Published by Institute of Physics Publishing for SISSA

Received: *July 1, 2005*
Revised: *August 16, 2005*
Accepted: *September 28, 2005*
Published: *October 11, 2005*

NLO-QCD corrections to dilepton production in the Randall-Sundrum model

Prakash Mathews,[a] Vajravelu Ravindran[b] and Krishnamoorthy Sridhar[c]

[a] *Theory Group, Saha Institute of Nuclear Physics*
1/AF Bidhan Nagar,Kolkata 700 064, India
[b] *Harish-Chandra Research Institute*
Chhatnag Road, Jhunsi, Allahabad, India
[c] *Department of Theoretical Physics, Tata Institute of Fundamental Research*
Homi Bhabha Road, Mumbai 400 005, India
E-mail: prakash.mathews@saha.ac.in, ravindra@mri.ernet.in, sridhar@theory.tifr.res.in

Abstract: The dilepton production process at hadron colliders in the Randall-Sundrum (RS) model is studied at next-to-leading order in QCD. The NLO-QCD corrections have been computed for the virtual graviton exchange process in the RS model, in addition to the usual γ, Z-mediated processes of standard Drell-Yan. K-factors for the cross-sections at the LHC and Tevatron for differential in the invariant mass, Q, and the rapidity, Y, of the lepton pair are presented. We find the K-factors are large over substantial regions of the phase space.

Keywords: NLO Computations, QCD, Beyond Standard Model, Hadronic Colliders.

© SISSA 2005

JHEP10(2005)031

In brane-world models, the four dimensional universe is a dynamical hypersurface: a D_3-brane (or 3-brane) existing in a higher dimensional spacetime. In many such models, the Standard Model (SM) fields are localized on the brane and only gravity can propagate in the bulk. The scale of quantum gravity can be lowered down from the Planck scale to the TeV scale in these models [1] making it exciting for high-energy physics not only because these suggest fresh perspectives to the solution of the hierarchy problem but also because these models throw open the possibility of the discovery of new physics at energies accessible to collider experiments. In addition, these models provide new frameworks for gauge symmetry and supersymmetry breaking and suggest theoretical approaches to the cosmological constant problem and dark-matter problem.

The simplest model seeking to address the gauge hierarchy problem was the the ADD model proposed by Arkani-Hamed, Dimopoulos and Dvali [2], where, starting from a higher dimensional theory, an effective four-dimensional theory at a scale $M_S \sim$ TeV is obtained. This is done by compactifying the extra dimensions to magnitudes which are large compared to the Planck length [3].

The main problem that one faces within the ADD model is the reappearance of disparate scales *viz.*, the string scale and the inverse of the compactification radius. It was an attempt to avoid this problem that led to the formulation of the Randall-Sundrum (RS) model [4]. In the RS model the single extra dimension ϕ is compactified on a $\mathbf{S}^1/\mathbf{Z}^2$ orbifold with a radius R_c which is somewhat larger than the Planck length. Two 3-branes, the Planck brane and the TeV brane, are located at the orbifold fixed points $\phi = 0,\ \pi$, with the SM fields localised on the TeV brane. The five-dimensional metric, which is *non-factorisable* or *warped* is of the form

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

The exponential warp factor $e^{-\mathcal{K}R_c\phi}$ serves as a conformal factor for fields localised on the brane. Thus the huge ratio $\frac{M_P}{M_{EW}} \sim 10^{15}$ can be generated by the exponent $\mathcal{K}R_c$ which needs to be only of $\mathcal{O}(10)$ thereby providing a way of avoiding the hierarchy problem. There remains the problems of stabilising R_c against quantum fluctuations but this can be done by introducing an extra scalar field in the bulk [5, 6].

The tower of massive Kaluza-Klein (KK) excitations of the graviton, $h_{\mu\nu}^{(\vec{n})}$, interact with the SM particles by:

$$\mathcal{L}_{\text{int}} \sim -\frac{1}{M_P}T^{\mu\nu}(x)h_{\mu\nu}^{(0)}(x) - \frac{e^{\pi\mathcal{K}R_c}}{M_P}\sum_{1}^{\infty}T^{\mu\nu}(x)h_{\mu\nu}^{(n)}(x)\,. \tag{2}$$

$T^{\mu\nu}$ is the symmetric energy-momentum tensor for the particles on the 3-brane. The masses of the $h_{\mu\nu}^{(\vec{n})}$ are given by

$$M_n = x_n\mathcal{K}\,e^{-\pi\mathcal{K}R_c}\,, \tag{3}$$

where the x_n are the zeros of the Bessel function $J_1(x)$. The zero-mode couples weakly and decouples but the couplings of the massive RS gravitons are enhanced by the exponential $e^{\pi\mathcal{K}R_c}$ leading to interactions of electroweak strength. Consequently, except for the overall

JHEP10(2005)031

warp factor in the RS case, the Feynman rules in the RS model are the same as those for the ADD case [7, 8].

The basic parameters of the RS model are

$$m_0 = \mathcal{K} e^{-\pi \mathcal{K} R_c} ,$$
$$c_0 = \frac{\mathcal{K}}{M_P} , \tag{4}$$

where m_0 is a scale of the dimension of mass and sets the scale for the masses of the KK excitations, and c_0 is an effective coupling. The interaction of massive KK gravitons with the SM fields can be written as

$$\mathcal{L}_{\rm int} \sim -\frac{c_0}{m_0} \sum_n^{\infty} T^{\mu\nu}(x) h_{\mu\nu}^{(n)}(x) . \tag{5}$$

Since $\mathcal{K}$ is related to the curvature of the fifth dimension we need to restrict it to small enough values to avoid effects of strong curvature. On the other hand $\mathcal{K}$ should not be too small compared to M_P because that would reintroduce a hierarchy. These considerations suggest $0.01 \leq c_0 \leq 0.1$. For our analysis we choose to work with the RS parameters c_0 and M_1 the first excited mode of the graviton rather then m_0.

The decoupling of the graviton zero-mode and the existence of a mass gap in the spectrum of KK gravitons imply that it is only the resonant production and decay of the heavier KK modes or the virtual effects of the KK modes that one can hope to detect in collider experiments. The phenomenology of resonant production of the KK excitations and the virtual effects have already been studied in processes like dilepton production [9], diphoton production [10], $t\bar{t}$ production at hadron colliders [11], τ-production at a linear collider [12] and pair production of KK modes in e^+e^- and hadron hadron colliders [13]. The sensitivity of the CMS experiment to the resonant production of RS graviton KK modes has been studied for electron pair production [14]. Recently DØ has reported the first direct search for RS graviton KK modes using dielectron, dimuon, and diphoton events [15].

In an earlier work we had presented NLO-QCD corrections for $e^+e^- \rightarrow$ hadrons [16] and dilepton pair production at hadron colliders [17] in the ADD model. These results for the dilepton pair production case are extended to the RS model, in this paper. We note that it is the same virtual graviton exchange process that contributes to dilepton production in both the ADD and RS models. The leading order process being the same, the QCD corrections are also not model-dependent. However, as explained above, the differences between the two models arise because of the difference in the summation over the tower of KK gravitons and also in the overall factors. Consequently, the relative weight of the subprocess cross-section due to graviton exchange vis-a-vis the SM subprocess will be different in the two models. This results in different K-factors in the ADD and RS models and the dependence of the K-factors on the kinematic variables are also different. In this letter, we present the results for dilepton production at the LHC and Tevatron in the RS model. The results presented here are only applicable for the original RS model [4] and not applicable to a wide class of RS models currently being studied.

The process we are interested in is where two hadrons P_1, P_2 scatter and give rise to leptonic final states, say μ^+, μ^-

$$P_1(p_1) + P_2(p_2) \to \mu^+(l_1) + \mu^-(l_2) + X(P_X)\,, \tag{6}$$

where p_1, p_2 are the momenta of incoming hadrons P_1 and P_2 respectively and μ^-, μ^+ are the outgoing leptons which have the momenta l_1, l_2. The final inclusive hadronic state is denoted by X and carries the momentum P_X. The hadronic cross section can be expressed in terms of partonic cross sections convoluted with appropriate parton distribution functions as follows

$$\begin{aligned} 2S\,\frac{d\sigma^{P_1P_2}}{dQ^2}\left(\tau, Q^2\right) &= \sum_{ab=q,\overline{q},g} \int_0^1 dx_1 \int_0^1 dx_2\; f_a^{P_1}(x_1)\; f_b^{P_2}(x_2) \times \\ &\quad \times \int_0^1 dz\, 2\hat{s}\, \frac{d\hat{\sigma}^{ab}}{dQ^2}\left(z, Q^2\right) \delta(\tau - z x_1 x_2)\,. \end{aligned} \tag{7}$$

The scaling variables are defined by $k_1 = x_1 p_1, k_2 = x_2 p_2$ where k_1, k_2 are the momenta of incoming partons.

$$\begin{aligned} (p_1+p_2)^2 \equiv S\,, \qquad & (k_1+k_2)^2 \equiv \hat{s}\,, \qquad & (l_1+l_2)^2 = q.q \equiv Q^2\,, \\ \tau = \frac{Q^2}{S}\,, \qquad & z = \frac{Q^2}{\hat{s}}\,, \qquad & \tau = x_1 x_2 z\,. \end{aligned} \tag{8}$$

The partonic cross section for the process $a(k_1) + b(k_2) \to j(-q) + \sum_i^m X_i(-p_i)$ is given by

$$2\hat{s}\,\frac{d\hat{\sigma}^{ab}}{dQ^2} = \frac{1}{2\pi} \sum_{jj'=\gamma,Z,G} \int dPS_{m+1}\, |M^{ab\to jj'}|^2 \cdot P_j(q) \cdot P_{j'}^*(q) \cdot \mathcal{L}^{jj'\to l^+l^-}(q)\,. \tag{9}$$

In the above equation, the sum over Lorentz indices between matrix element squared and the propagators is implicit through a symbol "dot product". The $m+1$ body phase space is defined as

$$\begin{aligned} \int dPS_{m+1} &= \int \prod_i^m \left(\frac{d^n p_i}{(2\pi)^n} 2\pi\delta^+(p_i^2) \right) \frac{d^n q}{(2\pi)^n} 2\pi\delta^+(q^2 - Q^2) \times \\ &\quad \times (2\pi)^n \delta^{(n)}(k_1 + k_2 + q + \sum_i^m p_i)\,, \end{aligned} \tag{10}$$

where n is the space-time dimension. The propagators are

$$P_\gamma(q) = -\frac{i}{Q^2} g_{\mu\nu}\,, \tag{11}$$

$$P_Z(q) = -\frac{i}{(Q^2 - M_Z^2 - iM_Z\Gamma_Z)} g_{\mu\nu}\,, \tag{12}$$

$$P_G(q) = \mathcal{D}(Q^2) B_{\mu\nu\lambda\rho}(q)\,, \tag{13}$$

JHEP10(2005)031

where

$$B_{\mu\nu\rho\sigma}(q) = \left(g_{\mu\rho} - \frac{q_\mu q_\rho}{{M_n}^2}\right)\left(g_{\nu\sigma} - \frac{q_\nu q_\sigma}{{M_n}^2}\right) + \left(g_{\mu\sigma} - \frac{q_\mu q_\sigma}{{M_n}^2}\right)\left(g_{\nu\rho} - \frac{q_\nu q_\rho}{{M_n}^2}\right) - \\ -\frac{2}{n-1}\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{{M_n}^2}\right)\left(g_{\rho\sigma} - \frac{q_\rho q_\sigma}{{M_n}^2}\right). \tag{14}$$

The function $\mathcal{D}(Q^2)$ in the graviton propagator eq. (13), results from summing over the KK modes, given by

$$\mathcal{D}(Q^2) = \sum_{n=1}^{\infty} \frac{1}{Q^2 - M_n^2 + iM_n\Gamma_n} \equiv \frac{\lambda}{m_0^2}, \tag{15}$$

where M_n are the masses of the individual resonances and the Γ_n are the corresponding widths. The graviton widths are obtained by calculating their decays into final states involving SM particles. λ is defined as

$$\lambda(x_s) = \sum_{n=1}^{\infty} \frac{x_s^2 - x_n^2 - i\frac{\Gamma_n}{m_0}x_n}{x_s^2 - x_n^2 + \frac{\Gamma_n}{m_0}x_n}, \tag{16}$$

where $x_s = Q/m_0$. We have to sum over all the resonances to get the value of $\lambda(x_s)$. This is done numerically and for a given value of x_s, we retain all resonances which contribute with a significance greater than one per mil, and treat the remaining KK modes as virtual particles (in which case the sum can be done analytically).

The leptonic tensor is computed using the square of the matrix element for the process $\gamma/Z/G \to \mu^+ + \mu^-$ and the 2-body phase space integral

$$\mathcal{L}^{jj'\to\mu^+\mu^-}(q) = \int \prod_{i=1}^{2}\left(\frac{d^n l_i}{(2\pi)^n} 2\pi\delta^+(l_i^2)\right)(2\pi)^n \delta^{(n)}(q - l_1 - l_2)|M^{jj'\to\mu^+\mu^-}|^2. \tag{17}$$

Hence, we obtain

$$2S\frac{d\sigma^{P_1P_2}}{dQ^2}(\tau, Q^2) = \frac{1}{2\pi}\sum_{jj'=\gamma,Z,G} \tilde{P}_j(Q^2)\ \tilde{P}^*_{j'}(Q^2)\ L_{jj'}(Q^2)\ W^{P_1P_2}_{jj'}(\tau, Q^2). \tag{18}$$

The hadronic structure function is equal to

$$W^{P_1P_2}_{jj'}(\tau, Q^2) = \sum_{ab,jj'} \int dx_1 \int dx_2\, f_a^{P_1}(x_1)\, f_b^{P_2}(x_2) \times \\ \times \int dz\, \delta(\tau - zx_1x_2) \int dPS_{m+1}|M^{ab\to jj'}|^2\ T_{jj'}(q), \tag{19}$$

with

$$T_{jj'} = \eta_{\mu\nu}(q), \qquad jj' = \gamma\gamma, \gamma Z, ZZ, \\ T_{GG} = B_{\mu\nu\rho\sigma}(q). \tag{20}$$

JHEP10(2005)031

The Q^2 distribution of the di-lepton pairs is computed by substituting the matrix element squared $|M^{ab\to jj'}|^2\, T_{jj'}(q)$ in eq. (19) and performing the integrations over dPS_{m+1} and dz in a convenient frame.

We define the bare partonic coefficient function $\bar{\Delta}_{ab}^{jj'}(z,Q^2)$ as

$$\bar{\Delta}_{ab}^{jj'}(z,Q^2) = C_{jj'} \int dPS_{m+1} |M^{ab\to jj'}|^2 \; T_{jj'}(q)\,, \tag{21}$$

where

$$\begin{aligned} C_{jj'} &= \frac{1}{e^2} \qquad && jj' = \gamma\gamma, ZZ, \gamma Z\,, \\ &= \frac{1}{Q^2\kappa^2} \qquad && jj' = GG\,. \end{aligned} \tag{22}$$

There are two types of processes that contribute to the partonic cross section. The first one has only a virtual photon or a Z boson whereas the second one only contains a graviton in the intermediate state. The interference between first and second type diagrams identically vanish when the phase space integration is performed.

At LO the following processes contribute when a photon or Z-boson appears in the intermediate state

$$q + \bar{q} \to \gamma^*/Z^*\,. \tag{23}$$

In the case the Graviton appears in the intermediate state, we have two processes at LO

$$q + \bar{q} \to G^*\,, \qquad g + g \to G^*\,. \tag{24}$$

In NLO for the photon or Z-boson we have the following $2 \to 2$ reactions

$$\begin{aligned} &q + \bar{q} \to \gamma^*/Z^* + q\,, \qquad && q + \bar{q} \to \gamma^*/Z^* + \text{one loop}\,, \\ &q + g \to \gamma^*/Z^* + q\,, \qquad && \bar{q} + g \to \gamma^*/Z^* + \bar{q}\,, \end{aligned} \tag{25}$$

and for the graviton we have

$$\begin{aligned} &q + \bar{q} \to G^* + q\,, \qquad && q + \bar{q} \to G^* + \text{one loop}\,, \\ &q + g \to G^* + q\,, \qquad && \bar{q} + g \to G^* + \bar{q}\,, \\ &g + g \to G^* + g\,, \qquad && g + g \to G^* + \text{one loop}\,. \end{aligned} \tag{26}$$

At next to leading order level, one encounters the computation of one loop virtual gluon corrections and real gluon bremsstrahlung contributions to leading order processes. We also include processes with a gluon in the initial state. Since we are dealing with energy momentum tensor coupled to gravity expressed in terms of renormalised fields and masses, there is no overall ultraviolet renormalisation required. But soft and collinear divergences appear in our computation. We have used n-dimensional regularisation to regulate both these divergences. We have defined $n = 4 + \varepsilon$ where n is the space-time dimension. The soft divergences coming from virtual gluons and bremsstrahlung contributions cancel exactly according to the Bloch-Nordsieck theorem. The remaining collinear divergences

JHEP10(2005)031

are removed by mass factorisation in $\overline{MS}$ scheme. This is achieved by redefining the bare parton densities as

$$f_a^P(z) = \sum_b \Gamma_{ab}^{-1}(z, \mu_F^2) \otimes f_b^P(z, \mu_F^2)\,, \tag{27}$$

The factorisation scale is given by μ_F and $\otimes$ is the convolution symbol defined as

$$f(z) \otimes g(z) = \int_z^1 \frac{dy}{y} f(y)\, g\left(\frac{z}{y}\right), \tag{28}$$

and the kernel $\Gamma_{cd}(z)$ in the $\overline{MS}$ scheme is given by

$$\begin{aligned}
\Gamma_{cd}(z, \mu_F) &= \delta_{cd}\delta(1-z) + a_s \frac{1}{\varepsilon} \Gamma_{cd}^{(1)}(z, \mu_F) \\
&= \delta_{cd}\delta(1-z) + a_s \frac{1}{\varepsilon} \left(\frac{\mu_F^2}{\mu^2}\right)^{\varepsilon/2} P_{cd}^{(0)}(z)\,,
\end{aligned} \tag{29}$$

where $P_{cd}^{(0)}(z)$ are the leading order Altarelli-Parisi splitting functions.

The Drell-Yan coefficient function after mass factorisation, denoted by $\Delta_{ab}^i(z, Q^2, \mu_F^2)$, are found to be

$$\bar{\Delta}_{ab}^i\left(z, Q^2, \frac{1}{\varepsilon}\right) = \sum_{c,d} \Gamma_{ca}\left(z, \mu_F^2, \frac{1}{\varepsilon}\right) \otimes \Gamma_{db}\left(z, \mu_F^2, \frac{1}{\varepsilon}\right) \otimes \Delta_{cd}^i(z, Q^2, \mu_F^2)\,, \tag{30}$$

where $\bar{\Delta}_{ab}^i(z, Q^2, 1/\varepsilon)$ is the bare partonic coefficient function before mass factorisation is carried out.

Next, to compute the rapidity distribution of the di-lepton pair, we define the rapidity Y as

$$Y = \frac{1}{2} \log\left(\frac{p_2 \cdot q}{p_1 \cdot q}\right). \tag{31}$$

In the CM frame of the hadron (CMH), this is nothing but

$$Y = \frac{1}{2} \log\left(\frac{q_{CMH}^0 - q_{CMH}^3}{q_{CMH}^0 + q_{CMH}^3}\right). \tag{32}$$

We compute the distribution in Y by introducing the identity

$$\int dY\, \delta\left(Y - \frac{1}{2}\log\left(\frac{p_2 \cdot q}{p_1 \cdot q}\right)\right) = 1\,, \tag{33}$$

in eq. (7) and bringing the measure dY to the left. Hence we find

$$2S \frac{d\sigma^{P_1 P_2}}{dQ^2 dY}(\tau, Y, Q^2) = \frac{1}{2\pi} \sum_{jj'=\gamma,Z,G} \tilde{P}_j(Q^2)\, \tilde{P}_{j'}^*(Q^2)\, L_{jj'}(Q^2)\, \frac{dW_{jj'}^{P_1 P_2}}{dY}(\tau, Y, Q^2)\,. \tag{34}$$

JHEP10(2005)031

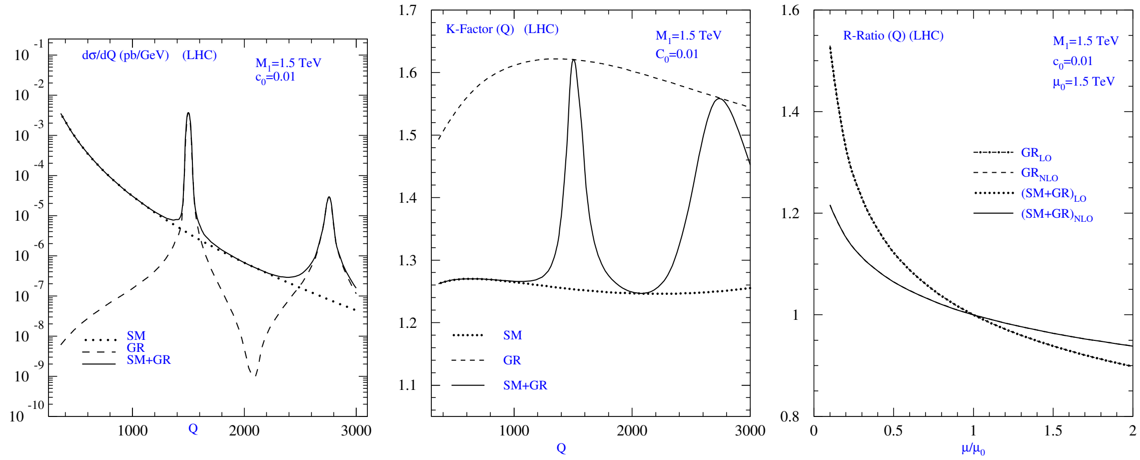

Figure 1: (a) The cross section is plotted as a function of invariant mass Q of the lepton pair for $M_1 = 1.5\,\text{TeV}$ at LHC. (b) The corresponding K-factor for Q distribution SM, gravity and SM plus gravity. (c) Scale variation of the cross section at LO and NLO as defined in eq. (38) for $Q = 1.5\,\text{TeV}$.

The hadronic structure function equals

$$\frac{dW^{P_1P_2}_{jj'}}{dY}(\tau, Y, Q^2) = \sum_{ab,jj'} \int dx_1 \int dx_2\, f^{P_1}_a(x_1)\, f^{P_2}_b(x_2) \times$$
$$\times \int dz \int dPS_{m+1} |M^{ab\to jj'}|^2\, T_{jj'}(q)\, \delta(\tau - zx_1x_2) \times$$
$$\times \delta\left(Y - \frac{1}{2}\log\left(\frac{p_2\cdot q}{p_1\cdot q}\right)\right). \tag{35}$$

We can perform z and phase space integration using the above two delta functions in a convenient frame. The soft divergences cancel between virtual and real diagrams. The remaining collinear divergences are removed by mass factorisation following the similar procedure that we followed for Q^2 distribution.

We now present the distributions in the invariant lepton pair mass, Q, and the rapidity of the lepton pair, Y at the LHC ($\sqrt{S} = 14$ TeV) and Tevatron ($\sqrt{S} = 1.96\,\text{TeV}$). From these distributions the effects of the NLO-QCD corrections can be clearly discerned. For the parton density sets we adopt in leading order (LO) MRST 2001 LO ($\Lambda = 0.1670$ GeV) and in next-to-leading order the MRST 2001 NLO ($\Lambda = 0.2390\,\text{GeV}$). For LHC we choose the kinematic ranges 300 GeV $< Q <$ 3000 GeV and $|Y| < 2.2$ at $Q = 1.5\,\text{TeV}$. For Tevatron 300 GeV $< Q <$ 1000 GeV and $|Y| < 0.9$ at $Q = 300\,\text{GeV}$. The renormalisation scale is taken to be same as the factorization scale μ_F and μ_F si chosen to be $\mu_F = Q$.

The cross-section $d\sigma/dQ$ as a function of Q to NLO is presented in figure 1a for LHC. For the figure, we have chosen the representative values of the RS model parameters: $M_1 = 1.5\,\text{TeV}$ the first RS resonance mass and the coupling constant $c_0 = 0.01$. The width of the resonance is related to c_0 and hence a smaller c_0 corresponds to a narrow resonance.

JHEP10(2005)031

The subsequent resonance are determined by m_0 and x_n. To LO the dilepton case has been presented in [9]. To see the effect of the NLO effect we study the K-factor for the Q and Y distribution.

The K-factor for the invariant lepton pair mass distribution defined by

$$K^I = \left[\frac{d\sigma^I_{LO}(Q)}{dQ}\right]^{-1} \left[\frac{d\sigma^I_{NLO}(Q)}{dQ}\right], \tag{36}$$

where $I = SM$, $I = SM + GR$ for both SM and gravity combined and $I = GR$ for only gravity. It is possible to define K^{GR} for the invariant lepton pair mass distribution, as there is no interference with SM [17]. The results are presented in figure 1b. The parameters chosen are the same as in figure 1a. In order to understand the behaviour of K-factor of the model involving both SM and gravity, it is useful to express it as

$$K^{(SM+GR)}(Q) = \frac{K^{SM} + K^{GR}K^{(0)}}{1 + K^{(0)}}, \tag{37}$$

where we have introduced a quantity $K^{(0)}$, defined as the ratio of the LO distribution of gravity to SM, given by

$$K^{(0)}(Q) = \left[\frac{d\sigma^{SM}_{LO}(Q)}{dQ}\right]^{-1} \left[\frac{d\sigma^{GR}_{LO}(Q)}{dQ}\right]. \tag{38}$$

The behaviour of $K^{(0)}(Q)$ is governed by competing couplings constants of SM and gravity and the parton fluxes. In the RS case the gravity contribution is significant in the resonance region, (see figure 1a). In the off resonance region the K-factor is hence purely K^{SM}. In the resonance region where the gravity effect dominates the $K^{(SM+GR)}$ factor shifts to the K^{GR} value (see figure 1b). This behaviour of the K-factor of the RS case is very distinct from the corresponding case we presented in the ADD case [17]. To incorporate the NLO effects for an appropriate distribution one needs to take into account the behaviour of the K-factor accordingly. For $M_1 = 300\,\mathrm{GeV}$ the K-factor is about 1.5 in the resonance region. This is due to the fact that at loq Q ($Q = 300$ GeV) the gluon flux becomes dominant at Tevatron. The behaviour of K^{GR} is the same as in the ADD case [17].

In figure 1c, we have plotted the scale variations of the Q distribution for both LO and NLO cross sections. We define R^I for the invariant lepton mass distribution as

$$R^I_{LO} = \left[\frac{d\sigma^I_{LO}(Q, \mu = \mu_0)}{dQ}\right]^{-1} \left[\frac{d\sigma^I_{LO}(Q, \mu)}{dQ}\right],$$

$$R^I_{NLO} = \left[\frac{d\sigma^I_{NLO}(Q, \mu = \mu_0)}{dQ}\right]^{-1} \left[\frac{d\sigma^I_{NLO}(Q, \mu)}{dQ}\right], \tag{39}$$

where μ_0 is a fixed scale which is chosen to be $\mu_0 = 1.5\,\mathrm{TeV}$ for LHC. As can be seen from the figure, the inclusion of the NLO corrections stabilises the cross-section with respect to the scale μ. Here we have chosen $\mu_0 = 1.5\,\mathrm{TeV}$, ie. the first resonance region. The scale variation is driven by the gravity part as its the dominant contribution.

JHEP10(2005)031

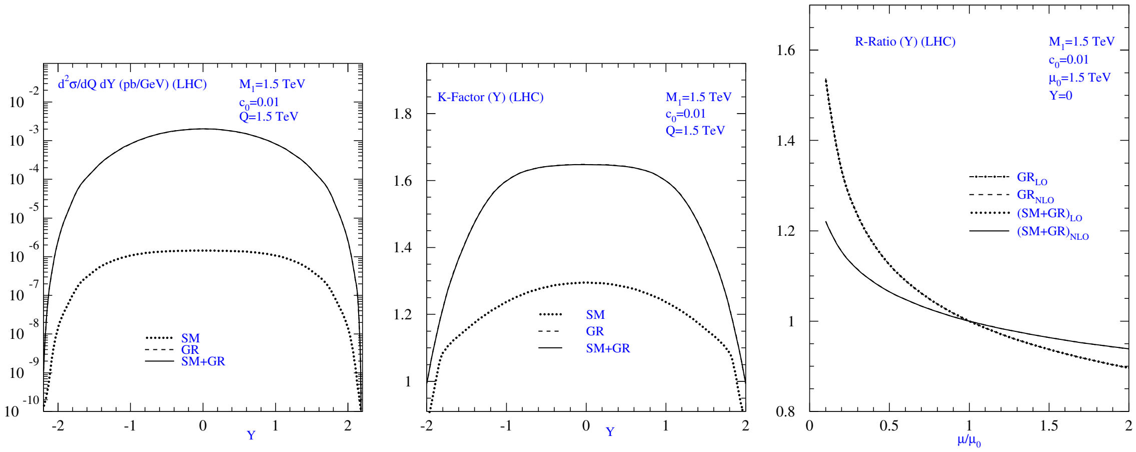

Figure 2: (a) The double differential cross section $d^2\sigma/dQdY$ is plotted as a function of rapidity Y for $Q = 1.5\,\text{TeV}$ at LHC. (b) The K-factor for the distribution in (a) is plotted for the rapidity range. (c) The scale variation of the ratio R is plotted as a function of μ/μ_0 for $Y = 0$.

In figure 2a the double differential cross section $d^2\sigma/dQdY$ is displayed for rapidity region $|Y| \leq 2.2$ for a Q value of 1.5 TeV. To plot this distribution the Q value is chosen such that it lies at the first resonance, where the gravity effect dominates. Hence the dominant contribution is purely gravity. The RS model parameters remain the same as before. The K factor as a function of Y is plotted for a choice of Q in the resonance region where the dominant contribution to $K^{(SM+GR)}$ factor comes from the gravity part figure 2b. The R ratio using the Y distribution is plotted in figure 2c for the central region of rapidity and for a Q value of 1.5 TeV. In this region the scale variation is also dictated by the gravity contribution.

The corresponding analysis for the Tevatron is done for the Q range $300 < Q < 1000\,\text{GeV}$ and for the RS parameter $M_1 = 300\,\text{GeV}$ and the coupling $c_0 = 0.01$. At low Q the gravity effects of the RS model is dominant in the resonance and off the resonance region the effect is negligible. As Q increases the effect of gravity starts to become comparable to the SM contribution as is seen towards the third resonance in figure 3a. In figure 3b we have plotted the K-factor for Q distribution at the Tevatron. Using eq. (37) we can understand the behaviour of K^{SM+GR}. As expected the behaviour of K^{GR} is same as the ADD case [17]. The double differential cross section $d^2\sigma/dQdY$ for $Q = 300\,\text{GeV}$ is plotted as a function of rapidity Y. In the resonance region the dominant contribution is from the RS. In contrast for ADD [17] only at large Q the gravity effects became comparable to the SM at Tevatron. The corresponding K-factor is plotted in figure 4b. Scale variation for the Q and double differential $dQdY$ is given in figure 3c and figure 4c respectively.

In a recent analysis by DØ [15], the LO cross section was scaled by a constant K-factor of 1.34 to account for the NLO effect for the RS case. This does not yield a realistic picture as can be seen from figure 3b. In the RS case due to the resonant production, the K-factor is very different from the ADD case reported earlier [17].

In summary, we have presented the results for the cross-section for dilepton production in the Randall-Sundrum model at the LHC and Tevatron. The large incident gluon flux

JHEP10(2005)031

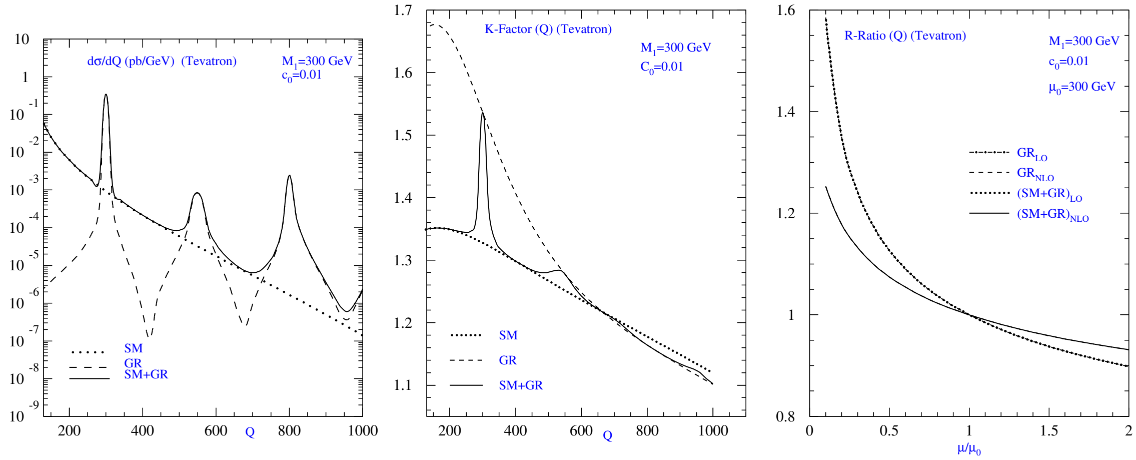

Figure 3: (a) The cross section is plotted as a function of invariant mass Q of the lepton pair for $M_1 = 300\,\text{GeV}$ and $c_0 = 0.01$ at the Tevatron. (b) The K-factor for Q distribution for the same RS parameters in (a) is plotted. (c) The variation of the cross section with respect to the scale.

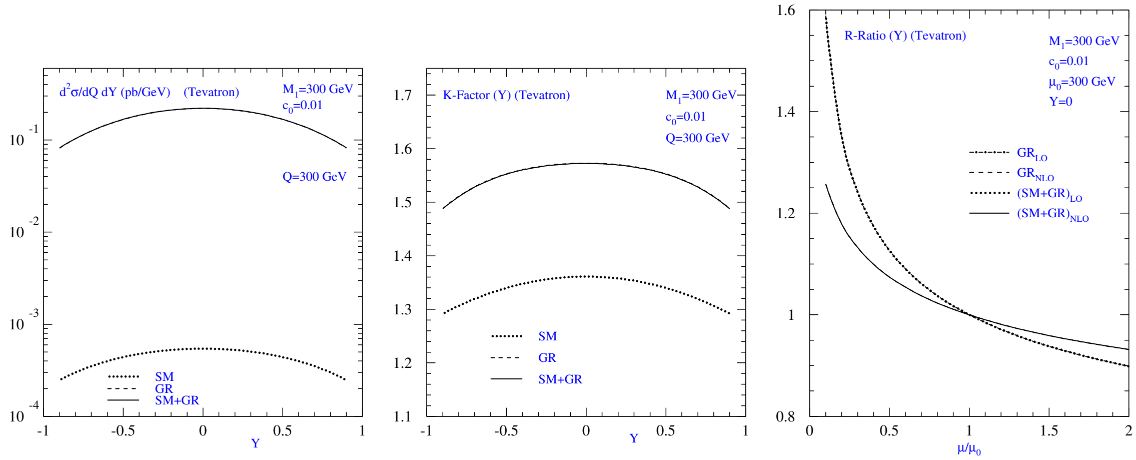

Figure 4: (a) The double differential cross section $d^2\sigma/dQdY$ is plotted as a function of rapidity Y for $Q = 300\,\text{GeV}$ at the Tevatron for the RS parameters $M_1 = 300\,\text{GeV}$ and $c_0 = 0.01$. (b) The K-factor for the distribution in (a) is plotted for the rapidity range. (c) The scale variation of the ratio R is plotted as a function of μ/μ_0 for the central rapidity region $Y = 0$.

at the LHC makes the NLO QCD corrections very important. Moreover, when the NLO corrections are taken into account the cross-sections are stabilised with respect to scale variations. In order to derive robust bounds on the RS model at the LHC using the dilepton production process, the inclusion of the NLO QCD corrections in the cross-section is crucial.

Acknowledgments

PM thanks S. Moretti for useful discussion. VR would like to thank Prof. W. L. van Neerven for discussion. The work of PM and KS is part of a project (IFCPAR Project No. 2904-2)

JHEP10(2005)031

on 'Brane-World Phenomenology' supported by the Indo-French Centre for the Promotion of Advanced Research, New Delhi, India. PM would also like to thank IPPP, Durham for warm hospitality where part of this work was done. PM and VR thank S. Raychaudhuri for providing the code that evaluates the RS KK mode sum in the propagator.

References

[1] P. Hořava and E. Witten, *Heterotic and type-I string dynamics from eleven dimensions*, *Nucl. Phys.* **B 460** (1996) 506 [hep-th/9510209];
J.D. Lykken, *Weak scale superstrings*, *Phys. Rev.* **D 54** (1996) 3693 [hep-th/9603133];
E. Witten, *Strong coupling expansion of Calabi-Yau compactification*, *Nucl. Phys.* **B 471** (1996) 135 [hep-th/9602070].

[2] N. Arkani-Hamed, S. Dimopoulos and G. Dvali, *The hierarchy problem and new dimensions at a millimeter*, *Phys. Lett.* **B 429** (1998) 263 [hep-ph/9803315];
I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G.R. Dvali, *New dimensions at a millimeter to a Fermi and superstrings at a TeV*, *Phys. Lett.* **B 436** (1998) 257 [hep-ph/9804398].

[3] For a review of the ADD model, see I. Antoniadis and K. Benakli, *Large dimensions and string physics in future colliders*, *Int. J. Mod. Phys.* **A 15** (2000) 4237 [hep-ph/0007226];
A. Perez-Lorenzana, *Theories in more than four dimensions*, *AIP Conf. Proc.* **562** (2001) 53–85 [hep-ph/0008333];
K. Sridhar, *Large extra dimensions at linear colliders*, *Int. J. Mod. Phys.* **A 15** (2000) 2397 [hep-ph/0004053].

[4] L. Randall and R. Sundrum, *A large mass hierarchy from a small extra dimension*, *Phys. Rev. Lett.* **83** (1999) 3370 [hep-ph/9905221].

[5] W.D. Goldberger and M.B. Wise, *Modulus stabilization with bulk fields*, *Phys. Rev. Lett.* **83** (1999) 4922 [hep-ph/9907447]; *Phenomenology of a stabilized modulus*, *Phys. Lett.* **B 475** (2000) 275 [hep-ph/9911457].

[6] C. Csáki, M. Graesser, L. Randall and J. Terning, *Cosmology of brane models with radion stabilization*, *Phys. Rev.* **D 62** (2000) 045015 [hep-ph/9911406];
C. Csáki, M.L. Graesser and G.D. Kribs, *Radion dynamics and electroweak physics*, *Phys. Rev.* **D 63** (2001) 065002 [hep-th/0008151].

[7] G.F. Giudice, R. Rattazzi and J.D. Wells, *Quantum gravity and extra dimensions at high-energy colliders*, *Nucl. Phys.* **B 544** (1999) 3 [hep-ph/9811291].

[8] T. Han, J.D. Lykken and R.-J. Zhang, *On Kaluza-Klein states from large extra dimensions*, *Phys. Rev.* **D 59** (1999) 105006 [hep-ph/9811350].

[9] H. Davoudiasl, J.L. Hewett and T.G. Rizzo, *Phenomenology of the randall-sundrum gauge hierarchy model*, *Phys. Rev. Lett.* **84** (2000) 2080 [hep-ph/9909255]; *Experimental probes of localized gravity: on and off the wall*, *Phys. Rev.* **D 63** (2001) 075004 [hep-ph/0006041].

[10] K. Sridhar, *Constraining the Randall-Sundrum model using diphoton production at hadron colliders*, *JHEP* **05** (2001) 066 [hep-ph/0103055].

[11] S. Lola, P. Mathews, S. Raychaudhuri and K. Sridhar, *Extra dimensions: a view from the top*, hep-ph/0010010.

JHEP10(2005)031

[12] N. Mahajan, *τ polarization and Randall-Sundrum scenario at e^+e^- colliders*, *J. Phys.* **G 29** (2003) 2677 [hep-ph/0207065].

[13] P. Jain and S. Panda, *Two graviton production at e^+e^- and hadron hadron colliders in the Randall-Sundrum model*, *JHEP* **03** (2004) 011 [hep-ph/0401222].

[14] C. Collard and M.-C. Lemaire, *Search with the CMS detector for Randall-Sundrum excitations of gravitons decaying into electron pairs*, CMS NOTE 2004/024.

[15] D0 collaboration, V.M. Abazov, *Search for Randall-Sundrum gravitons in dilepton and diphoton final states*, *Phys. Rev. Lett.* **95** (2005) [hep-ex/0505018].

[16] P. Mathews, V. Ravindran and K. Sridhar, *NLO-QCD corrections to $e^+e^- \to$ hadrons in models of TeV- scale gravity*, *JHEP* **08** (2004) 048 [hep-ph/0405292].

[17] P. Mathews, V. Ravindran, K. Sridhar and W.L. van Neerven, *Next-to-leading order QCD corrections to the Drell-Yan cross section in models of TeV-scale gravity*, *Nucl. Phys.* **B 713** (2005) 333 [hep-ph/0411018].

JHEP10(2005)031