Randall-Sundrum scenario with small curvature and dilepton production at LHC

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Abstract
The brief review of the recent results obtained in the Randall-Sundrum scenario with the small curvature of the five-dimensional space-time is presented.

1 RSSC model
In the recent papers [1], [2] the dilepton (dimuon and dielectron) production at the LHC was studied in the framework of the RSSC model (Randall-Sundrum-like model with the small curvature) [3]-[5].

The classical action of the model is
\begin{align}
S &= \int d^4x \int_{-\pi r_c}^{\pi r_c} dy \sqrt{G} \left( 2\bar{M}_5^2 \mathcal{R} - \Lambda \right) \\
&\quad + \int d^4x \sqrt{|g^{(1)}|} (\mathcal{L}_1 - \Lambda_1) + \int d^4x \sqrt{|g^{(2)}|} (\mathcal{L}_2 - \Lambda_2),
\end{align}
where $G_{MN}(x,y)$ is the 5-dimensional metric, with $M, N = 0, 1, 2, 3, 4, \mu = 0, 1, 2, 3$, and $y$ is the 5-th dimension coordinate of the size $r_c$. The quantities
\begin{align}
g_{\mu\nu}^{(1)}(x) &= G_{\mu\nu}(x, y = 0), \quad g_{\mu\nu}^{(2)}(x) = G_{\mu\nu}(x, y = \pi r_c)
\end{align}

* Talk presented at the International School-Seminar “New Physics and Quantum Chromodynamics at External Conditions”, May 22-24, 2013, Dnipropetrovsk, Ukraine.
are induced metrics on the branes, $\mathcal{L}_1$ and $\mathcal{L}_2$ are brane Lagrangians, $G = \det(G_{MN})$, $g^{(i)} = \det(g^{(i)}_{\mu\nu})$.

As in the original RS model [6], the periodicity $y = y + 2\pi r_c$ is imposed and the points $(x_\mu, y)$ and $(x_\mu, -y)$ are identified. Thus, we get the orbifold $S^1/Z_2$. There are two 3D branes located at the fixed points $y = 0$ (Plank brane) and $y = \pi r_c$ (TeV brane). The SM fields are constrained to the TeV brane, while the gravity propagates in all spatial dimensions.

In order to solve Einstein-Hilbert’s equations which follow from the action (1), it is assumed that the background metric respects 4-dimensional Poincare invariance

$$ds^2 = e^{-2\sigma(y)} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2,$$

Thus, the 5-dimensional metric tensor has the form

$$G_{MN} = \begin{pmatrix} g_{\mu\nu} & 0 \\ 0 & -1 \end{pmatrix},$$

where

$$g_{\mu\nu} = e^{-2\sigma(y)} \eta_{\mu\nu},$$

and $\eta_{\mu\nu}$ is the Minkowski tensor $(1, -1, -1, -1)$.

The background metric was found to be [2]

$$\sigma(y) = \frac{\kappa}{2} (|y| - |\pi r_c - y|) - \frac{\kappa \pi r_c}{2},$$

with the fine tuning

$$\Lambda = -6\bar{M}_5^3\kappa^2[\varepsilon(y) + \varepsilon(\pi r_c - y)]^2,$$

$$\Lambda_1 = -\Lambda_2 = 12\bar{M}_5^3\kappa.$$

The quantity $\kappa$ defines the curvature of the 5-dimensional space-time.

In the RSSC model the hierarchy relation looks like

$$\bar{M}_{P1}^2 = \frac{\bar{M}_5^3}{\kappa} \left( e^{2\pi \kappa r_c} - 1 \right),$$

where $\bar{M}_{P1} = M_{P1}/\sqrt{8\pi}$ is the reduced Planck scale, and $\bar{M}_5$ is the reduced fundamental gravity scale. $\bar{M}_5$ is related to the 5-dimensional Planck scale as

$$\bar{M}_5 = (2\pi)^{-1/3} M_5.$$
The masses of the Kaluza-Klein (KK) graviton excitations \( h_{\mu\nu}^{(n)} \) are proportional to \( \kappa \),
\[
m_{n} = x_{n}\kappa , \quad n = 1, 2, \ldots .
\] (10)
The interaction Lagrangian of gravitons is given by [3], [4]
\[
\mathcal{L}_{\text{int}} = -\frac{1}{M_{5}^{3/2}} \sum_{n=1}^{\infty} \int dy \sqrt{G} h_{\mu\nu}^{(n)}(x, y) T_{\alpha\beta}(x) g^{\mu\alpha} g^{\nu\beta} \delta(y - \pi \kappa r_{c})
\]
\[
= -\frac{1}{\Lambda_{\pi}} T_{\alpha\beta}(x) \sum_{n=1}^{\infty} h_{\mu\nu}^{(n)}(x) \eta^{\mu\alpha} \eta^{\nu\beta},
\] (11)
where \( T_{\alpha\beta}(x) \) is the energy-momentum tensor of the SM fields on the TeV brane, and
\[
\Lambda_{\pi} = M_{Pl} e^{-\pi \kappa r_{c}}.
\] (12)

Note that in the RSSC model the mass spectrum (10) and experimental signature are similar to those in the ADD model with one flat extra dimension [7]. Let us remember that the original RS model predicts heavy graviton resonances.

2 Graviton contribution to dilepton production at the LHC

In the framework of the RSSC model [4], [5], gravity effects can be searched for in the dilepton production \((l = \mu \text{ or } e)\),
\[
pp \rightarrow l^{+}l^{-} + X .
\] (13)
In particular, the \( p_{\perp} \)-distribution of the final leptons in the process (13) is given by the formula
\[
\frac{d\sigma}{dp_{\perp}}(pp \rightarrow l^{+}l^{-} + X) = 2p_{\perp} \sum_{a,b=q,q,\bar{q}} \int \frac{d\tau}{\sqrt{\tau - x_{\perp}}} \int \frac{dx_{1}}{x_{1}} f_{a/p}(\mu^{2}, x_{1})
\]
\[
\times f_{b/p}(\mu, \tau/x_{1}) \frac{d\hat{\sigma}}{dt}(ab \rightarrow l^{+}l^{-}) ,
\] (14)
Here \( f_{c/p}(\mu^{2}, x) \) is the distribution of the parton of the type \( c \) in momentum fraction \( x \) inside the proton taken at the scale \( \mu \). \( d\hat{\sigma}/dt \) is the differential
cross section of the subprocess $ab \to l^+ l^-$. In eq. (14) two dimensionless variables are introduced

$$x_\perp = \frac{2p_\perp}{\sqrt{s}}, \quad \tau = x_1 x_2,$$

where $x_2$ is the momentum fraction of the parton $b$ inside the proton.

The contribution of the virtual gravitons to lepton pair production comes from the quark-antiquark annihilation and gluon-gluon fusion,

$$\frac{d\hat{\sigma}}{dt}(q\bar{q} \to l^+ l^-) = \frac{\hat{s}^4 + 10\hat{s}^3\hat{t} + 42\hat{s}^2\hat{t}^2 + 64\hat{s}\hat{t}^3 + 32\hat{t}^4}{1536 \pi \hat{s}^2} |S(\hat{s})|^2,$$

$$\frac{d\hat{\sigma}}{dt}(gg \to l^+ l^-) = -\frac{i(\hat{s} + \hat{t})(\hat{s}^2 + 2\hat{s}\hat{t} + 2\hat{t}^2)}{256 \pi \hat{s}^2} |S(\hat{s})|^2,$$

where $\hat{s}$ and $\hat{t}$ are Mandelstam variables of the subprocess. The sum

$$S(s) = \frac{1}{\Lambda^2} \sum_{n=1}^{\infty} \frac{1}{s - m_n^2 + i m_n \Gamma_n}$$

is the invariant part of the partonic matrix elements, with $\Gamma_n$ being total width of the graviton with the KK number $n$ and mass $m_n$.

$$\Gamma_n = \eta m_n \left( \frac{m_n}{\Lambda} \right)^2, \quad \eta \simeq 0.09.$$

Note that the function $S(s)$ is universal for all processes mediated by $s$-channel virtual gravitons.

In the RSSC model the explicit expression was obtained for $S(s)$ at $s \sim M_5 \gg \kappa$

$$S(s) = -\frac{1}{4M_5^3\sqrt{s}} \frac{\sin 2A + i \sinh 2\varepsilon}{\cos^2 A + \sinh^2 \varepsilon},$$

where

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

In papers contributions from $s$-channel gravitons to the $p_\perp$-distributions of the final leptons were calculated in the RSSC model by using eqs. (14)-(20). The calculations were made for different values of 5-dimensional Planck
scale $\bar{M}_5$. The MSTW 2008 NNLO parton distributions $^8$ were used. The PDF scale $\mu$ was taken to be equal to the invariant mass of the lepton pair, $\mu = M_{l^+l^-} = \sqrt{s}$.

The CMS cuts on the lepton pseudorapidities were imposed. For the dimuon events the cut looks like

$$|\eta| < 2.4 ,$$

while for the dielectron events the cuts are the following

$$|\eta| < 1.44 , \quad 1.57 < |\eta| < 2.50 .$$

The reconstruction efficiency of 85\% was assumed for the dilepton events $^9$.

In Fig.\ref{fig:dimuon} the cross sections for the dimuon production at the LHC are presented. The gravity mediated contributions to the cross sections do not include the SM contribution. Fig.\ref{fig:dielectron} demonstrates that an ignorance of the graviton widths would be a rough approximation since it results in very large suppression of the gravity contributions. The $p_\perp$-distributions for the dielectron production are shown in Fig.\ref{fig:dielectron_8TeV} and Fig.\ref{fig:dielectron_13TeV} for $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV, respectively.

Let $N_S(N_B)$ be a number of signal (background) dilepton events with $p_\perp > p_\perp^{\text{cut}}$,

$$N_B = \int_{p_\perp > p_\perp^{\text{cut}}} d\sigma_{\text{SM}} dp_\perp , \quad N_S = \int_{p_\perp > p_\perp^{\text{cut}}} d\sigma_{\text{grav}} dp_\perp .$$

\begin{equation}
N_B = \int_{p_\perp > p_\perp^{\text{cut}}} d\sigma_{\text{SM}} dp_\perp , \quad N_S = \int_{p_\perp > p_\perp^{\text{cut}}} d\sigma_{\text{grav}} dp_\perp .
\end{equation}
Then one can define the statistical significance

$$S = \frac{N_S}{\sqrt{N_B + N_S}},$$

(24)

and require a 5$\sigma$ effect. In Fig. 5, the statistical significance is shown for $\sqrt{s} = 7$ TeV as a function of the transverse momentum cut $p^\perp_{\text{cut}}$ and reduced 5-dimensional Planck scale $\tilde{M}_5$. Fig. 6 represents the statistical significance for the dimuon events at $\sqrt{s} = 14$ TeV. The statistical significances for the dielectron events are shown in Fig. 7 and Fig. 8.

To take into account higher order contributions, the $K$-factor of 1.5 for the SM background was taken, while the factor $K = 1$ was used for the signal.

As a result, LHC discovery limits on the 5-dimensional Planck scale $M_5$ were obtained. In particular, for the (7+8) TeV LHC with the integrated luminosity $(5+20)$ fb$^{-1}$ the search limit in the dielectron production is equal to

$$M_5 = 6.35 \text{ TeV}.$$  

(25)

For the 13 TeV dielectron events with the integrated luminosity 30 fb$^{-1}$ the
Figure 5: The statistical significance $S$ for the dimuon production at the LHC for $\sqrt{s} = 7$ TeV and integrated luminosity $5 \text{ fb}^{-1}$ as a function of the transverse momentum cut $p_{\text{cut}}^\perp$ and reduced gravity scale $\bar{M}_5$. The plane $S = 5$ is also shown.

Figure 6: The same as in Fig. 5, but for $\sqrt{s} = 14$ TeV and integrated luminosity $30 \text{ fb}^{-1}$.

Figure 7: The statistical significance for the dielectron production at the LHC for $\sqrt{s} = (7 + 8)$ TeV and integrated luminosity $(5+20)$ fb$^{-1}$.

Figure 8: The same as in Fig. 7, but for $\sqrt{s} = 13$ TeV and integrated luminosity $30 \text{ fb}^{-1}$. 
search limit was found to be \( M_5 = 8.95 \text{ TeV} \). \( (26) \)

Let us underline that in the RSSC model these bounds do not depend on the curvature \( \kappa \), contrary to the original RS model \( [6] \).

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