Production of a neutral scalar associated with a photon at the LHC in the topcolor-assisted technicolor model*

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Abstract: In the context of the topcolor-assisted technicolor (TC2) model, we consider the production of the neutral scalar S (π_t^0 or h_t^0) associated with a photon at the LHC and compare our results with those given by the minimal supersymmetric extension of the Standard Model (MSSM). We find that its production cross section is larger or smaller than that of the scalar particle predicted by the MSSM model, depending on the values of the relevant free parameters.

Key words: topcolor-assisted technicolor, production cross section, scalar particle

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1 Introduction

The Higgs mechanism for electroweak symmetry breaking (EWSB) is still an untested part of the Standard Model (SM). The search for the SM Higgs boson is one of the main tasks of the LHC [1]. However, if the LHC finds evidence for a new scalar state, it may not necessarily be the SM boson. Most of the new physics models beyond the SM predict the existence of new neutral scalars. These new particles may have production cross sections and breaching ratios which differ from those of the SM Higgs boson. Testing the various new physics models is an important goal of the LHC [2]. Thus, studying the production of the new scalar at the LHC is of special interest.

At the LHC, the neutral scalar S is mainly produced via gluon-gluon fusion $gg \to S$ [3]. For $S\gamma$ associated production, this production channel is forbidden by C-parity conservation, so quark-antiquark annihilation becomes dominant and its production cross section is very small in the SM [4]. However, the cross section for $S\gamma$ associated production may be enhanced in some popular new physics models. For example, in the framework of the minimal supersymmetric extension of the SM (MSSM), for the production of CP-odd Higgs boson A associated with a photon, bottom quark annihilation $b\bar{b} \to A\gamma$ is of particular importance due to the Yukawa coupling enhanced by the large $\tan\beta$ [5]. Its cross section can be significantly large, which can be used to probe the bottom quark density in the proton as well as the bottom quark Yukawa coupling. Refs. [6, 7] have studied the production of the technipion in association with a photon via its anomalous couplings to electroweak gauge bosons and via a technivector meson resonance, and discussed the possibility of detecting the signatures of technicolor models at high-energy collider experiments.

It is well known that the existence of the physical top-pions ($\pi_t^{\pm}$, π_t^0) and top-Higgs (h_t^0) in low-energy spectrum can be seen as characteristic of the topcolor scenario, regardless of the dynamics responsible for EWSB and other quark masses [8]. π_t^0 and h_t^0 have large Yukawa coupling to the top quark and their anomalous couplings to gauge boson (γ, Z, and g) can be significantly enhanced. So, in the present

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work, we will consider the $\pi_t^0(h_t^0)\gamma$ associated production at the LHC. The topcolor-associated technicolor (TC2) model [9] has almost all the essential features of the topcolor scenario, and thus we will give our numerical results in detail under this model in the following section.

2 Calculation formula and numerical results

In the TC2 model, the interactions of the topquark with scalar S (π_t^0 or h_t^0) are approximately given by [9, 10]

$$\mathcal{L}_t = \frac{m_t(1-\varepsilon)}{\sqrt{2}F_t}\frac{\sqrt{v_w^2-F_t^2}}{v_w}[i\bar{t}\gamma^5 t\pi_t^0 + t\bar{t}h_t^0], \quad (1)$$

where $v_w = v/\sqrt{2} = 174$ GeV, and $F_t \approx 50$ GeV is the top-pion decay constant. The free parameter ε parameterizes the portion of the extended technicolor contribution to the top quark mass, which is assumed to be in the range of 0.01–0.1. The couplings $\pi_t^0 b\bar{b}$ and $h_t^0 b\bar{b}$ can be approximately written as [11]

$$\mathcal{L}_b = \frac{m_b}{v}\frac{F_t}{\sqrt{v_w^2-F_t^2}}[i\bar{b}\gamma^5 b\pi_t^0 + b\bar{b}h_t^0]. \quad (2)$$

From the above discussions, we can see that in the TC2 model, the production of the neutral scalar S (π_t^0 or h_t^0) associated with a photon at the LHC is induced by the large anomalous couplings $S\gamma\gamma$ and $S\gamma Z$ and the t-channel process $b\bar{b}\to S\gamma$. The relevant Feynman diagrams are shown in Fig. 1. Taking the anomalous couplings $S\gamma\gamma$ and $S\gamma Z$ as effective vertices, the production cross section of the subprocess $q\bar{q}\to\gamma, Z\to S\gamma$ can be written as

$$\hat{\sigma}_q(\hat{s}) = \frac{\alpha_e^3}{48\pi^2 v^2}\left(1-\frac{M_s^2}{\hat{s}}\right)^3 \times\left[Q_q^2 I_{S\gamma\gamma}^2 + \frac{2Q_q I_{S\gamma\gamma}I_{S\gamma Z}g_{Zqq}^V}{1-\frac{M_Z^2}{\hat{s}}} + \frac{I_{S\gamma Z}^2[(g_{Zqq}^V)^2+(g_{Zqq}^A)^2]}{\left(1-\frac{M_Z^2}{\hat{s}}\right)^2}\right], \quad (3)$$

where $\sqrt{\hat{s}}$ is the center-of-mass (c.m.) energy of the subprocess. Since there is always $M_s > m_t$, we have neglected the decay width of the gauge boson Z.

$$g_{Zqq}^V = -\frac{1}{2S_W C_W}(I_3 - 2Q_q S_W^2)$$

and

$$g_{Zqq}^A = \frac{1}{2S_W C_W}I_3,$$

in which I_3 is the third component of the isospin and Q_q is the electric charge of the quark q (u, c, d, s, and b). π_t^0 cannot couple to the gauge boson pairs WW, while the coupling $h_t^0 WW$ is suppressed by the anomalous factor F_t/v_w with respect to the SM coupling HWW. Thus, the factors $I_{\pi_t\gamma\gamma}$ and $I_{\pi_t\gamma Z}$ are only induced by the top quark loop, which can be obtained by multiplying the factor

$$\frac{(1-\varepsilon)\sqrt{v_w^2-F_t^2}}{F_t}$$

to the corresponding SM Higgs factors $I_{H\gamma\gamma}$ and $I_{H\gamma Z}$. Their expression forms have been reviewed in Ref. [12]. The W boson loop also contributes to the anomalous factors $I_{h_t\gamma Z}$ and $I_{h_t\gamma\gamma}$. However, the contributions are suppressed by the factor F_t/v_w as compared with the SM Higgs boson.

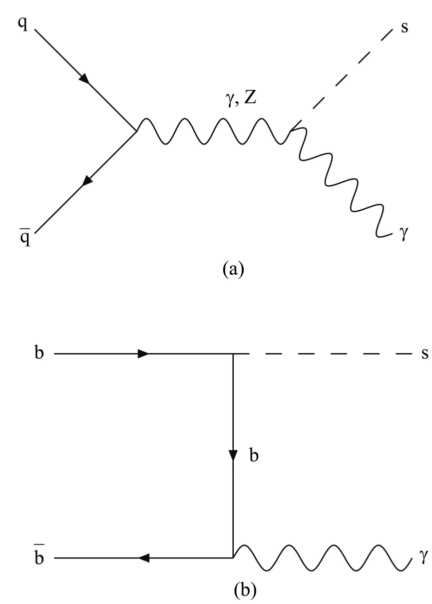

Fig. 1. Feynman diagrams for the partonic processes $q\bar{q}\to S\gamma$ (q=u, c, d, s, and b).

The production cross section of the subprocess $b\bar{b}\to S\gamma$ is given by [5]

$$\hat{\sigma_b}(\hat{s}) = \frac{\alpha_e m_b^2}{54v^2\hat{s}}\frac{F_t^2}{v_w^2-F_t^2}\left[\frac{1+r_s^2}{1-r_s}\log\left(\frac{1+\sqrt{\Delta}}{1-\sqrt{\Delta}}\right) - 2\frac{m_b^2}{(P_T^{cut})^2}\sqrt{\Delta}r_s(1-r_s)\right], \quad (4)$$

where $r_s = M_s^2/\hat{s}$ and $\Delta = 1-4(P_T^{cut})^2/[\hat{s}(1-r_s)^2]$. P_T^{cut} is the photon transverse momentum.

The hadronic cross section $\sigma(s)$ for the process $\mathrm{pp}\rightarrow \mathrm{S}\gamma$ can be obtained by folding the cross sections $\hat{\sigma_{\mathrm{q}}}(\hat{s})$ and $\hat{\sigma_{\mathrm{b}}}(\hat{s})$ with the parton distribution functions (PDFs)

$$\sigma = \sum_{\mathrm{q}}\int_{x_{\min}}^{1}\mathrm{d}x_1\int_{x_{\min}/x_1}^{1}\mathrm{d}x_2 f_{\mathrm{q/p}}(x_1)f_{\bar{\mathrm{q}}/\mathrm{p}}(x_2)\hat{\sigma}_{\mathrm{q}}(\hat{s}) + \int_{x_{\min}}^{1}\mathrm{d}x_1\int_{x_{\min}/x_1}^{1}\mathrm{d}x_2 f_{\mathrm{b/p}}(x_1)f_{\bar{\mathrm{b}}/\mathrm{p}}(x_2)\hat{\sigma}_{\mathrm{b}}(\hat{s}), \quad (5)$$

where $\hat{s} = x_1x_2s$, $\sqrt{s}$ is the c.m. energy of the LHC. To make our numerical results more realistic, we impose a minimal cut $P_{\mathrm{T}}^{\mathrm{cut}} = 30$ GeV on the photon transverse momentum, thus $x_{\min} = (P_{\mathrm{t}}^{\mathrm{cut}} + \sqrt{(P_{\mathrm{t}}^{\mathrm{cut}})^2+(M_{\mathrm{s}})^2})^2/s$. In our numerical calculation, we will use CTEQ6L PDFs [13] for the quark and antiquark PDFs. The renormalization scale μ_{R} and the factorization scale μ_{F} are chosen to be $\mu_{\mathrm{R}}=\mu_{\mathrm{F}}=M_{\mathrm{s}}/2$.

To obtain numerical results, we need to specify the relevant SM input parameters. We take the SM input parameters as $m_{\mathrm{t}}=172$ GeV, $m_{\mathrm{b}}=4.19$ GeV, $S_{\mathrm{W}}^2=0.231$, $\alpha_{\mathrm{e}}=1/128$ [14]. Except for these SM input parameters, the production cross section σ of the process $\mathrm{pp}\rightarrow\mathrm{S}\gamma$ is dependent on the free parameter ε and the mass parameters $m_{\pi_{\mathrm{t}}}$ and $m_{\mathrm{h_t}}$. To make the topcolor interactions contribute to the main part of the top mass and generate small contributions to EWSB, the free parameter ε should be very small, i.e. $\varepsilon\ll 1$ [9]. The $\mathrm{S}\gamma$ production cross section σ depends on the free parameter ε only via the factor $(1-\varepsilon)^2$, thus the value of σ is not sensitive to the free parameter ε and we will take $\varepsilon=0.05$. As a numerical estimation, we will assume $M_{\pi_{\mathrm{t}}}\approx M_{\mathrm{h_t}} = M$ =200–500 GeV. Our numerical results are summarized in Fig. 2, in which we have plotted the cross section σ as a function of the mass parameter M for the free parameter $\varepsilon=0.05$ and the c.m. energy $\sqrt{s}=7$ TeV and 14 TeV. The cross section for the production of the scalar S (π_{t}^0 or $\mathrm{h}_{\mathrm{t}}^0$) associated with the photon is mainly induced by the large anomalous couplings $\mathrm{S}\gamma\gamma$ and $\mathrm{S}\gamma\mathrm{Z}$. The contribution of the subprocess $\mathrm{b}\bar{\mathrm{b}}\rightarrow\mathrm{S}\gamma$ to the cross section σ is smaller than 1 fb. The value of σ is larger or smaller than that for the scalar particle predicted by the MSSM model [5], depending on the values of the relevant free parameters. For $\sqrt{s}=14$ TeV and 200 GeV$\leqslant M \leqslant$500 GeV, the values of the cross sections for $\pi_t^0\gamma$ and $\mathrm{h}_{\mathrm{t}}^0\gamma$ are in the ranges of 0.01 fb∼9.6 fb and 0.01 fb∼8.8 fb, respectively, while, for $\sqrt{s}=7$ TeV, all of their values are smaller than 2.5 fb in almost the parameter space of the TC2 model.

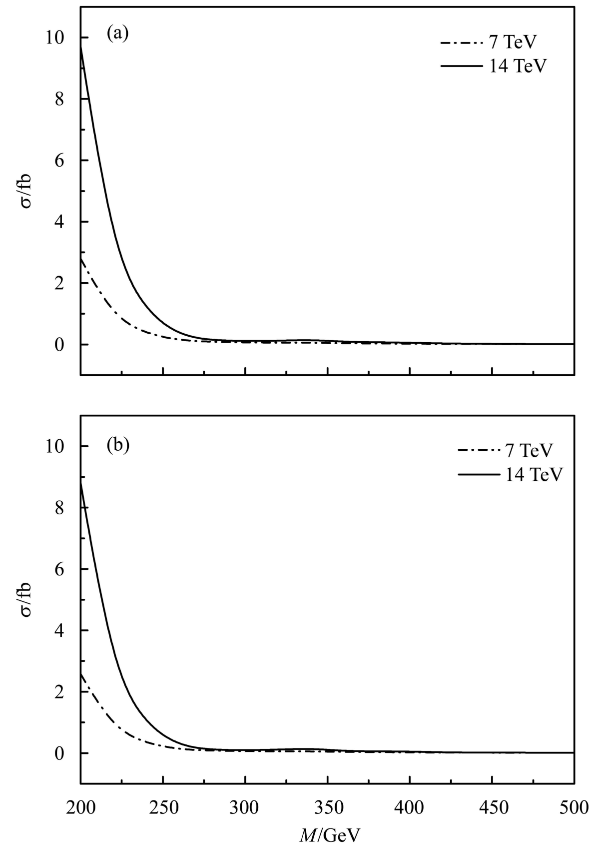

Fig. 2. The production cross section σ of the processes $\mathrm{p\bar{p}}\rightarrow\pi_{\mathrm{t}}^0\gamma$ (a) and $\mathrm{p\bar{p}}\rightarrow\mathrm{h}_{\mathrm{t}}^0\gamma$ (b) as a function of the mass parameter M for the c.m. energy $\sqrt{s}=7$ TeV and 14 TeV.

For $M\leqslant 2m_{\mathrm{t}}$, the neutral scalars π_{t}^0 and $\mathrm{h}_{\mathrm{t}}^0$ mainly decay to $\bar{\mathrm{t}}\mathrm{c}$ and $\mathrm{t}\bar{\mathrm{c}}$, while they mainly decay to $\mathrm{t}\bar{\mathrm{t}}$ for $M>2m_{\mathrm{t}}$. The relevant branching ratios have been calculated in Refs. [15, 16]. Thus, for $m_{\mathrm{t}}<M\leqslant 2m_{\mathrm{t}}$, the associated production of S with a photon can easily transfer to the $\mathrm{tc}\gamma$ signal state. This kind of signal state is almost free from the SM backgrounds, which can generate characteristic signatures at the LHC experiments. The peak of the invariant mass distribution of the tc is narrow. To identify the tc, one can reconstruct the top quark from its main decay mode Wb. Certainly, the c-tagging is needed. We define the background-free observable cross section $\overline{\sigma}$ as the effective cross section including c-tagging efficiency (ϵ_{c}) and top quark reconstruction efficiency (ϵ_{t}): $\overline{\sigma}=\epsilon_{\mathrm{c}}\epsilon_{\mathrm{t}}\sigma$. We plot $\overline{\sigma}$ as a function of the mass parameter M in Fig. 3, in which we have included the contributions of the neutral scalars π_{t}^0 and $\mathrm{h}_{\mathrm{t}}^0$, and assumed $\sqrt{s}=14$ TeV, $\epsilon_{\mathrm{t}}=80\%$ and $\epsilon_{\mathrm{c}}=35\%$. From this figure one can see that several hundred $\mathrm{tc}\gamma$ events will be generated per year at the LHC with the yearly integrated luminosity $\mathcal{L}_{\mathrm{int}}=100\ \mathrm{fb}^{-1}$. Thus, we ex-

pect that the possible signals of the neutral scalar with $m_t < M \leqslant 2m_t$ might be detected via the process $pp \to S\gamma \to (\bar{t}c + t\bar{c})\gamma$ at the LHC with $\sqrt{s} = 14$ TeV.

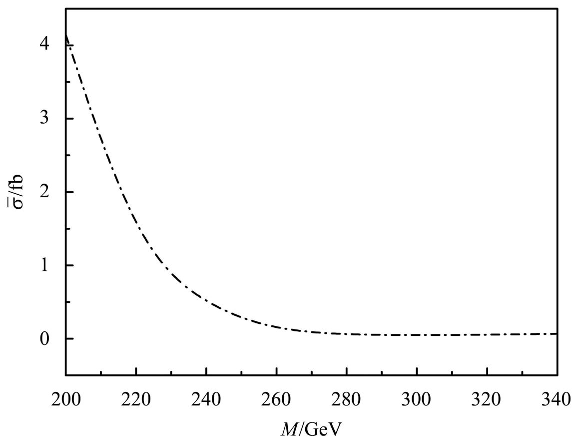

Fig. 3. The effective cross section $\bar{\sigma}$ as a function of the mass parameter M for $\sqrt{s}$ = 14 TeV.

For $M > 2m_t$, the neutral scalar S mainly decays to $t\bar{t}$ and the process $pp \to S\gamma$ can give rise to the $t\bar{t}\gamma$ final state. Although the high p_T photon can be used to distinguish the signal event $t\bar{t}\gamma$ from the huge $t\bar{t}$ background, its production rate is smaller than 2 fb, which is too small to be detected at the LHC.

3 Conclusion

In the framework of the TC2 model, we have considered the production of the neutral scalar (π_t^0 or h_t^0) associated with a high P_T photon at the LHC. We find that its production rate is larger or smaller than that of the scalar particle predicted by the MSSM model [5], depending on the values of the relevant free parameters. For the heavy scalar $M > 350$ GeV, the $pp \to \pi_t^0\gamma$ process cannot give an observable signal at the LHC. However, the possible signals of the neutral scalar S with $m_t < M \leqslant 2m_t$ might be detected at the LHC via the decay channel $S \to \bar{t}c + t\bar{c}$.

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