Production of the neutral top-pion $\pi^0_t$ in association with a high-$p_T$ jet at the LHC

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December 8, 2008

Abstract

In the framework of the topcolor-assisted technicolor (TC2) model, we study production of the neutral top-pion $\pi^0_t$ in association with a high-$p_T$ jet at the LHC, which proceeds via the partonic processes $gg \rightarrow \pi^0_t g$, $gq \rightarrow \pi^0_t q$, $q\bar{q} \rightarrow \pi^0_t g$, $gb(b) \rightarrow \pi^0_t b(b)$, and $b\bar{b} \rightarrow \pi^0_t g$. We find that it is very challenging to detect the neutral top-pion $\pi^0_t$ via the process $pp \rightarrow \pi^0_t + jet + X \rightarrow t\bar{t} + jet + X$, while the possible signatures of $\pi^0_t$ might be detected via the process $pp \rightarrow \pi^0_t + jet + X \rightarrow (\bar{t}c + t\bar{c}) + jet + X$ at the LHC.

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1. Introduction

The Higgs mechanism for the electroweak symmetry breaking (EWSB) is still the untested part of the standard model (SM). Searching for the SM Higgs boson is one of the main tasks of the forthcoming Large Hadron Collider (LHC), which has considerable capability to discover and measure almost all of its quantum properties [1]. However, if the LHC finds evidence for a new scalar state, it may not necessarily be the SM Higgs boson. Most of new physics models beyond the SM predict the existence of new scalar states. These new particles may have production cross sections and branching ratios which differ from those of the SM Higgs boson. Distinguishing the various new physics scenarios is an important task for current and near future high energy collider experiments. Thus, studying the production and decay of the new scalar states at the LHC is of special interest.

Due to the large gluon luminosity, the main production mechanism for a scalar Higgs boson at the LHC is the partonic gluon fusion process $gg \rightarrow H$ [2], which is the so-called inclusive single Higgs boson production channel. In order to fully explore the Higgs detection capabilities of the LHC, one should investigate more exclusive channels, like e.g. Higgs production in association with a high-$p_T$ hadronic jet [3]. The main advantage of this channel is the richer kinematical structure of the events which allows for refined cuts increasing the signal-to-background ratio. So far, this production channel has been extensively studied in the SM [4,5]. In the minimal supersymmetric standard model (MSSM), the analogous process, i.e. scalar Higgs production in association with a high-$p_T$ jet was also extensively studied in Refs.[6,7].

Among various kinds of dynamical EWSB theories, the topcolor scenario is attractive because it can explain the large top quark mass and provides a possible EWSB mechanism [8]. The topcolor-assisted technicolor (TC2) model [9] is one of the phenomenologically viable models, which has all essential features of the topcolor scenario. This model predicts three $CP$ odd top-pions ($\pi_t^0, \pi_t^\pm$) with large Yukawa couplings to the third family. The aim of this paper is to consider the production of the neutral top-pion $\pi_t^0$ associated with a high-$p_T$ jet and compare our results with those for the Higgs boson from the SM or the
MSSM. We hope that our work can help the upcoming LHC to test topcolor scenario and to differentiate various kinds of new physics models.

In the rest of this paper, we will give our results in detail. In section 2, we will calculate the production cross section of the hadronic process $pp \rightarrow \pi_0^t + jet + X$ and give a simply phenomenological analysis at the LHC. Our conclusion is represented in section 3.

2. Production of the neutral top-pion $\pi_0^t$ associated with a high-$p_T$ jet

In the TC2 model [9], topcolor interactions, which are not flavor-universal and mainly couple to third generation fermions, generally generate small contributions to EWSB and give rise to the main part of the top quark mass. Thus, the top-pions $\pi_0^t, \pi_{0,\pm}^t$ have large Yukawa couplings to the third generation fermions. Such features can result in large tree-level flavor changing couplings of the top-pions to the fermions when one writes the interactions in the fermion mass eigen-basis. Just as for the SM Higgs boson, the couplings of the top-pion to a pair of quarks are proportion to the quark masses. The explicit form for the couplings of the neutral top-pion $\pi_0^t$ to quarks, which are related to our calculation, can be written as [9,10]:

$$\frac{im_t}{\sqrt{2}F_t} \frac{\nu_W^2 - F_t^2}{\nu_W} \left[ k_{UR}^{tt} k_{UL}^{tt} \gamma^5 t_0 \pi_0^t + \frac{m_b - m'_b}{m_t} \bar b \gamma^5 b \pi_0^t + k_{UR}^{tc} k_{UL}^{tt} \bar c \gamma^5 c \pi_0^t \right],$$  \hspace{1cm} (1)

where $\nu_W = \nu/\sqrt{2} \approx 174 GeV$, $P_R = (1 + \gamma^5)/2$ is the right-handed projection operator, $F_t \approx 50 GeV$ is the top-pion decay constant, and $m'_b \approx 0.1 \varepsilon m_t$ is the part of the bottom quark mass generated by extended technicolor interactions. $k_{UL(R)}$ are rotation matrices that diagonalize the up-quark mass matrix $M_U$ for which the Cabibbo-Kobayashi-Maskawa (CKM) matrix is defined as $V_{CKM} = k_{UL}^{+} k_{DL}$. To yield a realistic form of $V_{CKM}$, it has been shown that the values of the matrix elements $k_{UL(R)}^{ij}$ can be taken as [10]:

$$k_{UL}^{tt} \approx 1, \quad k_{UR}^{tt} = 1 - \varepsilon, \quad k_{UR}^{tc} \leq \sqrt{2\varepsilon - \varepsilon^2}. \hspace{1cm} (2)$$

In our numerical estimation, we will take $k_{UR}^{tc} = \sqrt{2\varepsilon - \varepsilon^2}$ and take $\varepsilon$ as a free parameter, which is assumed to be in the range of $0.01 \sim 0.1$. 

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Figure 1: Feynman diagrams for the partonic processes contributing to the hadronic process $pp \rightarrow \pi_t^0 + jet + X$ at the leading order. The other diagrams obtained by exchanging the gluons or exchanging $\pi_t^0$ are not shown here.
Similar to the Higgs boson predicted by the SM or the MSSM, the neutral top-pion $\pi_t^0$ can be produced at the LHC in association with a high-$p_T$ jet through three partonic processes: gluon fusion ($gg \rightarrow g\pi_t^0$), quark-gluon scattering ($q(\bar{q})g \rightarrow q(\bar{q})\pi_t^0$), and quark-antiquark annihilation ($qq \rightarrow g\pi_t^0$). Although the gluon fusion and quark-gluon scattering partonic processes give main contributions to the production cross section for the hadronic process $pp \rightarrow \pi_t^0 + jet + X$ at the LHC, our numerical analysis include all of above three processes, which proceed at one-loop, as shown in Fig.1(a) $\sim$ (e). Considering the small value of the decay constant $F_t$ and the relatively large bottom-quark mass, we also consider the contributions of the tree-level partonic processes $gb \rightarrow \pi_t^0 b$ and $b\bar{b} \rightarrow \pi_t^0 g$, as shown in Fig.1(f) $\sim$ (h).

The variant amplitudes corresponding to the Feynman diagrams as shown in Fig.1 can be written as:

$$M_{(a)} = \frac{i}{4\sqrt{2}\pi^2} T_{ij}c_{c_j}f_{c_i c_j} g_s^3 m^2(1 - \varepsilon)^{3}\sqrt{\nu_W^2 - F_t^2} C_{0(a)}[(p_2 - p_1)_{\mu}\varepsilon(1)_{\cdot}(p_2)_{\mu} + (2p_2 - p_1)_{\mu}\varepsilon(1)_{\cdot}(p_2)_{\mu}(p_1)_{\cdot} \varepsilon(p_1)_{\mu}(p_2)_{\cdot} \varepsilon(p_2)_{\mu}]$$

$$M_{(b)} = \frac{i}{4\sqrt{2}\pi^2} T_{ij}c_{c_j}f_{c_i c_j} g_s^3 m^2(1 - \varepsilon)^{3}\sqrt{\nu_W^2 - F_t^2} C_{0(b)}[((p_2 - p_1)_{\mu}\varepsilon(p_2)_{\mu}){(p_1)}_{\cdot} \varepsilon(p_1)_{\mu}(p_2)_{\cdot} \varepsilon(p_2)_{\mu}]$$

$$M_{(c)} = \frac{i}{4\sqrt{2}\pi^2} T_{ij}c_{c_j}f_{c_i c_j} g_s^3 m^2(1 - \varepsilon)^{3}\sqrt{\nu_W^2 - F_t^2} C_{0(c)}[p_{\cdot}\varepsilon(p_2)_{\mu} + (2p_2 - p_1)_{\mu}\varepsilon(1)_{\cdot}(p_2)_{\mu}(p_1)_{\cdot} \varepsilon(p_1)_{\mu}(p_2)_{\cdot} \varepsilon(p_2)_{\mu}]$$
Here $p_1, p_2$ are the momenta of the incoming states, and $p_3, p_4$ are the momenta of the outgoing final states. The $T_{ij}^c$ are the $SU(3)$ color matrices and the $f_{c_1c_2c_3}^i$ are the antisymmetric $SU(3)$ structure constants in which $i, j$ are the color indices and $c_1, c_2, c_3$ are the indices of gluon. The three-point and four-point standard functions $C_0, D_0, D_1, D_\nu$ \cite{11,12} for different Feynman diagrams are defined as:

\[
C_{0(a)} = C_{0(a)}(p_1 + p_2, -p_3, m_t, m_t, m_t), \quad C_{0(b)} = C_{0(b)}(p_1 - p_3, p_2, m_t, m_t, m_t),
\]

\[
C_{0(d)} = C_{0(d)}(p_1 - p_3, p_2, m_t, m_t, m_t), \quad C_{0(c)} = C_{0(c)}(p_1 + p_2, -p_3, m_t, m_t, m_t);
\]

\[
D_{0(c)} = D_{0(c)}(p_1, p_2, -p_3, m_t, m_t, m_t), \quad D_{1(c)} = D_{1(c)}(p_1, p_2, -p_3, m_t, m_t, m_t),
\]

\[
D_\nu(c) = p_{1\nu} * D_1(c)(1) + p_{2\nu} * D_1(c)(2) + p_{3\nu} * D_1(c)(3).
\]

Each loop diagram is composed of some scalar loop functions, which are calculated by using LoopTools \cite{12}.

The hadronic cross section at the $LHC$ is obtained by convoluting the partonic cross sections with the parton distribution functions ($PDFs$). In our numerical calculation, we
will use CTEQ6L PDFs [13] for the gluon and quark PDFs. The renormalization scale \(\mu_R\) and the factorization scale \(\mu_F\) are chosen to be \(\mu_R = \mu_F = m_{\pi_t}\) for the gluons and the light quarks, and to be \(\mu_R = \mu_F = m_{\pi_t}/4\) for the bottom-quark, in which \(m_{\pi_t}\) is the mass of the neutral top-pion \(\pi^0_t\). To make our predictions more realistic and high-\(p_T\) jet not too close to the beam axis, we require that the transverse momentum \(p_T\) and pseudorapidity \(\eta\) of the hadronic jet satisfy: \(p_T > 30 GeV\) and \(|\eta| < 4.5\), which have been used in previous MSSM studies for the LHC [6,7].

![Figure 2](image)

**Figure 2:** The total cross section of the hadronic process \(pp \to \pi^0_t + \text{jet} + X\) as a function of the \(\pi^0_t\) mass \(m_{\pi_t}\) for three values of the free parameter \(\varepsilon\).

From the above discussions we can see that the production cross section \(\sigma\) for the hadronic process \(pp \to \pi^0_t + \text{jet} + X\) is dependent on the free parameters \(\varepsilon\) and \(m_{\pi_t}\). Similar with Ref.[14], we will assume that the free parameters \(\varepsilon\) and \(m_{\pi_t}\) are in the range of \(0.01 \sim 0.1\) and \(200 GeV \sim 500 GeV\), respectively.

Our numerical results are shown in Fig.2, in which we plot the cross section \(\sigma\) as a function of the mass parameter \(m_{\pi_t}\) for three values of the parameter \(\varepsilon\). One can see from Fig.2 that \(\sigma\) is insensitive to the free parameter \(\varepsilon\). For \(\varepsilon = 0.05\) and \(200 GeV \leq m_{\pi_t} \leq 500 GeV\), the value of the production cross section \(\sigma\) is in the range of \(18.3 pb \sim 2.1 pb\).
Observably, if we assume that the $\pi^0_t$ mass $m_{\pi_t}$ is equal to that of the $SM$ Higgs boson $H$ or the $MSSM$ Higgs boson $H^0$, the cross section for the production of the neutral top-pion $\pi^0_t$ associated with a high-$p_T$ is significantly larger than that of the $SM$ Higgs boson $H$ [4,5] or the $MSSM$ Higgs boson $H^0$ [6,7]. This is because the $\pi^0_t t\bar{t}$ coupling is larger than that for the $SM$ Higgs boson $H$ or the $MSSM$ Higgs boson $H^0$.

To see contributions of the different partonic processes to the total hadronic cross section, we plot the hadronic cross sections of the partonic processes $gg \rightarrow \pi^0_t g$, $gg \rightarrow q\pi^0_t (q = u, c, d, s, \bar{u}, \bar{c}, \bar{d}, \bar{s})$, $q\bar{q} \rightarrow \pi^0_t g (q = u, c, d, s)$, $gb(\bar{b}) \rightarrow \pi^0_t b(\bar{b})$, and $b\bar{b} \rightarrow \pi^0_t g$ for $\varepsilon=0.05$ in Fig.3. We see that the production of the neutral top-pion $\pi^0_t$ in association with a high-$p_T$ jet is dominated by the partonic process $gg \rightarrow \pi^0_t g$, which is similar with the Higgs boson production associated with a high-$p_T$ in the $SM$ and the $MSSM$. However, for the $MSSM$ model, the contributions of the $b\bar{b}$ channel can be significantly large, depending the free parameters. However, this is not the case for the $TC2$ model. For $0.02 \leq \varepsilon \leq 0.08$ and $200GeV \leq m_{\pi_t} \leq 500GeV$, the hadronic cross section for the partonic process $b\bar{b} \rightarrow \pi^0_t g$ is only in the range of $1.6fb \sim 46fb$, which is several orders
of magnitude smaller than that for the partonic process $gg \rightarrow \pi_0^t g$.

Figure 4: The number of the $tc + jet$ event as a function of the $\pi_0^t$ mass $m_{\pi_t}$ for three values of the parameter $\varepsilon$.

It is well known that the mass of the $SM$ Higgs boson $H$ is generally smaller than 200$GeV$, one can use the decay channels $H \rightarrow \gamma\gamma$, $H \rightarrow \tau^+\tau^-$ or $H \rightarrow W^+W^-$ to consider the $SM$ Higgs boson signatures generated by the hadronic process $pp \rightarrow H + jet + X$ at the LHC [5]. For the neutral top-pion $\pi_0^t$, its main decay modes are $\bar{t}t, \bar{t}c(t\bar{c}), b\bar{b}, gg$, and $\gamma\gamma$. For $m_t \leq m_{\pi_t} \leq 2m_t$, $\pi_0^t$ mainly decays to $\bar{t}c$ and $t\bar{c}$. It has been shown that the value of the branching ratio $Br(\pi_0^t \rightarrow \bar{t}c + t\bar{c})$ is larger than 90% for $m_{\pi_t} = 250GeV$ and $\varepsilon \geq 0.02$ [15]. Thus, for $m_t < m_{\pi_t} \leq 2m_t$, the production of neutral top-pion $\pi_0^t$ associated with a high-$p_T$ hadronic jet can easily transfer to the $tc + jet$ event. This final state generates characteristic signatures at the LHC experiments. So we further calculate its production rate. We find that, for $\varepsilon \leq 0.08$ and $m_{\pi_t} \leq 350GeV$, the production cross section of the hadronic process $pp \rightarrow (\bar{t}c + t\bar{c}) + jet + X$ is larger than 19.4$pb$. If we assume the yearly integrated luminosity $L_{int} = 100fb^{-1}$ for the LHC with $\sqrt{s} = 14TeV$, then there will be $1.94 \times 10^6 \sim 5.3 \times 10^5$ $tc + jet$ events to be generated per year for $0.02 \leq \varepsilon \leq 0.08$ and
$200 \text{GeV} \leq m_{\pi_t} \leq 340 \text{GeV}$, as shown in Fig.4.

For the $tc + \text{jet}$ event, the peak of the invariant mass distribution of $tc$ is narrow. To identify $tc$, one needs reconstruct top quark from its mainly decay mode $Wb$ and the b-tagging and c-tagging are also needed. Furthermore, in the case of the $W$ hadronic decay, the $tc + \text{jet}$ event will generate the $bjjcj$ final state, while for the $W$ leptonic decay, it will generate the $bl\nu cj$ final state. For the former final state, the SM background is $jjjjj$ and the SM backgrounds of the later final state mainly come from the $t\bar{t}$, $tW$ and $Wjjj$ production process, which have been analyzed in Ref.[16]. They have shown that suitable kinematical cuts on the observed particles is more than enough to obtain a clear and statistically meaningful flavor-changing signal. Thus we expect that the possible signatures of the neutral top-pion $\pi_t^0$ might be detected via the decay channel $\pi_t^0 \to \bar{t}c + t\bar{c}$ at the LHC experiments.

For $m_{\pi_t} > 2m_t$, the neutral top-pion $\pi_t^0$ mainly decays to $t\bar{t}$ and the hadronic process $pp \to \pi_t^0 + \text{jet} + X$ can give rise to the $t\bar{t} + \text{jet}$ event. Its production rate can reach $15\text{pb}$ for $m_{\pi_t} \geq 400\text{GeV}$ and $\varepsilon \leq 0.08$. This kind of events have been calculated at $NLO$ in the SM [17]. It has shown that, for the renormalization and factorization scales having $\mu_R = \mu_F = \mu = m_t$, the $NLO$ cross section for $t\bar{t} + \text{jet}$ production at the LHC is larger than $500\text{pb}$. Thus, the production cross section of the $t\bar{t} + \text{jet}$ final state coming from TC2 is smaller than that coming from the SM by at least two orders of magnitude. It is very challenging to detect the possible signals of $\pi_t^0$ via the process $pp \to \pi_t^0 + \text{jet} + X \to t\bar{t} + \text{jet} + X$.

3. Conclusion

The production of a scalar state (the SM Higgs boson, the MSSM Higgs boson, etc) associated with a high-$p_T$ jet allows for refined cuts increasing the signal-to-background ratio, which is considered advantageous for scalar detection even though its production rate is lower than that for totally inclusive single scalar state production. In the context of the TC2 model, we consider the production of the neutral top-pion $\pi_t^0$ accompanied by a high-$p_T$ jet at the LHC. This production channel proceeds by the partonic processes $gg \to \pi_t^0 g$, $gq \to \pi_t^0 q$, $q\bar{q} \to \pi_t^0 g$, $gb(\bar{b}) \to \pi_t^0 b(\bar{b})$, and $b\bar{b} \to \pi_t^0 g$. We find that,
for $m_{\pi_t}$ equaling to the mass of the scalar state predicted by the MSSM, the hadronic production cross section of the process $pp \rightarrow \pi_t^0 + jet + X$ is much larger than that for the MSSM scalar state. For $m_t < m_{\pi_t} \leq 2m_t$, the main decay channel is $\pi_t^0 \rightarrow t\bar{c} + t\bar{c}$. There will be a large number of the $tc + jet$ events to be generated which can generate characteristic signal at the LHC experiment. So we might detect the possible signatures of the neutral top-pion $\pi_t^0$ via the process $pp \rightarrow \pi_t^0 + jet + X \rightarrow (\bar{t}c + t\bar{c}) + jet + X$ at the LHC.

Acknowledgments

Shi-Hai Zhu would like to thank Lei Wang for useful discussions. This work was supported in part by the National Natural Science Foundation of China under Grants No.10675057 and Foundation of Liaoning Educational Committee(2007T086).
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