Search for and identification of indirect and direct graviton effects at LHC

A.A. Pankov*

October 18, 2004

Pavel Sukhoi Technical University of Gomel, 246746 Belarus

Abstract

We study the possibility of using the center–edge asymmetry to distinguish graviton exchange within the ADD and RS scenarios from other new physics effects in lepton-pair production at the LHC. We find that spin-2 and spin-1 exchange can be distinguished up to $M_H \approx$ 5 TeV in the ADD scenario. The LHC detectors will be capable of discovering and identifying graviton resonances predicted in a range of models within the RS scenario.

1 Introduction

Many types of new physics (NP) scenarios are determined by non-standard dynamics involving new forces mediated by exchange corresponding to heavy states with mass scales Λ much greater than M_W. Some of these different scenarios are: composite models of quarks and leptons [1]; exchanges of heavy Z' [2] and (scalar and vector) leptoquarks [3]; R-parity breaking sneutrino exchange [4]; anomalous gauge boson couplings [5]; Kaluza–Klein (KK) graviton exchange, exchange of gauge boson KK towers or string excitations, *etc.* [6]. Unambiguous confirmation of such dynamics would require the experimental discovery of the envisaged new heavy objects and the measurement of their coupling constants to ordinary quarks and leptons. There is a hope that new physics effects will be observed either directly, as in the case of new particle production, e.g., Z' and W' vector bosons, SUSY or Kaluza-Klein

*pankov@ictp.ts.it

(KK) resonances, or indirectly through deviations, from the SM predictions, of observables such as cross sections and asymmetries.

Over the last years, intensive studies have been carried out, of how different scenarios involving extra dimensions would manifest themselves at high energy colliders such as the Large Hadron Collider (LHC) and an e^+e^- Linear Collider (LC) [6]. We shall consider the possibility of distinguishing such effects of extra dimensions from other NP scenarios at hadron colliders, focusing on two specific models involving extra dimensions, namely the Arkani-Hamed–Dimopoulos–Dvali (ADD) [7] and Randall–Sundrum (RS) [8] scenarios with emphasis on the lepton pair production process. These models lead to very different phenomenologies and collider signatures.

The large extra dimension scenario (ADD) predicts the emission and exchange of KK towers of gravitons. The effect of the graviton towers can be described through a set of dimension-8 operators characterized by a large cut-off scale, M_H [6]. The distortion of the differential Drell-Yan cross section at large values of the dilepton invariant mass through these dimension-8 operators can probe such high mass scales in a manner similar to searches for contact interactions in composite models. The shape of the invariant mass distribution will tell us that the underlying physics arises from dimension-8 operators, while the angular distribution of the leptons at large dilepton invariant masses would have the shape expected from the exchange of a spin-2 object, confirming the gravitational origin of the effect.

The phenomenology of the RS model with warped extra dimensions is very different from the ADD model in two aspects: (i) the spectrum of the graviton KK states are discrete and unevenly spaced while it is uniform, evenly spaced, and effectively a continuous spectrum in the ADD model, and (ii) each resonance in the RS model has a coupling strength of 1/TeV while in the ADD model only the collective strength of all graviton KK states gives a coupling strength 1/TeV. The RS model predicts TeV-scale graviton resonances which might be produced in many channels, including the dilepton channel. The spin-2 nature of the graviton resonance can be determined from the distinct shape of the angular distribution of the final state leptons in Drell-Yan production at the Tevatron and LHC.

Many different NP scenarios may lead to the same or very similar experimental signatures. Therefore, searching for effects of extra dimensions can be jeopardized by the misidentification of their signal with other possible sources of new phenomena. Thus, it is important to study how to differentiate the corresponding signals.

One can develop techniques which will help dividing models into distinct subclasses. In this note we shall discuss a technique [9] that makes use of the specific modifications in angular distributions induced by spin-2 exchanges.

This method is based on the center-edge asymmetry $A_{\rm CE}$ [9, 11], an integrated observable which offers a way to uniquely identify KK graviton exchange (or any other spin-2 exchange).

2 The center–edge asymmetry $A_{\rm CE}$

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

$$q\bar{q} \to \gamma, Z \to l^+l^-, \tag{2.1}$$

where we shall use $l = e, \mu$. If gravity can propagate in extra dimensions, the possibility of KK graviton exchange opens up two tree-level channels at hadron colliders in addition to the SM channels, namely

$$\begin{aligned} q\bar{q} &\to G \to l^+l^-, \\ gg &\to G \to l^+l^-, \end{aligned} \tag{2.2}$$

where G represents the gravitons of the KK tower. The Feynman diagrams of this process are shown in Fig. 1. At the LHC, the gluon-fusion channel can give an important contribution, since it has a different angular distribution arising from the difference between the gluon-graviton and quark-graviton couplings, combined with the high gluon luminosities.

Consider a lepton pair of invariant mass M at rapidity y (of the parton c.m. frame) and with $z = \cos\theta_{\rm cm}$, where $\theta_{\rm cm}$ is the angle, in the c.m. frame of the two leptons, between the lepton (l^-) and the proton P_1. The inclusive differential cross section for producing such a pair, can at the LHC proton-proton collider be expressed as

$$\begin{aligned} \frac{d\sigma_{q\bar{q}}}{dM\,dy\,dz} &= K\frac{2M}{s}\sum_q \Bigg\{ [f_{q|P_1}(\xi_1,M) f_{\bar{q}|P_2}(\xi_2,M) \\ &\qquad + f_{\bar{q}|P_1}(\xi_1,M) f_{q|P_2}(\xi_2,M)] \frac{d\hat{\sigma}^{\rm even}_{q\bar{q}}}{dz} \\ &\qquad + [f_{q|P_1}(\xi_1,M) f_{\bar{q}|P_2}(\xi_2,M) \\ &\qquad - f_{\bar{q}|P_1}(\xi_1,M) f_{q|P_2}(\xi_2,M)] \frac{d\hat{\sigma}^{\rm odd}_{q\bar{q}}}{dz} \Bigg\}, \\ \frac{d\sigma_{gg}}{dM\,dy\,dz} &= K\frac{2M}{s}\, f_{g|P_1}(\xi_1,M) f_{g|P_2}(\xi_2,M) \frac{d\hat{\sigma}_{gg}}{dz}. \end{aligned} \tag{2.3}$$

Here, $d\hat{\sigma}^{\rm even}_{q\bar{q}}/dz$ and $d\hat{\sigma}^{\rm odd}_{q\bar{q}}/dz$ are the even and odd parts (under $z \leftrightarrow -z$) of the partonic differential cross section $d\hat{\sigma}_{q\bar{q}}/dz$, and the minus sign in the

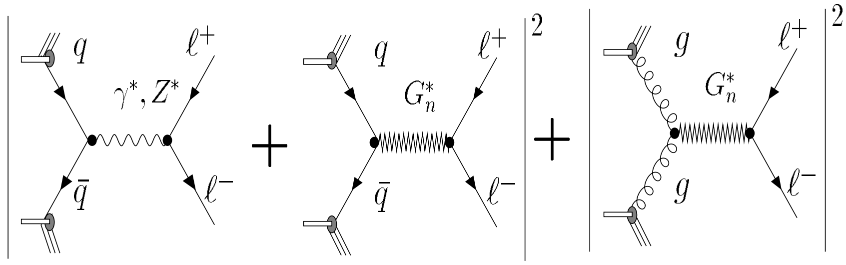

Figure 1: Feynman diagrams for virtual graviton exchange. In the virtual exchange process KK towers of gravitons G_n can be exchanged in the s channel together with the photon (γ) and the Z. There is also a new contribution to the lepton pair production from the gluon-gluon initiated process (gg) in addition to the usual quark-quark $q\bar{q}$ initial state.

odd term allows us to interpret the angle in the parton cross section as being relative to the quark momentum (rather than P_1). Furthermore, K is a factor accounting for higher order QCD corrections (we take $K = 1.3$, which is a typical value), $f_{j|P_i}(\xi_i, M)$ are parton distribution functions in the proton P_i, and the ξ_i are fractional parton momenta

$$\xi_1 = \frac{M}{\sqrt{s}} e^{y}, \qquad \xi_2 = \frac{M}{\sqrt{s}} e^{-y}. \tag{2.4}$$

We also made use of the relation $d\xi_1\, d\xi_2 = dM(2M/s)dy$ and have $M^2 = \xi_1 \xi_2 s$, with s the pp c.m. energy squared.

The center–edge and total cross sections can at the parton level be defined like for initial-state electrons and positrons [9, 10, 11]:

$$\hat{\sigma}_{\rm CE} \equiv \left[\int_{-z^*}^{z^*} - \left(\int_{-1}^{-z^*} + \int_{z^*}^{1}\right)\right] \frac{d\hat{\sigma}}{dz}\, dz, \quad \hat{\sigma} \equiv \int_{-1}^{1} \frac{d\hat{\sigma}}{dz}\, dz. \tag{2.5}$$

These will play a central role in the center–edge asymmetry at the hadron level. At this point, $0 < z^* < 1$ is just an arbitrary parameter which defines the border between the "center" and the "edge" regions.

At hadron colliders, the center–edge asymmetry can for a given dilepton invariant mass M be defined as

$$A_{\rm CE}(M) = \frac{d\sigma_{\rm CE}/dM}{d\sigma/dM}, \tag{2.6}$$

where we obtain $d\sigma_{\rm CE}/dM$ and $d\sigma/dM$ from (2.3) by integrating over z according to Eq. (2.5) and over rapidity between $-Y$ and Y, with $Y = \log(\sqrt{s}/M)$. Furthermore [see Eq. (2.3)],

$$\frac{d\sigma}{dM} = \frac{d\sigma_{q\bar{q}}}{dM} + \frac{d\sigma_{gg}}{dM}. \tag{2.7}$$

We note that terms in the parton cross sections that are odd in z do not contribute to $A_{\rm CE}$; and that

$$\left.\frac{d\sigma_{\rm CE}}{dM}\right|_{z^*=0} = -\frac{d\sigma}{dM}, \qquad \left.\frac{d\sigma_{\rm CE}}{dM}\right|_{z^*=1} = \frac{d\sigma}{dM}. \tag{2.8}$$

2.1 $A_{\rm CE}$ in the SM and ADD scenario

Let us now consider the ADD scenario [7], where gravity is allowed to propagate in two or more compactified, but still large, extra dimensions. This gives rise to a tower of (massive) KK gravitons with tiny mass splittings. In the Hewett approach [6], the summation over KK states (of mass $m_{\vec{n}}$) is performed by the following substitution:

$$\sum_{\vec{n}=1}^{\infty} \frac{G_{\rm N}}{M^2 - m_{\vec{n}}^2} \to \frac{-\lambda}{\pi\, M_H^4}, \tag{2.9}$$

where λ is a sign factor, and $G_{\rm N}$ is Newton's constant.

We then have the following parton differential cross sections, where double superscripts refer to interference between the respective amplitudes (with z the cosine of the quark-lepton angle in the dilepton c.m. frame, and averaged over quark and gluon colors):

$$\begin{aligned}
\frac{d\hat{\sigma}^{G}_{gg}}{dz} &= \frac{\lambda^2 M^6}{64\pi M_H^8}(1-z^4), \\
\frac{d\hat{\sigma}^{G}_{q\bar{q}}}{dz} &= \frac{\lambda^2 M^6}{96\pi M_H^8}(1-3z^2+4z^4), \\
\frac{d\hat{\sigma}^{G\gamma}_{q\bar{q}}}{dz} &= -\frac{\lambda\alpha Q_q Q_e M^2}{6M_H^4}z^3, \\
\frac{d\hat{\sigma}^{GZ}_{q\bar{q}}}{dz} &= \frac{\lambda\alpha M^2}{12M_H^4}[a_q a_e(1-3z^2)-2v_q v_e z^3]\mathrm{Re}\,\chi, \\
\frac{d\hat{\sigma}^{\mathrm{SM}}_{q\bar{q}}}{dz} &= \frac{\pi\alpha^2}{6M^2}[S_q\,(1+z^2)+2A_q\,z].
\end{aligned} \tag{2.10}$$

Here, fermion masses are neglected, and we define

$$\begin{aligned}
S_q &\equiv Q_q^2 Q_e^2 + 2Q_q Q_e v_q v_e\,\mathrm{Re}\,\chi + (v_q^2+a_q^2)(v_e^2+a_e^2)\,|\chi|^2, \\
A_q &\equiv 2Q_q Q_e a_q a_e \mathrm{Re}\,\chi + 4v_q a_q v_e a_e|\chi|^2.
\end{aligned}$$

We use a convention where $a_f = T_f$, $v_f = T_f - 2Q_f\sin^2\theta_W$ and the Z propagator is represented by

$$\chi = \frac{1}{\sin^2(2\theta_W)}\,\frac{M^2}{M^2-m_Z^2+im_Z\Gamma_Z}. \tag{2.11}$$

From Eqs. (2.5) and (2.10), we obtain the following parton level center–edge cross sections

$$\begin{aligned}
\hat{\sigma}^{G}_{gg,\mathrm{CE}} &= \frac{\lambda^2 M^6}{40\pi M_H^8}[\tfrac{1}{2}z^*(5-z^{*\,4})-1], \\
\hat{\sigma}^{G}_{q\bar{q},\mathrm{CE}} &= \frac{\lambda^2 M^6}{60\pi M_H^8}[2z^{*\,5}+\tfrac{5}{2}z^*(1-z^{*\,2})-1], \\
\hat{\sigma}^{G\gamma}_{q\bar{q},\mathrm{CE}} &= 0, \\
\hat{\sigma}^{GZ}_{q\bar{q},\mathrm{CE}} &= \frac{\lambda\alpha a_q a_e M^2}{3M_H^4}\,\mathrm{Re}\,\chi[z^*(1-z^{*\,2})], \\
\hat{\sigma}^{\mathrm{SM}}_{q\bar{q},\mathrm{CE}} &= \frac{4\pi\alpha^2}{9M^2}\,S_q\,[\tfrac{1}{2}z^*(z^{*\,2}+3)-1].
\end{aligned} \tag{2.12}$$

For the SM contribution to the center–edge asymmetry, we see that the convolution integrals, depending on the parton distribution functions, cancel, and the result is

$$A_{\mathrm{CE}}^{\mathrm{SM}} = \tfrac{1}{2}\,z^*(z^{*2}+3)-1, \tag{2.13}$$

which is independent of M and identical to the result for e^+e^- colliders [10]. Hence, in the case of no cuts, there is a unique value, z_0^*, of z^* for which $A_{\rm CE}^{\rm SM}$ vanishes:

$$z_0^* = (\sqrt{2}+1)^{1/3} - (\sqrt{2}-1)^{1/3} \simeq 0.596, \tag{2.14}$$

corresponding to $\theta_{\rm cm} = 53.4°$.

The structure of the differential SM cross section of Eq. (2.10) is particularly interesting in that it is equally valid for a wide variety of NP models: composite-like contact interactions, Z' models, TeV-scale gauge bosons, *etc.* Conventional four-fermion contact-interaction effects of the vector–vector kind would yield the same center–edge asymmetry as the SM. If however KK graviton exchange is possible, the tensor couplings would yield a different angular distribution, hence a different dependence of $A_{\rm CE}$ on z^*. In particular, the center–edge asymmetry would not vanish for the same choice of $z^* = z_0^*$ and, moreover, 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 NP.

The other important difference from the spin-1 exchange originating from $q\bar{q}$ annihilation is that the graviton also couples to gluons, and therefore, it has the additional gg initial state available, see Eq. (2.10). As a result of including graviton exchange, the center–edge asymmetry is no longer the simple function of z^* in Eq. (2.13).

In Fig. 2.1 we show $A_{\rm CE}$ (for $z_0^* \simeq 0.596$) in the ADD model as a function of invariant dilepton mass, M, with $M_H = 4$ TeV, $\lambda = \pm 1$ and $\sqrt{s} =$ 14 TeV (LHC). The SM contribution, $A_{\rm CE}^{\rm SM}$, to the center–edge asymmetry vanishes. To compute cross sections we use the CTEQ6 parton distributions [12]. Here we see that the contribution from gluon fusion (dash-dotted) actually is the most important one. As a result, $A_{\rm CE}$ becomes positive at large M, independent of the sign of λ.

2.2 $A_{\rm CE}$ in the RS scenario

Another scenario involving extra dimensions, is the RS scenario [8]. Here we shall consider the simplest version of this scenario, with only one extra dimension. The main difference from the ADD scenario is that there will be narrow graviton resonances with masses of the order of TeV, with couplings comparable to weak couplings.

In the RS scenario, the spacing between KK resonances can give some hints to the underlying physics. However, it is conceivable that the second resonance would be outside the accessible range of the experiment, such that only the first one would be discovered. It would then be of great interest to determine whether it is a graviton resonance or something less exotic, like a

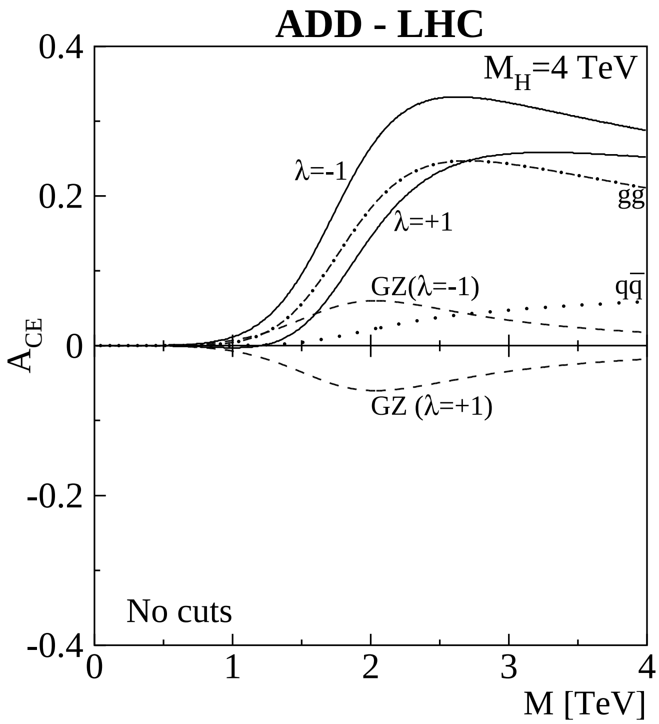

Figure 2: Different contributions to $A_{\rm CE}(M)$ in the ADD scenario at LHC, $\sqrt{s} = 14$ TeV. Solid curves: total center–edge asymmetry ($\lambda = \pm 1$), dash-dotted: gg contribution, dotted: $q\bar{q}$ with graviton exchange, dashed: $q\bar{q}$ interference between graviton and Z (labeled GZ).

Z' with vector couplings.

This model has two independent parameters, which we take to be $k/\bar{M}_{\rm Pl}$ and m_1, where k is a constant of $\mathcal{O}(\bar{M}_{\rm Pl})$ ($k/\bar{M}_{\rm Pl}$ is in the range 0.01 to 0.1, and m_1 is the mass of the first graviton resonance. The summation over KK states is performed without using the substitution in Eq. (2.9), but instead modifying in the left-hand side the graviton coupling to matter

$$G_{\rm N} \to \frac{x_1^2}{8\pi m_1^2}\left(\frac{k}{\bar{M}_{\rm Pl}}\right)^2, \tag{2.15}$$

while keeping the sum over propagators. Here, $x_1 = 3.8317$ is the first root of the Bessel function $J_1(x_n) = 0$ [8].

The deviations of $A_{\rm CE}$ from the SM value (which is zero for $z^* = z_0^*$ as defined in (2.14), still without introducing any cuts) are localized in the invariant mass of the lepton pair around the resonance mass, as is illustrated in Fig. 2.2 for $k/\bar{M}_{\rm Pl} = 0.05$ and $m_1 = 2.5$ TeV) at the LHC. For this choice of parameters, it is unlikely that the second resonance will be discovered. We have used the definition of $A_{\rm CE}$ given in Eq. (2.6).

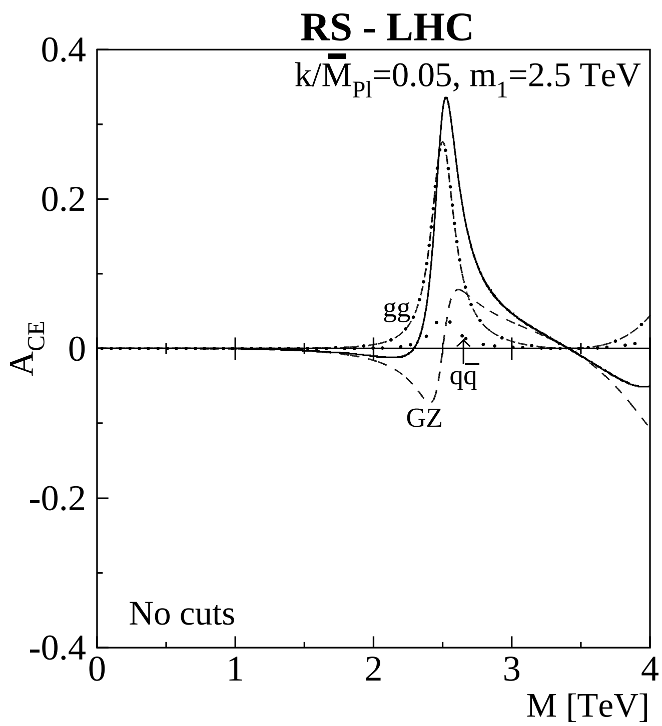

Figure 3: Different contributions to $A_{\rm CE}(M)$ in the RS scenario, with $k/\bar{M}_{\rm Pl} = 0.05$ at LHC, $\sqrt{s} = 14$ TeV, $m_1 = 2.5$ TeV. Solid curves: total center–edge asymmetry, dash-dotted: gg contribution, dotted: $q\bar{q}$ with graviton exchange, dashed: $q\bar{q}$ interference between graviton and Z.

3 Identification of spin-2 and concluding remarks

In this section we assume that a deviation from the SM is discovered in the cross section, either in the form of a contact interaction or a resonance. We will here investigate in which regions of the ADD and RS 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 can be used to exclude spin-1 exchange beyond that of the SM.

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,

$$A_{\rm CE}(i) = \frac{\displaystyle\int_i \frac{d\sigma_{\rm CE}}{dM} dM}{\displaystyle\int_i \frac{d\sigma}{dM} dM}. \tag{3.16}$$

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

$$\Delta A_{\rm CE}(i) = A_{\rm CE}(i) - A_{\rm CE}^{\text{spin-1}}(i). \tag{3.17}$$

The bin-integrated statistical uncertainty is then given as

$$\delta A_{\rm CE}(i) = \sqrt{\frac{1 - A^2_{\rm CE}(i)}{\epsilon_l \mathcal{L}_{\rm int} \sigma(i)}}, \tag{3.18}$$

based on the number of events that are effectively detected and the $A_{\rm CE}$ that is actually measured. We take the efficiency for reconstruction of lepton pairs, $\epsilon_l = 90\%$ and sum over $l = e, \mu$.

The statistical significance, $\mathcal{S}_{\rm CE}(i)$ is defined as:

$$\mathcal{S}_{\rm CE}(i) = \frac{|\Delta A_{\rm CE}(i)|}{\delta A_{\rm CE}(i)}. \tag{3.19}$$

In the ADD scenario, the identification reach in M_H can be estimated from a χ^2 analysis:

$$\chi^2 = \sum_i \left[\mathcal{S}_{\rm CE}(i)\right]^2, \tag{3.20}$$

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.

At the LHC, with 100 fb^{-1}, we require $M > 400$ GeV and divide the data into 200 GeV bins as long as the number of events in each bin, $\epsilon_l \mathcal{L}_{\rm int} \sigma(i)$, is larger than 10. Therefore, the number of bins will depend on the magnitude of the (discovered) deviation from the SM. We impose angular cuts relevant to the LHC detectors, in order to account for the fact that detectors have a region of reduced or no efficiency close to the beam direction. The lepton pseudorapidity cut is $|\eta| < \eta_{\rm cut} = 2.5$ for both leptons, and in addition to the angular cuts, we impose on each lepton a transverse momentum cut $p_\perp > p_\perp^{\rm cut} = 20$ GeV.

We find that at the 95% CL, the *identification* reach at the LHC, where one can distinguish between the ADD and an alternative spin-1 based scenario, is $M_H = 4.77$ TeV and 5.01 TeV for $\lambda = +1$ and -1, respectively. In

Table 1: Identification reach on M_H (in TeV) at 95% CL from $A_{\rm CE}$.

Collider	$\lambda = +1$	$\lambda = -1$
LHC 100 fb^{-1}	4.8	5.0
LHC 300 fb^{-1}	5.4	5.9

Table 1 we summarize the results, and also include the identification reach corresponding to an integrated luminosity of 300 fb^{-1} at the LHC.

A very distinct feature of the RS scenario is that the resonances are unevenly spaced. If the first resonance is sufficiently heavy, the second resonance would be difficult to resolve within the kinematical range allowed experimentally. For $m_1 > 1.7, 2.5, 2.8$ TeV for $k/\bar{M}_{\rm Pl} = 0.01, 0.05, 0.1$, respectively, the second resonance would contain less than 10 events at the LHC, for 100 fb^{-1} (in the narrow-width approximation). In this situation it would be of crucial importance to have a method of distinguishing between spin-1 and spin-2 resonances and, indeed, this is what the center–edge asymmetry can offer.

At the LHC, we choose a 200 GeV bin around the resonance mass m_1, and obtain the results presented in Fig. 3, where we display the 2, 3 and 5σ contours. In order not to create additional hierarchies, we require the scale of physical processes on the 'TeV brane', $\Lambda_\pi = m_1/[x_1(k/\bar{M}_{\rm Pl})] < 10$ TeV, as indicated in the figure.

Exploring the center–edge asymmetry at hadron colliders is a good strategy to distinguish between spin-1 and spin-2 exchange. The proposed center-edge asymmetry may be seen as a possible alternative or supplement to a direct fit to the differential angular distribution [13].

In conclusion, we have considered the ADD scenario parametrized by M_H, and the RS scenario parametrized by m_1 and $k/\bar{M}_{\rm Pl}$. Although somewhat higher sensitivity reaches on M_H or m_1 than obtained here are given by other approaches, this method based on $A_{\rm CE}$ is suitable for actually pinning down the spin-2 nature of the KK gravitons up to very high M_H or m_1. This is different from just detecting deviations from the Standard Model predictions,

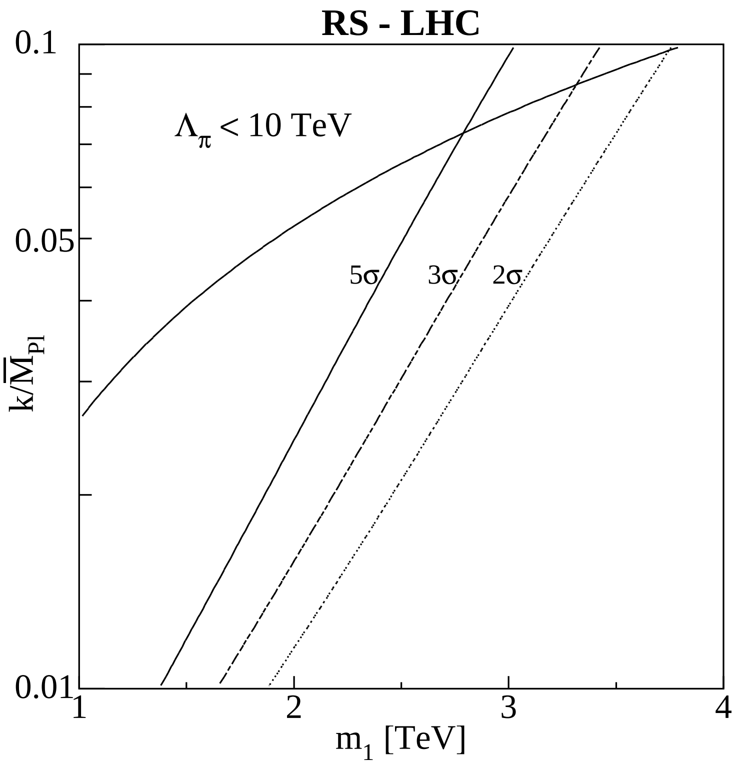

Figure 4: Spin-2 identification of an RS resonance, using the center–edge asymmetry. We integrate over bins of 200 GeV around the peak at the LHC. The theoretically favored region, $\Lambda_\pi < 10$ TeV, is indicated.

and is a way to obtain additional information on the underlying new-physics scenario.

Acknowledgment

I would like to thank E.W. Dvergsnes, P. Osland, and N. Paver for the enjoyable collaboration on the subject matter covered here.

References

[1] E. Eichten, K. D. Lane and M. E. Peskin, Phys. Rev. Lett. **50** (1983) 811;
R. Ruckl, Phys. Lett. B **129** (1983) 363.

[2] For reviews see, *e.g.*: J. L. Hewett and T. G. Rizzo, Phys. Rept. **183** (1989) 193;
A. Leike, Phys. Rept. **317** (1999) 143 [arXiv:hep-ph/9805494];

[3] W. Buchmuller, R. Ruckl and D. Wyler, Phys. Lett. B **191** (1987) 442 [Erratum-ibid. B **448** (1999) 320].

[4] T. G. Rizzo, Phys. Rev. D **59** (1999) 113004 [arXiv:hep-ph/9811440].

[5] G. J. Gounaris, D. T. Papadamou and F. M. Renard, Phys. Rev. D **56** (1997) 3970 [arXiv:hep-ph/9703281].

[6] J. L. Hewett, Phys. Rev. Lett. **82** (1999) 4765 [arXiv:hep-ph/9811356].

[7] N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B **429** (1998) 263 [arXiv:hep-ph/9803315].

[8] L. Randall and R. Sundrum, Phys. Rev. Lett. **83** (1999) 3370 [arXiv:hep-ph/9905221].

[9] For details of the analysis and original references, see E.W. Dvergsnes, P. Osland, A. A. Pankov and N. Paver, Phys. Rev. D **69**, 115001 (2004).

[10] P. Osland, A. A. Pankov and N. Paver, Phys. Rev. D **68**, 015007 (2003) [arXiv:hep-ph/0304123].

[11] A. A. Pankov, N. Paver and C. Verzegnassi, Int. J. Mod. Phys. A **13**, 1629 (1998) [arXiv:hep-ph/9701359].

[12] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. Nadolsky and W. K. Tung, JHEP **0207** (2002) 012 [arXiv:hep-ph/0201195].

[13] B. C. Allanach, K. Odagiri, M. A. Parker and B. R. Webber, JHEP **0009**, 019 (2000) [arXiv:hep-ph/0006114].