Kaluza-Klein gravitons at the LHC and in extensive air showers[*]

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Abstract

The small curvature option of the Randall-Sundrum model with two branes is considered which has almost continuous spectrum of low-mass Kaluza-Klein gravitons. It is shown that gravity effects related with these excitations can be detected in double diffractive events at the LHC and in inclined air showers induced by interactions of cosmic neutrinos with atmospheric nucleons at ultra-high energies.

Introduction

One of the most important problem of the particle physics is the problem of hierarchy between the electro-weak and Planck scales. To explain this hierarchy, a number of theories with extra spacial dimensions have been proposed (see, for instance, Ref. [1]). The model which solves the problem most economically is the so-called RS1 model with a single extra dimension [2]. The background (warped) metric of the model is of the form:

$$ds^2 = e^{2\kappa(\pi r_c - |y|)} \, \eta_{\mu\nu} \, dx^\mu dx^\nu + dy^2 \; . \tag{1}$$

Here $y = r_c \theta$ $(-\pi \leq \theta \leq \pi)$, r_c being a "radius" of the extra dimension, while $\{x^\mu\}$, $\mu = 0, 1, 2, 3$, are the coordinates in four-dimensional space-time. The parameter κ defines the scalar curvature in five dimensions. Note that

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the points (x^μ, y) and $(x^\mu, -y)$ are identified, and the periodicity condition, $(x^\mu, y) = (x_\mu, y + 2\pi r_c)$, is imposed. The tensor $\eta_{\mu\nu}$ in (1) is the Minkowski metric.

There are two 3-dimensional branes with equal and opposite tensions located at the point $y = 0$ (called the *Plank brane*) and point $y = \pi r_c$ (referred to as the *TeV brane*). All SM fields are constrained to the TeV brane. Then one can derive the relation between the 4-dimensional (reduced) Planck scale, $\bar{M}_{Pl}$, and (reduced) gravity scale in five dimensions, $\bar{M}_5$,

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

The masses of the Kaluza-Klein (KK) graviton excitations are given by

$$m_n = x_n \, \kappa, \qquad n = 1, 2 \ldots , \tag{3}$$

where x_n are zeros of the Bessel function $J_1(x)$. The zero graviton mode, $h_{\mu\nu}^{(0)}$, and massive graviton modes, $h_{\mu\nu}^{(n)}$, are coupled to the energy-momentum tensor of the matter, $T^{\mu\nu}$, as follows:

$$\mathcal{L}_{int} = - \frac{1}{\bar{M}_{Pl}} T^{\mu\nu} \, h_{\mu\nu}^{(0)} - \frac{1}{\Lambda_\pi} T^{\mu\nu} \sum_{n=1}^{\infty} h_{\mu\nu}^{(n)} , \tag{4}$$

with

$$\Lambda_\pi = \left(\frac{\bar{M}_5^3}{\kappa} \right)^{1/2} \tag{5}$$

being a physical scale on the TeV brane.

In Ref. [3] it has been proposed to study the "*small curvature option*" of the RS1 model:

$$\kappa \ll \bar{M}_5 \sim 1 \text{ TeV} . \tag{6}$$

In such a case, we get an almost continuous spectrum of low-mass graviton excitations with a small mass splitting $\Delta m \simeq \pi\kappa$. Note that in the usually used scenario of the RS1 model one has a series of KK graviton resonances with the lightest one having a mass of order 1 TeV.

1 KK graviton production at the LHC

One of the possibilities to check the RS1 model with the small curvature (6) is to search for an exclusive production of the KK gravitons in double diffractive events at the LHC.

Since the widths of the graviton with the KK number n and mass m_n is extremely small,

$$\Gamma_n \simeq 0.1 \, \frac{m_n^3}{\Lambda_\pi^2} \; , \tag{7}$$

a distinctive signature of the production of such fields will be an imbalance in missing mass of final states. Because of the small mass splitting in the KK graviton spectrum, we expect a continuous distribution in missing mass.

In other words, one has to look for the process

$$p + p \to p + \text{``nothing''} + p \; . \tag{8}$$

The distribution in missing mass M_{miss} for the production of the KK gravitons in double diffractive events was calculated in Ref. [4]. The results of these calculation are presented in Fig. 1 for various values of $\bar{M}_5$, the gravity scale in five warped dimensions.

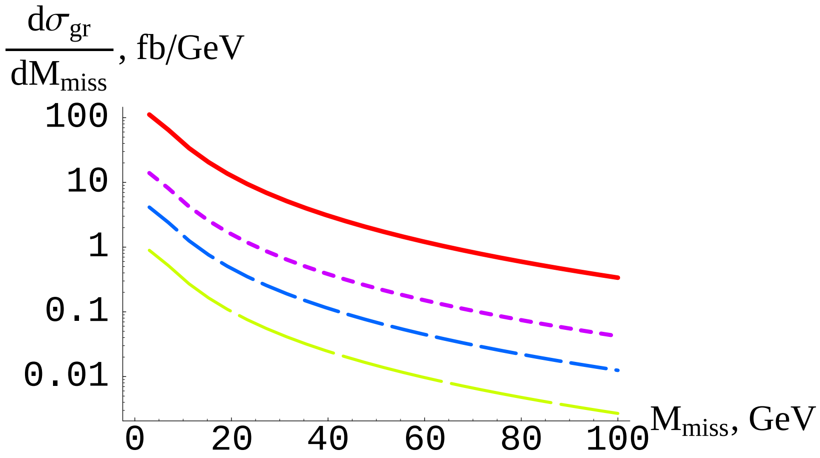

Figure 1: The distribution in the missing mass in the double diffractive production of the KK gravitons. The curves correspond (from top to bottom) to $\bar{M}_5 = 1$ TeV, 2 TeV, 3 TeV, and 5 TeV.

Let us stress that $d\sigma_{gr}/dM_{miss}$ is defined by $\bar{M}_5$ only, not by the values of κ and Λ_π separately. The smallness of the graviton coupling ($\sim 1/\Lambda_\pi^2$) is compensated by the large number of the produced gravitons ($\sim 1/\kappa$). As a result, the corresponding cross sections appeared to be large enough, as one can see in the next Fig. 2.

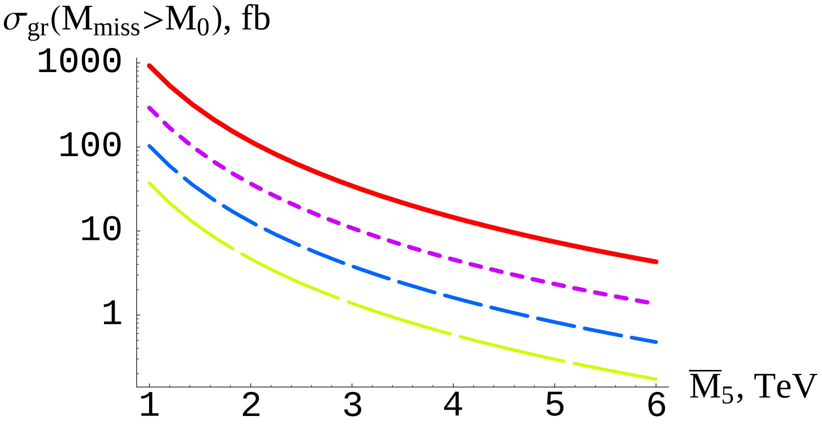

Figure 2: The cross section for double diffractive production of the KK gravitons with masses larger that M_0 as a function of $\bar{M}_5$. The curves correspond (from top to bottom) to $M_0 = 3$ GeV, 14 GeV, 30 GeV, and 50 GeV. The lowest value of M_0 is imposed to avoid the influence of the soft photon production, the highest concerns a neutrino background from Z-decays.

We expect that the signals from the production of the KK gravitons in double diffractive events could be detected at the LHC in a joint experiment of the CMS and TOTEM Collaborations [5].

2 Gravi-Reggeons and cosmic neutrinos

Another possibility to detect effects induced by low-mass KK gravitons is to look for their contributions to the scattering of the brane fields in the trans-Planckian kinematical region [3]

$$\sqrt{s} \gg \bar{M}_5, \qquad s \gg -t \; , \tag{9}$$

with $\sqrt{s}$ being the colliding energy and $t = -q_\perp^2$ being the four-dimensional momentum transfer. Note that regime (9) dominates the whole value of both elastic and inelastic cross sections.

In the eikonal approximation, an elastic scattering amplitude in the kinematical region (9) is given by the sum of gravi-Reggeons, i.e. reggeized gravitons in t-channel. Because of a presence of extra dimension, the Regge trajectory of the graviton is splitting into an infinite sequence of trajectories enumerated by the KK number n [6]:

$$\alpha_n(t) = 2 + \alpha'_g t - \alpha'_g\, m_n^2, \quad n = 0, 1, \ldots . \tag{10}$$

Let us now consider scattering of ultra-high energy cosmic neutrinos off the atmospheric nucleons in order to compare effects induced by extra dimension with the SM predictions [7]. The gravity contribution to the neutrino-proton cross section

$$\sigma_{\mathrm{in}}^{\nu\mathrm{p}}(s) = \int d^2 b \, \{1 - \exp\left[\, - 2\mathrm{Im}\, \chi_{\nu\mathrm{p}}(s,b)\right]\} \ , \tag{11}$$

is defined by the eikonal

$$\chi_{\nu\mathrm{p}}(s,b) = \frac{1}{4\pi s} \int\limits_0^\infty q_\perp dq_\perp \, J_0(q_\perp b)\, A_{\nu\mathrm{p}}^B(s, -q_\perp^2) \ , \tag{12}$$

where b denotes an impact parameter.

The Born amplitude was calculated in Ref. [3]:

$$A_{\nu\mathrm{p}}^B(s,t) = \frac{\alpha'_g \, s^2}{2\sqrt{\pi}\, \bar{M}_5^3} \sum_i \int dx \, x^2 \, \frac{1}{R_g(sx)} \, \exp\left[t \, R_g^2(sx)\right] F_i(x,t) \ , \tag{13}$$

where $F_i(x,t)$ is a t-dependent distribution of parton i in momentum fraction x inside the proton (see [3] for details). It coincides with a starndard parton distribution, $f_i(x)$, at $t = 0$. The quantity $R_g(s) = \alpha'_g \ln s$ is the gravitational interaction radius, where α'_g is the gravi-Reggeon slope (10).

The gravitational part of the inelastic cross section is presented in Fig. 3 in comparison with the SM prediction, σ_{SM}, and black hole production cross section, σ_{bh}. For the latter, a geometrical form, $\sigma_{\mathrm{bh}} = \pi R_S^2(s)$, is assumed, with 5-dimensional Schwarzschild radius [8]

$$R_S(s) = \frac{1}{\sqrt{3}\pi} \, \frac{s^{1/4}}{\bar{M}_5^{3/2}} \ . \tag{14}$$

As one can see, gravi-Reggeon interactions can dominate black hole production at $E_\nu > 10^9 - 10^{10}$ GeV, depending on the gravity scale $\bar{M}_5$ and minimal value of the black hole mass $M_{\mathrm{bh}}^{\mathrm{min}}$.

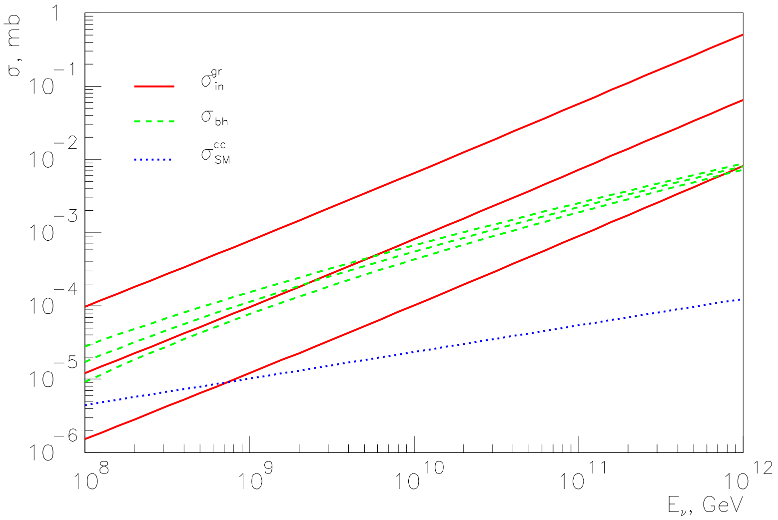

Figure 3: The gravitational inelastic neutrino-proton cross-sections (solid lines) vs. black hole production cross sections (dashed lines) and SM cross section (dotted line). The solid curves correspond to $\bar{M}_5 = 0.25$ TeV, 0.5 TeV, 1 TeV (from the top). The dash lines correspond to $\bar{M}_5 = 0.5$ TeV and $M_{\rm bh}^{\rm min} = 0.5$ TeV, 1 TeV, 2 TeV (from the top).

Let us stress that usually the eikonalization is made at the parton level, e.i. before the convolution of the cross section with the parton distributions. In such a case, the neutrino-proton cross section is of the form:

$$\sigma_{\rm in}^{\nu{\rm p}}(s) = \sum_i \int dx \, \hat{\sigma}(xs) \, f_i(x) \ , \tag{15}$$

where $\hat{\sigma}_i$ is the cross section for the scattering of the neutrino off parton i. For the gravitational interaction, it does not depend on i and it is equal to

$$\hat{\sigma}(s) = \int d^2 b \, \{ 1 - \exp \left[- 2 {\rm Im} \, \hat{\chi}(s,b) \right] \} \ . \tag{16}$$

The gravitational part of the eikonal for the neutrino scattering off a parton looks like [3]

$${\rm Im} \, \hat{\chi}(s,b) = \frac{\alpha_g' \, s}{16\sqrt{\pi} \, R_g^3(s) \, \bar{M}_5^3} \, \exp \left[- b^2 / 4 R_g^2(s) \right] . \tag{17}$$

The results of numerical calculations made with the use of formulas (15)-(17) are presented in Fig. 4. It shows that the inelastic cross sections rise with energy slower that in the case when the eikonalization is made at the hadronic level (see Eqs. (11)-(13)).

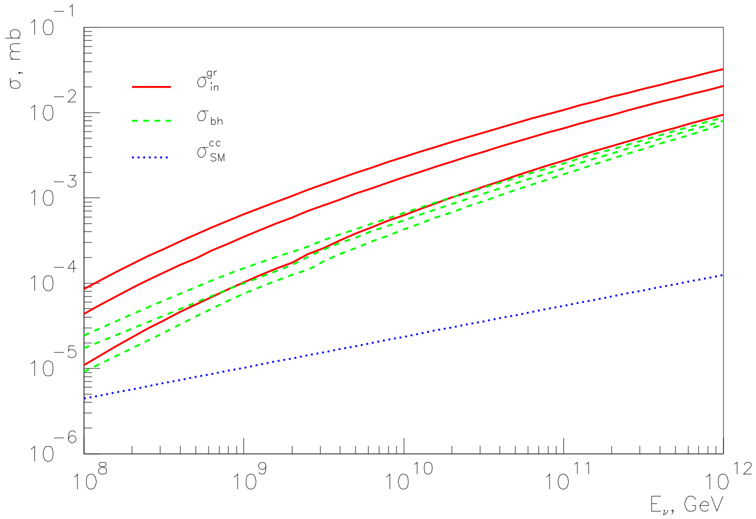

Figure 4: The same as in Fig. 3, but with the eikonalization made at the partonic level (see the main text for details).

These neutrino-proton cross sections can be probed by the Pierre Auger Observatory [9]. In order to isolate neutrino-induced events, inclined (quasi-horizontal) air showers should be looked for [10]. For the "Waxman-Bahcall" neutrino flux [11], we expect the following number of the inclined air showers induced by ultra-high energy cosmic neutrinos (with zenith angle $\theta > 70°$):

$$N_{\rm ev} = \begin{cases} 4.9 \ {\rm yr}^{-1}, & \bar{M}_5 = 1 \ {\rm TeV} \\ 1.6 \ {\rm yr}^{-1}, & \bar{M}_5 = 2 \ {\rm TeV} \end{cases} \tag{18}$$

These estimates should be compared with the SM prediction, 0.08 events per year for the same neutrino flux.

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