Top-charm associated production at hadron colliders in the standard model with large extra dimensions *

Zhou Hong\textsuperscript{2}, Ma Wen-Gan\textsuperscript{1,2}, and Zhang Ren-You\textsuperscript{2}
\textsuperscript{1} CCAST (World Laboratory), P.O.Box 8730, Beijing 100080, P.R.China
\textsuperscript{2} Department of Modern Physics, University of Science and Technology of China (USTC), Hefei, Anhui 230027, P.R.China

Abstract

The precise calculations are carried out on the flavor changing neutral current couplings in the process $pp \rightarrow gg \rightarrow t\bar{c}(t\bar{c})$ at the large hadron collider (LHC) and very large hadron collider (VLHC) in both frameworks of the minimal standard model (MSM) and its extension with extra dimensions. We find that the effects from the large extra dimensions can enhance the total cross section up to about several hundred times as that in the MSM, quantitatively.

\textbf{PACS}: 04.50.+h, 12.60.-i, 13.85.-t

\textbf{Keywords}: Extra dimensions, Top-charm associated production

*Supported by National Natural Science Foundation of China.
It is known that the minimal standard model (MSM) has achieved a great success under the electroweak energy scale, $m_{EW}$, which is about $10^2 \text{ GeV}$ energy scale [1]. But there still exist several problems, such as hierarchy problem, which can not been solved in this theory. There are many extensions of MSM being proposed to solve these problems, such as supersymmetric models. Recently, a new framework for solving the hierarchy problem, which does not rely on either supersymmetry or technicolor, was established by Arkani-Hamed, Dimopoulos and Dvali (ADD) [2]. They predicted that if we confine the matter fields to our 4-dimensional world, the size of extra dimensions could be large enough to be detectable. In this model, the gravitation and gauge interactions are united at the weak scale, $M_D$, which is the only fundamental scale in this theory, although it is now a model-dependent parameter, and no new low-energy predictions can be derived. This has the exciting implication that future high-energy collider experiments can directly probe the physics of quantum gravity. Above $\text{TeV}$ energy scale, completely new phenomena could emerge as resonant production of the Regge recurrences of string theory or excitations of Kaluza-Klein modes of ordinary particles [3].

There are stringent experimental constraints against the existence of tree-level flavor changing scalar interactions (FCSI’s) involving the light quarks. This leads to the suppression of the flavor changing neutral current (FCNC) couplings, an important feature of MSM, which is explained in terms of the Glashow-Illiopoulos-Maiani (GIM) [4]. The advantage of examining top quark physics than other quark physics is that one can directly determine the properties of top quark itself and does not need to worry about non-perturbative QCD effects which are difficult to attack because there exist no top-flavored hadron states at all. The properties of top quark makes the study on the FCNC couplings to be one of important fields in top physics. The FCNC couplings correlated with top quarks can be probed either in rare decays of $t$-quark or via top-charm associated production which appear at loop-level and offer a good place to test quantum effects of the fundamental quantum field theory. In models beyond MSM, new particles may appear in the loop and have significant contributions to flavor changing transitions. Any positive experimental observation of FCNC existence deviated from that in the MSM would unambiguously pronounce the presence of new physics [5]. On the contrary, in case no deviation from the SM is observed, they define in a quantitative way the strategy to obtain lower bounds on the new physics energy scale.

In this letter we shall investigate the process $pp \rightarrow \bar{t} \bar{c}(\bar{t}c)$ at hadron colliders in the MSM extension with large extra dimensions. The cross section of the subprocess $pp \rightarrow d\bar{d} \rightarrow \bar{t}c(\bar{t}c)$ is proportional to $|V_{dt}^* \cdot V_{dc}|^2$, but that of the subprocess $pp \rightarrow gg \rightarrow \bar{t}c(\bar{t}c)$ is approximately proportional to $|V_{bt}^* \cdot V_{bc}|^2$ for $|V_{bt}^* \cdot V_{bc}|^2 \simeq |V_{st}^* \cdot V_{sc}|^2$. According to the latest data from Ref. [6], $\frac{|V_{bt}^* \cdot V_{bc}|^2}{|V_{dt}^* \cdot V_{dc}|^2} \simeq 2.5 \times 10^3$. The luminosity of gluon from proton at hadron colliders is much larger than that of $d$-quark. Although the process $gg \rightarrow \bar{t}c$ appears at one-loop level, while the process $d\bar{d} \rightarrow \bar{t}c$ does at tree level, we can still conclude that the cross section of the
first one will be much larger than that of the later process. We found exactly that the cross section of \( pp \rightarrow gg \rightarrow t\bar{c} \) is almost 100 times large as that of \( pp \rightarrow d\bar{d} \rightarrow t\bar{c} \) after a precise numerical computing. So we will focus only on the process \( pp \rightarrow gg \rightarrow t\bar{c} \) in the following investigation.

There were some discussions about \( t\bar{c} \) production at the LHC based on the THDM and the R-violating MSSM[7]. The results of Ref. [7] show that the signs of the \( t\bar{c} \) production induced by those models maybe observable, but strongly depends on the chosen parameters. The research on \( t\bar{c} \) production at \( e^+e^- \) in the SM was presented in Ref.[8], in the THDM-III in Ref.[9] and in the MSSM in Ref.[10]. In this work we consider the process \( pp \rightarrow t\bar{c} \) at hadron colliders in the MSM extension with large extra dimensions.

Within the framework of the MSM with extra dimensions, the Feynman diagrams with graviton appear only in the \( s \)-channel and the graviton presents as a propagator in the \( t\bar{c} \) association production, but not appears in loop. Then in this process the FCNC couplings originates still in CKM mixing matrix rather than other new mechanics. Since the scale of reaction energy at the LHC and VLHC has gone up to 14 \( TeV \) and 100 \( TeV \), respectively, the effects of the new dimensions will be expected emerge observably. There are eighteen diagrams including the three diagrams involving graviton for the subprocess \( gg \rightarrow t\bar{c} \) as shown in Fig.1.

Here we present the relevant Feynman rules for our calculation which can be extracted from Ref.[2]. The relevant Feynman rules are listed below,

For Fig.2(a),
\[
\frac{1}{2k^2 - m^2} \left( \eta_{\mu\nu} \eta_{\alpha\beta} + \eta_{\mu\alpha} \eta_{\nu\beta} - \frac{2}{D-2} \eta_{\mu\nu} \eta_{\alpha\beta} \right),
\]
for Fig.2(b),
\[
\frac{\kappa}{\sqrt{V_\delta}} \left[ B_{\mu\nu\alpha\beta} m_A^2 + (C_{\mu\nu\alpha\beta\rho\sigma} - C_{\mu\nu\alpha\beta\rho\sigma}) \right] \delta^{ab},
\]
for Fig.2(c),
\[
-i \frac{\kappa}{8\sqrt{V_\delta}} \left[ \gamma_\mu (p_1 + p_2)_\nu + \gamma_\nu (p_1 + p_2)_\mu - 2 \eta_{\mu\nu} (p_1 + p_2 - 2m_\psi) \right],
\]
respectively, where the flat metric \( \eta_{\mu\nu} = diag\{+1,-1,-1,-1\} \). \( \delta = D - 4 \) is the number of the extra dimensions. \( V_\delta \) is the volume of the compactified space. \( B_{\mu\nu\alpha\beta} \) and \( C_{\mu\nu\alpha\beta\rho\sigma} \) are defined as below
\[
B_{\mu\nu\alpha\beta} = \frac{1}{2} (\eta_{\mu\nu} \eta_{\alpha\beta} - \eta_{\mu\alpha} \eta_{\nu\beta} - \eta_{\mu\beta} \eta_{\nu\alpha}),
\]
\[
C_{\mu\nu\alpha\beta\rho\sigma} = \frac{1}{2} (\eta_{\mu\rho} \eta_{\nu\sigma} \eta_{\alpha\beta} - (\eta_{\mu\rho} \eta_{\nu\sigma} \eta_{\alpha\beta} + \eta_{\mu\sigma} \eta_{\nu\rho} \eta_{\alpha\beta} + \eta_{\mu\alpha} \eta_{\nu\beta} \eta_{\rho\sigma} + \eta_{\mu\beta} \eta_{\nu\alpha} \eta_{\rho\sigma})).
\]

For the \( s \)-channel virtual graviton exchange diagram, the sum over all Kaluza-Klein modes has to be performed at the amplitude level (The detailed deduction can be found in Refs.[11]). In order to absorbing the factor \( \frac{\kappa}{\sqrt{V_\delta}} \) of the interaction vertex for which we have the
The equation is \( \frac{\kappa}{\sqrt{V_\delta}} = \frac{2}{\bar{M}_P} \), where \( \bar{M}_P = M_P/\sqrt{8\pi} = 2.4 \times 10^{18} \text{GeV} \) is the reduced Plank mass. The we can define

\[
D(s) = \frac{1}{\bar{M}_P^2} \sum_n \frac{1}{s - m_n^2}.
\]

Converting the sum into an integral which can be evaluated using dimensional regularization, we have

\[
D(s) = -\frac{1}{M_{D+\delta}^2} S_{\delta-1} \frac{\Lambda^{\delta-2}}{2} C
\]

for \( \delta > 2 \). Where \( M_D \sim 10^2 \text{ GeV} \) is the only fundamental mass scale in the model, \( S_{\delta-1} \) is the hypersurface of a unit-radius sphere in \( \delta \) dimensions, \( \Lambda \) is the ultraviolet cutoff, \( C \) is an unknown coefficient. So \( D(s) \) is fixed by several uncertain parameter. Here we can postulate \( C \approx 1, \Lambda \approx M_D \) and have

\[
D(s) = -\frac{1}{M_D^4} S_{\delta-1} \frac{1}{2}.
\]

In our calculation we take \( M_D \) in the range of \( 100 \sim 500 \text{ GeV} \).

In the numerical calculations the following input values of the parameters have been employed [6]

\[
m_t = 174.3 \text{ GeV}, \quad m_c = 1.25 \text{ GeV}, \quad m_b = 4.2 \text{ GeV}, \quad m_s = 0.12 \text{ GeV} \quad m_W = 80.42 \text{ GeV}, \quad \alpha = \frac{1}{128}, \quad \alpha_s = 0.117.
\]

We take the "standard" parameterization of CKM matrix [8] and chose

\[
s_{12} = 0.221814, \quad s_{23} = 0.0459998, \quad s_{13} = 0.0050002, \quad \delta_{13} = 0.
\]

The total cross section for parent process at pp collider can be obtained by folding the cross section of subprocess \( \hat{\sigma}(gg \rightarrow t\bar{c}) \) with the gluon luminosity.

\[
\sigma(s, pp \rightarrow gg \rightarrow t\bar{c} + X) = \int_{m_t + m_c}^{1/\sqrt{s}} \frac{dL_{gg}}{d\tau} \frac{d\tau}{d\sigma(gg \rightarrow t\bar{c} at \hat{s} = \tau s)}, \quad (1)
\]

where \( \sqrt{s} \) and \( \sqrt{\hat{s}} \) are the pp and gg c.m.s. energies respectively, at the LHC \( \sqrt{s} = 14 \text{ TeV} \) and the VLHC \( \sqrt{s} = 100 \text{ TeV} \), and \( dL_{gg}/d\tau \) is the distribution function of gluon luminosity, which is defined as

\[
\frac{dL_{gg}}{d\tau} = \int_{\tau}^{1} \frac{dx_1}{x_1} \left[ f_g(x_1, Q^2)f_{\bar{g}}(\frac{\tau}{x_1}, Q^2) \right], \quad (2)
\]

where \( \tau = x_1 x_2 \), the definitions of \( x_1 \) and \( x_2 \) are from Ref. [7], and in our calculation we adopt the CTEQ5L parton distribution functions [12]. The factorization scale \( Q \) is chosen as the average of the final particles masses \( \frac{1}{2}(m_t + m_c) \). The total cross section of \( pp \rightarrow t\bar{c}(\bar{t}c) + X \)
is obtained by multiplying the cross section of $pp \rightarrow t \bar{c} + X$ by factor 2. We have the total cross section in the MSM $4.23 \times 10^{-3} fb$ at the LHC and $0.105 fb$ at the VLHC.

The cross sections of parent process $pp \rightarrow gg \rightarrow t \bar{c} + t \bar{c} + X$ at the LHC as the functions of $M_D$ are depicted in Fig.3 with $\delta = 3, 5, 7$, respectively. The figure shows that when $M_D = 100 GeV$, the cross sections are about 1 $fb$ and sharply decrease with the increment of $M_D$ at first, then approach asymptotically to the cross section in the MSM after the point of $M_D = 400 GeV$. In Fig.5 the curves describe the relations between the cross sections of parent process $pp \rightarrow gg \rightarrow t \bar{c} + t \bar{c} + X$ and $M_D$ at the VLHC, which is almost the same feature as that at the LHC but the cross sections at the VLHC are generally as several hundred times as those at the LHC. So if we take $M_D = 100 GeV$ and assume that the LHC and the VLHC run with integrated luminosity of $L \simeq 300 [fb]^{-1}$ in one year, there will be the order of $10^2 \sim 10^3$ events per year accumulated at the LHC and $10^4 \sim 10^5$ at the VLHC, respectively. In Fig.4 and Fig.6, we present the cross section relative enhancement $(\sigma - \sigma_{SM})/\sigma_{SM}$ by the virtual graviton exchange as the functions of $M_D$ at the LHC and the VLHC, respectively. Since $M_D$ appears in denominator of graviton propagator, the cross section decreases with the increment of $M_D$ as shown in the figures. We can figure out that the correction from the large extra dimensions to the SM cross section is approximately proportional to $M_D^{-4}$. The contribution of $\delta$ origins mainly in the hypersurface of a unit-radius sphere in $\delta$ dimensions. As we know, $S_{\delta-1} = \pi^{\frac{\delta}{2}}/\Gamma(\frac{\delta}{2})$. We have $S_{\delta-1}|_{\delta=3} < S_{\delta-1}|_{\delta=5} < S_{\delta-1}|_{\delta=7}$, so the cross sections of $\delta = 7$ are larger than those of $\delta = 5(\delta = 3)$ in the same condition as shown in all figures.

To summarize, we find that the the cross section of top-charm associated production at hadron colliders is largely enhanced due to large extra dimensions within the framework of the MSM with large extra dimensions, and can be detectable both at the LHC and the VLHC with the favorable parameters. This cross section enhancement for the $t \bar{c}(t \bar{c})$ association production process is strongly related to the energy scale $M_D$. When $M_D$ is above $400 GeV$, the difference between the cross sections in the MSM with and without large extra dimensions is indistinctly demonstrated. The measurement of the cross section of $pp \rightarrow gg \rightarrow t \bar{c} + t \bar{c} + X$ process can be used to give the constraint on the fundamental energy scale $M_D$.

Acknowledgements:
This work was supported in part by the National Natural Science Foundation of China and a grant from University of Science and Technology of China.

References

[1] For recent reviews, see e.g., ALEPH Collaboration, Phys.Lett. B526 (2002) 191-205; Carmine Pagliarone, Elena Vataga, Carma Pagliarone, Elena Vataga, hep-ex/0111064; P. Janot, hep-ex/0110070.

[2] Nima Arkani-Hamed, Savas Dimopoulos, Gia Dvali, Phys.Lett. B429 (1998) 263-272.
[3] I. Antoniadis, K. Benakli, and M. Quiros, Phys.Lett.B 331,313(1994).

[4] S. L. Glashow, J. Iliopoulos, L. Maiani, Phys. Rev. D 2(1970) 1285.

[5] The recent proceeding about $t$ decay, see
J. M. Yang, B.-L. Young and X. Zhang, Phys. Rev. D58(1998)055001;
G. Eilam, A. Gemintern, T. Han, J.M. Yang, X. Zhang, Phys.Lett. B510 (2001) 227-235;
S. Bar-Shalom, G. Eilam, A. Soni, Phys. Rev. D60(1999)035007;
J. Guasch and J. Sola, Nucl.Phys. B562 (1999) 3-28.

[6] Particle Data Group, Eur. Phys. J. C15(2000)110.

[7] Chao-Hsi Chang, Liang Han, Yi Jiang, et al., Phys.Rev. D62 (2000) 034012; Zhou Hong, Ma Wen-Gan, Jiang Yi, et al., Phys.Rev.D64 (2001)095006, and references therein.

[8] C.-H. Chang, X.-Q. Li, J.-X. Wang and M.-Z. Yang, Phys. Lett. B313(1993)389;
C.-S. Huang, X.-H. Wu and S.-H. Zhu, Phys. Lett. B452(1999)143.

[9] D. Atwood, L. Reina, and A. Soni, Phys.Rev.D53(1996)1199.

[10] Uma Mahanta, Ambar Ghosal, Phys.Rev. D57 (1998) 1735;
Z. H. Yu, H. Pietschmann, W. G. Ma, L. Han and Y. Jiang, Eur. Phys. J. C16(2000)695.

[11] Gian F. Giudice, Riccardo Rattazzi, James D. Wells, Nucl.Phys. B544 (1999)3-38; Tao Han, Joseph D. Lykken, Ren-Jie Zhang, Phys. Rev. D59 (1999) 105006.

[12] H. L. Lai et al., Eur. Phys. J. C12(2000)375.

Figure Captions

Fig.1 The Feynman diagrams of the subproocesses $gg \rightarrow t\bar{c} + \bar{t}c$.

Fig.2 (a) The propagator of graviton. (b) The coupling between the graviton and gluons. (c) The coupling between the graviton and fermions.

Fig.3 The cross sections of $pp \rightarrow gg \rightarrow t\bar{c} + \bar{t}c + X$ at the LHC as the functions of the energy scale $M_D$.

Fig.4 The enhancement to the cross sections of $pp \rightarrow gg \rightarrow t\bar{c} + \bar{t}c + X$ at the VLHC as the functions of the energy scale $M_D$.

Fig.5 The cross sections of $pp \rightarrow gg \rightarrow t\bar{c} + \bar{t}c + X$ at the LHC as the functions of the energy scale $M_D$.

Fig.6 The enhancement to the cross sections of $pp \rightarrow gg \rightarrow t\bar{c} + \bar{t}c + X$ at the VLHC as the functions of the energy scale $M_D$. 
Fig. 1
Fig. 2(a)
Fig. 2(c)
Fig. 3

σ(pp→t c+b→t bar c)[fb]

M_{b}[GeV]

- δ=3
- δ=5
- δ=7
Fig. 5

The plot shows the cross-section \( \sigma(pp -> t \bar{t} c \bar{c}) \) [fb] as a function of the mass \( M_0 \) [GeV]. The curves are labeled with different values of \( \delta \): 
- \( \delta = 3 \) (solid line)
- \( \delta = 5 \) (dashed line)
- \( \delta = 7 \) (dotted line)

The cross-section decreases exponentially with increasing mass.
