Center-Edge Asymmetry as a Tool for Revealing Large Extra Dimensions at LHC

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Abstract

Arkani-Hamed, Dimopoulos and Dvali proposed a model in which gravity propagates freely in d extra compact spatial dimensions. The prospects of discovery and identification of large extra spatial dimensions effects in the processes of lepton and photon pair production at the Large Hadron Collider (LHC) were studied. These effects can be found by the specific behavior of the invariant mass distributions of the lepton and photon pairs. Identification of the effects under study can be performed with angular distributions of lepton and photon pairs. Discovery and identification reach on the mass scale parameter M_S can be obtained for graviton Kaluza – Klein towers in lepton and photon pair production processes at the LHC.

1 Introduction

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,

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proposed by Arkani-Hamed, Dimopoulos, and Dvali [1], the fermions and gauge bosons of the Standard Model (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 $\mathcal{O}(1\text{ TeV})$, 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

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

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 dimensions.

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 [2–4]. In all of them, the effects of LED are parametrized via a single variable $\eta_G = \mathcal{F}/M_S^4$, where $\mathcal{F}$ is a dimensionless parameter of order one reflecting the dependence of virtual G_n^* exchange on the number of extra dimensions, and M_S is the ultraviolet cutoff. Different formalisms use different definitions of $\mathcal{F}$, which result in different definitions of M_S:

$$\mathcal{F} = \begin{cases} 1, & \text{(GRW [3]);} \\ \frac{2}{d-2}, d > 2, & \text{(HLZ [4]);} \\ \frac{2\lambda}{\pi} = \pm\frac{2}{\pi}, & \text{(Hewett [2]).} \end{cases} \tag{2}$$

Note that $\mathcal{F}$ 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 intereference 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:

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

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 the 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 5.2 TeV (ATLAS) [5] and 4.8 TeV (CMS) [6] 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 an alternative to LED 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

$$p + p \to l^+ l^- + X, \tag{4}$$

where $l = e, \mu$, and photon pair production at the LHC:

$$p + p \to \gamma\gamma + X. \tag{5}$$

2 Discovery reach in the dilepton channel

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

$$q\bar{q} \to \gamma, Z \to l^+ l^-. \tag{6}$$

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

$$q\bar{q} \to G_n^* \to l^+l^- \quad \text{and} \quad gg \to G_n^* \to l^+l^-, \tag{7}$$

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

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.

Discovery reach of graviton towers in the ADD model can be determined with χ^2 function defined as

$$\chi^2 = \sum_i \left(\frac{\Delta N_i}{\delta N_i}\right)^2, \tag{8}$$

where $N_i = \varepsilon_{l^+l^-}\mathcal{L}_{\text{int}}\sigma_i$, $\varepsilon_{l^+l^-} = 90\%$, $\Delta N_i = N_i^{\text{ADD}} - N_i^{\text{SM}}$, $\delta N_i = \sqrt{N_i}$. Here, $\mathcal{L}_{\text{int}}$ is time integrated luminosity, $\varepsilon_{l^+l^-}$ reconstruction efficiency of the dilepton, σ_i is integrated cross-section within the i-th bin. Summation in Eg. (8) runs over 15 bins with the width of 100 GeV in the range of 500 GeV and 2000 GeV. The results of the χ^2 analysis are demonstrated in Fig. 1. In particular, Fig. 1 shows discovery reach on cutoff scale M_S at 95% C.L. for $d = 3$ and $d = 6$ as a function of integrated luminosity of the LHC.

3 Center-edge asymmetry and identification reach in the dilepton channel

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 new physics (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

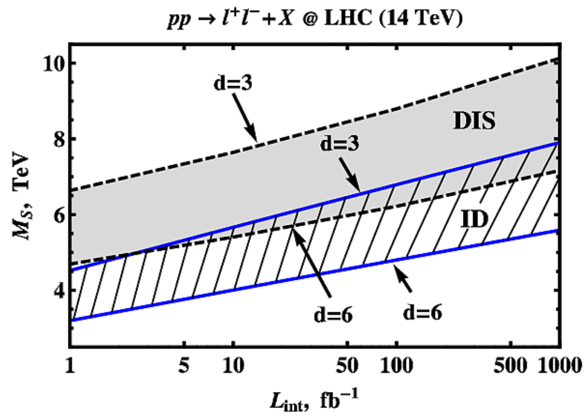

Figure 1: Discovery (gray band) and identification (hatched band) reaches on M_S (in TeV) at 95% CL as a function of integrated luminosity $\mathcal{L}_{\rm int}$ for different number of extra dimensions ($d = 3-6$) at the LHC with 14 TeV.

analysis, asymmetry is always adopted. In [7–9] 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:

$$\hat{\sigma}_{\rm CE} \equiv \left[\int_{-z^*}^{z^*} - \left(\int_{-1}^{-z^*} + \int_{z^*}^{1}\right)\right] \frac{d\hat{\sigma}}{dz}\, dz,$$
$$\hat{\sigma} \equiv \int_{-1}^{1} \frac{d\hat{\sigma}}{dz}\, dz, \tag{9}$$

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.

The center–edge asymmetry at hadron level for a given dilepton invariant mass M_{ll} can be defined as

$$A_{\rm CE}(M_{ll}) = \frac{d\sigma_{\rm CE}/dM_{ll}}{d\sigma/dM_{ll}}, \tag{10}$$

where a convolution over parton momenta is performed, and we obtain $d\sigma_{\rm CE}/dM_{ll}$ and $d\sigma/dM_{ll}$ from the inclusive differential cross sections $d\sigma_{\rm CE}/dM_{ll}\, dy\, dz$ and $d\sigma/dM_{ll}\, dy\, dz$, respectively, by integrating over z according to Eq. (9) and over rapidity y between $-Y$ and Y, with $Y = \log(\sqrt{s}/M_{ll})$.

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

$$A_{\rm CE}^{\rm SM} = \frac{1}{2} z^*(z^{*2} + 3) - 1. \tag{11}$$

This result is thus independent of the dilepton mass M_{ll}, and identical to the result for e^+e^- colliders. Hence, in the case of no cuts on the angular integration, there is a unique value, $z^* = z_0^* \simeq 0.596$, for which $A_{\rm CE}^{\rm SM}$ vanishes, corresponding to $\hat{\theta} = 53.4^\circ$.

The SM center-edge asymmetry of Eq. (11) is equally valid for a wide variety of NP models: composite-like contact interactions, heavy Z' bosons [10], 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 $A_{\rm CE}$ 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 $A_{\rm CE}$ different from $A_{\rm CE}^{\rm SM}$ 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. (7) 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. (11).

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 (10) can be used to exclude spin-1 exchange interactions beyond that of the SM.

We define the bin-integrated center–edge asymmetry:

$$A_{\rm CE}(i) = \frac{\displaystyle\int_i \frac{d\sigma_{\rm CE}}{dM_{ll}} dM_{ll}}{\displaystyle\int_i \frac{d\sigma}{dM_{ll}} dM_{ll}}, \tag{12}$$

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 measured center–edge asymmetry from that expected from pure spin-1 exchange, $A_{\rm CE}^{\rm spin-1}(i)$, in each i-th bin,

$$\Delta A_{\rm CE}(i) = A_{\rm CE}^{\rm spin-2}(i) - A_{\rm CE}^{\rm spin-1}(i). \tag{13}$$

The bin-integrated statistical uncertainty is then given as

$$\delta A_{\rm CE}(i) = \sqrt{\frac{1 - A_{\rm CE}^2(i)}{\epsilon_{l^+l^-}\mathcal{L}_{\rm int}\sigma(i)}}, \tag{14}$$

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

$$\chi^2 = \sum_i \left[\frac{\Delta A_{\rm CE}(i)}{\delta A_{\rm CE}(i)}\right]^2, \tag{15}$$

where i runs over the different bins in M_{ll}. The 95% CL is then obtained by requiring $\chi^2 = 3.84$, as pertinent to a 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. 1 which shows the identification reaches for different number of extra dimensions ($d = 3$, 6) as a function of integrated luminosity $\mathcal{L}_{\rm int}$.

In conclusion, a method proposed here and based on $A_{\rm CE}$ 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 $\mathcal{L}_{\rm int} = 100$ 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 $d = 3$.

4 Effects of LED in the diphoton channel

The process of photon pairs production

$$p + p \to \gamma\gamma + X \tag{16}$$

is one of the important processes at the hadron colliders and has been used to do precision of the SM. Also it provides a laboratory for probing new physics (CI, unparticles, supersymmetry, extra dimensions, etc.).

A unique feature of the process of photon pairs production in the ADD model compared with the lepton channel of Drell - Yan process is that intermediate states in this process can only be scalar and tensor particles whereas in dileptonic production does not exclude the possibility of the existence vector state. The Landau-Yang theorem [11, 12] forbids decays of vector particle into two photons. As an intermediate state, we consider the scalar unparticle [13, 14]. Reducing the number of hypothetical intermediate states in the Born approximation effectively leads to "enhance" the sensitivity of the observed values for dynamic parameters graviton towers and, thereby, expands the identification reach of graviton exchange towers in the ADD model.

4.1 Discovery reach

At hadron colliders in the ADD model photon pairs can be produced via the following parton-level process, namely

$$q + \overline{q} \to \gamma + \gamma \quad \text{and} \quad g + g \to \gamma + \gamma. \tag{17}$$

The differential cross section for the subprocess $q\overline{q} \to \gamma\gamma$, defined by the t - and u - channel diagrams in the SM and exchange graviton states in the s - channel, in the approximation of massless fermions can be written as:

$$\frac{d\sigma(q\bar{q} \to \gamma\gamma)}{dz} = \frac{1}{96\pi\hat{s}}\left[2e^4 Q_q^4 \frac{1+z^2}{1-z^2} + 2\pi e^2 Q_q^2 \frac{\hat{s}^2}{M_S^4}(1+z^2)\,\mathcal{F} + \frac{\pi^2}{2}\frac{\hat{s}^4}{M_S^8}(1-z^4)\,\mathcal{F}^2\right], \tag{18}$$

where $\mathcal{F}$ is defined in Eq.(2).

Here $\sqrt{\hat{s}} \equiv M_{\gamma\gamma}$ is an invariant mass of photon pairs, $z \equiv \cos\theta_{\rm cm}$, $\theta_{\rm cm}$ - angle in the center-of-mass photons, Q_q - quark electric charge q.

The differential cross section for the subprocess $gg \to \gamma\gamma$:

$$\frac{d\sigma(gg \to \gamma\gamma)}{dz} = \frac{\pi}{512}\frac{\hat{s}^3}{M_S^8}(1+6z^2+z^4)\,\mathcal{F}^2\ , \tag{19}$$

where the factor $\mathcal{F}$ is given in Eq.(2).

Discovery reach of graviton towers in the ADD model can be determined with χ^2 function. The requirement on the functions $\chi^2 = 3{,}84$ provides a limit on the parameter M_S, called as discovery reach with a confidence level is 95%.

4.2 Identification reach

The present analysis is aimed at determining an interval of values for the scale parameter M_S (at fixed d) such that, within this interval, the ADD model (which, in the following, is called a "correct" model) can be statistically separated at a preset confidence level from competing new physics models that could mimic experimentally effects of the correct model and which have a different physical nature (from Georgi's unparticle physics model in the case being considered) at any values of their parameters. Below, we refer to such competing models as tested models and to the boundary value for the M_S range in question as the identification reach for the ADD model. In order to separate effects of the correct and tested models, we introduce the function χ^2 by analogy with that which was used to estimate the identification reaches for M_S on the basis of expression (15). For the problem at hand, the function χ^2 has the form

$$\chi^2 = \left(\frac{A_{CE}^{\mathrm{ADD}} - A_{CE}^{\mathrm{NG}}}{\delta A_{CE}^{\mathrm{ADD}}} \right)^2 , \tag{20}$$

where A_{CE}^{NG} is the asymmetry center-edge in the Georgi's unparticle-physics model, $\delta A_{CE}^{\mathrm{ADD}}$ is the respective statistical uncertainty within the correct ADD model.

In order to separate effects induced by graviton towers and Georgi's unparticles in the process (4), we will make use of the criterion $\chi^2 = 3.84$ for the function χ^2 defined by expression (20). Results of numerical analysis for discovery and identification reach are shown in Fig. 2.

5 Conclusion

Along with contact interactions, effects of the exchange of KK graviton towers within the ADD model, which involves extra spatial dimensions, may become among the first new physics effects that would be discovered

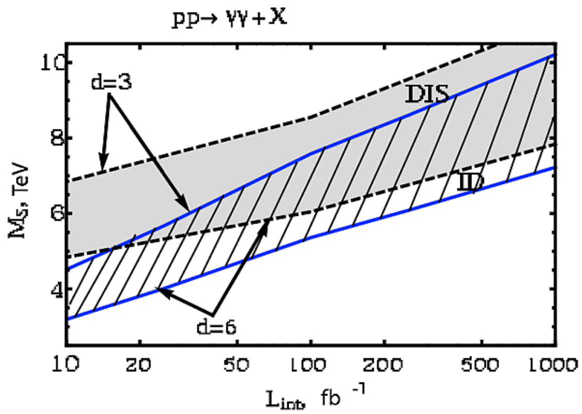

Figure 2: Discovery (gray band) and identification (hatched band) reaches on M_S (in TeV) at 95% CL as a function of integrated luminosity $\mathcal{L}_{\rm int}$ for different number of extra dimensions ($d = 3-6$) at the LHC with 14 TeV.

at the LHC. The Drell-Yan process of dilepton production is one of the most efficient channels of searches for new intermediate states owing to a strong suppression of background processes and a high efficiency of dilepton identification. In many respects, the same applies to diphoton production. If, in the dilepton and/or in the diphoton channel, experiments exhibit some indirect new physics effects, such as a deviation of the dilepton or diphoton invariant mass distribution from the respective predictions of the SM, then the next step in studying the nature of this new phenomenon will consist in determining the spin of the respective intermediate state. In the present study, we have explored prospects of the discovery and identification of indirect effects of the exchange of Kaluza-Klein graviton towers, whose existence is predicted by the ADD model featuring extra spatial dimensions, in the processes of dilepton and diphoton production in the ATLAS experiment at the LHC. Searches for these new effects are based on looking for characteristic features in the behavior of the dilepton and diphoton spectra. As for the identification of the intermediate state spin, it is being performed in terms of the center-edge asymmetry. The results of our numerical analysis aimed at the search for and the identification of effects of extra spatial dimensions in the dilepton and diphoton channels are summarized in Table. 1.

Table 1: Discovery and identification reach on M_S (in TeV) at the LHC

M_S (TeV)	l^+l^- DIS (ID)	$\gamma\gamma$ DIS (ID)
$d=3$	8.8 (6.8)	8.5 (7.6)
$d=6$	6.2 (4.8)	6.0 (5.4)

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