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Tevatron constraint on the Kaluza-Klein gluon of the Bulk Randall-Sundrum model

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Abstract: The Bulk Randall-Sundrum model, where all Standard Model particles except the Higgs are free to propagate in the bulk, predicts the existence of Kaluza-Klein (KK) modes of the gluon with a large branching into top-antitop pairs. We study the production of the lowest KK gluon mode at the Tevatron energy and use the data on the top cross-section from the Run II of Tevatron to put a bound on the mass of the KK gluon. The resulting bound of 770 GeV, while being much smaller than the constraints obtained on the KK gluon mass from flavour-changing neutral currents, is the first, direct collider bound which is independent of the specificities of the model.

Keywords: Beyond Standard Model, Hadronic Colliders, Compactification and String Models.

The past decade has been witness to a phase of intense theoretical activity in the area of extra space-dimensions and the resurgence of interest in the physics of extra dimensions, originally due to Kaluza and Klein, is due to the new paradigm of brane-worlds [1]. For high energy physics this is exciting because it provides fresh perspectives to the solution of the hierarchy problem and also suggests the discovery of new physics at TeV-scale colliders [2, 3].

In an attempt to find a genuine solution to the hierarchy problem Randall and Sundrum discovered a model now known in the literature as the Randall-Sundrum model or the RS model[1] [4]. In the RS model, one starts with a slice of anti-de Sitter spacetime in five dimensions (AdS5) with the fifth dimension ϕ compactified on a $\mathbf{S}^1/\mathbf{Z^2}$ orbifold with a radius R_c such that R_c^{-1} is somewhat smaller than M_P, the Planck length. Two D3-branes called the Planck brane and the TeV brane are located at $\phi = 0,\ \pi$, the orbifold fixed points, and the Standard Model (SM) fields are localised on the TeV brane. With a five-dimensional metric of the form

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

the model provides a novel solution to the hierarchy problem. Here $\mathcal{K}$ is a mass scale related to the curvature. The warp factor acts as a conformal factor for the fields localised on the brane and mass factors get rescaled by this factor. So $M_P = 10^{19}\,\mathrm{GeV}$ 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 $\frac{M_P}{M_{EW}} \sim 10^{15}$ by an exponent of order 30 and solves the hierarchy problem. In order to solve the dynamical problem of stabilising R_c against quantum fluctuations a scalar field in the bulk [6] with a stabilising potential is introduced. Interesting collider phenomenology of the model results due to the prediction of the existence of Kaluza-Klein (KK) excitations of the graviton [7].

Insights gleaned from studying the RS model [8] using the AdS/CFT correspondence [9] have suggested deformations of the original scenario. The AdS/CFT correspondence informs us that the RS model is dual to a 4-d effective theory incorporating gravity and a strongly-coupled sector. The dual theory is conformally invariant from the Planck scale down to the TeV scale and it is the existence of the TeV-brane that breaks conformal symmetry at the infrared scales. The KK excitations as well as the fields localised on the TeV brane are TeV-scale composites. In effect, the original RS theory is dual to a theory of TeV-scale compositeness of the entire SM. Given the unviability of such a scenario in the face of existing experimental information, 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 [10].

In order to veer towards specific model realisations of such a deformation of the RS model, flavour hierarchy, consistency with electroweak precision tests and avoidance of flavour-changing neutral currents can be used as guiding principles [11]. The location of

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[1] More precisely, these authors proposed two models at more or less the same time with different features of quantum gravity in each of these. These are now referred to as the RS1 [4] and RS2 [5] models. In our work, we will describe and work with the RS1 model and refer to it throughout as the RS model.

the fermions in the bulk, or equivalently the shape of the profiles of the SM fermions, is determined by the fact that to get a large Yukawa coupling i.e. overlap with the Higgs one needs to localise the fermion close to the TeV brane. Conversely, the fermions close to the Planck brane will have small Yukawa couplings. The top sector needs special attention, however: the large Yukawa of the top demands proximity to the TeV brane. However, 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 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 invokes a custodial symmetry or other discrete symmetries [12]. 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 [11] though this bound can be relaxed by enforcing additional symmetries. A review of the literature on this subject can be found in ref. [13].

There have been several studies of the phenomenology associated with this scenario presented in the recent literature [14]. In particular, some of these studies have focussed on graviton production in the context of these models [15]. One of the interesting signals for this scenario is 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 $\xi \equiv \sqrt{\log(M_{pl}/\mathrm{TeV})} \sim 5$. 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 [16].

In this paper, we investigate the production of KK gluons at the Tevatron and its decay into top pairs and use the measured top cross-section at the Tevatron to obtain a lower bound on the mass of the KK gluon. Given that the Tevatron reach is limited kinematically, it is not going to probe the range that is probed by precision electroweak tests, FCNCs, or by the LHC. Nevertheless, it is useful to determine what is the *direct, model-independent* bound that existing collider data can provide. To express it differently, even if a specific model avoids the problem of FCNCs through the incorporation of a new symmetry or by a novel choice of profiles of SM particles in the bulk and allows for the gluon KK modes to be much lower in mass, the Tevatron bound will still be applicable.

The cross-section for the production of a KK gluon of mass M_* via quark-antiquark

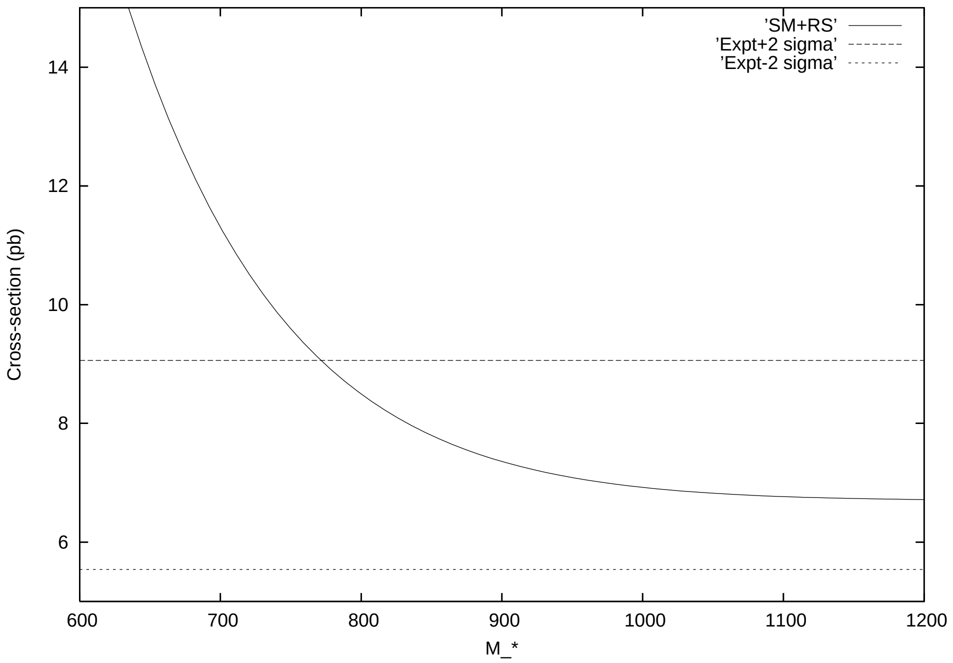

Figure 1: The cross-section for KK gluon production as a function of its mass. The horizontal lines show the 2-sigma allowed band from the CDF experiment.

annihilation is given by

$$\sigma = \frac{4\pi}{9} \frac{\Lambda_q^2}{M_*^2} \int dy \sum_q x_1 q(x_1, M_*^2) x_2 \bar{q}(x_2, M_*^2) + (x_1 \leftrightarrow x_2) \tag{2}$$

Λ_q is the coupling of the KK gluon to light quarks and is equal to $\sqrt{4\pi\alpha_s}/5$. 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% [16].

We use the formula given in eq. 2 to calculate the cross-section for the production of the KK gluon and then fold this cross-section with the branching ratio of the KK gluon into $t\bar{t}$ which is 92.5%. To this we then add the central value of the SM $t\bar{t}$ production cross-section ($\sigma_{\rm SM} = 6.7 \pm 0.8$ pb for a top mass of 175 GeV [17]). In Fig 1, we have plotted the cross-section as a function of the scale M_* for $p\bar{p}$ collisions at the Tevatron energy of $\sqrt{s} = 1.96$ TeV. We have used the CTEQ4M densities [18] and the parton distributions are taken from PDFLIB [19]. For the QCD scale, we use $Q = M_*/2$. For the experimental value of the cross-section we have used the value presented by the CDF collaboration (averaged over all channels) from the Run II of the Tevatron given in ref. [20] which is quoted as $\sigma_{t\bar{t}} = 7.3 \pm 0.5(stat) \pm 0.6(syst) \pm 0.4(lum)$. The central value and the 2σ band of this cross-section (with the errors added in quadrature) are also shown in Fig 1. We see that a bound of about 770 GeV results at the 95% confidence level. For other choices of scale and parton distributions, the cross-section varies by about 25% resulting in about a 20-30 GeV in the value of the bound on M_*.

In conclusion, one of the striking predictions of the bulk RS model is the existence of KK gluons which decay into a $t\bar{t}$ pair. We have computed the production cross-section of these particles at the Tevatron and compared it with the $t\bar{t}$ cross-section measurement from the Run II of the Tevatron. The lower bound on the KK gluon mass is obtained to be about 770 GeV at 95 % C.L. This is the first direct collider bound on the mass of the KK gluon in this model.

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