RS model with a small curvature and Drell-Yan process at the LHC

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Abstract

The $p_{\perp}$-distribution for a dilepton production at the LHC with high luminosity is calculated in the Randall-Sundrum scenario with a small curvature $\kappa$. The widths of massive gravitons are taken into account. The discovery limits on 5-dimensional gravity scale $M_5$ are obtained to be 17.8 TeV and 21.6 TeV for $\sqrt{s} = 14$ TeV and integrated luminosities $1000 \text{ fb}^{-1}$ and $3000 \text{ fb}^{-1}$, respectively. Contrary to the standard RS model, these limits do not depend on parameter $\kappa$.

1 Introduction

The Randall-Sundrum (RS) model [1] is a theory with one extra dimension (ED) in a slice of the AdS$_5$ space-time. In the present paper we will study the RS scenario with the 5-dimensional Planck scale $M_5$ in the TeV region and small curvature [2, 3] (see also Refs. [4]):

$$\kappa \ll \bar{M}_5.$$ (1)

It has the following background warped metric:

$$ds^2 = e^{2\kappa (\pi r_c - |y|)} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2,$$ (2)

where $y = r_c \theta (-\pi \leq \theta \leq \pi)$, $r_c$ being the “radius” of the ED, and $\eta_{\mu\nu}$ is the Minkowski metric. The points $(x_\mu, y)$ and $(x_\mu, -y)$ are identified, so one gets

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the orbifold $S^1/Z_2$. The parameter $\kappa$ defines a 5-dimensional scalar curvature of the AdS$_5$ space. In what follows, we will call it “curvature”.

We consider RS scheme with two 3D branes located in 5-th dimension at the points $y = \pi r_c$ (TeV brane) and $y = 0$ (Planck brane). If $\kappa > 0$, the tension on the TeV brane is negative, whereas the tension on the Planck brane is positive. The SM fields are constrained to the TeV brane, while the gravity propagates in all spatial dimensions.

It is necessary to note that metric (2) is chosen in such a way that 4-dimensional coordinates $x^\mu$ are Galilean on the TeV brane where all the SM fields live, since the warp factor is equal to unity at $y = \pi r_c$.

By integrating 5-dimensional action in variable $y$, one gets an effective 4-dimensional action which, in its turn, leads to the so-called “hierarchy relation” between the 5-dimensional reduced Planck mass $\bar{M}_{\text{Pl}}$ and 5-dimensional reduced gravity scale $\bar{M}_5$:

$$\bar{M}_{\text{Pl}}^2 = \frac{\bar{M}_5^3}{\kappa} (e^{2 \pi \kappa r_c} - 1) .$$  \hspace{1cm} (3)

Let us notice that $\bar{M}_5$ and 5-dimensional gravity scale $M_5$ are related as follows:

$$M_5 = (2\pi)^{1/3} \bar{M}_5 \simeq 1.84 \bar{M}_5 .$$  \hspace{1cm} (4)

In order the hierarchy relation (3) to be satisfied, it is enough to take $r_c \kappa \simeq 8 \div 9.5$ that corresponds to $r_c \simeq 0.15 \div 1.8$ fm. Thus, no large scales (of the order of the Planck mass) are introduced.

From the point of view of a 4-dimensional observer located on the TeV brane, in addition to the massless graviton, there exists an infinite number of its Kaluza-Klein (KK) excitations, $G^{(n)}_{\mu\nu}$, with the masses

$$m_n = x_n \kappa, \quad n = 1, 2, \ldots ,$$  \hspace{1cm} (5)

where $x_n$ are zeros of the Bessel function $J_1(x)$. Note that $x_n \simeq \pi(n + 1/4)$ at large $n$.

The interaction of the KK gravitons with the the SM fields on the TeV brane is described by the Lagrangian:

$$\mathcal{L}_{\text{int}} = -\frac{1}{\bar{M}_{\text{Pl}}} T^{\mu\nu} G^{(0)}_{\mu\nu} - \frac{1}{\Lambda_\pi} T^{\mu\nu} \sum_{n=1}^\infty G^{(n)}_{\mu\nu} .$$  \hspace{1cm} (6)
Here $T^{\mu\nu}$ is the energy-momentum tensor of the matter, and $n$ is the KK-number. The parameter

$$\Lambda_\pi = \bar{M}_5 \left( \frac{\bar{M}_5}{\kappa} \right)^{1/2}$$

(7)

is the physical scale on the TeV brane.

In a number of papers, the graviton contribution in the Drell-Yan process was studied in the standard RS model [1], in which $\kappa \sim \bar{M}_5 \sim M_{Pl}$ (see, for instance, [5]). In such a scheme, an experimental signature is a real or virtual production of massive KK graviton resonances. The bounds on the fundamental gravity scale and/or mass of the lightest resonance were obtained both at the Tevatron [6] and recently at the LHC [7]. Note that all these bounds significantly depend on a value of another parameter of the model $\kappa = 0.01 \div 0.1$.

The RS model with the small curvature has been checked by the DELPHI Collaboration [8] by studying photon energy spectrum in the process $e^+ e^- \rightarrow \gamma + \text{missing energy}$. The following bound was obtained:

$$\bar{M}_5 > 0.92 \text{ TeV}.$$ (8)

There are several reasons to consider RS scenario with the small curvature:

- There exists a serious shortcoming of the standard scenario with the curvature and fundamental gravity scale being of the order of the Planck mass, $\kappa \sim \bar{M}_5 \sim M_{Pl}$ [9].

- The spectrum of the KK gravitons (5) is very similar to that in the model with one ED [10]. Note that matrix elements for the scattering of the SM fields can be formally obtained from corresponding matrix elements calculated in the model with one flat dimension by using the following replacement [3]:

$$\bar{M}_{4+1} \rightarrow (2\pi)^{-1/3} \bar{M}_5, \quad R_c \rightarrow (\pi \kappa)^{-1}.$$ (9)

Here $\bar{M}_{4+1}$ is a 5-dimensional reduced Planck scale, $R_c$ being the radius of the extra flat dimension. As a result, all cross sections appear to be rather large (as in the ADD model with 4 + 1 dimensions).

- At the same time, astrophysical restrictions are not applied to the RS-like model with the small curvature, contrary to the ADD model with one or two EDs [3].
2 \textbf{KK graviton contribution to dilepton production}

Let us consider the dilepton production\cite{11,12} with high transverse momenta,

\[ p p \rightarrow l^+ l^- + X , \tag{10} \]

where \( l = e \) or \( \mu \).

The differential cross section of this process is equal to

\[
\frac{d\sigma}{dp_{\perp}}(pp \rightarrow l^+ l^- + X) = 2p_{\perp} \sum_{a,b=q,g} \int d\tau \frac{\sqrt{\tau}}{\sqrt{\tau - x_{\perp}^2}} \int \frac{dx_a}{x_a} f_{a/p}(\mu^2, x_a) \times f_{b/p}(\mu^2, \tau/x_a) \frac{d\hat{\sigma}}{dt}(ab \rightarrow l^+ l^-) , \tag{11} \]

where \( p_{\perp} \) is the transverse momenta of the leading lepton, and \( x_{\perp} = 2p_{\perp}/\sqrt{s} \).

The contribution of the virtual gravitons to the process (10) comes from the quark-antiquark annihilation, \( q \bar{q} \rightarrow G^{(n)} \rightarrow l^+ l^- \), and gluon-gluon fusion, \( gg \rightarrow G^{(n)} \rightarrow l^+ l^- \). The corresponding partonic cross sections are\cite{2}:

\[
\frac{d\hat{\sigma}}{dt}(q\bar{q} \rightarrow l^+ l^-) = \frac{\hat{s}^4 + 10\hat{s}^3 \hat{t} + 42\hat{s}^2 \hat{t}^2 + 64\hat{s}^3 + 32\hat{t}^4}{1536\pi \hat{s}^2} |S(\hat{s})|^2 , \tag{12} \]
\[
\frac{d\hat{\sigma}}{dt}(gg \rightarrow l^+ l^-) = -\frac{\hat{t}(\hat{s} + \hat{t})(\hat{s}^2 + 2\hat{s} \hat{t} + 2\hat{t}^2)}{256\pi \hat{s}^2} |S(\hat{s})|^2 , \tag{13} \]

where

\[
S(\hat{s}) = \frac{1}{\Lambda_{\pi}^2} \sum_{n=1}^{\infty} \frac{1}{\hat{s} - m_n^2 + i m_n \Gamma_n} . \tag{14} \]

Here \( \Gamma_n \) denotes a total width of the graviton with the KK number \( n \) and mass \( m_n \):

\[
\Gamma_n = \eta m_n \left( \frac{m_n}{\Lambda_{\pi}} \right)^2 , \tag{15} \]

with \( \eta \simeq 0.09 \)\cite{3}.

In the RS scenario with the small curvature, sum (14) was calculated analytically in Ref.\cite{3}:

\[
S(\hat{s}) = -\frac{1}{4M_{\delta}^3 \sqrt{\hat{s}}} \frac{\sin 2A + i \sinh 2\varepsilon}{\cos^2 A + \sinh^2 \varepsilon} , \tag{16} \]

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where

\[ A = \frac{\sqrt{s}}{\kappa}, \quad \varepsilon = \frac{\eta}{2} \left( \frac{\sqrt{s}}{M_5} \right)^3. \]  

(17)

In order to obtain search limits for the LHC, we have calculated contributions of \( s \)-channel gravitons to \( p_\perp \)-distributions of the final leptons for different values of \( \bar{M}_5 \) (see Fig. 1). We used the MSTW 2008 NNLO parton distributions [13], and convolute them with the partonic cross sections (12), (13) in Eq. (11). The PDF scale was taken to be equal to the invariant mass of the final leptons, \( \mu = \sqrt{s} \). The following limit on pseudorapidity of the final leptons was imposed:

\[ |\eta| \leq 2.5. \]  

(18)

It defines a region of integration in variables \( x_a, \tau \) in (11). The reconstruction efficiency of 90% was assumed for both electrons and muons [14].

![Figure 1: The KK graviton contribution to the Drell-Yan process for several values of 5-dimensional reduced Planck scale (solid curves) vs. SM contribution (dashed curve) at the LHC.](image)

Let us stress that in our scheme the “new physics” contribution do not depend on \( \kappa \), provided \( \kappa \ll M_5 \), in contrast to the RS model with the large curvature \( \kappa \) [1].
Note that an ignorance of the graviton widths would be a rough approximation. In such a case, we get from (14):

\[ \text{Im} \mathcal{S}(\hat{s}) = -\frac{1}{2M_5^3 \sqrt{\hat{s}}} , \quad \text{Re} \mathcal{S}(\hat{s}) = 0 . \]  

\[ (19) \]

Fig. 2 shows the graviton contribution to the \( p_\perp \)-distribution calculated with the use of Eqs. (19). As one can see, neglecting graviton widths results in very large suppression of the cross sections.

![Figure 2: Contributions to the dilepton production from KK gravitons with nonzero widths (solid curves) vs. contributions from zero width graviton (dashed curves) for different values of the reduced gravity scale at the LHC.](image)

To evaluate the event rates, we used a K-factor 1.5 for the SM background, while a conservative value of K=1 was taken for the signal. Only one type of leptons (electron or muon) was taken into account. Let \( N_S \) \( (N_B) \) be a number of signal (background) events with \( p_\perp > 400 \) GeV. Then we define the statistical significance \( S = N_S / \sqrt{N_B} \), and require a 5\( \sigma \) effect. A statistical significance is presented in Fig. 3 as a function of the 5-dimensional Planck scale \( M_5 \) for two values of an integrated luminosity. Remember that \( M_5 \) and \( \bar{M}_5 \) are related by Eq. (4).

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Figure 3: The statistical significance for the process $pp \rightarrow l^+l^- + X$ at the LHC with high integrated luminosity as a function of the 5-dimensional Planck scale $M_5$. 
3 Conclusions

We have considered the dilepton production in the scenario with one warped extra dimension and small curvature $\kappa$ \[2,3\]. In such a scheme, the reduced 5-dimensional Planck scale $\bar{M}_5$ can vary from one to tens TeV, while $\kappa \ll \bar{M}_5$. The mass spectrum is similar to that in the ADD model \[10\] with one flat extra dimension.

The $p_{\perp}$-distributions for the Drell-Yan process, $pp \to l^+l^- + X$ ($l = e$, or $\mu$), are calculated for the collision energy $\sqrt{s} = 14$ TeV. The following LHC discovery limits are obtained:

$$M_5 = \begin{cases} 
17.8 \text{ TeV}, & \mathcal{L} = 1000 \text{ fb}^{-1} \\
21.6 \text{ TeV}, & \mathcal{L} = 3000 \text{ fb}^{-1}
\end{cases} \tag{20}$$

It is important to note that these bounds on $M_5$ do not depend on $\kappa$, contrary to the standard RS model with the large curvature $\kappa$.

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