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SEARCH AND IDENTIFICATION OF EFFECTS OF EXTRA SPATIAL DIMENSIONS IN LEPTON PAIR PRODUCTION AT LHC

Abstract. N. Arkani-Hamed, S. Dimopoulous, and G. Dvali have proposed a model (ADD) of low-scale quantum gravity featuring large extra dimensions. In this model, the exchange of Kaluza – Klein towers of gravitons can enhance a production rate of lepton pairs at high invariant mass in proton-proton collisions at LHC. By considering the present and future LHC energy regimes, we have again analyzed the LHC potential to discover the effects of large extra dimensions and to discriminate between various theoretical models. Specifically, in the latter case we explore the LHC capability to distinguish spin-2 Kaluza – Klein towers of gravitons exchange from other new physics effects which might be conveniently parametrized by the four-fermion contact interactions. We find that LHC with planned energy of 14 TeV and luminosity of 100 fb^{-1} will be capable of discovering (and identifying) graviton exchange effects in the large extra dimensions with the cutoff parameter of the order M_S = 6.2 TeV (4.8 TeV) for d = 6 and M_S = 8.8 TeV (6.8 TeV) for d = 3.

Keywords: Kaluza – Klein models, large extra dimensions, four-fermion contact interactions, Large Hadron Collider

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ПОИСК И ИДЕНТИФИКАЦИЯ ЭФФЕКТОВ ДОПОЛНИТЕЛЬНЫХ ПРОСТРАНСТВЕННЫХ ИЗМЕРЕНИЙ В ПРОЦЕССЕ РОЖДЕНИЯ ПАР ЛЕПТОНОВ НА БОЛЬШОМ АДРОННОМ КОЛЛАЙДЕРЕ LHC

Н. Аркани-Хамед, С. Димопулос и Г. Двали предложили модель (ADD) низкоразмерной квантовой гравитации с большими пространственными измерениями. В этой модели обмен гравитонных башен Калуцы – Клейна может усилить величину сечения рождения лептонных пар при больших инвариантных массах дилептонов в протон-протонных столкновениях на коллайдере LHC. Принимая во внимание настоящий и будущий энергетические режимы коллайдера LHC, мы вновь проанализировали потенциальные возможности LHC по обнаружению эффектов больших дополнительных измерений, а также по разделению различных теоретических моделей. В частности, в последнем случае мы исследуем возможности LHC по разделению эффектов обмена гравитонными башнями Калуцы – Клейна со спином 2 и эффектов «новой» физики другой природы, которые могут быть удобно параметризованы четырехфермионными контактными взаимодействиями. Для LHC с планируемой энергией в 14 ТэВ и светимостью 100 фб$^{-1}$ мы определили граничные значения на параметр обрезания M_S, для которого LHC сможет обнаруживать (и идентифицировать) эффекты обмена гравитонными башнями, а именно: M_S = 6,2 ТэВ (4,8 ТэВ) для d = 6 и M_S = 8,8 ТэВ (6,8 ТэВ) для d = 3.

Ключевые слова: модели Калуцы – Клейна, большие дополнительные измерения, четырехфермионные контактные взаимодействия, Большой адронный коллайдер

Для цитирования. Поиск и идентификация эффектов дополнительных пространственных измерений в процессе рождения пар лептонов на Большом адронном коллайдере LHC / А. А. Панков [и др.] // Вес. Нац. акад. навук Беларусі. Сер. фіз.-мат. навук. – 2017. – № 4. – С. 44–50.

Introduction. The possibility that the universe has more than three spatial dimensions has long been discussed [1]. Recent developments in string theory suggest that there could be up to seven additional spatial dimensions, compactified at very small distances, on the order of 10^{-32} m. In a model [2], inspired by string theory, several of the compactified extra dimensions (ED) are suggested to be as large as 1 mm. These large ED are introduced to solve the hierarchy problem of the standard model (SM) by lowering the Planck scale, M_{Pl}, to the TeV energy range. The ED compactification radius, R, depends on the number of extra dimensions (d) and on the effective Planck scale [2]. Since Newton's law of gravity would be modified in the presence of compactified extra dimensions for interaction distances below the size of the largest extra dimension, current gravitational observations rule out the case of a single large extra dimension. The results from gravity experiments at submillimeter distances, as well as cosmological constraints from supernova cooling and distortion of cosmic diffuse gamma-radiation [3], indicate that the case of $d = 2$ is likely ruled out as well. However, for $d \geq 3$, the size of the ED becomes microscopic and therefore eludes the reach of direct gravitational measurements. Cosmological constraints are also weak in this case. Therefore, high energy colliders, capable of probing very short distances, are crucial to test theories of large ED. In these theories, the effects of gravity are enhanced at high energies due to the accessibility of numerous excited states of the graviton (referred to as a Kaluza – Klein (KK) [4] graviton, G_{KK}), corresponding to multiple winding modes of the graviton field around the compactified dimensions. Since gravitons couple to the energy-momentum tensor, they can be produced in any SM process.

Theories of low-scale quantum gravity featuring large extra spatial dimensions (LED) have attracted considerable interest because of their possible observable consequences at existing and future colliders. In scenario, proposed by Arkani-Hamed, Dimopoulos, and Dvali [2], the fermions and gauge bosons of the SM are confined to the three ordinary spatial dimensions, which form the boundary ("the brane") of a space with d compact spatial dimensions ("the bulk") in which gravitons alone can propagate. In this model, the Planck scale is lowered to the electroweak scale of O (1 TeV), which is postulated to be the only fundamental scale in nature. The fundamental Planck scale in the extra dimensions (M_S), the characteristic size of the d extra dimensions (R) and the Planck scale on the brane are related via

$$M_{Pl}^2 \sim M_S^{d+2} R^d, \tag{1}$$

a purely classical relationship calculated by applying the 4 + d dimensional Gauss's law. In this scenario, then, the weakness of gravity compared to the other SM interactions is explained by the suppression of the gravitational field flux by a factor proportional to the volume of the extra dimension.

Searches for virtual graviton effects are complementary to those for direct graviton emission, since the former depend on the ultraviolet cutoff of the KK spectrum, M_S, while the latter depends directly on the fundamental Planck scale M_D. While both scales are expected to be of the same order, it is quite possible that M_S is somewhat lower than M_D; thus the effects of extra dimensions might be detected in virtual graviton exchange before they are observed in direct emission.

While direct graviton emission cross section is well defined, the cross section for virtual graviton exchange depends on a particular representation of the interaction Lagrangian and the definition of the ultraviolet cutoff on the KK modes. Three such representations have appeared nearly simultaneously [5]. In all of them, the effects of ED are parameterized via a single variable $\eta_G = F / M_S^4$, where F is a dimensionless parameter of order one reflecting the dependence of virtual G_{KK} exchange on the number of extra dimensions, and M_S is the ultraviolet cutoff. Different formalisms use different definitions of F, which results in different definitions of M_S:

$$f = 1, \text{ (GRW [6]);}$$

$$F = \begin{cases} \log\left(\dfrac{M_s^2}{M_2}\right), d = 2 \\ \dfrac{2}{d-2}, d > 2 \end{cases}, \text{ (HLZ [7]);} \tag{2}$$

$$F = \frac{2\lambda}{\pi} = \pm\frac{2}{\pi}, \text{ (Hewett [5]).}$$

Note that F depends explicitly on d only within the HLZ formalism. In both the GRW and HLZ formalisms gravity effects interfere construtively with the SM diagrams. In Hewett's convention the sign of interference is not known, and the interference effects are parameterized via a parameter λ of order one, which is usually taken to be either +1 (constructive interference) or –1 (destructive interference). The parameter η_G has units of TeV^{-4} if M_S is expressed in TeV, and describes the strength of gravity in the presence of LED. The differential or total cross section in the presence of virtual graviton exchange can be parameterized as:

$$\sigma_{\rm tot} = \sigma_{\rm SM} + \eta_G \sigma_{\rm int} + \eta_G^2 \sigma_G, \qquad (3)$$

where $\sigma_{\rm SM}$ is the SM cross section for the process under study and $\sigma_{\rm int}$, σ_G are the interference and direct graviton effects, respectively. Existing collider experimental data analysis gave no observation of LED effects, but only constraints. Indirect graviton effects at LHC were searched for in processes of lepton and photon pair production. The corresponding constraints on M_S (HLZ) obtained from LHC data were found to be around 4.18 TeV (ATLAS) and 4.77 TeV (CMS) for $d = 3$.

A general feature of the different theories extending the SM of elementary particles is that new interactions involving heavy elementary objects and mass scales should exist, and manifest themselves *via* deviations of measured observables from the SM predictions. Here, we consider a case when the heavy intermediate states could not be produced even at the highest energy supercolliders and, correspondingly, only "virtual" effects can be expected. A description of the relevant new interaction in terms of "effective" contact-interaction (CI) is most appropriate in this case. Of course, since different interactions can give rise to similar deviations from the SM predictions, the problem is to identify, from a hypothetically measured deviation, the kind of new dynamics underlying it. We shall here discuss the possibility of distinguishing such effects of extra dimensions from other new physics (NP) scenarios in lepton pair production at the LHC:

$$q\bar{q} \to \gamma,\ Z \to l^+ l^-, \qquad (4)$$

where $l = e;\ \mu$. The dominant Feynman diagrams that contribute to this process in ADD model are shown in Fig. 1.

Since the LED contribution to SM pair production proceeds through a KK tower of graviton states with a closely spaced mass spectrum, the extra-dimensional signal does not appear as a single resonance, but rather as an enhancement of the production cross section at high invariant mass where the SM contribution is rapidly falling and a large number of gravitons can be produced or, equivalently, more modes of the momentum in the bulk can be excited.

Discovery reach. At hadron colliders in the SM lepton pairs can be produced at tree-level via the following parton-level process

$$q\bar{q} \to \gamma,\ Z \to l^+ l^-. \qquad (5)$$

Now, if gravity can propagate in extra dimensions, the possibility of KK graviton exchange opens up two tree-level channels in addition to the SM channels, namely

$$q\bar{q} \to G \to l^+ l^-,\ gg \to G \to l^+ l^-, \qquad (6)$$

where G_n^* represents the gravitons of the KK tower.

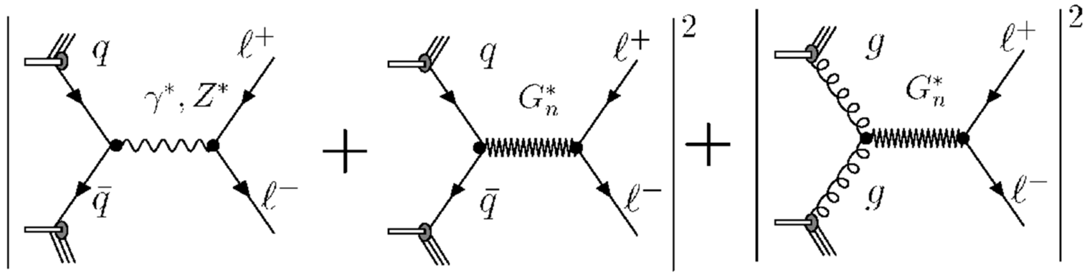

Fig. 1. Feynman diagrams for dilepton production at leading order in ADD model

To estimate the discovery reach of graviton towers in ADD model one can use the invariant mass distributions of lepton pairs that have significantly different behavior in the SM and the ADD model. As an illustration, Fig. 2 shows the dilepton invariant mass spectrum for the case of M_S = 6 TeV and d = 3 and d = 6 with constructive interference between the SM and LED diagrams. The LED signal clearly stands out above the background at higher values of the invariant mass.

The results of the χ^2 analysis are demonstrated in Fig. 4. In particular, Fig. 4 shows discovery reach on cutoff scale M_S at 95 % CL. for d = 3 and d = 6 as a function of integrated luminosity of the LHC.

Center-edge assymetry and identification reach. In practice the asymmetry, which is defined based on the angular distribution of the final states in scattering or decay processes, can be utilized to scrutinize underlying dynamics in NP beyond the SM. As one of the possible NP which might be discovered early at the LHC, LED are theoretical well motivated. Once LED are discovered at the LHC, it is crucial to discriminate the different NP scenarios that can lead to the same or very similar experimental signatures. In principle such task can be accomplished by measuring the angular distribution of the lepton final states which are produced via G_n^*-mediated processes. In the real data analysis, asymmetry is always adopted. In [6] center-edge asymmetry has been proposed at LHC for such kind of analysis.

The center–edge and total cross sections at the parton level can be defined as:

$$\hat{\sigma}_{CE} \equiv \left[\int_{-z^*}^{z^*} - \left(\int_{-1}^{-z^*} + \int_{z^*}^{1} \right) \right] \frac{d\hat{\sigma}}{dz} dz,$$

$$\hat{\sigma} = \int_{-1}^{1} \frac{d\hat{\sigma}}{dz} dz, \tag{7}$$

where $z = \cos\hat{\theta}$, with $\hat{\theta}$ the angle, in the c.m. frame of the two leptons, between the lepton and the proton. Here, $0 < z^* < 1$ is a parameter which defines the border between the "center" and the "edge" regions.

For illustrative purposes we show in Fig. 3 the bin integrated angular distributions for lepton pair production at LHC in the SM and ADD scenario integrated over lepton pair invariant mass in the range between 1500 GeV and 2000 GeV at M_S = 6 TeV and d = 3 and 6.

The center-edge asymmetry at hadron level for a given dilepton invariant mass can be defined as

$$A_{CE}(M_{ll}) = \frac{d\sigma_{CE}/dM_{ll}}{d\sigma/dM_{ll}}, \tag{8}$$

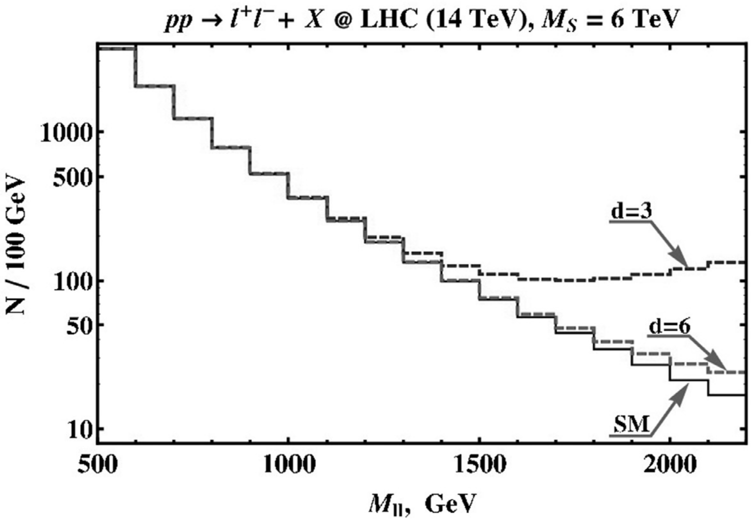

Fig. 2. Effects of extra dimensions on the dilepton mass spectrum at histograms show the spectrum in the SM as well as in ADD scenario with cutoff M_S = 6 TeV and different number of extra dimensions (d = 3 and 6) at LHC with s = 14 TeV and integrated luminosity 100 fb^{-1}

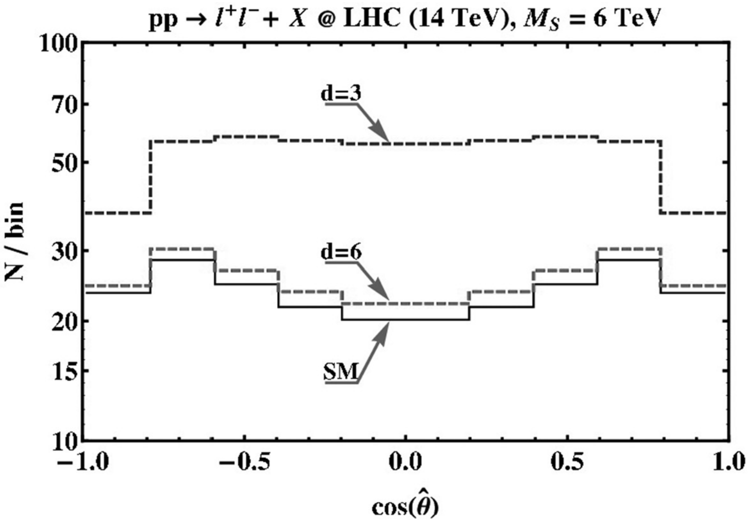

Fig. 3. Bin integrated angular distributions for lepton pair production at LHC in the SM and ADD scenario integrated over lepton pair invariant mass in the range between 1500 GeV and 2000 GeV at M_S = 6 TeV and d = 3 and 6

For the SM contribution to the center–edge asymmetry, the convolution integrals, depending on the parton distribution functions, cancel, and one finds

$$A_{CE}^{\rm SM} = \frac{1}{2} z^* \left(z^{*2} + 3 \right) - 1. \qquad (9)$$

This result is thus independent of the dilepton mass M_{ll}, and identical to the result for e^+e^- colliders.

The SM center-edge asymmetry of Eq. (9) is equally valid for a wide variety of NP models: composite-like contact interactions, heavy Z' bosons, TeV-scale gauge bosons, *etc*. However, if graviton tower exchange is possible, the graviton tensor couplings would yield a different angular distribution, leading to a different dependence of A_{CE} on z^*. In this case, the center-edge asymmetry would not vanish for the above choice of $z^* = z_0^*$. Furthermore, it would show a non-trivial dependence on M_{ll}. Thus, a value for A_{CE} different from $A_{CE}^{\rm SM}$ would indicate non-vector-exchange of NP.

Another important difference from the SM case and NP CI-like scenarios is that the graviton also couples to gluons, and therefore it has the additional gg initial state of Eq. (6) available. In summary then, including graviton exchange and also experimental cuts relevant to the LHC detectors, the center–edge asymmetry is no longer the simple function of z^* given by Eq. (9).

We assume now that a deviation from the SM is discovered in the cross section in the form of "effective" CI. We will here investigate in which regions of the ADD parameter spaces such a deviation can be *identified* as being caused by spin-2 exchange. More precisely, we will see how the center–edge asymmetry (9) can be used to exclude spin-1 exchange interactions beyond that of the SM.

We define the bin-integrated center–edge asymmetry:

$$A_{CE} = \frac{\int_i \frac{d\sigma_{CE}}{dM_{ll}} dM_{ll}}{\int_i \frac{d\sigma}{dM_{ll}} dM_{ll}}, \qquad (10)$$

where i being bin in M_{ll}. To determine the underlying new physics (spin-1 vs. spin-2 couplings) one can introduce the deviation of the measures center-edge asymmetry from that expected from pure spin-1 exchange, $A_{CE}^{\text{spin-1}}(i)$, in each i-th bin.

$$\Delta A_{CE}(i) = A_{CE}^{\text{spin-2}}(i) - A_{CE}^{\text{spin-1}}(i). \qquad (11)$$

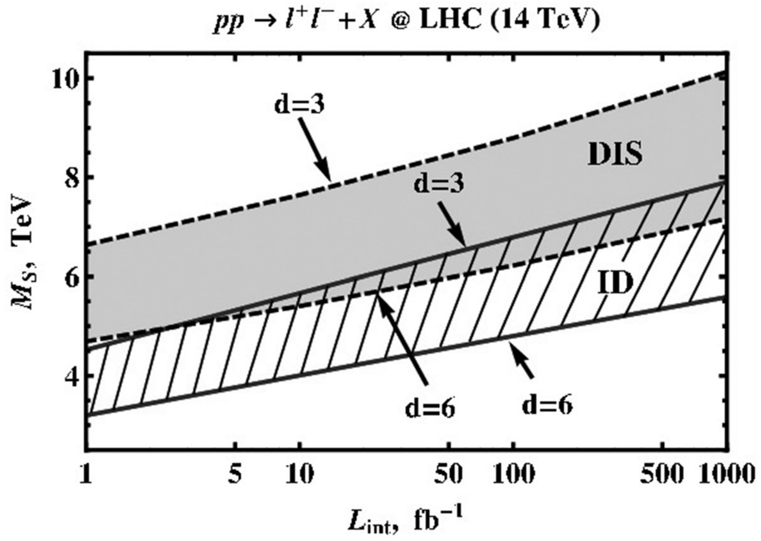

Fig. 4. Discovery (gray band) and identification (hatched band) reaches on M_S (in TeV) at 95% CL as a function of integrated luminosity L_{int} for different number of extra dimensions (d = 3–6) at the LHC with 14 TeV.

The bin-integrated statistical uncertainty is then given as

$$\delta A_{CE}(i) = \sqrt{\frac{1 \quad A_{CE}(i)}{\varepsilon_{ll} L_{\text{int}} \sigma(i)}} \tag{12}$$

based on the number of events that are effectively detected and the A_{CE} that is actually measured. In the ADD scenario, the identification reach in M_S can be estimated from a χ^2 analysis:

$$\chi^2 = \sum_i \left[\frac{\Delta A_{CE}(i)}{\delta A_{CE}(i)} \right]^2, \tag{13}$$

where i runs over the different bins in M_{ll} . The 95% CL is then obtained by requiring one-parameter fit.

From a conventional χ^2 analysis we find the ADD-scenario *identification* reach on M_S at the LHC. The results are summarized in Fig. 4 which shows the identification reaches for different number of extra dimensions (d = 3; 6) as a function of integrated luminosity L_{int}.

In conclusion, a method proposed here and based on A_{CE} is suitable for actually *pinning down* the spin-2 nature of the KK gravitons up to very high M_S close to discovery reach. Therefore, the analysis sketched here can potentially represent a valuable method complementary to the direct fit to the angular distribution of the lepton pairs. We find that for $\sqrt{s} = 14$ TeV and L_{int} = 100 fb^{-1} the LHC detectors will be capable of discovering and identifying graviton spin-2 exchange effects in the ADD scenario with M_S^{DIS} = 6.2 TeV (M_S^{ID} = 4.8 TeV) for d = 6 and M_S^{DIS} = 8.8 TeV (M_S^{ID} = 6.8 TeV) for d = 3.

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