Same-sign top pair production in an extra-dimension model of flavor at the CERN Large Hadron Collider

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Abstract

We study the same-sign top pair production mediated by the first Kluza-Klein (KK) excitation of the gluon in the Randall-Sundrum (RS) model with flavor violation at the Large Hadron Collider (LHC), in which the nonuniversal couplings between fermions and KK gauge bosons will lead to observable tree level flavor-changing neutral current (FCNC) effects. We find that the same-sign top quarks produced in our case have property of high energy and high transverse momentum, and lead to an observable signal in the same-sign dilepton channel even when the mass of the KK gluon reach up to 3 TeV. We further investigate the potential of the LHC to probe the flavor violating parameters and find that the LHC can probe their values down to 0.06.

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I. INTRODUCTION

Now search for extra dimensions has been one of the major objects at the LHC, since its physical effects can appear at the TeV energy scale. The idea of extra dimensions was revived in the 1990's [1, 2, 3], which brings new solutions to the gauge hierarchy problem and also can be used to resolve the fermion mass hierarchy problem. The RS model [3] with a warped geometry in five dimensions is one of the most important cases. In the RS model, the single extra dimension is compactified on a $S^1/Z_2$ orbifold with a radius $r$, which is not too large compared with the Planck length. Two 3-branes, the Planck brane and the TeV brane, are located at the orbifold fixed points $\phi = 0, \pi$, respectively, and the spacetime between the two 3-branes is simply a slice of a five-dimensional anti-de Sitter (AdS$_5$) geometry. The five-dimensional warped metric is given by

$$ds^2 = e^{-2kr|\phi|} \eta_{\mu\nu} dx^\mu dx^\nu - r^2 d\phi^2,$$

where $\phi$ is the five-dimensional coordinate, and $k \sim M_P$ is the curvature scale. By requiring $kr \sim 12$, one can suppress the Planck scale to $M_P e^{-k\pi r} \sim O(\text{TeV})$ on the TeV brane, and then solve the gauge hierarchy problem.

The original RS model has also been generalized to allow the standard model (SM) fields to reside in the bulk [4, 5, 6, 7, 8, 9, 10], which can generate the fermion mass hierarchy by exponential warped factors. For each fermion flavor $i$, we have two five-dimensional Dirac fermions $\Psi_{i,L}(x, y)$, and $\Psi_{i,R}(x, y)$, ($y = r\phi$), while for simplicity the Higgs field will be localized on the TeV brane. Thus, the Yukawa coupling of bulk fermions can be expressed as

$$\int d^4x dy \sqrt{-g} \lambda_{ij}^{(5)} (H(x)\bar{\Psi}_{i,L}(x,y)\Psi_{j,R}(x,y) + \text{h.c.}) \delta(y - \pi r)$$

$$\equiv \int d^4x \lambda_{ij} \left( H(x)\bar{\Psi}_{iL}^{(0)}(x)\Psi_{jR}^{(0)}(x) + \text{h.c.} + ... \right),$$

where $\lambda_{ij}^{(5)}$ are the five-dimensional Yukawa couplings and $\lambda_{ij}$ are the effective four-dimensional Yukawa couplings between the Higgs fields and the SM fermions, $\Psi_{iL}^{(0)}$ and $\Psi_{jR}^{(0)}$, which correspond to the zero KK modes. If each fermion field has a 5D bulk mass, which can be parameterized as $M_{f(i,j)(L,R)} \equiv kc_{iL}-c_{jR}kr$, then we can obtain

$$\lambda_{ij} = \frac{\lambda_{ij}^{(5)} k}{N_{iL}N_{jR}} e^{(1-c_{iL}-c_{jR})\pi kr},$$
with
\[ \frac{1}{N_{iL}^2} \equiv \frac{1/2 - c_{iL}}{e^{(1-2c_{iL})\pi kr} - 1}, \]
and similarly for \( N_{jR} \). For light fermions, by setting \( c_{iL}, c_{jR} \gtrsim 1/2 \), which means the light fermions are localized towards the Planck brane, one can generate exponentially-small Yukawa couplings. On the other hand, the third generation quarks can be close to the TeV brane and have \( O(1) \) Yukawa couplings by requiring \( c_{iL}, c_{jR} < 1/2 \).

Since the light fermions live towards the Planck brane, their couplings to KK gauge bosons will be small and universal. But for the right-handed top quark and the left-handed doublet \( Q^3 \), they could have rather strong couplings to the KK gauge bosons [7, 11]. These nonuniversal couplings will lead to observable FCNC effects at tree level, which have been extensively studied in Refs [11, 12].

In the SM, the same-sign top pair production rate is highly suppressed due to the GIM mechanism, but can be enhanced to an observable level in some new physics models, for example, supersymmetric standard model [13], topcolor-assisted technicolor model [14], and maximal flavor violation model [15]. The same-sign top pair can also be produced with the model-independent FCNC couplings, \( gtq, Ztq, \gamma tq, Htq \) and \( Z'tq \) [16]. All these processes can provide very clean signals due to the small SM backgrounds for the same-sign dilepton channel. In this paper we study the same-sign top pair production mediated by the first KK excitation of the gluon, \( G^{(1)} \), at the LHC and use this process to directly probe the FCNC couplings between the up-type quarks and the first KK gluon. And we show the production rate can be greatly enhanced due to the large FCNC couplings of the up-type quarks and the KK gluon.

The arrangement of this paper is as follows. In Sec. II, we give the relevant FCNC couplings and parameters. In Sec. III, we show the cuts for signal selection and numerical results. Sec. IV contains a brief conclusion.

II. FCNC COUPLINGS

In general, the top FCNC couplings in our case can be written as
\[
\mathcal{L}_{\text{FCNC}} = g_{tR} U^t_{tR} U^c_{tR} (i_R T^a \gamma^\mu c_R) G^{(1)a}_\mu + g_{tR} U^t_{tR} U^t_{tR} (i_R T^a \gamma^\mu u_R) G^{(1)a}_\mu \\
+ g_{tL} U^t_{tL} U^c_{tL} (i_L T^a \gamma^\mu c_L) G^{(1)a}_\mu + g_{tL} U^t_{tL} U^t_{tL} (i_L T^a \gamma^\mu u_L) G^{(1)a}_\mu + h.c.,
\]
where \( g_{tL}, g_{tR} \) are the coupling constants between top quark and \( G^{(1)} \), and \( U_L, U_R \) are the left-handed and right-handed rotation matrices that transform the up-type quarks from the weak eigenstate basis to the mass eigenstate basis. Other contributions from the first two generations can be neglected due to the smallness of the coupling constants. As pointed out in Refs. [17, 18, 19, 20], a KK gluon with mass \( M_{G^{(1)}} \) as low as 1 TeV is still possible, so we will consider \( M_{G^{(1)}} \) values from 1 TeV to 3 TeV below. Within this mass range, the authors of Ref. [11] discuss some interesting values of \( c_3^L \) and \( c_4^R \) which can generate the correct quark masses, mixings and also satisfy all the electroweak precision constraints, and give a possible range of the coupling constants, \( g_{tL} = [1.0, 2.8]g_s \), \( g_{tR} = [1.5, 5]g_s \), where \( g_s \) is the usual 4D strong interaction coupling constant.

The rotation matrixes \( U_L \) and \( U_R \) depend on the 5D Yukawa couplings and the bulk masses of the up-type quarks. In principle, we have little knowledge on the matrix elements, and the choice of their values has a great freedom. However, in order to generate the correct Cabibbo-Kobayashi-Maskawa (CKM) matrix, we have \( V_{CKM} = U_L^\dagger D_L \). By assuming \( U_L \sim \sqrt{V_{CKM}}, U_{tc}^L \) and \( U_{tu}^L \) are very small [11], so we will neglect the contributions from the left-handed FCNC couplings in our following calculations. On the other hand, there is no direct constraint on the elements of \( U_R \), so we treat \( U_{tt}^R, U_{tc}^R \) and \( U_{tu}^R \) as free real parameters as in Ref. [11], and investigate the LHC reach of the parameter region.

The relevant Feynman diagrams for same-sign top pair production are shown in Fig. 1. At the LHC, the main contribution to the same-sign top pair production arises from subprocess \( uu \rightarrow tt \) due to the high parton luminosity of the \( u \) quark. However, in order to probe \( U_{tc}^R \), we also include contributions from the subprocesses \( uc, cu, cc \rightarrow tt \). We define two flavor violating parameters \( \varepsilon_u \equiv |U_{tt}^R U_{tu}^u| \), and \( \varepsilon_c \equiv |U_{tt}^R U_{tc}^u| \), which must satisfy \( \varepsilon_c^2 + \varepsilon_u^2 \leq 0.5^2 \) due to the unitarity of \( U_R \). Note that our study is almost model-independent and depends only on \( \varepsilon_u, \varepsilon_c, g_{tR} \) and \( M_{G^{(1)}} \). In our numerical calculations, the CTEQ6L1 PDF set [21] is used, and renormalization and factorization scales are set to the top quark mass.

In Fig. 2 we show the transverse momentum distributions of the top quark in the same-sign top pair production at the LHC with the FCNC couplings mediated by Z boson and KK gluon, respectively, assuming \( M_{G^{(1)}} = 1 \) TeV. Due to the large mass difference, the top quarks are typically produced with much higher energy and transverse momentum in KK gluon exchange than in Z boson exchange. These properties can be further used to help us suppress the SM backgrounds. The total cross sections of the same-sign top pair production
| $M_{G(1)}$ | 1TeV | 2TeV | 3TeV |
|------------|------|------|------|
| $\varepsilon_u = 0.5, \varepsilon_c = 0$ | 16.4 | 1.71 | 0.41 |
| $\varepsilon_u = \varepsilon_c = 0.35$ | 4.75 | 0.48 | 0.11 |

TABLE I: The total cross sections (in pb) for $tt$ production at the LHC under different values of the KK gluon mass and flavor violating parameters, assuming $g_{tH} = 3g_s$.

mediated by KK gluon at the LHC are given in Table I, which shows the total cross section can reach as high as 16 pb.

III. SIGNAL AND BACKGROUNDSS

In order to distinguish our process from the SM $t\bar{t}$ production, we only consider the leptonic decays of the top quarks, $pp \to tt \to bbl^+l^+\nu_l\nu_l$, where $l = e$ or $\mu$. The resulting signal consists of two $b$ jets, two positive charged leptons, missing transverse energy and possible light jets from showering. We will combine two channels, one of which contains exactly one $b$-tagged jet in the final state, and the other contains two $b$-tagged jets. There are several main SM backgrounds for our process: (a) $pp \to W^+t\bar{t}$, $W^+W^{\pm}qq$, (b) $pp \to W^+Zqq$, when the $l^-$ from $Z$ decay is undetected. Other possible backgrounds like $pp \to W^+W^+W^-$, $ZZqq$, $W^+b\bar{b}$, $tW^-(\bar{t}W^+)$, and $t\bar{t}$ are very small according to our calculations, and can be neglected. The above backgrounds are simulated with MADEVENT [22], and the signal events are generated by COMPHEP 4.4 [23]. In our calculations, PYTHIA 6.4 [24] is used to treat parton showering, hadronization, and PGS4 [25] is used for detector simulations, in which $b$-tagging efficiency has been taken into account.

We use the following basic acceptance cuts on jets, leptons and missing transverse momentum,

\begin{align}
  p_T(j) > 15\text{GeV}, \quad |\eta(j)| < 3.0, \quad p_T(l) > 10\text{GeV}, \\
  |\eta(l)| < 2.4, \quad \Delta R_{jj} > 0.7, \quad \Delta R_{jl} > 0.4, \\
  \Delta R_{ll} > 0.4, \quad p_T > 20\text{GeV},
\end{align}

where $j$ can be either a light jet or a $b$ jet. In order to reduce the backgrounds in which the charged lepton comes from $b$ decay, we impose the lepton isolation cuts using PGS4, which
are especially important for suppressing $t\bar{t}$ backgrounds.

For the one $b$-tagged jet channel, we require the final state containing exactly one $b$-tagged jet, two positive charged leptons, and at most two light jets. Besides, we further require

$$p_T(j_{\text{max}}) > 20\text{GeV}, \quad p_T(b) > 20\text{GeV}, \quad p_T(l_{\text{max}}) > 50\text{GeV},$$
$$p_T(l_{\text{min}}) > 30\text{GeV}, \quad H_T > 300\text{GeV}, \quad m(llbj) > 400\text{GeV},$$

(7)

where we use $j_{\text{max}}$ to stand for the leading light jet, $H_T$ is the sum of transverse energy and $m(llbj)$ is the invariant mass of all the leptons and jets. As mentioned before, the final state of our signal comes from two almost back-to-back high $p_T$ top quarks, so the above cuts can improve the significance greatly. In order to further reduce the backgrounds, we use the following angular cuts,

$$\Delta \phi_{ll} > 2.2, \quad \Delta \phi_{bj_{\text{max}}} > 1.0,$$

(8)

and require at least one combination of the leptons satisfies

$$\Delta R_{lb} + \Delta R'_{lj_{\text{max}}} < 3.0.$$  

(9)

Some of the backgrounds contain one additional W boson which decays to two light jets, so we require the light jets invariant mass should not be within the W mass window:

$$m_{jj} < 60\text{GeV} \quad \text{or} \quad m_{jj} > 100\text{GeV}.$$

(10)

As for the two $b$-tagged jets channel, we require the final state containing two $b$-tagged jets, two positive charged leptons, and at most one light jet. All the additional cuts can be obtained by replacing the leading light jet in the one $b$-tagged channel cuts with a $b$ jet.

Table II shows the total cross sections for the signals and backgrounds with $g_{tr} = 3g_s$ after imposing all the cuts. We can see that the total backgrounds can be reduced to 0.03
fb, while the signal can reach 28 fb and 0.6 fb for $M_{G^{(1)}} = 1\text{TeV}$ and $3\text{TeV}$, respectively. To further investigate the LHC reach we show in Fig. 3 and 4 the $5\sigma$ discovery limits of $\varepsilon_u$ and $\varepsilon_c$ at the LHC, and we see that the LHC can probe an interesting region of $\varepsilon_u$ and $\varepsilon_c$ for $M_{G^{(1)}}$ up to 3TeV. Obviously, as mentioned above, our process is sensitive to $\varepsilon_u$ due to the large contribution from the subprocess $uu \rightarrow tt$, and not for $\varepsilon_c$. From Fig. 4 we find that the discovery limit of $\varepsilon_u$ can reach 0.1 for $g_{t_R} = 5g_s, M_{G^{(1)}} = 1\text{TeV}$ and an integrated luminosity of $10\text{fb}^{-1}$, while the discovery limit of $\varepsilon_u$ can be as low as 0.06 for a high integrated luminosity of $300\text{fb}^{-1}$. Comparing with the results in Ref. [11], ours are better for low luminosities and high KK gluon masses. Moreover, unlike Ref. [11], all the cuts we imposed are independent of the KK gluon mass and width, which allow us to probe the flavor violating parameters for a wide range of $g_{t_R}$ and $M_{G^{(1)}}$.

IV. CONCLUSIONS

In conclusion, we have studied the production of same-sign top pairs mediated by the KK gluon in the RS model with fermions and gauge bosons in the bulk at the LHC. For the same-sign dilepton channel, by imposing suitable cuts the backgrounds can be suppressed to about $0.03\text{ fb}$, which can lead to a sizable signal/background ratio, about $5\sim860$. We also investigated the LHC reach of the flavor violating parameters $\varepsilon_u$ and $\varepsilon_c$, and found that the LHC can probe an interesting region of the parameters even when the KK gluon mass is as large as 3 TeV. The discovery limit of $\varepsilon_u$ can reach 0.1 for $g_{t_R} = 5g_s, M_{G^{(1)}} = 1\text{TeV}$ and an integrated luminosity of $10\text{fb}^{-1}$. While for a high integrated luminosity of $300\text{fb}^{-1}$, the discovery limit of $\varepsilon_u$ can reach as low as 0.06.

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FIG. 1: Feynman diagram for the same-sign top pair production with FCNC couplings. There is also a corresponding u-channel diagram.

FIG. 2: Normalized top quark transverse momentum distribution in the same-sign top pair production with FCNC couplings mediated by KK gluon and Z boson at the LHC, assuming $\varepsilon_u = 0.5$, $\varepsilon_c = 0$ and $M_{G(1)} = 1$ TeV.
FIG. 3: $5\sigma$ discovery limit of $\varepsilon_u$ and $\varepsilon_c$ at the LHC for low and high integrated luminosities, assuming $g_{tt} = 3g_s$. 
FIG. 4: $5\sigma$ discovery limit of $\varepsilon_u$ and $\varepsilon_c$ at the LHC for low and high integrated luminosities, assuming $g_{tr} = 5g_s$. 