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Top spin correlations in theories with large extra-dimensions at the LHC

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In theories with large extra dimensions, we study the top spin correlations at the Large Hadron Collider. The *s*-channel process mediated by graviton Kaluza-Klein modes contributes to the top-antitop pair production in addition to the Standard Model processes, and affects the resultant top spin correlations. With the fundamental scale of the extra dimensional theory below 2 TeV, we find a sizable deviation of the top spin correlations from the Standard Model one.

International Workshop on Top Quark Physics
January 12-15, 2006
Coimbra, Portugal

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PoS(TOP2006)005

1. Introduction

Recently, the possibility that our space has more than three spatial dimensions has been vigorously studied [1, 2]. Typical setup is that the standard model (SM) fields reside on $3+1$-dimensional manifold called "3-brane" embedded in higher dimensional space-time while only graviton can propagate into the whole space-time dimensions. This setup opens up a new way to solve the gauge hierarchy problem, namely, a huge hierarchy between the electroweak scale and the 4-dimensional Planck scale, as addressed by Arkani-Hamed, Dimopoulos and Dvali (ADD) [1]. In their model, 4-dimensional Planck scale M_{pl} can be expressed by the fundamental scale of $4+n$ dimensions M_D and the common radius of the compactified n extra dimensions R such as $M_{pl} = M_D(M_D R)^{n/2}$. If the compactification radius is large enough (for example, $R \sim 0.1$ mm for $n = 2$), M_D can be $\mathscr{O}(1\mathrm{TeV})$ and thus the gauge hierarchy problem can be solved.

Effects of extra dimensions are recast in four dimensional effective theory valid below M_D [3, 4]. In the effective theory, the graviton propagating in the whole $4+n$ dimensions can be expressed as an infinite tower of Kaluza-Klein (KK) modes which contain spin-2 (KK-graviton), spin-1 (gravi-vector) and spin-0 (gravi-scalar) excitations. The KK gravitons and the gravi-scalars couple to the energy-momentum tensor of the SM fields and its trace, respectively, while the gravi-vector has no interaction with them. Since the trace of the energy-momentum tensor is vanishing for massless fields, we can ignore the gravi-scalar interaction at high energy processes. Although each vertex between the SM fields and the KK gravitons are suppressed by M_{pl}, the effective coupling is enhanced due to contributions of a large number of KK gravitons so as to be suppressed by $M_D = \mathscr{O}(1\mathrm{TeV})$. Therefore new phenomena induced by the KK gravitons, for example, the direct KK graviton emission processes and the virtual KK graviton exchange processes, can be expected at high energy collisions [5]. In particular, the virtual KK graviton exchange process is interesting, since it can give rise to characteristic spin configurations and angular distributions for outgoing particles, which reflect the spin-2 nature of the intermediate KK gravitons.

The top-antitop quark pair is a good candidate to study its spin correlations, since the top quark, with mass in the range of 175 GeV [6], decays electroweakly before hadronizing [7], and thus the possible polarization of the top-antitop quark pair is transferred to its decay products. There are thus significant angular correlations among the decay products of the top and the antitop quarks. For the hadronic top-antitop pair production process through the quantum chromodynamics (QCD) interaction, the spin correlations have been extensively studied [15, 16, 17]. It is found that there is a spin asymmetry between the produced top-antitop pairs, namely, the number of produced top-antitop quark pairs with both spin up or spin down is different from the number of pairs with the opposite spin combinations. If the top quark is coupled to new physics beyond the SM, the top-antitop spin correlations could be altered. Therefore the top-antitop correlations are useful information to test the SM and also possible new physics at hadron colliders.

Note that the Large Hadron Collider (LHC) has a big advantage to study them, since it will produce almost 10 millions top quarks per year. The sensitivity of the ATLAS experiment at LHC to the top quark spin correlations in the SM was estimated in Ref. [8]. A 4% precision on this effect measurement is possible with 10 fb^{-1}, after combining results from both, the semileptonic and dileptonic $t\bar{t}$ channels.

In the ADD model, there exists a new top-antitop pair production process through the virtual

KK graviton exchange in the s-channel. The effect of the virtual KK graviton exchange process has been studied for the total cross section of the top-antitop pair production process at hadron collider [9] and for polarized amplitudes at e^+e^- and $\gamma\gamma$ colliders [10, 11]. In this paper, we study the effect of the virtual graviton exchange process on the spin correlation in the top-antitop pair production process at the LHC. More detailed analysis is in our paper [12].

2. Theoretical framework

At hadron collider, top-antitop quark pair is produced through the processes of quark-antiquark pair annihilation and gluon fusion. The former is the dominant process at the Tevatron, while the latter is dominant at the LHC. The produced top-antitop pairs decay before hadronaization takes place. The main decay modes in the SM involve leptonic and hadronic modes:

$$t \to bW^+ \to bl^+\nu_l, bu\bar{d}, bc\bar{s}, \tag{2.1}$$

where $l = e, \mu, \tau$. The differential decay rates to a decay product $f = b, l^+, \nu_l$, etc. in the top quark rest frame can be parameterized as

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_f} = \frac{1}{2}(1 + \kappa_f \cos\theta_f), \tag{2.2}$$

where Γ is the partial decay width of the respective decay channel, θ_f is the angle between the chosen top spin axis and the direction of motion of the decay product f, and the coefficient κ_f is the top-spin analyzing power of a particle f. The SM values of κ_f at tree level have been computed [13], for instance, in the semi-leptonic decay, $\kappa_{l^+} = +1$ for the charged lepton, $\kappa_b = -0.41$ for b-quark and $\kappa_{\nu_l} = -0.31$ for ν_l, respectively. In hadronic decay modes, the role of the charged lepton is replaced by the d or s quark.

From the above discussion, it is clear that the best way to analyze the top-antitop spin correlations is to see the angular correlations of two charged leptons l^+l^- produced by the top-antitop quark leptonic decays. In the following, we consider only the leptonic decay channels. Using the total matrix element squared for the top-antitop pair production and their decay channel, we find the following double distribution [15, 16, 17],

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_{l^+}\, d\cos\theta_{l^-}} = \frac{1 - \mathscr{A}\kappa_{l^+}\kappa_{l^-}\cos\theta_{l^+}\cos\theta_{l^-}}{4}, \tag{2.3}$$

with $\kappa_{l^+} = \kappa_{l^-} = 1$. Here σ denotes the cross section for the process of the leptonic decay modes, and $\theta_{l^+}\,(\theta_{l^-})$ denotes the angle between the top (antitop) spin axis and the direction of motion of antilepton (lepton) in the top (antitop) rest frame. The coefficient $\mathscr{A}$ denotes the spin asymmetry between the produced top-antitop pairs with unlike and like spin pairs defined as

$$\mathscr{A} = \frac{\sigma(t_\uparrow\bar{t}_\uparrow) + \sigma(t_\downarrow\bar{t}_\downarrow) - \sigma(t_\uparrow\bar{t}_\downarrow) - \sigma(t_\downarrow\bar{t}_\uparrow)}{\sigma(t_\uparrow\bar{t}_\uparrow) + \sigma(t_\downarrow\bar{t}_\downarrow) + \sigma(t_\uparrow\bar{t}_\downarrow) + \sigma(t_\downarrow\bar{t}_\uparrow)}, \tag{2.4}$$

where $\sigma(t_\alpha\bar{t}_{\dot{\alpha}})$ is the cross section of the top-antitop pair production at parton level with denoted spin indices.

In the SM, at the lowest order of α_s, the spin asymmetry is found to be $\mathscr{A} = +0.302$ for the LHC. Since in the ADD model there is a new contribution to the top-antitop pair production process through the virtual KK graviton exchange in the s-channel, the spin asymmetry (2.4) can be altered from the SM one. In the 4-dimensional effective theory with energies smaller than the $4+n$ dimensional Planck scale M_D, the amplitude for the KK graviton exchange process would be described as [3]

$$\mathscr{M}_G = \frac{4\pi\lambda}{M_D^4} T^{\mu\nu}(k_1,k_2) T_{\mu\nu}(k_3,k_4), \tag{2.5}$$

where $T_{\mu\nu}$ is an energy momentum tensor of the SM, k_i $(i = 1,\ldots,4)$ are momentums of incoming and outgoing particles, and λ is an order one parameter, which encodes all the ambiguity such as the number of extra dimensions and the regularization procedure for the contributions from the infinite number of KK gravitons. Hereafter we consider the two cases $\lambda = \pm 1$. We calculated the density matrix (squared invariant amplitude) of the top-antitop quark pair production including the KK graviton exchange by using the formula (2.5). In our calculation, we have chosen the helicity basis useful for the energy range at the LHC, while the off-diagonal basis is suitable for the Tevatron [14]. Note that the effective invariant amplitude (2.5) grows rapidly with the center-of-mass energy of partons and it breaks unitarity. As was mentioned above, we (should) use the formula (2.5) at energies lower than M_D. Therefore, in order to make our analysis conservative, we take into account the contributions from the virtual graviton KK exchange processes only for the center-of-mass energy of colliding partons lower than M_D, namely, $\sqrt{s} \leq M_D$.

3. Numerical Results

Here we present relevant numerical results and demonstrate interesting properties of measurable quantities in the ADD model. In the following analysis, we use the parton distribution func-

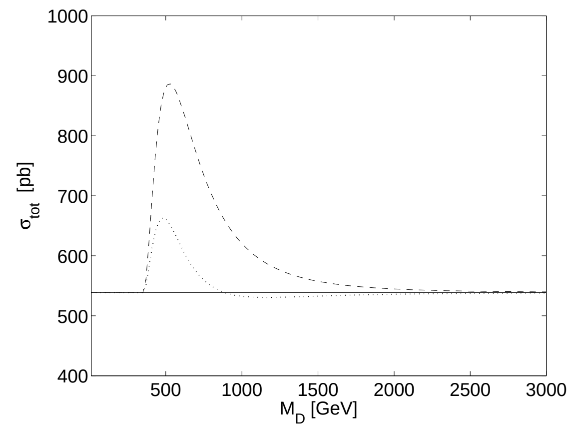


Figure 1: The total cross section as a function of the scale M_D at the LHC with center-of-mass energy 14 TeV. The solid line corresponds to the SM. The dashed and the dotted lines correspond to the cases of $\lambda = 1$ and $\lambda = -1$ in the ADD model, respectively.

tions of Ref. [18] (CTEQ5L) and its numerical implementation in PDFLIB [19] from the CERN Program Library with the constant scale $Q = m_t = 175$ GeV, $N_f = 5$ and $\alpha_s(Q) = 0.1156$.

Fig. 1 shows the total cross section of the top-antitop quark pair production and Fig. 2 shows the spin asymmetry at the LHC with the center-of-mass energy 14 TeV as a function of the scale M_D. The solid line corresponds to the SM. The dashed and the dotted lines correspond to the cases of $\lambda = 1$ and $\lambda = -1$ in the ADD model, respectively. For the completeness, in Fig. 3 the same dependency as in Fig. 2, but with the cut $M_{t\bar{t}} < 550$ GeV, which was used in [8], is shown. In both plots in Fig. 1 and Fig. 2, for the scale M_D below 2 TeV, we can see sizable deviations from the SM one. The cross section in the ADD model traces the SM line for large M_D. So do they for small M_D. This is because we have introduced the cut $s \leq M_D$ for the KK graviton mediated process in our analysis.

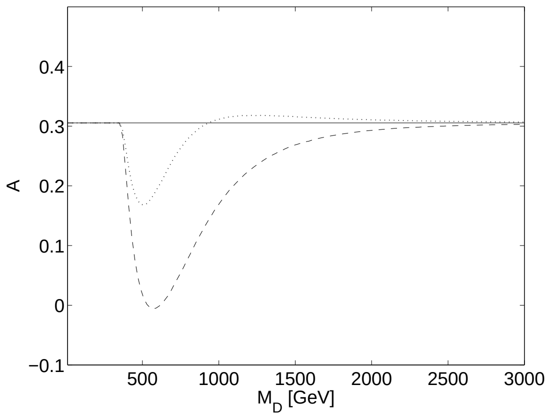


Figure 2: Spin asymmetry $\mathscr{A}$ as a function of the scale M_D at the LHC with $E_{CMS} = 14$ TeV. The solid line corresponds to the SM. The dashed and the dotted lines correspond to $\lambda = 1$ and $\lambda = -1$ cases in the ADD model, respectively.

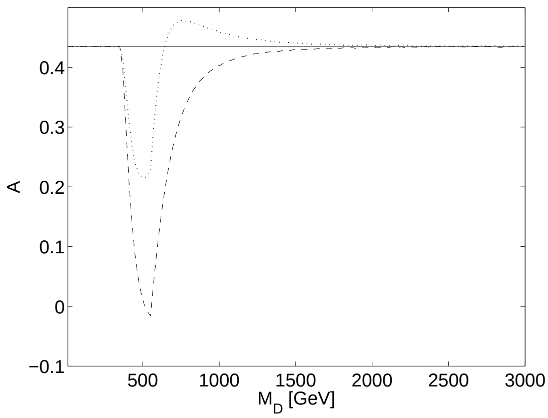
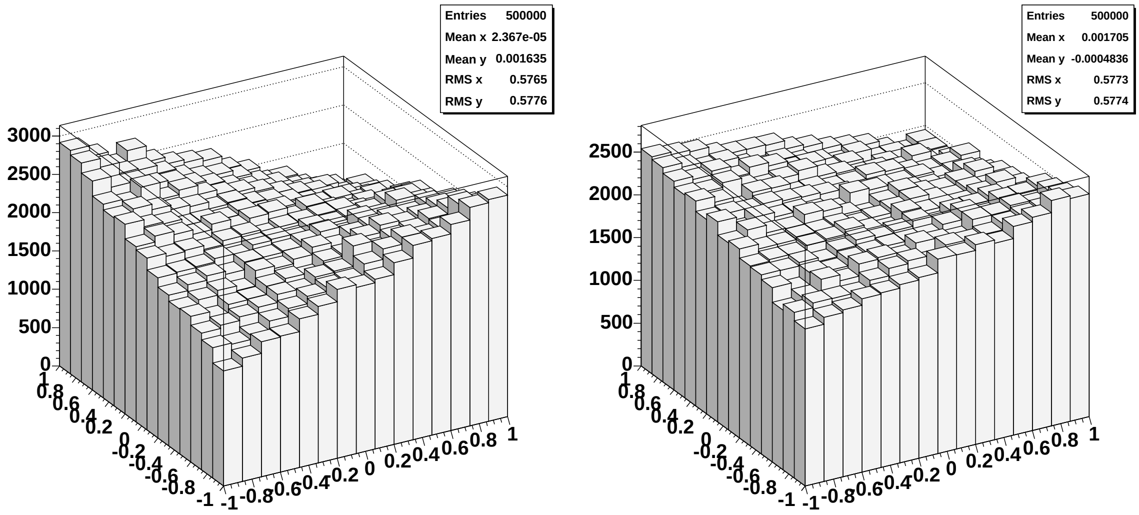


Figure 3: The same as Fig. 2, but with the cut $M_{t\bar{t}} <$ 550 GeV.

In Fig. 4, we show lego plots of $\cos\theta_{l^+}$ vs. $\cos\theta_{l^-}$ for the top-antitop events with spin correlations, $\mathscr{A} = 0.306$ (a) corresponding to the SM prediction, and $\mathscr{A} = 0.169$ (b) corresponding to the ADD model prediction with $\lambda = 1$ and $M_D = 1$ TeV. Two plots would be distinguishable.

4. Conclusion

In theories with large extra dimensions, we have studied the production of top-antitop pairs and the top spin correlations at the LHC. There is the new contribution to the top-antitop pair production process mediated by the virtual KK gravitons in the s-channel. We have computed the corresponding density matrices and presented the various numerical results. For the fundamental scale M_D lower than around 2 TeV, we have found the sizeable deviations of the top-antitop production rate, the spin asymmetry etc. from the ones in the Standard Model. From the results in [8] follows, the deviation of the top quark spin correlations could be measurable in the ATLAS experiment after starting the operation of the LHC.



(a) (b)

Figure 4: Lego plots of $\cos\theta_{l^+}$ vs. $\cos\theta_{l^-}$ for the top-antitop events with spin correlations with spin correlations, $\mathscr{A} = 0.306$ (a) corresponding to the SM prediction, and $\mathscr{A} = 0.169$ (b) corresponding to the ADD model prediction with $\lambda = 1$ and $M_D = 1$ TeV.

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