Nonlinear Phenomena in Complex Systems, vol. **17**, no. 4 (2014), pp. 417 - 419

Identifying Large Extra Dimensions in Dilepton Production at the Large Hadron Collider

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(Received 05 September, 2014)

By considering the present and future LHC energy regimes, we reanalyze the potential of the LHC to discover the effects of large extra dimensions and to discriminate between various theoretical models. We explore the capability of the LHC to distinguish spin-2 Kaluza–Klein towers of gravitons exchange from other new physics effects which might be conveniently parameterized by the four-fermion contact interactions. We find that the LHC with planned energy 14 TeV and luminosity 100 fb^{-1} will be capable of discovering (and identifying) graviton exchange effects in the large extra dimensions with the cutoff parameter of order $M_S = 6.2$ TeV (4.8 TeV) for $d = 6$ and $M_S = 8.8$ TeV (6.8 TeV) for $d = 3$.

PACS numbers: 12.60.-i, 14.80.Rt
Keywords: large extra dimensions, Kaluza–Klein towers, new physics effect

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, proposed by Arkani-Hamed, Dimopoulos, and Dvali [1], 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. 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 $M_{Pl}^2 \propto M_S^{d+2} R^d$, other SM interactions are explained by the suppression of the gravitational field flux by a factor proportional to the volume of the extra dimensions.

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 heavy intermediate states could not be produced even at the highest energy supercolliders and, correspondingly, only "virtual" effects can be expected. 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:

$$p + p \to l^+ l^- + X. \qquad (1)$$

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.

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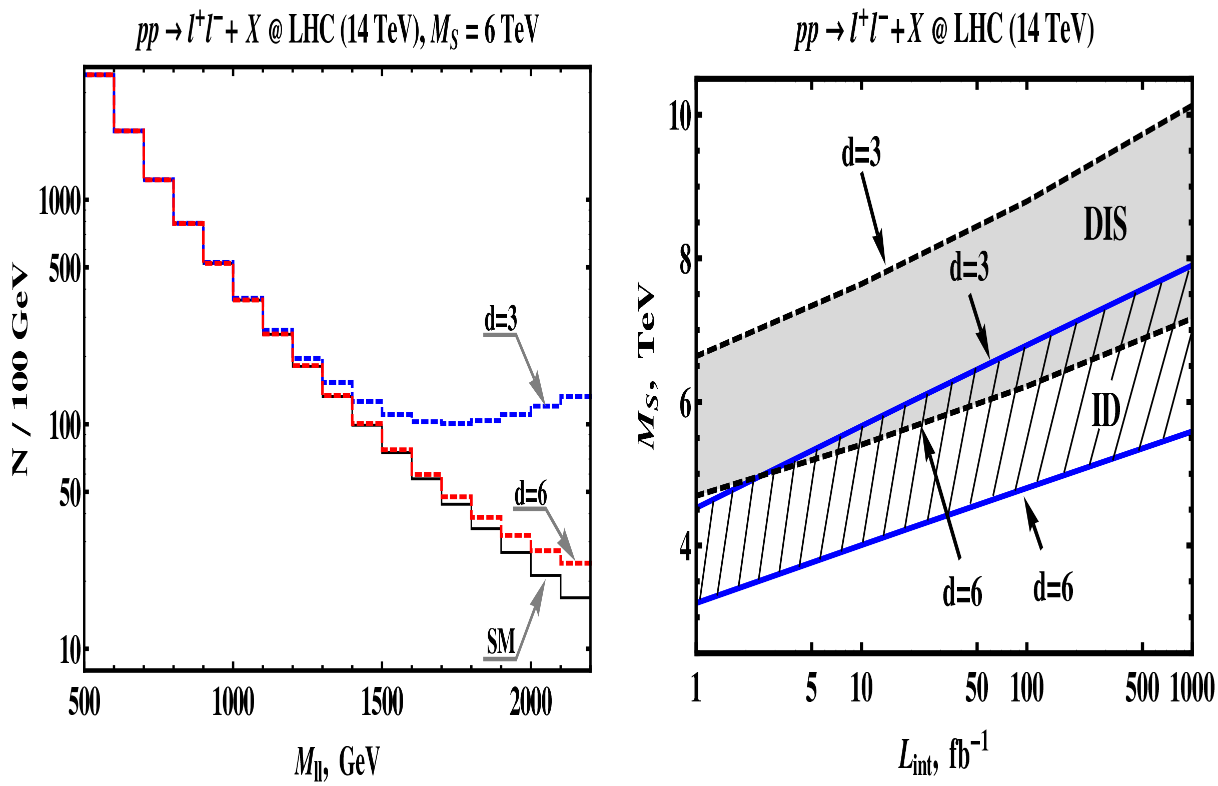

FIG. 1. Left panel: Histograms show the spectrum in the SM as well as in ADD scenario with cutoff $M_S = 6$ TeV and different number of extra dimensions ($d = 3$, 6) at the LHC with $\sqrt{s} = 14$ TeV and integrated luminosity 100 fb^{-1}. Right panel: Discovery (gray band) and identification (hatched 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.

2. Discovery reach

At hadron colliders in the SM lepton pairs can be produced at tree-level via the following parton-level process $q\bar{q} \to \gamma, Z \to l^+l^-$. 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 $q\bar{q} \to G_n^* \to l^+l^-$ and $gg \to G_n^* \to l^+l^-$, 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. 1 (left panel) 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 results of the χ^2 analysis are demonstrated in Fig. 1 (right panel). In particular, Fig. 1 (right panel) (gray band) 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 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 a task can be accomplished by measuring angular distribution of the lepton final states produced via G_n^*-mediated processes.

The center–edge and total cross sections at the parton level can be defined as [2–4]:

$$\hat{\sigma}_{\rm CE} \equiv \left[\int_{-z^*}^{z^*} - \left(\int_{-1}^{-z^*} + \int_{z^*}^{1}\right)\right] \frac{d\hat{\sigma}}{dz}\, dz\ , \qquad \hat{\sigma} \equiv \int_{-1}^{1} \frac{d\hat{\sigma}}{dz}\, dz, \tag{2}$$

where $z = \cos\hat{\theta}$, with $\hat{\theta}$ the angle (in the c.m. frame of 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 SM center-edge asymmetry 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 $A_{\rm CE}$ on z^*. Thus, a value for $A_{\rm CE}$ different from $A_{\rm CE}^{\rm SM}$ would indicate non-vector-exchange of NP. 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. 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 (right panel) which shows the identification reaches for different number of extra dimensions (d = 3, 6) as a function of integrated luminosity $\mathcal{L}_{\rm int}$.

4. 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. 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 $d = 3$.

Acknowledgement

This research has been partially supported by the Abdus Salam ICTP under the TRIL and the Associates Programmes.

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