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RS MODEL WITH A SMALL CURVATURE AND DIELECTRON PRODUCTION AT THE LHC

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In the framework of the Randall–Sundrum-like scenario with the small curvature κ (RSSC model), the $p_\perp$ distributions for the dielectron production at the LHC are calculated. For the summary statistics taken at 7 TeV ($L = 5$ fb^{-1}) and 8 TeV ($L = 20$ fb^{-1}), the exclusion limit on the 5-dimensional gravity scale M_5 is found to be 6.35 TeV at 95% C. L. For $\sqrt{s} = 13$ TeV and integrated luminosity 30 fb^{-1}, the LHC search limit is estimated to be 8.95 TeV. These limits on M_5 are independent of κ, provided the relation $\kappa \ll M_5$ is satisfied.

В рамках сценария Рандалл–Сундрума с малой кривизной κ (модель RSSC) вычислено распределение по поперечному импульсу $p_\perp$ пары электронов на БАК. Для суммарной статистики при 7 ТэВ ($L = 5$ фб$^{-1}$) и 8 ТэВ ($L = 20$ фб$^{-1}$) получено ограничение снизу на пятимерный гравитационный масштаб M_5, равное 6,35 ТэВ с достоверностью 95 %. Для 13 ТэВ и интегральной светимости 30 фб$^{-1}$ достижимый предел БАК равен 8,95 ТэВ. Указанные пределы на M_5 не зависят от κ при условии $\kappa \ll M_5$.

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1. DIELECTRON PRODUCTION IN THE RSSC MODEL

In the recent paper [1], the $p_\perp$ distributions for the *dimuon* production at the LHC were calculated in the framework of the Randall–Sundrum-like scenario with the small curvature (RSSC model [2–4]). The LHC discovery limits on the 5-dimensional gravity scale M_5 were obtained for both 7 and 14 TeV.

In contrast to the RS1 model [5], in the RSSC model the masses of the Kaluza–Klein (KK) excitations $h_{\mu\nu}^{(n)}(x)$ are proportional to the curvature parameter κ ($\kappa \ll M_5$) [3],

$$m_n = x_n \kappa, \quad n = 1, 2, \ldots, \tag{1}$$

where x_n are zeros of the Bessel function $J_1(x)$. The interaction of the gravitons with the SM fields is described by the Lagrangian

$$\mathcal{L}_{\rm int} = -\frac{1}{\overline{M}_{\rm Pl}} h_{\mu\nu}^{(0)}(x)\, T_{\alpha\beta}(x)\, \eta^{\mu\alpha}\eta^{\nu\beta} - \frac{1}{\Lambda_\pi} \sum_{n=1}^{\infty} h_{\mu\nu}^{(n)}(x)\, T_{\alpha\beta}(x)\, \eta^{\mu\alpha}\eta^{\nu\beta}, \tag{2}$$

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where $T_{\mu\nu}(x)$ is the energy-momentum tensor of the SM matter,

$$\Lambda_\pi \simeq \overline{M}_{\rm Pl}\, {\rm e}^{-\pi\kappa r_c}, \tag{3}$$

and $\overline{M}_{\rm Pl}$ is the reduced Planck mass.

The goal of this paper is to estimate gravity effects in the *dielectron* production,

$$pp \to e^+e^- + X, \tag{4}$$

at LHC energies in the RSSC model. The differential cross section of the process (4) is given by

$$\frac{d\sigma}{dp_\perp}(pp \to e^+e^- + X) = 2p_\perp \sum_{a,b=q,\bar{q},g} \int \frac{d\tau\sqrt{\tau}}{\sqrt{\tau - x_\perp^2}} \int \frac{dx_1}{x_1} f_{a/p}(\mu^2, x_1) \times \\ \times f_{b/p}(\mu^2, \tau/x_1)\, \frac{d\sigma}{d\hat{t}}(ab \to e^+e^-), \tag{5}$$

with the transverse energy of the electron pair equal to $2p_\perp$. In Eq. (5) two dimensionless quantities are introduced

$$x_\perp = \frac{2p_\perp}{\sqrt{s}}, \quad \tau = x_1 x_2, \tag{6}$$

where x_2 is the momentum fraction of the parton b in (5). Without cuts, integration variables in (5) vary within the following limits:

$$x_\perp^2 \leqslant \tau \leqslant 1, \quad \tau \leqslant x_1 \leqslant 1. \tag{7}$$

After imposing kinematical cut on electron rapidity, the integration region becomes more complicated (see Appendix A in [1]).

The SM contribution to the $p_\perp$ distribution looks like

$$\frac{d\sigma^{\rm SM}}{d\hat{t}}(q\bar{q} \to e^+e^-) = \frac{1}{48\pi s^2} \left[u^2(|G^{LL}|^2 + |G^{RR}|^2) + t^2(|G^{LR}|^2 + |G^{RL}|^2)\right],$$

with

$$G^{AB}(s) = \sum_{V=\gamma,Z} \frac{g_A(V \to e^+e^-)\, g_A(V \to q\bar{q})}{s - m_V^2 + i m_V \Gamma_V}.$$

Here $g_{L(R)}(\gamma \to e^+e^-) = g_{L(R)}(\gamma \to q\bar{q}) = e$, and

$$\begin{aligned} g_L(Z \to e^+e^-) &= -\frac{1}{2} + \sin^2\theta_W, \\ g_R(Z \to e^+e^-) &= \sin^2\theta_W, \\ g_L(Z \to q\bar{q}) &= T_3^q - e_q \sin^2\theta_W, \\ g_R(Z \to q\bar{q}) &= -e_q \sin^2\theta_W, \end{aligned} \tag{8}$$

with T_3^q being the third component of the quark isospin, e_q being the quark electric charge (in units of $|e|$).

The graviton contribution comes from both quark–antiquark annihilation and gluon–gluon fusion subprocesses (see, for instance, [2]):

$$\begin{aligned}\frac{d\sigma^{\rm grav}}{d\hat{t}}(q\bar{q}\to e^+e^-) &= \frac{\hat{s}^4 + 10\hat{s}^3\hat{t} + 42\,\hat{s}^2\hat{t}^2 + 64\hat{s}\,\hat{t}^3 + 32\,\hat{t}^4}{1536\,\pi\hat{s}^2}\,|\mathcal{S}(\hat{s})|^2\,, \\ \frac{d\sigma^{\rm grav}}{d\hat{t}}(gg\to e^+e^-) &= -\frac{\hat{t}(\hat{s}+\hat{t})(\hat{s}^2 + 2\hat{s}\,\hat{t} + 2\,\hat{t}^2)}{256\,\pi\hat{s}^2}\,|\mathcal{S}(\hat{s})|^2\,,\end{aligned} \tag{9}$$

where

$$\mathcal{S}(s) = \frac{1}{\Lambda_\pi^2}\sum_{n=1}^{\infty}\frac{1}{s - m_n^2 + i m_n\Gamma_n} \tag{10}$$

is the invariant part of the partonic matrix elements, with Γ_n being the total width of the graviton with the KK number n and mass m_n [4]:

$$\Gamma_n = \eta m_n\left(\frac{m_n}{\Lambda_\pi}\right)^2, \quad \eta \simeq 0.09. \tag{11}$$

Let us note that $\mathcal{S}(s)$ is a universal function for processes mediated by s-channel virtual gravitons.

In the RSSC model, an explicit expression for the sum (10) was obtained in [4],

$$\mathcal{S}(s) = -\frac{1}{4\overline{M}_5^3\sqrt{s}}\,\frac{\sin 2A + i\sinh 2\varepsilon}{\cos^2 A + \sinh^2\varepsilon}, \tag{12}$$

where $\overline{M}_5 = M_5/(2\pi)^{1/3}$ is the *reduced* 5-dimensional gravity scale, and

$$A = \frac{\sqrt{s}}{\kappa}, \qquad \varepsilon = \frac{\eta}{2}\Big(\frac{\sqrt{s}}{\overline{M}_5}\Big)^3. \tag{13}$$

Let us underline that the magnitude of $\mathcal{S}(s)$ is defined by the scale $\overline{M}_5$, not by the coupling Λ_π in the Lagrangian (2). In general, this property is valid in the RSSC model for both real and virtual production of the KK gravitons [3,4].

2. NUMERICAL CALCULATION OF $p_\perp$ DISTRIBUTIONS

Taking into account that the transition region $1.44 < |\eta| < 1.57$ ($1.37 < |\eta| < 1.52$) between the ECAL barrel and endcap calorimeters is usually excluded in the CMS (ATLAS) experiment, we impose the CMS cut on the electron pseudorapidity,

$$|\eta| < 1.44, \quad 1.57 < |\eta| < 2.50. \tag{14}$$

The reconstruction efficiency 85% is assumed for the dielectron events [6]. We use the MSTW NNLO parton distributions [7], and convolute them with the partonic cross sections. The PDF scale is taken to be equal to the invariant mass of the electron pair, $\mu = M_{e^+e^-}$. In order to take into account SM higher-order corrections, the K factor 1.5 is used for the SM background, while a conservative value of $K = 1$ is taken for the signal.

The differential cross section of the process under consideration has three terms:

$$d\sigma = d\sigma(\mathrm{SM}) + d\sigma(\mathrm{grav}) + d\sigma(\mathrm{SM} - \mathrm{grav}), \tag{15}$$

where the last one comes from the interference between the SM and graviton interactions. Since the SM amplitude is pure real, while the real part of each graviton resonance is antisymmetric with respect to its central point, the interference term has appeared to be negligible in comparison with the pure gravity and SM terms after integration in partonic momenta.

The account of the *graviton widths* is a crucial point for both analytical calculations and numerical estimations. As was shown in [1,8], an ignorance of the graviton widths is a *rough* approximation, since it results in very large suppression of the cross sections. The reason lies partially in the fact that

$$\frac{d\sigma(\mathrm{grav})}{dp_\perp} \sim \frac{1}{p_\perp^3} \left(\frac{\sqrt{s}}{\overline{M}_5}\right)^3, \tag{16}$$

while in zero-width approximation one gets

$$\left.\frac{d\sigma(\mathrm{grav})}{dp_\perp}\right|_{\texttt{zero width}} \sim \frac{1}{\overline{M}_5^3} \left(\frac{\sqrt{s}}{\overline{M}_5}\right)^3. \tag{17}$$

Let us stress that in the RSSC model the gravity cross sections *do not depend* on the curvature κ (up to small power corrections), provided $\kappa \ll \overline{M}_5$, in contrast to the RS1 model [5], in which all bounds on $\overline{M}_5$ depend on the ratio $\kappa/\overline{M}_{\mathrm{Pl}}$.

In Fig. 1, the results of our calculations of gravity cross sections for the dielectron production at 8 TeV LHC are presented. The differential cross sections for 13 TeV are shown in Fig. 2. Note that the gravity mediated contributions to the cross sections do not include the SM contribution (i.e., solid curves in the figures correspond to pure gravity contributions).

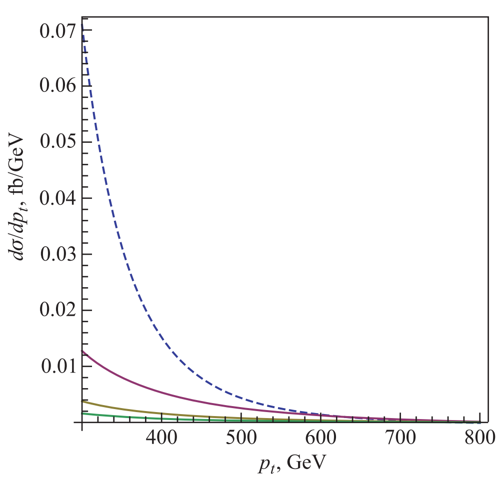

Fig. 1. The KK graviton contribution to the dielectron production for $\overline{M}_5 = 2,\ 4,\ 6$ TeV (solid curves, from above) vs. the SM (Born) contribution (dashed curve) at $\sqrt{s} = 8$ TeV

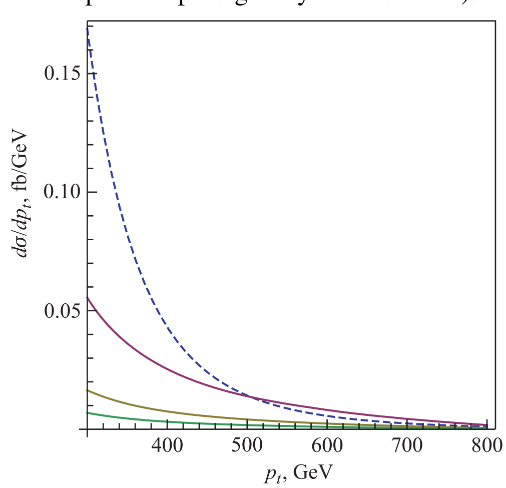

Fig. 2. The KK graviton contribution to the dielectron production for $\overline{M}_5 = 4, 6, 8$ TeV (solid curves, from above) vs. the SM (Born) contribution (dashed curve) at $\sqrt{s} = 13$ TeV

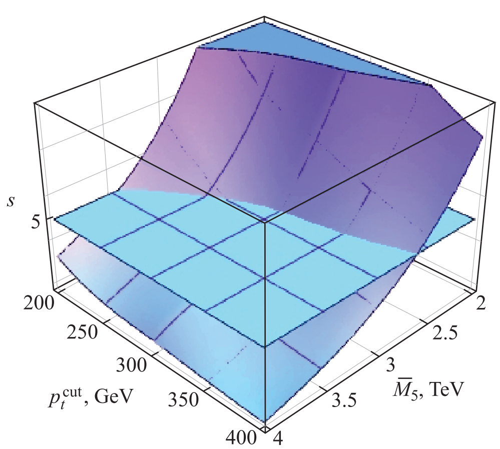

Fig. 3. The statistical significance $\mathcal{S}$ for the dielectron production at the LHC for $\sqrt{s} = (7+8)$ TeV and integrated luminosity $(5+20)$ fb^{-1} as a function of the transverse momentum cut $p_\perp^{\rm cut}$ and *reduced* 5-dimensional gravity scale $\overline{M}_5$. The plane $\mathcal{S} = 5$ is also shown

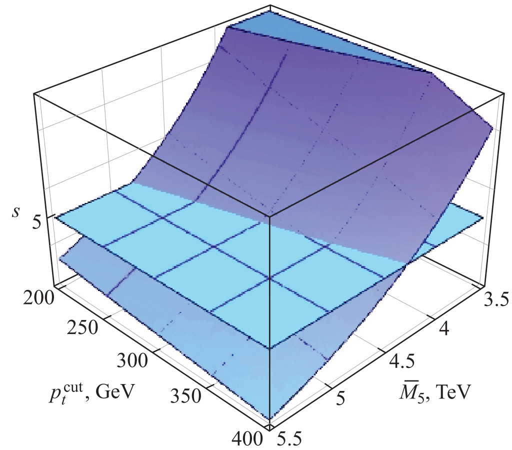

Fig. 4. The same as in Fig. 3, but for $\sqrt{s} = 13$ TeV and integrated luminosity 30 fb^{-1}

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

$$N_S = \int\limits_{p_\perp > p_\perp^{\rm cut}} \frac{d\sigma({\rm grav})}{dp_\perp}\, dp_\perp, \quad N_B = \int\limits_{p_\perp > p_\perp^{\rm cut}} \frac{d\sigma({\rm SM})}{dp_\perp}\, dp_\perp. \tag{18}$$

Then, we define the statistical significance $\mathcal{S} = N_S/\sqrt{N_B + N_S}$, and require a 5σ effect. In Fig. 3, the statistical significance is shown for total number of «events» with $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV as a function of the transverse momentum cut $p_\perp^{\rm cut}$ and *reduced* 5-dimensional gravity scale $\overline{M}_5$. The integrated luminosity was taken to be 5 and 20 fb^{-1} for $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, respectively. Figure 4 represents the significance $\mathcal{S}$ for the dielectron events with $\sqrt{s} = 13$ TeV and 30 fb^{-1}.

Previously, calculations of dilepton cross sections were done in [2] *without* taking into account finite widths of the KK gravitons. As was shown in [1] (see also [8]), in zero-width approximation the gravity cross sections are very small in comparison with the background cross section at low and moderate values of $p_\perp$. That is why, a high cut $p_\perp^{\rm cut}$ is needed in order to get N_S comparable with N_B. Correspondingly, the LHC search limits in [2] are significantly smaller than in nonzero approximation for the graviton widths.

CONCLUSIONS

In the present paper, the RSSC model [3, 4] is considered, in which the *reduced* 5-dimensional Planck scale $\overline{M}_5$ is much larger than the curvature κ. In such a model the mass spectrum and experimental signatures are similar to those in the ADD model [9] with one flat extra dimension.

The $p_\perp$ distributions for the electron pairs production with high $p_\perp$ at the LHC are calculated for the collision energies 7, 8 and 13 TeV, see Figs. 1 and 2 (figures for 7 TeV are not shown). Let us underline that the account of the KK graviton widths was the crucial point for our calculations.

The statistical significance as a function of the *reduced* 5-dimensional Planck scale $\overline{M}_5$ and cut on the lepton transverse momentum $p_\perp^{\rm cut}$ is calculated (Figs. 3 and 4). No significant deviations from the SM prediction were seen in the dielectron events at $(7+8)$ TeV LHC with the integrated luminosity $(5+20)$ fb^{-1}. By using our calculations, we come to the conclusion that the region

$$M_5 < 6.35 \text{ TeV} \tag{19}$$

is excluded by experimental data. We also obtain the discovery limit for the 13 TeV LHC with the integrated luminosity 30 fb^{-1},

$$M_5 = 8.95 \text{ TeV}. \tag{20}$$

Let us stress that these bounds on M_5 do not depend on the curvature κ (up to small power-like corrections), contrary to the RS1 model [5], in which estimated bounds on M_5 significantly depend on the ratio $\kappa/\overline{M}_{\rm Pl}$.

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