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Associated production of a Kaluza–Klein excitation of a gluon with a $t\bar{t}$ pair at the LHC

M. Guchait [a], F. Mahmoudi [b], K. Sridhar [c,*]

[a] Department of High Energy Physics, Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400 005, India
[b] High Energy Physics, Uppsala University, Box 535, 75121 Uppsala, Sweden
[c] Department of Theoretical Physics, Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400 005, India

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ABSTRACT

In certain model-realizations of the Randall–Sundrum scenario, the Kaluza–Klein (KK) excitations of the gluon, g_{KK} have enhanced couplings to right-handed top quarks. In the absence of a ggg_{KK} coupling in these models, the single production of a g_{KK} from an initial gg state is not possible. The search for other production mechanisms at the LHC, therefore, becomes important. We suggest that the associated production of a g_{KK} with a $t\bar{t}$ pair is such a mechanism. Our parton-level study, which neglects detection efficiencies, shows that through this process the LHC can probe KK gluon masses in the range of 2.8–3.0 TeV.

The Randall–Sundrum (RS) model [1] is a five-dimensional model with the fifth dimension ϕ compactified on a $\mathbf{S}^1/\mathbf{Z}^2$ orbifold. The compactification radius R_c is somewhat larger than M_P^{-1}, the Planck length. The fifth dimension is a slice of anti-de Sitter space-time and is strongly curved. At the fixed points $\phi = 0,\ \pi$ of the orbifold, two D-3 branes are located and are known as the Planck brane and the TeV brane, respectively. The Standard Model fields are localised on the TeV brane while gravitons exist in the full five-dimensional spacetime. The five-dimensional spacetime metric is of the form

$$ds^2 = e^{-\mathcal{K} R_c \phi} \eta_{\mu\nu}\, dx^\mu\, dx^\nu + R_c^2\, d\phi^2. \qquad (1)$$

Here $\mathcal{K}$ is a mass scale related to the curvature. The factor $\exp(-\mathcal{K} R_c \phi)$ is called the warp factor and serves to rescale masses of fields localised on the TeV-brane. For example, $M_P = 10^{19}$ GeV for the Planck brane at $\phi = 0$ gets rescaled to $M_P \exp(-\mathcal{K} R_c \pi)$ for the TeV brane at $\phi = \pi$. The warp factor generates $\frac{M_P}{M_{\mathrm{EW}}} \sim 10^{15}$ by an exponent of order 30 and solves the hierarchy problem. For this mechanism to work, one will have to ensure that the radius R_c is stabilised against quantum fluctuations and this can be done by introducing a bulk scalar field which generates a potential that allows for the stabilisation [2]. The model predicts a discrete spectrum of Kaluza–Klein (KK) excitations of the graviton and these couple to the Standard Model fields with a coupling that is enhanced by the warp factor to be of the order of electroweak strength. Several collider implications of these gravitons resonances have been studied in the literature [3].

The AdS/CFT correspondence [4] allows us to get an understanding of the RS model in terms of a dual theory—a strongly coupled gauge theory in four dimensions [5]. This four-dimensional theory is conformal all the way from the Planck scale down to the TeV scale and it is only the presence of the TeV brane that breaks the conformal symmetry. The KK excitations as well as the fields localised on the TeV brane are TeV-scale composites of the strongly interacting theory. Since in the RS model, all SM fields are localised on the TeV brane, the AdS/CFT correspondence tells us that the RS model is dual to a theory of TeV-scale compositeness of the entire SM. Such a composite theory is clearly unviable: but is there a way out? There seems to be—and the simplest possibility is to modify the model so that only the Higgs field is localised on the TeV brane while the rest of the SM fields are in the bulk [6].

Flavour hierarchy, consistency with electroweak precision tests and avoidance of flavour-changing neutral currents can be used as guiding principles in constructing such models [7]. In particular, in order to avoid an unacceptably large contribution to the electroweak T parameter an enhanced symmetry in the bulk like $SU(2)_L \times SU(2)_R \times U(1)_{(B-L)}$ may be used. The heavier fermions need to be closer to the TeV brane so as to get a large Yukawa coupling i.e. overlap with the Higgs. In other words, the profiles of the heavier fermions need to be peaked closer to the TeV-brane. Conversely, the fermions close to the Planck brane will have small Yukawa couplings. However, while the large Yukawa of the top demands proximity to the TeV brane, the left-handed electroweak doublet, $(t, b)_L$, cannot be close to the TeV brane because that induces non-universal couplings of the b_L to the Z constrained by $Z \to b\bar{b}$. So the doublet needs to be as far away from the TeV

* Corresponding author.
E-mail addresses: guchait@tifr.res.in (M. Guchait), nazila.mahmoudi@tsl.uu.se (F. Mahmoudi), sridhar@theory.tifr.res.in (K. Sridhar).

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brane as allowed by R_b whereas the t_R needs to be localised close to the TeV brane to account for the large Yukawa of the top. We stress that this is one model realisation; a different profile results, for example, in models that invoke other symmetry groups in the bulk [8]. It has been found that in order to avoid huge effects of flavour-changing neutral currents (FCNCs) and to be consistent with precision tests of the electroweak sector, the masses of the KK modes of the gauge bosons have to be strongly constrained. The resulting bounds on the masses of the KK gauge bosons are found to be in the region of 2–3 TeV [7] though this bound can be relaxed by enforcing additional symmetries. A review of the literature on this subject can be found in Ref. [9].

The collider implications of this scenario has been studied recently [10]. While some of these studies have focussed on graviton production [11], the interesting signals for this scenario is the production of KK gauge bosons and, for the LHC in particular, the production of KK gluons. The KK gluon couples strongly to the t_R, with a strength which is enhanced by a factor ξ compared to the QCD coupling where $\xi \equiv \sqrt{\log(M_P/\mathrm{TeV})} \sim 5$. Consequently, it decays predominantly to tops if produced. To the left-handed third-generation quarks, the KK gluon couples with the same strength as the QCD coupling whereas to the light quarks its couplings are suppressed by a factor $1/\xi$. The problem in producing the KK gluon at a collider, however, is that its coupling to two gluons vanishes because of the orthogonality of the profiles of these particles and, therefore, the gluon production mechanism at a hadron collider cannot produce the KK gluon at leading order. The KK gluon can, therefore, be produced by annihilation of light quarks and this production mechanism has been studied in the context of the LHC [12–14]. The same mechanism has also been studied in the context of Tevatron to derive a model-independent bound of 770 GeV from the Tevatron top cross-section [15].

In this Letter, we study the production of KK gluons in association with a $t\bar{t}$ pair. A similar process has been recently discussed in Ref. [16]. In this process the $t\bar{t}$ pair can be produced from both gg and $q\bar{q}$ initial states through the usual QCD processes and the KK gluon, g_{KK} can then be radiated from one of the heavy-quark legs. The fact that the gg initial state contributes to the associated production process makes it appealing. Also the process directly probes the coupling of the g_{KK} to the tops which is an important feature of the new dynamics.

The Feynman diagrams for the $q\bar{q} \to g_{\mathrm{KK}} t\bar{t}$ and the $gg \to g_{\mathrm{KK}} t\bar{t}$ subprocess are shown in Fig. 1. We have computed the matrix elements for these subprocesses using FORM. The g_{KK} is produced on-shell and we ignore virtual effects. The produced g_{KK} decays into a $t\bar{t}$ pair yielding two pairs of $t\bar{t}$ in the final state. The background to this signal of two non-resonant $t\bar{t}$ pairs coming from QCD processes has been computed using ALPGEN [17]. The squared-matrix elements for the signal are available in the form of a Fortran code but the expressions are too lengthy to reproduce here. A KK gluon with a mass just a little above the $t\bar{t}$ threshold has a very large branching into top pairs: the branching ratio is about 92.5% [12]. Since we are interested in KK gluon masses well above the $t\bar{t}$ threshold we will assume that the produced g_{KK} decays with this branching ratio into a $t\bar{t}$ pair.

For the signal kinematics, we have used that originally proposed by Gottschalk and Sivers [18] for three-jet production suitably modified to take into account the fact that all three final-state particles in our case are massive. In this description of the kinematics, the z-axis of the co-ordinate system is chosen to be the direction of one of the final-state particles rather than the initial beam axis. We choose this particle (labelled p_5) as the g_{KK}. The momentum assignments that we start with are:

$$p_1: \quad \frac{\sqrt{\hat{s}}}{2}(1,\ \sin\theta\cos\phi,\ \sin\theta\sin\phi,\ \cos\theta)$$

$$p_2: \quad \frac{\sqrt{\hat{s}}}{2}(1,\ -\sin\theta\cos\phi,\ -\sin\theta\sin\phi,\ \cos\theta)$$

$$p_3: \quad \frac{\sqrt{\hat{s}}}{2}x_3(1,\ \beta_3\cos\theta_{35},\ \beta_3\sin\theta_{35},\ 0)$$

$$p_4: \quad \frac{\sqrt{\hat{s}}}{2}x_4(1,\ \beta_4\cos\theta_{45},\ \beta_4\sin\theta_{45},\ 0)$$

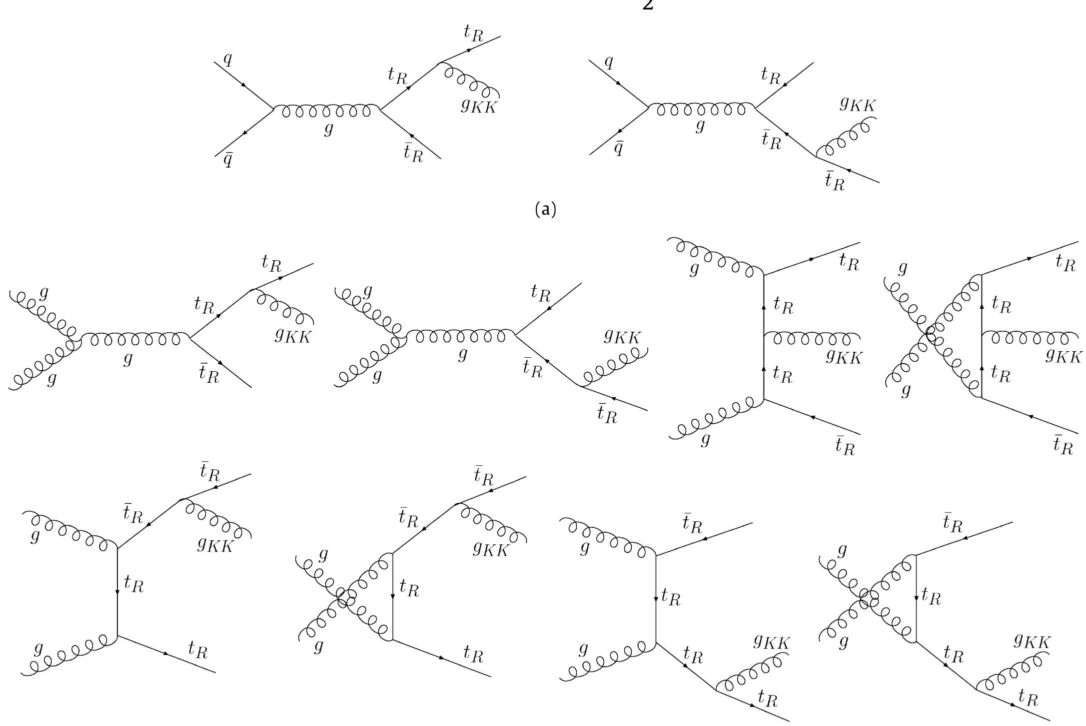

Fig. 1. The Feynman diagrams for the processes: (a) $q\bar{q} \to g_{\mathrm{KK}} t_R \bar{t}_R$ and, (b) $gg \to g_{\mathrm{KK}} t_R \bar{t}_R$.

$$p_5: \quad \frac{\sqrt{\hat{s}}}{2}x_5(1,\ \beta_5,\ 0,\ 0). \tag{2}$$

In the above equation, p_1 and p_2 are the 4-momenta of the initial partons, p_3 and p_4 are the 4-momenta of the t and the $\bar{t}$ and p_5 is the 4-momentum of the KK gluon. The β_i's are given by:

$$\beta_i = \sqrt{1 - \frac{4m_i^2}{x_i^2 \hat{s}}}. \tag{3}$$

Energy conservation implies

$$x_3 + x_4 + x_5 = 2, \tag{4}$$

and, using 3-momentum conservation, one can get

$$\cos\theta_{35} = \frac{x_4^2\beta_4^2 - x_3^2\beta_3^2 - x_5^2\beta_5^2}{2x_3x_5\beta_3\beta_5},$$
$$\cos\theta_{45} = \frac{x_3^2\beta_3^2 - x_4^2\beta_4^2 - x_5^2\beta_5^2}{2x_4x_5\beta_4\beta_5}. \tag{5}$$

Using the above, all relevant momenta and angles may be constructed. For example, the transverse momentum of the g_{KK} is given by

$$p_T(g_{\mathrm{KK}}) = \frac{\sqrt{\hat{s}}}{2}x_5\beta_5\sqrt{\cos^2\theta + \sin^2\theta\sin^2\phi}. \tag{6}$$

The kinematics for the decay of the g_{KK} into a $t\bar{t}$ pair is the standard two-particle decay kinematics.

Defining the variables τ and y_{boost} through the equations:

$$\tau = \frac{\hat{s}}{s} = x_1x_2,$$
$$x_1 = \sqrt{\tau}e^{y_{\mathrm{boost}}},$$
$$x_2 = \sqrt{\tau}e^{-y_{\mathrm{boost}}}, \tag{7}$$

the differential cross-section for $g_{\mathrm{KK}}t\bar{t}$ production assumes the form:

$$\frac{d\sigma}{d\sqrt{\hat{s}}\,dy_{\mathrm{boost}}\,dx_3\,dx_4\,d\Omega} = \int dx_1\,dx_2\frac{\alpha_s^2\Lambda_t^2\tau}{8\pi\sqrt{\hat{s}}}\sum_{ij}\frac{1}{1+\delta_{ij}} \times \left[f_i^{(a)}(x_1, Q^2)f_j^{(b)}(x_2, Q^2)|M_{ij}|^2 + i \leftrightarrow j\right], \tag{8}$$

where, $f^{(a)}$, $f^{(b)}$ are the parton densities evaluated at the scale Q^2, $|M_{ij}|^2$ is the squared-matrix element and Λ_t is the coupling of the KK gluon to the t_R and is given by $5\sqrt{4\pi\alpha_s}$.

Since the g_{KK} masses we are interested in are large, we expect the $t\bar{t}$ pair coming from the decay of the g_{KK} to have large momenta. The other $t\bar{t}$ pair is expected to have more moderate values of momenta. This simple fact may allow one to enhance the quality of the g_{KK} signal over the QCD background. As a first guess, we choose to put a lower cut of 300 GeV on the p_T of the t and the $\bar{t}$ coming from the decay of the g_{KK} and a cut of 50 GeV on the each of the other pair. We use these cuts to calculate the cross-section for the associated production of the KK gluon with a $t\bar{t}$ pair.

In Fig. 2, we have plotted this cross-section as a function of the mass of the KK gluon, M, for pp collisions at the LHC energy of $\sqrt{s} = 14$ TeV. We have done this for two different choices of parton density sets: the CTEQ4M NLL densities [19] and the MRST LO densities [20]. The parton distributions are taken from PDFLIB [21]. For the QCD scale, we use $Q = \sqrt{\hat{s}}/2$. In fact, a proper evaluation of the cross-section ought to be done with leading-order densities because the signal matrix-elements that we have computed are at leading order. The cross-section computed with the MRS LO densities turn out to be a factor of two lower than that computed with the CTEQ NLL densities. On the other hand, the effect of including higher-order QCD corrections to the process at hand are also likely to bring in large K-factors. QCD corrections to a related SM process namely the associated production of a Z-boson with a $t\bar{t}$ pair have been recently computed [22]. This process is similar to the one we have studied in this Letter: it involves the production of a heavy spin-one particle in association with a $t\bar{t}$ pair. There is, of course, a crucial difference which is that the gauge boson we are interested in is coloured which will bring in more diagrams than that considered in Ref. [22]. However, Ref. [22] gives a rough, and possibly conservative, indication of the size of the K-factor. We find that for reasonable choices of renormalization scale the K-factor computed for the associated Z process is about 2. If we go with this expectation we can expect our cross-section to be a factor of 2 larger than that computed with LO matrix-elements and LO parton densities. We would, therefore, take the CTEQ4M prediction for the cross-section as a better estimate of the experimental signal cross-section. For the choice of parameters and cuts discussed above, we have used ALPGEN to compute the background and we find a background cross-section of 0.33 fb. Assuming an integrated luminosity of 100 fb^{-1}, we find from Fig. 2 that a significance ($\equiv S/\sqrt{B}$) of 5 is obtained for $M = 2790$ GeV. The fact that the kinematic reach that this channel provides in searching for the KK gluon at the LHC is of the same order of magnitude as allowed by precision electroweak measurements is encouraging. Note that we have made no attempt to optimise the significance of the signal and a more judicious choice of cuts could conceivably help in increasing the reach.

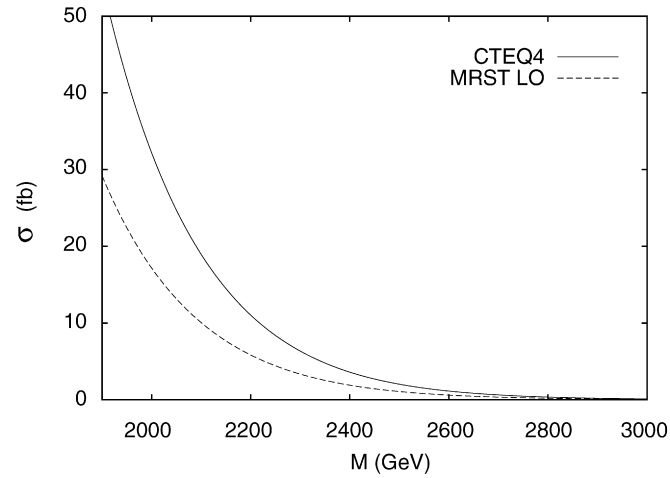

Fig. 2. The cross-section for the production of a KK gluon in association with a $t\bar{t}$ pair at the LHC energy as a function of the KK gluon mass and with p_T cuts as described in the text.

Since the choice of 300 GeV for the value of the cut on the p_T of the top quarks coming from the decay of the KK gluon was only an educated guess, we also studied the effect of changing this cut on the significance of the signal. In Fig. 3, we have displayed the results of varying the cut on p_T assuming an integrated luminosity of 100 fb^{-1}. For different values of the cut we have plotted the value, M^*, of the mass of the g_{KK} for which a significance of 5 is obtained. The results of Fig. 3 along with the number of signal and background events for an integrated luminosity of 100 fb^{-1} is presented in Table 1.

We find that changing the cut from 200 GeV to 600 GeV increases the reach by about 300 GeV. But in choosing a larger p_T cut one loses out on the number of events so that there are hardly a couple of background events at a p_T cut of 600 GeV. Therefore,

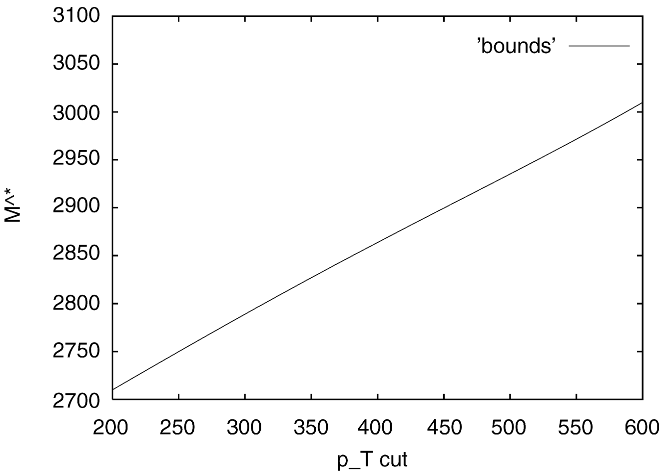

Fig. 3. The reach, M^*, in KK gluon mass at the LHC as a function of the p_T cut.

Table 1
The numbers of signal and background events for an integrated luminosity of 100 fb^{-1} for different values of p_T-cut and the corresponding values of M^*

p_T-cut (GeV)	M^* (GeV)	Signal events	Background events
200	2710	49.2	97
300	2790	28.7	33
400	2870	16.5	11
500	2930	10.0	4
600	3010	6.5	1.7

one may have to optimise the cut by choosing it to be around 300 or 400 GeV which leaves us with a sizeable number of events.

It is in order that we compare the reach of the associated production process studied here with the studies of direct KK gluon production process studied in papers cited in Refs. [12,13]. In Ref. [13] it has been shown that the direct production process can be used to probe values of KK gluon mass upto 6 TeV if the QCD background can be reduced by a factor of 10. The 6 TeV limit quoted in this Letter is significantly higher than what we find in this Letter. In contrast, Ref. [12] quotes a much smaller reach at the LHC for the KK gluon using the direct production process. The Letter quotes a significance of 5 for a KK gluon mass of about 4 TeV. This smaller number is a result of the fact that this Letter accounts for detector efficiencies which have been neglected by Ref. [13] and also in the parton-level analysis presented in this Letter. Our 3 TeV reach should strictly be compared with the 6 TeV limit presented in Ref. [13]. In addition to the kinematic efficiencies which are included in our parton-level analysis, if we also include a 10% efficiency due to b-tagging, detector effects and branching ratios then even for a p_T cut of 200 GeV we would be left with only about 5 signal events. With 5 signal events, we can get a significance of 5 for a M^* value of about 2.5 TeV. If we demand that we have a substantial number of signal events ($\geqslant 10$ events, say) and if we use a more conservative 1% estimate for the overall efficiency then we would have to lower the p_T cut significantly which will be at the expense of the signal-to-background discrimination. Consequently, we may need to use other strategies like tuning $t\bar{t}$ invariant mass cuts to improve the signal quality over the background [23].

We now attempt to compare our results with those presented in Ref. [16] which has studied the production of a KK gluon is association with a $b\bar{b}$ pair. A direct comparison of our results with these become difficult because (i) Ref. [16] does not present results for associated $t\bar{t}$ production; (ii) Ref. [16] studies four different models of fermion localization in the bulk; and, (iii) because the results presented in Ref. [16] are generated using CompHep and no details of the calculations are available. Nevertheless, we see that for a 3 TeV KK gluon the best significance that is obtained in Ref. [16] is about 4 (assuming an LHC luminosity of 100 fb^{-1}). Our results for the significance obtained from $t\bar{t}$ associated production are in the same ball-park.

The preferential coupling of $g_{\rm KK}$ to t_R as opposed to t_L can be exploited to increase the significance of this signal. The chiral coupling of the $g_{\rm KK}$ suggests that the polarization of the top quarks, studied by looking at its decay products, can prove to be a very useful discriminator between the signal and the background, as shown in Ref. [12].

However, in the present Letter which is based on a parton-level Monte Carlo study, we have limited ourselves to studying the kinematic reach of the LHC in the associated production process because the 4-top final state that we have focussed on here is not going to be an easy final state to analyze at the LHC experiments given the combinatorial backgrounds from this state that would have to be dealt with to extract a realistic signal. We have deferred a more detailed study of this signal after implementing it in a hadron-level Monte Carlo. This will enable us to present various kinematic distributions and top-polarization studies. Nevertheless, the results presented in this Letter are interesting enough to urge experimentalists at the LHC to consider this process seriously.

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