SLAC-PUB-8960/ P3-02

Signals For Extra Dimensions at the VLHC

Thomas G. Rizzo*
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309 USA
(Dated: August 25, 2001)

A brief overview of the signatures for several different models with extra dimensions at the stage II, $\sqrt{s} = 175 - 200$ TeV VLHC is presented. In all cases the search reaches for these models in the Drell-Yan channel are found to be in the range of 15-80 TeV.

I. INTRODUCTION

There are now many models with extra spatial dimensions that predict the appearance of new physics signatures at colliders that can probe energy scales in excess of ∼1 to a few TeV. These models generally fall into three distinct classes which lead to very different phenomenologies and collider signatures: (*i*) those based on the large extra dimensions scenario of Arkani-Hamed, Dvali and Dimopoulos(ADD)[1], which predicts the emission and exchange of large Kaluza-Klein(KK) towers of gravitons that are finely-spaced in mass; (*ii*) those with TeV-scale dimensions(TeV)[2], which predict the existence of KK excitations of the SM gauge (and possibly other) fields at the TeV scale and (*iii*) those with warped extra dimensions, such as the Randall-Sundrum Model(RS)[3], which predict graviton resonances with both weak scale masses and couplings to matter. The stage II VLHC with a center of mass energy $\sqrt{s} \sim 175 - 200$ TeV and a integrated luminosity in the range of 200-1000 fb^{-1} will be able to search for and/or make detailed studies of models in all three classes. For most models of type (*i*) or (*iii*) which deal with the hierarchy problem, if no signal is observed by the time the mass scales probed by the VLHC are reached, the motivation behind these particular models will be greatly weakened if not entirely removed. In what follows, for simplicity and in order to avoid potentially difficult detector issues associated with such high energies and luminosities, we will focus on searches involving only the simple Drell-Yan process $pp \to e^+e^- + X$. From studies performed for the Tevatron and LHC we know that this channel provides an excellent probe of the parameter spaces of extra-dimensional models and we expect that this will continue to be true at even higher energies.

II. SIGNATURES

In the SM, the Drell-Yan reaction is a result of photons and Z's mediating the sub-process $q\bar{q} \to e^+e^-$. In the ADD model, graviton towers can also be exchanged and an additional sub-process $gg \to e^+e^-$, mediated solely by gravitons, also contributes[4] at the same order. When summed, the effect of the graviton towers can be described through a set of dimension-8 operators in the limit that the center of mass energy of the collision process lies sufficiently below the cut-off scale, M_s, which is of order the size of the Planck scale in the extra dimensional space. In the convention used by Hewett[4], the contribution of spin-2 tower exchange can be expressed in terms of the scale, M_s, and a sign, λ. In the Drell-Yan case, the deviations of the cross section are found to be essentially λ-independent but with a strong M_s dependence. Current experimental constraints from LEP and the Tevatron[5] tell us that $M_s \geq 1$ TeV, and values for M_s as large as the low 10's of TeV may be conceivable in this framework. The distortion of the Drell-Yan cross section at large lepton pair invariant masses at the VLHC through these dimension-8 operators can trivially probe such high mass scales in a manner similar to searches for compositeness-type contact interactions. The shape of the deviation from the SM with varying dilepton mass will tell us that the underlying physics arises due to dimension-8 operators; in addition at large masses the dilepton angular distribution would conform to the shape expected due to the dominance of spin-2 exchange thus nailing down the gravitational origin of these effects. These types of deviations can be easily seen in Fig. 1 for two different center of mass energies and integrated luminosities. It is clear from these results that there are enough statistics available in the high mass dilepton data to provide sensitivity to values of M_s in excess of 25-40 TeV at the VLHC. Of course, in the ADD model, we would expect to see new physics in other channels as well, in particular the existence of monojets from graviton emission.

---

*rizzo@slac.stanford.edu

*Work supported by Department of Energy contract DE-AC03-76SF00515.

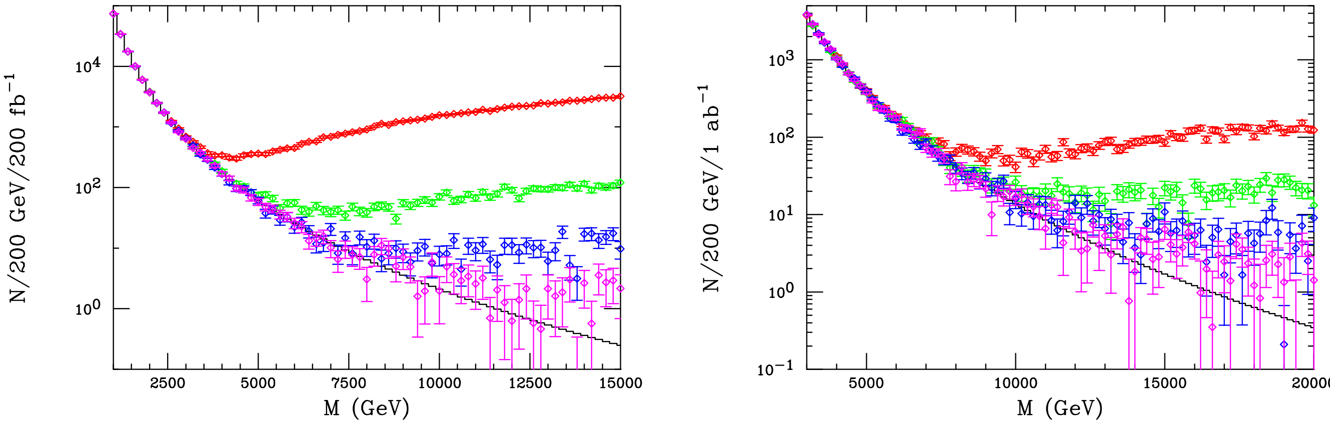

FIG. 1: Event rate per 200 GeV mass bin for the Drell-Yan process as a function of the lepton pair invariant mass at a $\sqrt{s} = 175(200)$ stage II VLHC in the left(right) panel for different integrated luminosities. A rapidity cut $\eta_l < 2.5$ on both leptons has been applied. The solid histogram is the SM background in both cases whereas the 'data' points are the predictions of the ADD model. In the left(right) panel the red, green, blue and magenta points correspond to the assumption that $M_s = 10, 15, 20$ or $25(20, 25, 30$ or $35)$ TeV, respectively.

In the simplest versions of TeV scale theories with extra dimensions, only the SM gauge fields are in the bulk whereas the fermions remain at the orbifold fixed points; Higgs fields may lie at the fixed points or propagate in the bulk. Of course, more complicated scenarios with very different phenomenology are possible. In such a simple case with only one extra dimension it has been shown that the current high precision electroweak data can place a lower bound on the mass of the first KK excited gauge boson in excess of $\simeq 4$ TeV[6]. In such a model, to a good approximation, the masses of the KK tower states are given by $M_n = nM_c$, where M_c is the compactification scale. For this one extra dimensional example all of the excited KK states have identical couplings to the SM fermions. In this case, while the first KK state may be observable at the LHC the higher KK modes will not be due to their rather small cross sections arising from their large masses and a higher energy machine will be necessary to explore the KK spectrum. Fortunately the VLHC does provide a window into such high scales as can be seen from Fig. 2. Here one observes that for 'low' values of the compactification scale, $M_c \leq 10$ TeV, as many as 5 to 6 KK excitations will be easily observable and that values of M_c as large as $\sim 50 - 60$ TeV will be directly probed in Drell-Yan by the stage II VLHC.

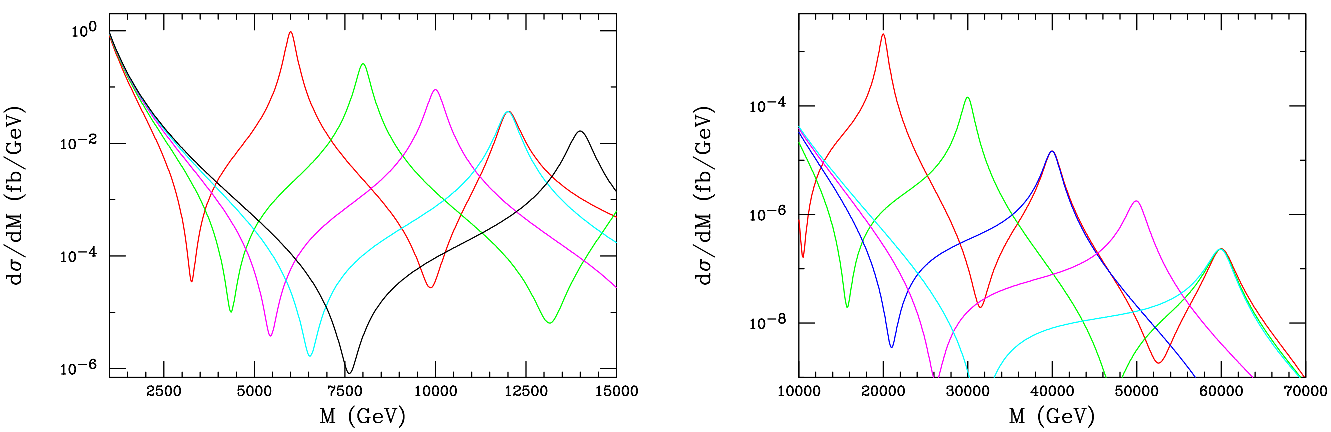

FIG. 2: Spectra for γ/Z KK excitations in Drell-Yan assuming only one extra dimension and all SM fermions sitting at the same orbifold fixed point. In the left(right) panel the subsequent curves(from left to right) correspond to compactification scales of 6,8,10, 12 and 14 (20,30,40,50 and 60) TeV, respectively. $\sqrt{s} = 175$ TeV and a rapidity cut as above have been assumed.

The VLHC may be even more useful if the number of extra dimensions is greater than or equal to two; in this case, still keeping the fermions at the orbifold fixed points, the bounds from precision data are expected to be stricter than in the one-dimensional case but are less quantitatively precise since the naive evaluation of the relevant sums over KK states are divergent. (Hence the exact limits are sensitive to the physics that cuts off these sums.) Also one finds that the masses and couplings of KK excitations become both level and compactification-scheme dependent thus leading to a rather complex KK spectrum in Drell-Yan. In fact it will be necessary to observe a rather large part of the lower portion of the spectrum in order to experimentally determine the number of extra dimensions and how they are compactified. Fortunately the VLHC may allow for such a detailed study provided M_c is not too large.

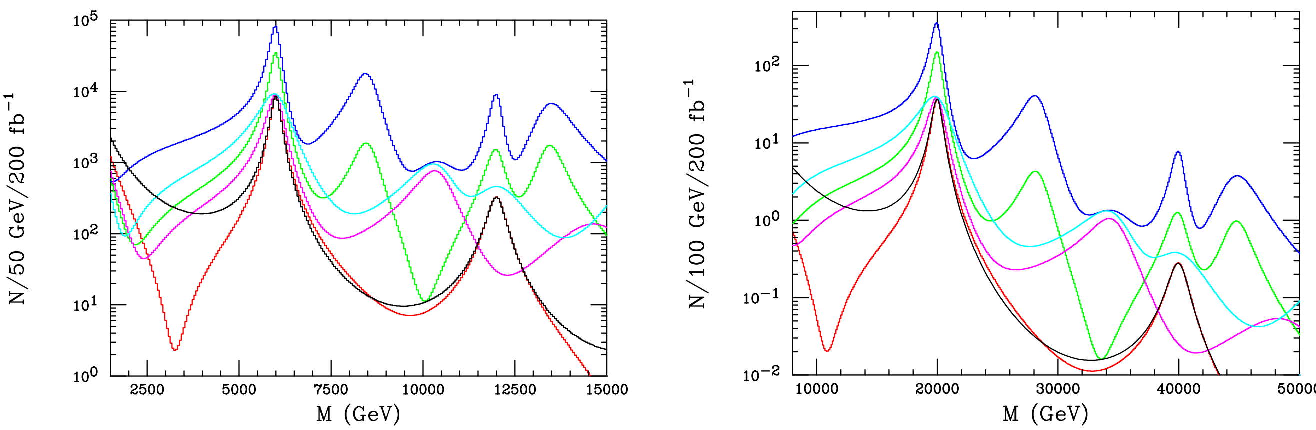

FIG. 3: Binned excitation spectra in Drell-Yan for several models with one or more extra dimensions at the VLHC for $\sqrt{s} = 175$ TeV and with the same rapidity cut as above. In the left(right) panel $M_c = 6(20)$ TeV has been assumed.

Some sample KK excitation spectra for a number of different TeV-scale models of this kind with more than one extra dimension are shown in Fig. 3. Note that these various spectra are quite distinctive. Specifically, the measurements of the locations of the peaks and their relative heights and widths can be used to uniquely identify a given extra-dimensional model. From this figure it is clear that the VLHC can be used to differentiate the many possible models even for large compactification scales $\simeq$ 20 TeV or higher through detailed cross section measurements.

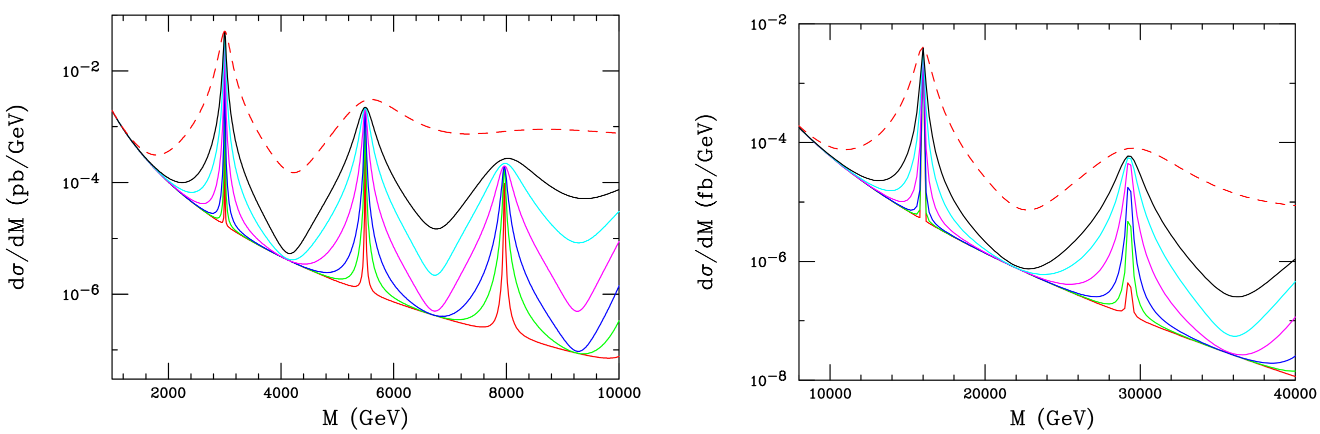

FIG. 4: Excitation of KK gravitons in the RS model in Drell-Yan collisions at the $\sqrt{s} = 175$ TeV VLHC. From most narrow to widest the curves correspond to values of the parameter $c = k/\overline{M}_{Pl}$ of 0.01,0.02,0.03,0.05,0.075,0.1 and 0.2, respectively. The left(right) panel assumes that the lightest KK graviton excitation has a mass of 3(16) TeV.

The last case we consider is the RS model wherein, as discussed above, we expect to produce TeV-scale graviton resonances in many channels[7] including Drell-Yan. In its simplest version, with only one extra dimension, two distinct branes, and with all of the SM fields remaining on the TeV-brane, this model has only two fundamental parameters: the mass of the first KK state (from which all the others can be determined) and an additional parameter, $c = k/\overline{M}_{Pl}$, which we expect to be smaller than but not too far from unity. This parameter essentially controls the effective coupling strength of the gravitons(when expressed in terms of the mass of the lowest lying KK state) and thus also the widths of the corresponding resonances in Drell-Yan. This implies that the overall production cross section is highly c-dependent which can be seen explicitly in Fig. 4. Here we find that a 200 TeV VLHC with 1 ab^{-1} of integrated luminosity will be able to observe the first RS KK excitation for masses as large as 15-30 TeV for values of c in the interesting range $\sim$0.01-0.2. By studying the lepton pair mass bins near the resonance, the decay angular distribution may be determined. This would demonstrate that a spin-2 particle is being produced while measurements of the relative branching fractions to other clean decay modes, such as $\gamma\gamma$, can prove that we are producing gravitons. We also see that for a lighter KK spectrum, the VLHC will observe and determine the masses of a reasonable number of KK resonances. Using the ratios of these KK masses one would be able to demonstrate that we had discovered the states as predicted by the five-dimensional RS model since their masses are in the ratios of the roots of the J_1 Bessel function. With it's high luminosity it also seems possible that the VLHC will be able to perform a detailed study of some of the more exotic decays of the heavier graviton states[8] that may occur in this model; to examine this possibility will require more elaborate simulations.

III. DISCUSSION AND CONCLUSION

From the discussion above it is clear that the mass reach in Drell-Yan at the stage II VLHC offers an excellent window on many different models with extra dimensions. In some cases the lack of observation of a positive signature at such mass scales would serious weaken the justification for these models.

---

[1] N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, Phys. Lett. **B429**, 263 (1998), and Phys. Rev. **D59**, 086004 (1999); I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, and G. Dvali, Phys. Lett. **B436**, 257 (1998).

[2] See, for example, I. Antoniadis, Phys. Lett. **B246**, 377 (1990); I. Antoniadis, C. Munoz and M. Quiros, Nucl. Phys. **B397**, 515 (1993); I. Antoniadis and K. Benalki, Phys. Lett. **B326**, 69 (1994)and Int. J. Mod. Phys. **A15**, 4237 (2000); I. Antoniadis, K. Benalki and M. Quiros, Phys. Lett. **B331**, 313 (1994).

[3] L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999).

[4] For an introduction to ADD phenomenology, see G.F. Giudice, R. Rattazzi and J.D. Wells, Nucl. Phys. **B544**, 3 (1999); T. Han, J.D. Lykken and R. Zhang, Phys. Rev. **D59**, 105006 (1999), E.A. Mirabelli, M. Perelstein and M.E. Peskin, Phys. Rev. Lett. **82**, 2236 (1999); J.L. Hewett, Phys. Rev. Lett. **82**, 4765 (1999); T.G. Rizzo, Phys. Rev. **D60**, 115010 (1999).

[5] For a summary of bounds, see G. Landsberg, these proceedings.

[6] See, for example, T.G. Rizzo and J.D. Wells, Phys. Rev. **D61**, 016007 (2000); P. Nath and M. Yamaguchi, Phys. Rev. **D60**, 116006 (1999); M. Masip and A. Pomarol, Phys. Rev. **D60**, 096005 (1999); L. Hall and C. Kolda, Phys. Lett. **B459**, 213 (1999); R. Casalbuoni, S. DeCurtis, D. Dominici and R. Gatto, Phys. Lett. **B462**, 48 (1999); A. Strumia, Phys. Lett. **B466**, 107 (1999); F. Cornet, M. Relano and J. Rico, Phys. Rev. **D61**, 037701 (2000); C.D. Carone, Phys. Rev. **D61**, 015008 (2000); T.G. Rizzo, Phys. Rev. **D61**, 055005 (2000) and Phys. Rev. **D64**, 015003 (2001).

[7] For an overview of RS phenomenology, see H. Davoudiasl, J.L. Hewett and T.G. Rizzo, Phys. Rev. Lett. **84**, 2080 (2000); Phys. Lett. **B493**, 135 (2000); and Phys. Rev. **D63**, 075004 (2001).

[8] H. Davoudiasl and T.G. Rizzo, Phys. Lett. **B512**, 100 (2001).