria, G. Macorini, F.M. Renard, C. Verzegnassi, Phys. Rev. D **73**, 093001 (2006)
17. D0 Collaboration, V.M. Abazov et al., Phys. Lett. B **622**, 265 (2005)
18. C.-S. Li, R. Oakes, J.-M. Yang, H.-Y. Zhou, Phys. Rev. D **57**, 2009 (1998); S. Bar-Shalom, D. Atwood, A. Soni, Phys. Rev. D **57**, 1495 (1998)
19. T. Tait, C.-P. Yuan, Phys. Rev. D **63**, 014018 (2000)
20. Z. Sullivan, Phys. Rev. D **66**, 075011 (2002)
21. H.E. Logan, hep-ph/0307340; C.-X. Yue, F. Zhang, W. Wang, Chin. Phys. Lett. **22**, 1083 (2005)