Detecting the neutral top-pion at future muon colliders

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The signals of the neutral top-pion π_t^0 at the first muon collider (FMC) are discussed by calculating its contributions to the processes $\mu^+\mu^-\to b\overline{b}$ and $\mu^+\mu^-\to \overline{t}c$. We find that the contributions to the process $\mu^+\mu^-\to b\overline{b}$ are very small and the ratio of the signal over the square root of the background $(S/\sqrt{B})$ is smaller than 0.2. However, in most of the parameter space, the π_t^0 can generate 36 and up to 649 observable $\overline{t}c$ events at the FMC. The signals of the neutral top-pion π_t^0 may be detected via the process $\mu^+\mu^-\to \overline{t}c$ at the FMC.

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I. INTRODUCTION

A muon collider is an excellent tool to study the properties of a heavy scalar or pseudoscalar [1,2]. It is thought that the first muon collider (FMC) can achieve the same integrated luminosity and energy as a high-energy e^+e^- collider. The FMC can explore all the same physics that is accessible at an e^+e^- collider of the same energy. Furthermore, it has been shown that a large number of Higgs bosons [1] or new particles, such as technihadrons and technipions [3,4], can be produced through an *s*-channel resonance process and the flavor changing scalar (FCS) couplings [5] can be tested at the FMC. Thus, the FMC makes possible precise measurements of the total widths and masses of the various neutral particles, which will open a window towards the new physics.

Until a Higgs boson with large coupling to a gauge boson pair is discovered, the possibility of electroweak symmetry broken by new strong interactions still exists [6]. The most commonly studied class of theories is technicolor (TC) [7], which dynamically breaks the electroweak symmetry. Although TC models have many theoretical problems as well as conflicts with data, and broad classes of these models have been ruled out, there are still viable models worthy of investigation in light of the capabilities of the current collider experiments. Top-color-assisted technicolor (TC2) models [8] are such a type of examples.

The common feature of all TC2 models is that top-color interactions generate the main part of large top-quark mass and only make small contributions to electroweak symmetry breaking (EWSB). In order for top-color interactions to be natural—i.e., without introducing large isospin violation—it is necessary that EWSB be still mainly generated by TC interactions. For TC2 models, extended TC (ETC) interactions are still needed to generate the masses of light quarks and contribute a few GeV to top-quark mass: i.e., εm_t with $\varepsilon \ll 1$ [8]. Thus, the presence of a number of pseudo Goldstone bosons (PGB's), including technipions in the TC sector and three top-pions ($\pi_t^{\pm,0}$) in the top-color sector, in the low-energy spectrum is an inevitable feature of these models. These new particles are most directly related to EWSB. Thus, studying the possible signatures of these new particles at present and future high-energy experiments would provide crucial information on EWSB and fermion flavor physics as well.

The production and decay of the technipions and top-pions have been extensively studied in several instances [9,10]. Combining resonance and nonresonance contributions, the signals of technipions were recently studied at lepton colliders and hadron colliders [11]. Reference [12] has discussed the single production of the neutral top-pion π_t^0 at hadron colliders and high-energy e^+e^- colliders (LCs). The observability of the neutral top-pion π_t^0 and the charged top-pions $\pi_t^{\pm}$ has been studied via considering single top production at hadron colliders and linear colliders [13,14].

The effects of the top-pion on physical observables are governed by its mass m_{π_t}, while the large couplings of top-pions to quarks and to gauge bosons are to a large degree model independent [15]. Thus, if the neutral top-pion π_t^0 is discovered at the CERN Large Hadron Collider (LHC) or other future collider experiments, it is needed to consider its resonance production at the FMC, which can make possible precise measurements of the couplings and mass of the neutral top-pion π_t^0. In this paper, we consider the *s*-channel resonance production of the neutral top-pion π_t^0 at the FMC with a center-of-mass energy $\sqrt{s}=200$–500 GeV and explore the potential of the FMC for detecting this new particle.

This paper is organized as follows: in Sec. II, we give the possible couplings of the neutral top-pion π_t^0 to ordinary particles. The resonance production cross section $\sigma(b\overline{b})$ of the process $\mu^+\mu^-\to\pi_t^0\to b\overline{b}$ and the ratio of the signal over

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the square root of the background ($S/\sqrt{B}$) are calculated in Sec. III. For TC2 models, the top-color interactions are nonuniversal, and the neutral top-pion π_t^0 has large FCS coupling $\pi_t^0\bar{t}c$. The possibility of detecting π_t^0 via the process $\mu^+\mu^-\to\pi_t^0\to\bar{t}c$ is studied in Sec. III. Our conclusions are given in Sec. IV.

II. COUPLINGS OF THE NEUTRAL TOP-PION π_t^0 TO ORDINARY PARTICLES

For TC2 models [8], TC interactions play a main role in breaking the electroweak symmetry. Top-color interactions make small contributions to EWSB and give rise to the main part of the top-quark mass, $(1-\varepsilon)m_t$, with the parameter $\varepsilon\ll 1$. Thus, there is the relation

$$\nu_\pi^2+F_t^2=\nu_W^2, \tag{1}$$

where ν_π represents the contributions of TC interactions to EWSB and $\nu_W=\nu/\sqrt{2}=174$ GeV. Here $F_t=50$ GeV is the physical top-pion decay constant, which can be estimated from the Pagels-Stokar formula. This means that the masses of the gauge bosons W and Z are given by absorbing the linear combination of the top-pions and technipions. The orthogonal combination of the top-pions and technipions remains unabsorbed and physical. However, the absorbed Goldstone linear combination is mostly technipions while the physical linear combination is mostly top-pions, which are usually called physical top-pions ($\pi_t^\pm,\pi_t^0$). The existence of physical top-pions in the low-energy spectrum can be seen as characteristics of the top-color scenario, regardless of the dynamics responsible for EWSB and other quark masses [15].

For TC2 models, the underlying interactions, top-color interactions, are nonuniversal and therefore do not possess a Glashow-Iliopoulos-Maiani (GIM) mechanism. The nonuniversal gauge interactions result in new FC coupling vertices when one writes the interactions in the quark mass eigenbasis. Thus, the top-pions have large Yukawa couplings to the third-generation quarks and can induce the new FCS couplings. The couplings of the neutral top-pion π_t^0 to the third-generation quarks including the t-c transition can be written as [8,14]

$$\frac{m_t}{\sqrt{2}F_t}\frac{\sqrt{\nu_W^2-F_t^2}}{\nu_W}\left[K_{UR}^{tt}K_{UL}^{tt}\bar{t}_Lt_R\pi_t^0+\frac{m_b-m_b'}{m_t}\bar{b}_Lb_R\pi_t^0+K_{UR}^{tc}K_{UL}^{tt}\bar{t}_Lc_R\pi_t^0+\text{H.c.}\right], \tag{2}$$

where m_b' is the ETC-generated part of the bottom-quark mass. Similar to Ref. [10], we take $m_b'=0.1\varepsilon m_t$. Here K_{UL}^{tt} is the matrix element of the unitary matrix K_{UL} from which the Cabibbo-Kobayashi-Maskawa (CKM) matrix can be derived as $V=K_{UL}^{-1}K_{DL}$ and K_{UR}^{ij} are the matrix elements of the right-handed rotation matrix K_{UR}. Their values can be written as [14]

$$K_{UL}^{tt}=1,\quad K_{UR}^{tt}=1-\varepsilon,\quad K_{UR}^{tc}\leqslant\sqrt{2\varepsilon-\varepsilon^2}. \tag{3}$$

In the following calculation, we will take $K_{UR}^{tc}=\sqrt{2\varepsilon-\varepsilon^2}$ and take the parameter ε as a free parameter.

The couplings of the neutral top-pion π_t^0 to first- and second-generation fermions and third-generation leptons can be written as

$$\frac{m_f}{\sqrt{2}F_t}\frac{F_t}{\nu_W}\bar{f}\gamma^5f\pi_t^0=\frac{m_f}{\nu}\bar{f}\gamma^5f\pi_t^0. \tag{4}$$

The neutral top-pion π_t^0, as an isospin triplet, can couple to a pair of gauge bosons through the top-quark triangle loop in an isospin violating way similar to the couplings of the QCD pion π^0 to a pair of gauge bosons. The relevant formula of these couplings has been given in Ref. [10].

Reference [8] has estimated the mass of the top-pion in the fermion loop approximation and given 180 GeV$\leqslant m_{\pi_t}\leqslant$240 GeV for $m_t=175$ GeV and $0.03\leqslant\varepsilon\leqslant 0.1$. The limits on the mass of the top-pion may be obtained via studying its effects on various experimental observables. For example, Ref. [16] has shown that for the process $b\to s\gamma$, B-$\bar{B}$ mixing and D-$\bar{D}$ mixing demand that the top-pions are likely to be light, with masses of the order of a few hundred GeV. Since the negative top-pion corrections to the $Z\to b\bar{b}$ branching ratio R_b become smaller when the top-pion is heavier, the CERN e^+e^- collider LEP or SLAC Large Detector (SLD) data of R_b give rise to a certain lower bound on the top-pion mass [15]. It was shown that the top-pion mass should not be lighter than the order of 1 TeV to make TC2 models consistent with the LEP-SLD data [17]. We restudied the problem in Ref. [18] and found that the top-pion mass m_{π_t} is allowed to be in the range of a few hundred GeV depending on the models. Thus, the value of the top-pion mass m_{π_t} remains subject to a large uncertainty [7]. Furthermore, Refs. [13,14] have shown that the top-pion mass m_{π_t} can be explored up to 300–350 GeV via the processes $p\bar{p}\to\pi_t^0\to\bar{t}c$ and $p\bar{p}\to\pi_t^\pm x$ at the Tevatron and LHC. Thus, we will take m_{π_t} as a free parameter and assume it to vary in the range of 200–400 GeV in this paper. In this case, the possible decay modes of π_t^0 are $b\bar{b},\bar{t}c,f\bar{f}$ (f is the first- or second-generation fermions or the third-generation leptons), $t\bar{t}$ (if kinematically allowed), gg, $\gamma\gamma$, and $Z\gamma$. The total decay width of π_t^0 can be written as

$$\begin{aligned}\Gamma_{\pi_t}=&\Gamma(\pi_t^0\to b\bar{b})+\Gamma(\pi_t^0\to\bar{t}c)+\Gamma(\pi_t^0\to f\bar{f})\\&+\Gamma(\pi_t^0\to gg)+\Gamma(\pi_t^0\to\gamma\gamma)+\Gamma(\pi_t^0\to Z\gamma)\\&+\Gamma(\pi_t^0\to t\bar{t})(m_{\pi_t}\geqslant 2m_t).\end{aligned} \tag{5}$$

III. SIGNALS OF THE NEUTRAL TOP-PION π_t^0 AT THE FMC

From the above discussions, we can see that the neutral top-pion π_t^0 can be produced at the FMC, operating at a

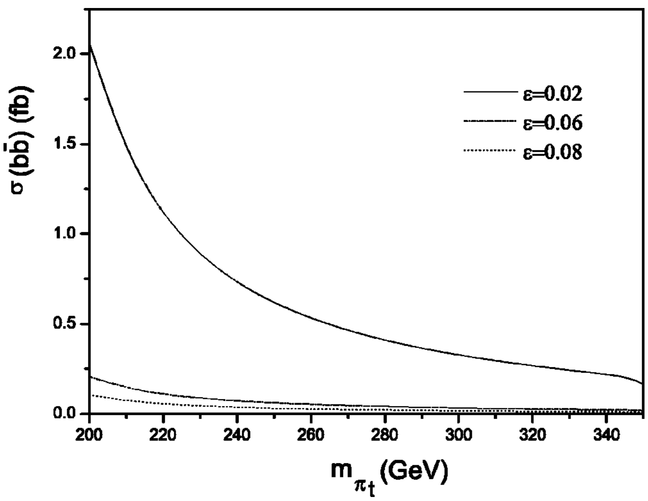

FIG. 1. The resonance production cross section $\sigma(b\overline{b})$ versus the top-pion mass m_{π_t}.

center-of-mass energy $\sqrt{s}$ of up to 500 GeV. In spite of the fact that the coupling $\pi_t^0\mu^+\mu^-$, being proportional to m_μ/ν, is very small, if the FMC runs on π_t^0 resonance ($\sqrt{s}=m_{\pi_t}$), the π_t^0 may be produced at an appreciable rate. For $m_{\pi_t}\leqslant 2m_t$, the main decay modes of π_t^0 are $\overline{t}c, b\overline{b}$, and gg. So, in this section, we will consider the possibility of detecting π_t^0 via the processes $\mu^+\mu^-\rightarrow\pi_t^0\rightarrow b\overline{b}$ and $\mu^+\mu^-\rightarrow\pi_t^0\rightarrow\overline{t}c$ at the FMC.

A. Neutral top-pion π_t^0 and the process $\mu^+\mu^-\rightarrow b\overline{b}$

Convoluted with the collider energy distribution, the s-channel resonance cross section for the production of a final state x generated by the neutral top-pion π_t^0 at the FMC is given by [1]

$$\sigma(x)\approx\frac{4\pi}{m_{\pi_t}^2}\frac{B_r(\pi_t^0\rightarrow\mu^+\mu^-)B_r(\pi_t^0\rightarrow x)}{\left[1+\frac{8}{\pi}\left(\frac{\sigma_{\sqrt{s}}}{\Gamma_{\pi_t}}\right)^2\right]^{1/2}}. \quad (6)$$

The Gaussian spread in the beam energy $\sqrt{s}$ is given by $\sigma_{\sqrt{s}}=(R/\sqrt{2})\sqrt{s}$. The energy resolution R of each beam is expected to be in the range of 0.003%–0.05% and we will take $R=0.03\%$.

In Fig. 1, we plot the resonance production section $\sigma(b\overline{b})$ versus the top-pion mass m_{π_t} for $\sqrt{s}=m_{\pi_t}$ and three values of the parameter ε. We can see from Fig. 1 that $\sigma(b\overline{b})$ decreases with the top-pion mass m_{π_t} and the parameter ε increasing. The value of $\sigma(b\overline{b})$ is in the range of 2.1—0.01 fb for $0.02\leqslant\varepsilon\leqslant 0.08$ and 200 GeV$\leqslant m_{\pi_t}\leqslant$350 GeV. Thus, there may be 1–42 $b\overline{b}$ events to be produced at the FMC with $\sqrt{s}=$200–500 GeV and a yearly integrated luminosity of $L=20$ fb^{-1}. To see whether the neutral top-pion π_t^0 can be detected via the process $\mu^+\mu^-\rightarrow b\overline{b}$ at the FMC, it is need to further calculate the ratio of signal over square root of the background, $S/\sqrt{B}$.

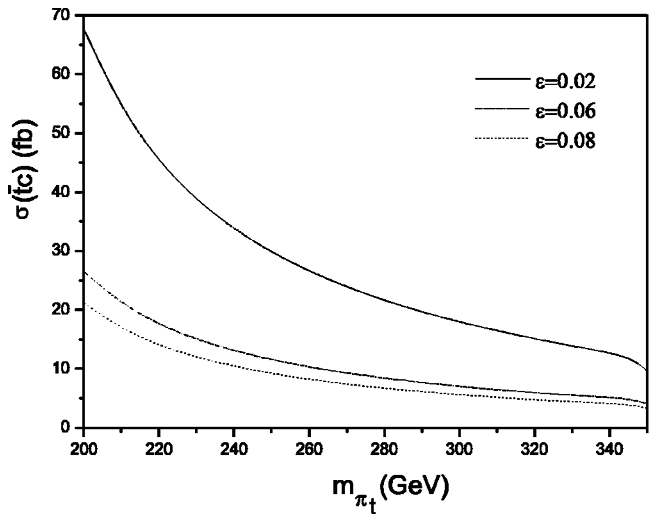

FIG. 2. The resonance production cross section $\sigma(\overline{t}c)$ as a function of m_{π_t} for three values of the parameter ε.

To solve the phenomenological difficulties of the traditional TC models [7], TC2 models [8] were proposed by combining technicolor interactions with top-color interactions for third-generation quarks. TC2 models predict a number of technipions in the TC sector. References [3,4] have pointed out that the color-singlet technipion P^0 can be significantly produced in the s channel. Thus, the backgrounds of the process $\mu^+\mu^-\rightarrow\pi_t^0\rightarrow b\overline{b}$ mainly come from the exchange of the gauge bosons γ, Z and of the color-singlet technipion P^0 in the s channel. We calculate the value of $S/\sqrt{B}$ and find that it is smaller than 0.2 in the entire parameter space. So the neutral top-pion π_t^0 cannot be detected via the process $\mu^+\mu^-\rightarrow b\overline{b}$ at the FMC.

B. Neutral top-pion π_t^0 and the process $\mu^+\mu^-\rightarrow\overline{t}c$

From Sec. II we can see that the most dominant decay mode of the neutral top-pion π_t^0 is $\overline{t}c$ for $m_{\pi_t}\leqslant$350 GeV. Thus, compared to the process $\mu^+\mu^-\rightarrow b\overline{b}$, π_t^0 can give significant contributions to the process $\mu^+\mu^-\rightarrow\overline{t}c$ via the π_t^0 exchange in the s channel. Furthermore, it is well known that there is no flavor changing neutral current (FCNC) at the tree level in the standard model (SM). The production cross sections of the FCNC process are very small at the one-loop level due to the unitary of the CKM matrix. The FCNC processes can be used to search for new physics. Any observation of the FC coupling deviated from that in the SM would unambiguously signal the presence of new physics. Thus, the process $\mu^+\mu^-\rightarrow\pi_t^0\rightarrow\overline{t}c$ will give a signal which should be easy to identify. The neutral top-pion π_t^0 may be easy detected via this process at the FMC.

In Fig. 2 we show the resonance production cross section $\sigma(\overline{t}c)$ as a function of the top-pion mass m_{π_t} for $\sqrt{s}=m_{\pi_t}$ and three values of the parameter ε. We can see from Fig. 2

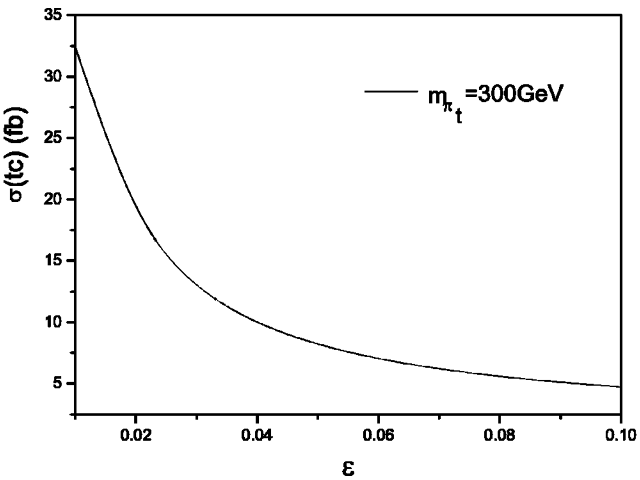

FIG. 3. The resonance production cross section $\sigma(\overline{t}c)$ as a function of the $\sqrt{s}=m_{\pi_t}=300$.

that the $\sigma(\overline{t}c)$ decreases with m_{π_t} and the parameter ε increasing. For $m_{\pi_t}\geqslant 2m_t$, the cross section σ drops considerably since the $t\overline{t}$ channel opens up and the branching ratio $B_r(\pi_t^0\to\overline{t}c)$ drops substantially. The value of the $\sigma(\overline{t}c)$ is larger than 3.7 fb for $\varepsilon\leqslant 0.08$ and $200\ \text{GeV}\leqslant m_{\pi_t}\leqslant 350\ \text{GeV}$. Thus, the FMC with $\sqrt{s}=200$–500 GeV and a yearly integrated luminosity of $L=20\ \text{fb}^{-1}$ will generate tens and up to a thousand $\overline{t}c$ events for $200\ \text{GeV}\leqslant m_{\pi_t}\leqslant 350$ GeV and $0.02\leqslant\varepsilon\leqslant 0.08$. For example, it will generate 280 $\overline{t}c$ events per year for $m_{\pi_t}=300$ GeV and $\varepsilon=0.06$. Thus, we can study the signals and observability of the neutral top-pion π_t^0 via the process $\mu^+\mu^-\to\overline{t}c$ at the FMC.

The parameter ε of TC2 models represents the contributions of ETC interactions or other interactions to the mass of the top quark and is in the range of 0.02—0.1 [8]. The current constraints on the free parameter ε from low-energy data (such as D-$\overline{D}$ and B-$\overline{B}$ mixing and the $b\to s\gamma$ rate) are rather weak. To see the effects of the parameter ε on the resonance production cross section $\sigma(\overline{t}c)$, we plot $\sigma(\overline{t}c)$ as a function of the parameter ε for $\sqrt{s}=m_{\pi_t}=300$ GeV in Fig. 3. We can see from Fig. 3 that the cross section $\sigma(\overline{t}c)$ is larger than 5.6 fb for $\varepsilon\leqslant 0.08$ and the number of yearly generated $\overline{t}c$ events is larger than 110.

The possible observable final states of the FCNC process $\mu^+\mu^-\to\overline{t}c$ are $\overline{b}cj_1j_2$, where j_1 and j_2 are light jets coming from $t\to bW^+$ followed by $W^+\to u\overline{d}$ or $c\overline{s}$, and $\overline{b}cl^+\nu_l$, which come from $t\to bW^+\to bl^+\nu_l$ with $l=e,\mu$ or τ. These two final states occur with branching of 2/3 and 1/3, respectively. The leading SM backgrounds of the FCNC process $\mu^+\mu^-\to\overline{t}c$ mainly come from W pair production and from W bremsstrahlung in $\mu^+\mu^-\to W+2$-jets. The techniques for suppressing this kind of backgrounds were discussed in Ref. [19].

We define the background-free observable cross section $\overline{\sigma(\overline{t}c)}$ as the effective cross section including b-tagging efficiency (ε_b) and top-quark reconstruction efficiency (ε_t): $\overline{\sigma(\overline{t}c)}=\varepsilon_b\varepsilon_t\sigma(\overline{t}c)$. In order to estimate the number of observable events, we assume $\varepsilon_b=60\%$ and $\varepsilon_t=80\%$ as done in Ref. [19]. Then the yearly production observable $\overline{t}c$ events at the FMC can be easily estimated. The FMC with $\sqrt{s}=200$–500 GeV and yearly integrated luminosity of $L=20\ \text{fb}^{-1}$ will generate 36 and up to 649 observable $\overline{t}c$ events for $200\ \text{GeV}\leqslant m_{\pi_t}\leqslant 350$ GeV and $0.02\leqslant\varepsilon\leqslant 0.08$. Thus, it is easy to detect the neutral top-pion π_t^0 via the process $\mu^+\mu^-\to\pi_t^0\to\overline{t}c$. We can study the properties of the neutral top-pion π_t^0 via the process $\mu^+\mu^-\to\overline{t}c$ at the FMC.

IV. CONCLUSIONS

The top quark, with a mass of the order of the electroweak scale, is singled out to play a key role in the dynamics of EWSB and flavor symmetry breaking. There may be a common origin for EWSB and top quark mass generation. Much theoretical work has been carried out in connection to the top quark and EWSB. Various kinds of strong top dynamical models have been proposed, including TC2 models [8], flavor-universal TC2 models [20], top seesaw models [21], and top-flavor seesaw models [22]. The common feature of such types of models is that top-color interactions generate the main part of the top-quark mass and also make small contributions to EWSB. EWSB is mainly generated by TC interactions or other interactions. Then, the presence of physical top-pions in the low-energy spectrum is an inevitable feature of these models. Thus, studying the production and decay of these new particles at present or future high-energy colliders is of special interest. It will be helpful to test the top-color scenario and understand EWSB mechanism.

In this paper, we have studied the possibility of detecting the neutral top-pion π_t^0 at the FMC via the processes $\mu^+\mu^-\to\pi_t^0\to b\overline{b}$ and $\mu^+\mu^-\to\pi_t^0\to\overline{t}c$. We find that the resonance-produced cross section $\sigma(b\overline{b})$ is very small and in the range of 10^{-1}–10^{-3} fb in most of the parameter space. Furthermore, the backgrounds of the final state $b\overline{b}$ are very large; the value of $S/\sqrt{B}$ is smaller than 0.2 in the entire parameter space. Thus, it is very difficult to detect the neutral top-pion π_t^0 via this process. However, for the process $\mu^+\mu^-\to\pi_t^0\to\overline{t}c$, this is not this case. As long as the neutral top-pion mass m_{π_t} is below the $t\overline{t}$ threshold, the π_t^0 can generate 36 and up to 649 observable $\overline{t}c$ events at the FMC with $\sqrt{s}=200$–500 GeV. Even if we take the parameter $\varepsilon=0.08$ and $m_{\pi_t}=350$ GeV, π_t^0 also can generate 36 observable $\overline{t}c$ events. Thus, the process $\mu^+\mu^-\to\pi_t^0\to\overline{t}c$ might give a signal which should be easy to identify. The properties of the neutral top-pion π_t^0 can be studied via the process $\mu^+\mu^-\to\overline{t}c$ at a future muon collider.

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