Production of $hh\bar{t}$ and $ht\bar{T}$ in the littlest Higgs model with T parity

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In the littlest Higgs model with T parity, which predicts a pair of T-even and T-odd partners for the top quark, the top-quark interactions are altered with respect to the standard model predictions and the deviation will manifest in various top-quark processes. In this work we examine the effects in $ht\bar{t}$ productions at the International Linear Collider and CERN LHC. We find that, in the allowed parameter space, the cross sections can be significantly deviated from the standard model predictions and thus provide a good test for the littlest Higgs model with T parity. We also examine the new production channel, $ht\bar{T}$ or $hT\bar{t}$ production, at the LHC, which gives the same final states as $ht\bar{t}$ production due to the dominant decay $T \to Wb$. We find that, compared with $ht\bar{t}$ production, this new production channel can have a sizable production rate for a T quark below the TeV scale. Such a production will be counted into $ht\bar{t}$ events or possibly extracted from $ht\bar{t}$ events, depending on if we can distinguish the T quark from the top quark from mass reconstructions.

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I. INTRODUCTION

To solve the fine-tuning problem of the standard model (SM), the little Higgs theory [1] was proposed as a kind of electroweak symmetry breaking mechanism accomplished by a naturally light Higgs sector. The Higgs boson remains light, being protected by the approximate global symmetry and free from one-loop quadratic sensitivity to the cutoff scale. The littlest Higgs model [2] provides an economical approach which implements the idea of the little Higgs theory. Most of the constraints from the electroweak precision tests on little Higgs models [3] come from the tree-level mixing of heavy and light mass eigenstates, which would require raising the mass of the new particles to be much higher than the TeV scale and thus reintroduce the fine-tuning in the Higgs potential [4]. However, these tree-level contributions can be avoided by introducing a discrete symmetry called T parity [5]. In such a scenario, the top quark has a T-even partner (denoted as T) and a T-odd partner (denoted as T_-). As a result, the top-quark interactions are altered with respect to the SM predictions, which will manifest in various top-quark processes. In this work, we will examine such effects in the associated $ht\bar{t}$ productions at the CERN LHC and the International Linear Collider (ILC), and also study the $ht\bar{T}$ and $hT\bar{t}$ productions at the LHC (due to the heaviness of the T quark, $ht\bar{T}$ is beyond the threshold of the ILC).

The reason for studying $ht\bar{t}$ production as a test of the littlest Higgs model with T parity is obvious. First, the large top-quark Yukawa coupling is speculated to be sensitive to new physics and the $ht\bar{t}$ productions may be a sensitive probe of the littlest Higgs model with T parity. In this model the top-quark Yukawa coupling has a deviation from the SM prediction, which will affect the $ht\bar{t}$ productions. Also the T quark can contribute to the $ht\bar{t}$ productions through its virtual effects. Second, $ht\bar{t}$ production will first be searched at the LHC and can be precisely measured at the ILC [6,7]. At the ILC the top-quark Yukawa coupling can be measured with an accuracy of about 5% through the production of $ht\bar{t}$ [8] and the polarized beams can further improve the measurement precision [9]. The precision measurements of $ht\bar{t}$ production make it possible to unravel the new physics effects in this process.

In addition, the new production channel at the LHC, $ht\bar{T}$ or $hT\bar{t}$ production, should also be considered since they give the same final states as $ht\bar{t}$ production due to the dominant decay $T \to Wb$. As will be shown in our study, compared with $ht\bar{t}$ production, this new production channel can have a sizable production rate for a T quark below the TeV scale. Such a production will be counted into $ht\bar{t}$ events or possibly extracted from $ht\bar{t}$ events, depending on if we can distinguish the T quark from the top quark from mass reconstructions.

This work is organized as follows. In Sec. II we recapitulate the littlest Higgs model with T parity. In Secs. III and IV we study the $ht\bar{t}$ productions at the ILC and LHC, respectively. In Sec. V we study the new $ht\bar{T}$ or $hT\bar{t}$ production channel at the LHC. Finally, we give our conclusion in Sec. VI.

II. LITTLEST HIGGS MODEL WITH T PARITY

Before our calculations we recapitulate the littlest Higgs model with T parity [5,10]. The gauge sector of this model can be simply obtained from the usual littlest Higgs model [2]. T parity acts as an automorphism which exchanges the $[SU(2) \times U(1)]_1$ and $[SU(2) \times U(1)]_2$ gauge factors. Before electroweak symmetry breaking, the gauge boson mass eigenstates have the simple form

$$W_{\pm}^{\alpha} = \frac{W_1^{\alpha} \pm W_2^{\alpha}}{\sqrt{2}}, \qquad B_{\pm} = \frac{B_1 \pm B_2}{\sqrt{2}}, \tag{1}$$

where W_j^{α} and B_j are $SU(2)_j$ and $U(1)_j$ ($j = 1, 2$) gauge fields. W_+^{α} and B_+ are the SM gauge bosons and have even T parity, whereas W_-^{α} and B_- are additional heavy gauge bosons and have odd T parity. After electroweak symmetry breaking, the new mass eigenstates in the neutral heavy sector will be a linear combination of W_-^{α} and B_- gauge bosons, producing B_H and Z_H. The B_H is typically the lightest T-odd state and may be a candidate for dark matter. Because of T parity, the new gauge bosons do not mix with the SM gauge bosons and thus they generate no corrections to precision electroweak observables at tree level. The top-quark sector contains a T-even and a T-odd partner, with the T-even one mixing with the top quark and canceling the quadratic divergence contribution of the top quark to Higgs boson mass. The masses of the T-even partner (denoted as T) and the T-odd partner (denoted as T_-) are given by

$$m_T \approx \frac{m_t f}{v}\left(r + \frac{1}{r}\right), \qquad m_{T_-} \approx m_T s_{\lambda}, \tag{2}$$

where v is the electroweak breaking scale (≈ 246 GeV), $r = \lambda_1/\lambda_2$ with λ_1 and λ_2 being the coupling constants in the Lagrangian of the top-quark sector [5,10,11], and $s_{\lambda} = 1/\sqrt{1 + r^2}$.

The mixing of the T quark with the top quark will alter the SM top-quark couplings and induce the couplings between t and T [10,11], which are given by

$$V_{ht\bar{T}} = -m_t\left(\frac{s_{\lambda}^2}{f} P_R - \frac{c_{\lambda}}{s_{\lambda} v} P_L\right), \tag{3}$$

$$V_{Zt\bar{T}}^{\mu} = -\gamma^{\mu} \frac{e}{2S_W C_W} c_{\lambda}^2 \frac{v}{f} P_L, \tag{4}$$

$$V_{Zt\bar{t}}^{\mu} = \gamma^{\mu} \frac{e}{S_W C_W}\left[\left(\frac{1}{2} - \frac{2}{3} S_W^2 - \frac{c_{\lambda}^4}{2} \frac{v^2}{f^2}\right) P_L - \frac{2}{3} S_W^2 P_R\right], \tag{5}$$

$$V_{ht\bar{t}} = -\frac{m_t}{v}\left(1 - \frac{3 + 2r^2 + 3r^4}{4(1 + r^2)^2} \frac{v^2}{f^2}\right), \tag{6}$$

where $P_{R,L} = (1 \pm \gamma^5)/2$ and $c_{\lambda} = r/\sqrt{1 + r^2}$. The hZZ coupling involved in our calculations will also be different from the SM coupling, which is given by

$$V_{hZZ}^{\mu\nu} = \frac{2m_Z^2}{v}\left(1 - \frac{1}{4} \frac{v^2}{f^2}\right) g^{\mu\nu}. \tag{7}$$

In the littlest Higgs model with T parity, the T quark can decay into Wb, ht, Zt, and $B_H T_-$, among which the decay $T \to Wb$ is the most important channel [10–12]. As shown in Fig. 12 of [11], BR($T \to Wb$) is over 46% for $r = 1.0$ and 500 GeV $\leq f \leq 2$ TeV. When f is 500 GeV, BR($T \to Wb$) can be over 50%. For comparison, the subdominant decay $T \to Zt$ can have a branching ratio of about 20% at most in the parameter space for $r = 1.0$ and 500 GeV $\leq f \leq 2$ TeV.

III. PRODUCTION OF $ht\bar{t}$ AT THE ILC

Now we look at the process $e^+e^- \to t\bar{t}h$ in the littlest Higgs model with T parity. The Feynman diagrams are shown in Fig. 1. In the SM it proceeds mainly through the s-channel γ and Z exchange diagrams with the Higgs boson radiated from the top quark, as shown in Figs. 1(a) and 1(b). Although a contribution can also come from Fig. 1(e) with the Higgs boson radiated from the gauge boson Z, such a contribution is relatively small. In the littlest Higgs model with T parity we have additional diagrams, Figs. 1(c) and 1(d), mediated by the T quark. Because of the T parity, other new particles, such as new heavy gauge bosons Z_H and B_H, do not participate in this process.

We calculate the cross section numerically by Monte Carlo simulation. The cross section in the littlest Higgs model with T parity depends on two free parameters: the symmetry breaking scale f and the ratio $r = \lambda_1/\lambda_2$. Considering the electroweak precision constraints [13], we vary them in the range $0.5 \leq r \leq 5.0$ and 500 GeV $\leq f \leq$ 2 TeV. The SM parameters involved are taken as $m_t =$ 172.7 GeV [14], $m_h = 120$ GeV, $\alpha_{\rm EW} = 1/128.8$, $\sin^2\theta_W = 0.2315$, and $m_Z = 91.187$ GeV [15].

The c.m. energy is assumed to be 800 GeV. Considering the polarization of the initial electron and positron beams, the cross section of $e^+e^- \to t\bar{t}h$ is given by [16]

$$\sigma = \tfrac{1}{4}[(1 + p_e)(1 + p_{\bar{e}})\sigma_{RR} + (1 - p_e)(1 - p_{\bar{e}})\sigma_{LL} + (1 + p_e)(1 - p_{\bar{e}})\sigma_{RL} + (1 - p_e)(1 + p_{\bar{e}})\sigma_{LR}], \tag{8}$$

where σ_{RL} is the cross section for the right-handed e^- beam ($p_e = +1$) and the left-handed e^+ beam ($p_{\bar{e}} = -1$),

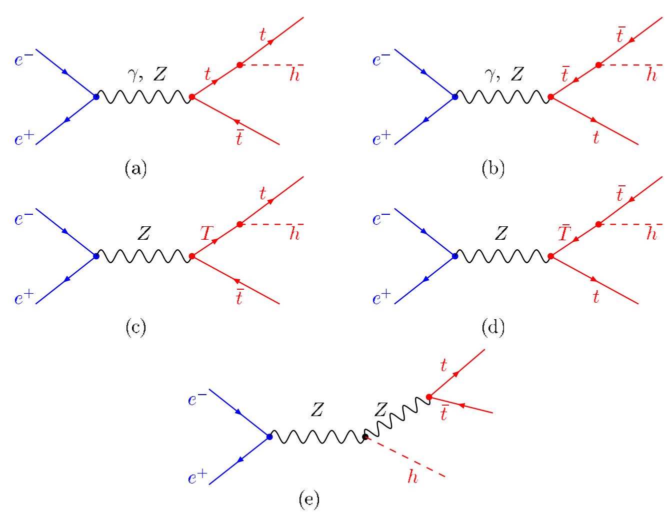

FIG. 1 (color online). Feynman diagrams for $e^+e^- \to t\bar{t}h$ in the littlest Higgs model with T parity.

and other cross sections σ_{RR}, σ_{LL}, and σ_{LR} are defined analogously. As in [9], we assume $p_e = -0.8$ and $p_{\bar{e}} = 0.6$ in our calculations.

In Fig. 2 we plot some contours for the deviation from the SM cross section in the plane of r versus the symmetry breaking scale f. For comparison we also show the corresponding results for unpolarized beams. We see that the polarized beams lead to a more sizable deviation and thus make the collider more powerful in probing such new physics effects. Figure 2 shows that the contributions of this model decrease the SM cross section in the allowed parameter space, and the magnitude of such corrections depends on the parameters r and f. The corrections are more sizable for lower values of the scale f, and in a large part of the parameter space the contributions can alter the SM cross section by over 5%. When f is lower than 1 TeV, the corrections can be over 10% in magnitude.

So far the electroweak precision data have constrained the parameter space of r and f. But, as studied in [13], such constraints depend on additional parameters, i.e., the masses of extra T-odd fermions and the parameter δ_c whose value is dependent on the details of the UV physics. Therefore, we did not show these electroweak precision constraints in Fig. 2.

Another remarkable feature of our results is that the corrections are very sensitive to the scale f, but not so sensitive to the parameter r when r is larger than about 2, as shown in Fig. 2. This means that we can use this process to determine or constrain the scale f if r is large.

In Fig. 2 we also plotted the 2σ statistical significance, obtained by assuming a luminosity of 1000 fb^{-1} and an efficiency of 10% for events counting (due to kinematical cuts and b-tagging, etc.). We see that a large part of parameter space is within the 2σ statistical sensitivity. Of course, we should note that some inevitable systematic error will worsen the probing limits. Detector-dependent Monte Carlo simulations are necessary in order to figure out the more practical probing limits.

Note that, in the littlest Higgs model without T parity, the new neutral gauge bosons Z_H and B_H can also contribute to the process $e^+e^- \to t\bar{t}h$ at tree level via s-channel resonances [17]. In this case, the large values of f required by the precision electroweak data suppress the contributions of these new particles and, as a result, the T-quark effects are very small. However, in the littlest Higgs model with T parity considered in this work, T parity forbids the tree-level contributions of the new gauge bosons Z_H and B_H to the process since they are T-odd. Thus in this scenario only the T quark with even T parity can contribute to the process at tree level, and due to the relaxed constraint on f (as low as 500 GeV is still allowed), such T-quark effects may be sizable. (However, we noticed that there is an alternative implementation of the T parity [18], in which all new particles that cancel the quadratic divergence of Higgs mass are T-odd, including the top-quark sector. Thus, there is no T quark with even T parity, and the T quarks cannot contribute to the process $e^+e^- \to ht\bar{t}$ at tree level.)

IV. PRODUCTION OF $ht\bar{t}$ AT THE LHC

The production of $ht\bar{t}$ at the LHC can proceed through gg fusion or $q\bar{q}$ annihilation, as shown in Fig. 3. In the littlest Higgs model with T parity the $ht\bar{t}$ coupling is different from the SM prediction, as shown in Eq. (6). This will cause a correction to the production cross section,

$$R = \frac{\sigma - \sigma^{SM}}{\sigma^{SM}} = \frac{V_{ht\bar{t}}^2 - V_{ht\bar{t}}^2(\mathrm{SM})}{V_{ht\bar{t}}^2(\mathrm{SM})}. \quad (9)$$

Here, $V_{ht\bar{t}}(\mathrm{SM})$ and $V_{ht\bar{t}}$ are the top-quark Yukawa couplings in the SM and the littlest Higgs model with T parity [10,11], respectively.

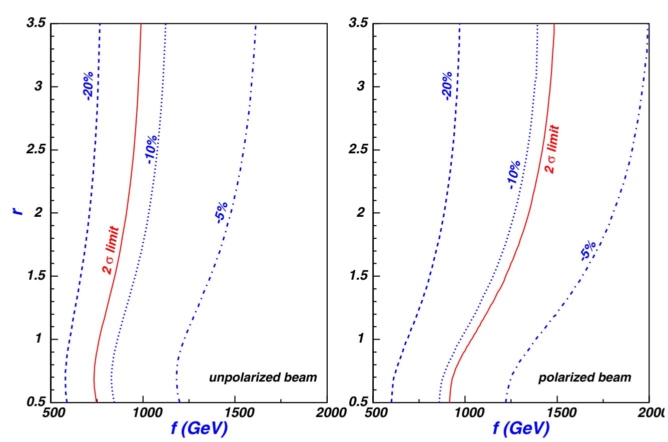

FIG. 2 (color online). The contours of the deviation from the SM cross section $(\sigma - \sigma^{SM})/\sigma^{SM}$ for $e^+e^- \to t\bar{t}h$ in the plane of r versus the symmetry breaking scale f. The solid curves are the 2σ statistical significance.

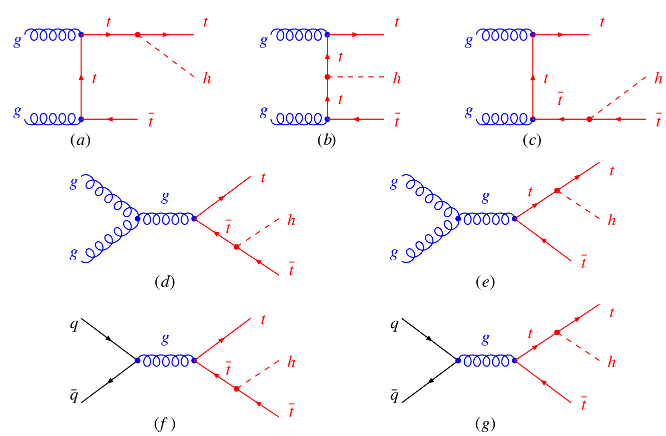

FIG. 3 (color online). The parton-level Feynman diagrams for $ht\bar{t}$ production at the LHC. In the littlest Higgs model with T parity, the $ht\bar{t}$ vertex deviates from the SM value, as shown in Eq. (6). The u-channel diagrams by exchanging the two gluons in (a)–(c) are not shown here.

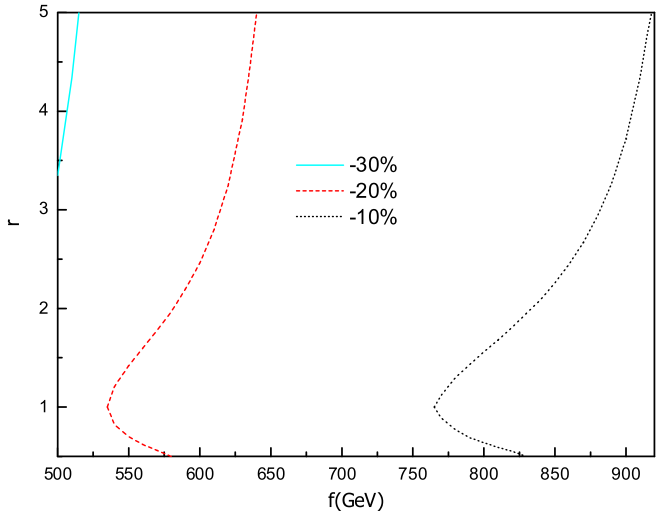

FIG. 4 (color online). The contours of the deviation from the SM cross section $(\sigma - \sigma^{SM})/\sigma^{SM}$ for the process $pp \to ht\bar{t} + X$ at the LHC.

Figure 4 shows some contours for the deviation from the SM cross section in the plane of r versus the symmetry breaking scale f. From this figure we see that the corrections decrease the SM cross section in the allowed parameter space. The corrections are more sizable for lower values of the scale f. In a large part of the parameter space with $f < 650$ GeV, the corrections can be over 20% in magnitude.

V. PRODUCTION OF $ht\bar{T}$ AND $hT\bar{t}$ AT THE LHC

Like $ht\bar{t}$ production, the production of $ht\bar{T}$ or $hT\bar{t}$ can proceed through gg fusion or $q\bar{q}$ annihilation at the LHC, as shown in Fig. 5. In the littlest Higgs model with T parity, the T quark can decay into Wb, ht, Zt, and $B_H T_-$, among which the decay $T \to Wb$ is the most important channel [10–12]. Therefore, the final states of $ht\bar{T}$ or $hT\bar{t}$ production are the same as $ht\bar{t}$ production. If we do not try to distinguish the T quark from the top quark by mass reconstruction, the productions $ht\bar{T}$ and $hT\bar{t}$ will be counted into $ht\bar{t}$ events.

In Fig. 6 we plot the ratio $\sigma(ht\bar{T} + hT\bar{t})/\sigma^{SM}(ht\bar{t})$ as a function of T-quark mass. In our calculations we used the CTEQ5M patron distribution functions [19] with $Q = 2m_t + m_h$ and the two-loop running coupling constant $\alpha_s(Q)$ with $\alpha_s(m_Z) = 0.118$. From Fig. 6 we see that the ratio can be over 10% for m_T below the TeV scale. When m_T is 700 GeV, the ratio can reach 40%. With the increase of m_T, the production cross section becomes small because of the phase space suppression.

Note that, due to the large mass difference between m_T and m_t, we may try to extract the signal of $ht\bar{T}$ production from $ht\bar{t}$ events by mass reconstructions. This is not easy since it requires the mass reconstruction for both t and $\bar{t}$.

Given the analyses in both this section and the preceding section, we would like to remark on the overall impact of the modified cross sections for the Higgs discovery at the LHC. As shown in [20], the $ht\bar{t}$ production channel will be hard to observe at the LHC. As shown in Sec. IV, the contribution of the littlest Higgs model with T parity can decrease the SM $ht\bar{t}$ cross section by 20%, which thus makes the observation of this production channel even harder. But, at the same time, the new channels of $hT\bar{t}$ and $ht\bar{T}$ production may open up. As shown in Fig. 6, for 700 GeV $< m_T <$ 800 GeV the production of $hT\bar{t}$ and $ht\bar{T}$ can have a cross section of 20%–40% with respect to the SM $ht\bar{t}$ cross section. Considering the heaviness of the T quark, the production of $ht\bar{T} + hT\bar{t}$ may have less background than $ht\bar{t}$ production, and thus this new channel may likely be observable at the LHC.

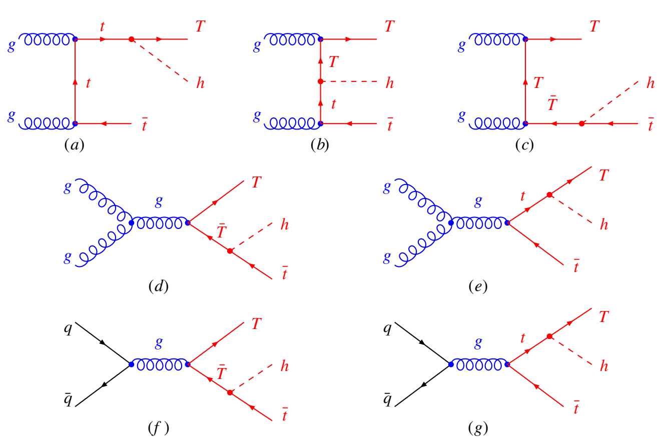

FIG. 5 (color online). The parton-level Feynman diagrams for $hT\bar{t}$ production at the LHC in the littlest Higgs model with T parity. The u-channel diagrams by exchanging the two gluons in (a)–(c) are not shown here.

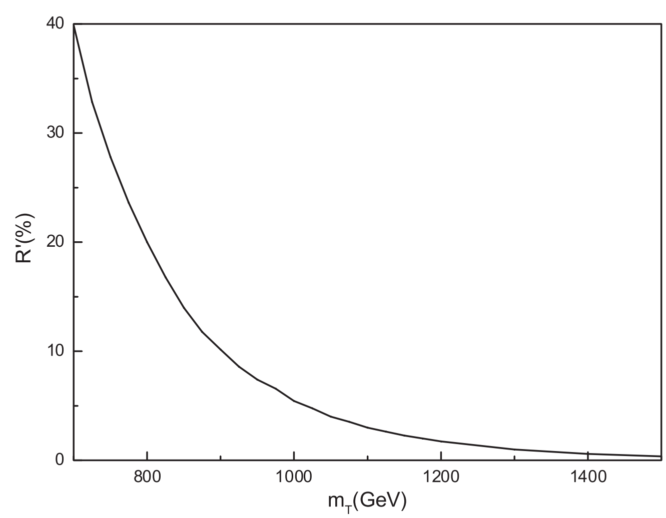

FIG. 6. The ratio $R' = [\sigma(ht\bar{T} + hT\bar{t})]/\sigma^{SM}(ht\bar{t})$ at the LHC as a function of m_T for $r = 1.0$.

VI. CONCLUSION

We studied top-quark pair production associated with a light Higgs boson as a test of the littlest Higgs model with T parity at the ILC and LHC. For the production of $ht\bar{t}$ at the ILC, we found that in a large part of the allowed parameter space the cross section can deviate from the SM prediction by over 10% and thus may be observable. Also, we found that the polarized beams lead to more sizable deviation and thus make the ILC more powerful in probing such effects. For the production of $ht\bar{t}$ at the LHC, we found that in a large part of the parameter space the deviation from the SM cross section can be over 20%. For the new production channel of $ht\bar{T}$ or $hT\bar{t}$, we found that their cross section can be over 10% of the SM $ht\bar{t}$ production for m_T below the TeV scale.

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