SEARCH FOR AND IDENTIFICATION OF GRAVITON EXCHANGE EFFECTS IN DRELL-YAN PROCESS AT LARGE HADRON COLLIDER

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ABSTRACT. New physics signatures arising from different sources may be confused when first observed at future colliders. Thus it is important to examine how various scenarios may be differentiated given the availability of only limited information. Here, we explore the capability of the Large Hadron Collider (LHC) 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 the LHC with planned energies and luminosities will be capable of discovering (and identifying) graviton exchange effects in the large extra dimensions with the cutoff parameter of order 4.6 - 9.4 TeV (3.6 - 6.0 TeV) depending on energy, luminosity and number of extra dimensions.

Key words: Kaluza-Klein models, extra dimensions, four-fermion contact interactions; Large Hadron Collider, ADD model

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 one such scenario, proposed by Arkani-Hamed, Dimopoulos, and Dvali (ADD) [Arkani-Hamed, 1998], 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 n 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 n extra dimensions (R) and the Planck scale on the brane (M_{Pl}) are related via

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

a purely classical relationship calculated by applying the $4+n$ 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.

One important consequence for physics in the brane is that the discrete momentum modes of excitation of the graviton transverse to the brane propagate in our three ordinary dimensions as different mass states. Analogously to the momentum states, the spacing between these mass states is proportional to $1/R$. This collection of mass states forms what is known as a Kaluza-Klein (KK) tower of gravitons. The tower can in principle extend up to infinity, but there is a cutoff imposed by the fact the effective theory breaks down at scales above M_S and this effective theory is valid up to a scale of about M_S. Specifically, the sum over the (almost continuous) spectrum of KK states (of mass $m_{\vec{n}}$) can be expressed as [Hewett, 1999]:

$$\sum_{\vec{n}=1}^{\infty} \frac{G_{\rm N}}{M^2 - m_{\vec{n}}^2} \to \frac{-\lambda}{\pi\, M_S^4}, \tag{2}$$

where λ is a sign factor, $G_{\rm N}$ is Newton's constant, and M_S is the cutoff scale, expected to be of the order of the TeV scale. Equation (2) can be considered as an effective interaction at the scale M_S. λ is a dimensionless parameter of $\mathcal{O}(1)$. The different signs of λ allow for different signs of the interference between SM and LED graphs.

There are several conventions for the parameter λ/M_S^4. In Hewett convention [Hewett, 1999], $\lambda = 1$ for constructive interference and $\lambda = -1$ for destructive interference. Other popular conventions are those of Giudice, Rattazzi, Wells (GRW) [Giudice, 1999], and Han, Lykken, Zhang (HLZ) [Han, 1999]. To translate results from Hewett to GRW convention one simply multiplies M_S(Hewett) by $\sqrt[4]{\pi/2}$ (constructive interference only). In HLZ convention the dependence on the number of extra dimensions n is calculated and it is incorporated into λ. For $n > 2$:

$$M_S(\mathrm{HLZ}) = \sqrt[4]{\frac{\pi}{2}\left(\frac{2}{n-2}\right)}\, M_S(\mathrm{Hewett}). \qquad (3)$$

Note, that at $n = 5$, $M_S(\mathrm{HLZ}) \approx M_S(\mathrm{Hewett})$. In both the GRW and HLZ formalisms gravity effects interfere constructively with the SM diagrams. Throughout the paper we will follow the HLZ parametrization.

The existence of KK gravitons can be tested at colliders by searching for two different processes: real graviton emission and virtual graviton exchange. At leading order, virtual graviton exchange includes processes in which a virtual graviton is produced by the annihilation of two SM particles in the initial state, the graviton then propagates in the extra dimension and finally decays into SM particles that appear in the brane. Real graviton production occurs when a graviton is produced together with something else by the interaction of SM particles and escapes into the extra dimensions, leaving behind missing energy. 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 boson pair production. The corresponding constraints on M_S (HLZ) obtained from LHC data was found to be around 4.18 TeV for $n = 3$ [Aad, 2013].

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. While for the supersymmetric extensions of the SM, there is confidence that the new particles could be directly produced and their properties studied, in numerous other cases, such as the composite models of fermions and the exchange of leptoquarks, existing limits indicate that the heavy 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 these cases. 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:

$$p + p \to l^+l^- + X, \qquad (4)$$

where $l = e, \mu$. The dominant Feynman diagrams that contribute to this process in ADD model is shown in Fig. 1. When KK gravitons are included, new diagrams with respect to the SM ones appear as shown in Fig. 1.

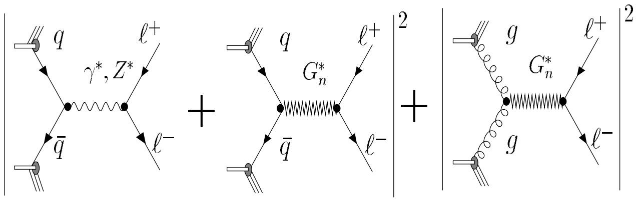

Figure 1: Feynman diagrams for dilepton production at leading order in ADD model.

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.

2. Discovery reach

In the SM, lepton pairs can at hadron colliders 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

$$q\bar{q} \to G_n^* \to l^+l^- \quad \text{and} \quad gg \to G_n^* \to l^+l^-, \qquad (6)$$

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. As an illustration, Fig. 2 shows the dilepton invariant mass spectrum for the case of $M_S = 4$ TeV and $n = 3$, 4, 5 and 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. Events predicted by the SM are generated by the PYTHIA 6.325 Monte Carlo (with default PDF CTEQ6L) while ADD expectations were generated by STAGEN 1.05 code.

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

$$\chi^2 = \sum_{bin}\left(\frac{\Delta N_{bin}}{\delta N_{bin}}\right)^2, \qquad (7)$$

where $N_{bin} = \varepsilon_{l^+l^-}\mathcal{L}_{\mathrm{int}}\sigma_{bin}$, $\varepsilon_{l^+l^-} = 90\%$, $\Delta N_{bin} = N_{bin}^{\mathrm{ADD}} - N_{bin}^{\mathrm{SM}}$, $\delta N_{bin} = \sqrt{N_{bin}}$. Here, $\mathcal{L}_{\mathrm{int}}$ is time integrated luminosity, $\varepsilon_{l^+l^-}$ reconstruction efficiency of

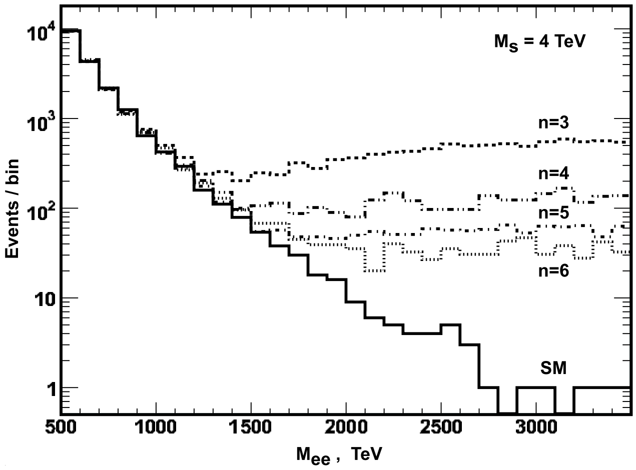

Figure 2: Effects of extra dimensions on the dilepton mass spectrum at LHC. Histograms show the spectrum in the SM as well as in ADD scenario with cutoff $M_S =$ 4 TeV and different number of extra dimensions ($n = 3 - 6$) and at integrated luminosity 100 fb^{-1}.

the dilepton, σ_{bin} is integrated cross-section within the bin. Summation in Eg. (7) runs over 17 bins with the width of 100 GeV in the range of 500 GeV and 2200 GeV.

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

3. Center–Edge Asymmetry $A_{\rm CE}$

The center–edge and total cross sections can at the parton level be defined as [Osland, 2003], [Osland, 2008]:

$$\hat{\sigma}_{\rm CE} \equiv \left[\int_{-z^*}^{z^*} - \left(\int_{-1}^{-z^*} + \int_{z^*}^{1}\right)\right] \frac{d\hat{\sigma}}{dz}\,dz,$$
$$\hat{\sigma} \equiv \int_{-1}^{1} \frac{d\hat{\sigma}}{dz}\,dz, \qquad (8)$$

where $z = \cos\theta_{\rm cm}$, with $\theta_{\rm cm}$ 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 can then for a given dilepton invariant mass M be defined as

$$A_{\rm CE}(M) = \frac{d\sigma_{\rm CE}/dM}{d\sigma/dM}, \qquad (9)$$

where a convolution over parton momenta is performed, and we obtain $d\sigma_{\rm CE}/dM$ and $d\sigma/dM$ from the inclusive differential cross sections $d\sigma_{\rm CE}/dM\,dy\,dz$ and $d\sigma/dM\,dy\,dz$, respectively, by integrating over z according to Eq. (8) and over rapidity y between $-Y$ and Y, with $Y = \log(\sqrt{s}/M)$.

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

$$A_{\rm CE}^{\rm SM} = \frac{1}{2}z^*(z^{*2}+3) - 1. \qquad (10)$$

This result is thus independent of the dilepton mass M, 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 $\theta_{\rm cm} = 53.4°$.

The SM center-edge asymmetry of Eq. (10) is equally valid for a wide variety of NP models: composite-like contact interactions, Z' models, TeV-scale gauge bosons, *etc.* However, if graviton 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. 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 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. (10).

4. Numerical analysis and concluding remarks

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. At the LHC, with luminosity $\mathcal{L}_{\rm int} = 10$, 100 and 1000 fb^{-1}, we require the invariant lepton mass $M > 500$ GeV and divide the data into 100 GeV bins as long as the number of events in each bin, $\epsilon_l \mathcal{L}_{\rm int}\sigma(i)$, is larger than 10. Here, ϵ_l ($l = e, \mu$) is the experimental reconstruction efficiency and $\sigma(i)$ the cross section in bin i.

In order to get more statistics, one may integrate over bins i in M. We therefore define the bin-integrated center–edge asymmetry by introducing such an integration,

$$A_{\rm CE}(i) = \frac{\displaystyle\int_i \frac{d\sigma_{\rm CE}}{dM} dM}{\displaystyle\int_i \frac{d\sigma}{dM} dM}. \qquad (11)$$

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, $A_{\rm CE}^{\rm spin-1}(i)$ (which in our approach is zero), in each bin,

$$\Delta A_{\rm CE}(i) = A_{\rm CE}^{\rm spin-2}(i) - A_{\rm CE}^{\rm spin-1}(i). \qquad (12)$$

The bin-integrated statistical uncertainty is then given as

$$\delta A_{\rm CE}(i) = \sqrt{\frac{1 - A^2_{\rm CE}(i)}{\epsilon_l \mathcal{L}_{\rm int} \sigma(i)}}, \qquad (13)$$

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:

$$\chi^2 = \sum_i \left[\frac{|\Delta A_{\rm CE}(i)|}{\delta A_{\rm CE}(i)}\right]^2, \qquad (14)$$

where i runs over the different bins in M. The 95% CL is then obtained by requiring $\chi^2 = 3.84$, as pertinent to a one-parameter fit.

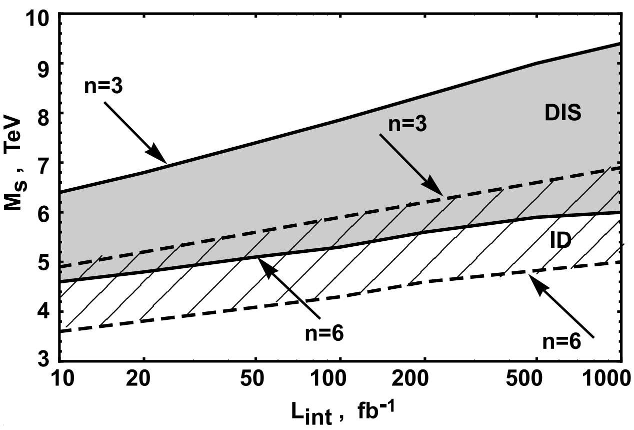

Figure 3: Discovery (gray band) and identification (hatched band) reaches on M_S (in TeV) at 95% CL for different number of extra dimensions ($n = 3 - 6$) at the LHC with 14 TeV.

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. 3 which shows the identification reaches for different number of extra dimensions (n = 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 the LHC detectors will be capable of discovering and identifying graviton spin-2 exchange effects in the ADD scenario with M_S ranging in 4.6 - 9.4 TeV (3.6 - 6.0 TeV) depending on luminosity and number of extra dimensions.

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