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Influence of graviton on top-antitop production at the LHC

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Abstract. We examine the top quark production in the brane world scenario. We study two typical models - the model proposed by Arkani-Hamed, Dimopoulos and Dvali (ADD) and the model of Randall and Sundrum (RS). In addition to the Standard Model processes, there is a new contribution to the top-antitop pair production process mediated by graviton Kaluza-Klein modes in the s-channel. We calculated the density matrix for the top-antitop pair production including the new contribution. With a reasonable parameter choice, we find a sizable deviation of the top-antitop quark spin correlations from those in the Standard Model.

1. Introduction

During the past several decades the gauge hierarchy problem has been a guiding principle to propose beyond the standard model (SM), and many new physics models have been proposed to solve this problem. Brane world scenario recently proposed provides a possible solution for this problem. In this scenario whole space has more than three spatial dimensions and the SM fields are confined on a 4-dimensional hypersurface called “D3-brane”. There are two typical models based on this setup. One is the so-called ADD model proposed by Arkani-Hamed, Dimopoulos and Dvali (ADD) [1] and the model proposed by Randall and Sundrum (RS) [2]. In these models, effects of extra-dimensions are essentially encoded in graviton. We examined the effect of the virtual Kaluza-Klein (KK) graviton exchange process on the spin correlations of the top-antitop pairs produced at the LHC [3, 4] in the ADD and RS scenario.

2. Spin correlations

At hadron collider, the top-antitop quark pair is produced through the processes of quark-antiquark pair annihilation and gluon fusion:

\[ i \rightarrow t + \bar{t}, \quad i = q\bar{q}, gg. \]

The former is the dominant process at the Tevatron, while the latter is dominant at the LHC.
The best way to analyze the top-antitop spin correlations is to see the angular correlations of two charged leptons produced by the top-antitop quark leptonic decays. The decay can be parametrized as

\[
\frac{d^2\sigma}{\sigma \, d \cos \theta_{t^+} \, d \cos \theta_{t^-}} = 1 - \frac{\mathcal{A} \kappa_{t^+} \kappa_{t^-} \cos \theta_{t^+} \cos \theta_{t^-}}{4},
\]

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

\[
\mathcal{A} = \frac{\sigma(t\bar{t}) + \sigma(t\bar{t}) - \sigma(t\bar{t}) - \sigma(t\bar{t})}{\sigma(t\bar{t}) + \sigma(t\bar{t}) + \sigma(t\bar{t}) + \sigma(t\bar{t})}.
\]

In the Standard Model (SM), at the lowest order of \( \alpha_s \), the spin asymmetry is \( \mathcal{A} = 0.319 \) for the LHC.

3. ADD scenario

In the ADD model, there are \( n \)-extra dimensions compactified on \( n \)-torus with common radius \( R \) and a D3-brane embedded in \( (4 + n) \)-dimensional bulk is introduced on which the SM fields reside. This setup gives a relation \( M_{pl} = M_D(M_D R)^{n/2} \) between the 4-dimensional Planck mass \( M_{pl} \) and the Planck scale of \( (4 + n) \)-dimensions \( M_D \). If the compactification radius is large enough (for instance, \( R \sim 0.1 \) mm for \( n = 2 \)), \( M_D \) can be \( \mathcal{O}(1 \text{ TeV}) \) and thus one obtains a solution to the gauge hierarchy problem.

The results for the spin asymmetry \( \mathcal{A} \) as a function of the scale \( M_D \) in the ADD model calculated from density matrix [3] are presented in Fig. 1 (the parameter \( \lambda = \pm 1 \) encodes the ambiguity of the regularization procedure for the contributions from the infinite number of KK gravitons). We can see sizable deviations from the SM at the scale below \( \sim 2 \) TeV.

4. RS scenario

The RS scenario is a 5-dimensional model, where one extra-dimension is compactified on a S\(^1\)/Z\(_2\) orbifold and a negative cosmological constant is introduced in the bulk. Two D3-branes are placed at fixed points of the orbifold \( \phi = 0 \) and \( \phi = \pi \) (\( \phi \) is an angle of S\(^1\)) with opposite brane tensions. A brane at \( \phi = 0 \) with a positive tension is called the hidden brane and the
other one at $\phi = \pi$ with a negative tension is called the visible brane on which the SM fields are confined. Solving the Einstein equation of this system, the 5-dimensional bulk geometry is found to be a slice of anti-de Sitter (AdS$_5$) space, $ds^2 = e^{-2\kappa r_c |\phi|} \eta_{\mu\nu} dx^\mu dx^\nu - r_c^2 d\phi^2$, where $\kappa$ is the AdS curvature in five dimensions, and $r_c$ is a compactification radius. This background geometry allows us to take the Planck scale as a fundamental scale. Indeed, in an effective 4-dimensional description an effective mass scale on the visible brane is warped down such as $\Lambda_\pi = \bar{M}_{pl} e^{-\pi \kappa r_c}$ due to effect of the warped geometry, where $\bar{M}_{pl}$ is the reduced Planck mass. Therefore, with a mild parameter tuning, $\kappa r_c \simeq 12$, we can realize $\Lambda_\pi = O(1 \text{ TeV})$ and obtain a natural solution to the gauge hierarchy problem.

We study the top spin correlations in the RS scenario. The free parameters in the model are the mass of the lightest Kaluza-Klein graviton $m_1$ (we use $m_1 = 600 \text{ GeV}/c^2$) and $\kappa/\bar{M}_{pl}$, where $\kappa$ is curvature in five dimensions and $\bar{M}_{pl}$ is the reduced Plack mass.

We computed the density matrix describing the production of the top-antitop pairs in the RS model [4]. In Fig. 2, the spin asymmetry $A$ as a function of the top-antitop invariant mass $M_{t\bar{t}}$ is presented. The resonant production of the Kaluza-Klein gravitons give rise to a remarkable enhancement of the deviations from the Standard Model. In Fig. 3, we show the spin correlations $A$ as a function of $\kappa/\bar{M}_{pl}$. We can see a sizable deviation from the Standard Model.

![Figure 2](image1.png) ![Figure 3](image2.png)

**Figure 2.** Spin asymmetry $A$ as a function of the top-antitop invariant mass $M_{t\bar{t}}$. The solid line corresponds to the SM, while the dashed lines correspond to the RS model with $\kappa/\bar{M}_{pl} = 0.01, 0.04, 0.07$ and 0.1 from up to down.

**Figure 3.** Spin asymmetry $A$ as a function of $\kappa/\bar{M}_{pl}$ at the LHC with $E_{CMS} = 14 \text{ TeV}$. As $\kappa/\bar{M}_{pl} \to 0$, $A$ becomes the SM value, 0.319.

5. Conclusion
We studied the top-antitop pair production and the top spin correlations at the LHC in the ADD and RS model. With a reasonable parameter choice, we found a sizable deviation of the top-antitop spin correlations from those in the Standard Model.

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