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# Direct collider signatures of large extra dimensions <sup>1</sup>

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## ABSTRACT

The realization of low (TeV) scale strings usually requires the existence of large (TeV) extra dimensions where gauge bosons live. The direct production of Kaluza–Klein excitations of the photon and  $Z$ -boson at present and future colliders is studied in this work. At the LEP II, NLC and Tevatron colliders, these Kaluza–Klein modes lead to deviations from the standard model cross-sections, which provide lower bounds on their mass. At the LHC the corresponding resonances can be produced and decay on-shell, triggering a characteristic pattern in the distribution of dilepton invariant mass.

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# Introduction

There has been recently a lot of interest in the possibility that string theories become relevant at low energies, accessible to future accelerators [1]–[4]. This is realized for instance if the string tension is in the TeV range [5], which is also motivated by an alternative solution to the gauge hierarchy problem [6, 7]. The realization of this idea in weakly coupled type I theories [8] implies the existence of large extra dimensions, in the millimetre to Fermi range. These dimensions are seen only by gravity, while the standard model interactions are confined to (D+3)-branes transverse to them. One of the main predictions of these theories is that gravity becomes strong in the TeV region, and so it can have important observable effects in particle accelerators at energies close to the string scale [9].

Besides this effect from the transverse dimensions, there may be some longitudinal dimensions (seen by gauge interactions), which are also in the TeV range [1]–[17]. Such dimensions are always present, with the only exception of having six transverse dimensions at the Fermi scale. Moreover, they can have a size a bit larger than the string length, which is motivated either by supersymmetry breaking through the compactification [1–4, 10, 11], or by power-law running of couplings [18] to achieve unification of gauge interactions [12, 13], or by anisotropic compactifications [14].

A scenario similar to the type I strings where the longitudinal dimensions are present might also be studied in Hořava–Witten compactifications of M-theory [19, 20]. On the other hand, the realization of TeV strings in weakly coupled type II theories does not require the existence of large transverse dimensions since, in these theories, the weakness of gravitational interactions can be accounted for by the smallness of the string coupling [21]. They also allow for a scenario with the string scale at intermediate energies while keeping two extra-dimensions at the TeV. As a result, there are no strong quantum gravity effects at TeV energies and the only observable effects below the string scale are due to the presence of longitudinal dimensions.

In this work we study virtual effects and possible on-shell production of Kaluza–Klein (KK) excitations of gauge bosons in present and future accelerators. Production of a single KK excitation assumes non-conservation of the momenta along the extra-dimension. This possibility is realized in a large class of models, where quarks and leptons are localized at particular points of the internal (longitudinal) space, similar to the twisted states of the heterotic string. We restrict our analysis to such models and leave for a future study those

where quarks and leptons also have KK-excitations.

For the case of one large extra dimension we find that existing colliders, LEP II and Tevatron, will be able to exclude compactification scales less than  $\sim 1.9$  TeV. Low-energy precision data [15, 16, 17] seem to provide stronger constraints  $\sim 2.5$  TeV. This is because of the large number of events that allow us to have a very high precision on the width of  $Z$  boson and the Fermi constant. These results imply that it is unlikely that we observe effects of KK excitations of gauge bosons at present colliders.

The Next Linear Colliders (NLC) with centre-of-mass energy of 500 GeV and 1 TeV will easily probe (through virtual effects) compactification scales up to around 8 TeV and 13 TeV, respectively. At the LHC we find that the non-observation of deviations from the standard model prediction of the total number of lepton pairs with centre-of-mass energy above 400 GeV would translate into a lower bound of the order of 6.7 TeV and 9 TeV, for one and two large extra-dimensions, respectively. Hadronic colliders allow the most exciting possibility of direct production of KK excitations by Drell-Yan processes [4]. A characteristic signature will be the appearance of two overlapping narrow resonances, corresponding to the first excited state of the photon and the  $Z$  gauge boson, for every longitudinal large dimension. Our analysis indicates that in the case of one dimension (or many dimensions with the same values of the compactification scales) it is likely that only the first peak could be seen in the first run. However this scenario can be differentiated from  $Z'$  models because of the presence of excitations of  $W$  bosons. The present analysis completes the original work of the authors [4] where specific couplings were assumed.

## Production at $e^+e^-$ colliders

The exchange of KK excitations of the photon and  $Z$  boson leads to modifications of the cross section  $e^+e^- \rightarrow \mu^+\mu^-$ . As the invariant mass of the produced fermion pairs is (to a first approximation) of the order of the machine energy, resonances cannot be directly observed unless the machine energy happens to be very close to the mass of one of the excitations, or else a scanning of energies is made. Because of the clean environment, these experiments allow the performance of high-precision tests and the extraction of bounds on the new physics.

The total cross section for the annihilation of unpolarized electron-positron pairs  $e^+e^-$ , with a centre-of-mass energy  $\sqrt{s}$ , to lepton pairs  $l^+l^-$ , through the exchange of vector bosons

in the s-channel, is given by:

$$\sigma_T^0(s) = \frac{s}{12\pi} \sum_{\alpha,\beta=\gamma,Z,KK} g_\alpha^2(\sqrt{s})g_\beta^2(\sqrt{s}) \frac{(v_e^\alpha v_e^\beta + a_e^\alpha a_e^\beta)(v_l^\alpha v_l^\beta + a_l^\alpha a_l^\beta)}{(s - m_\alpha^2 + i\Gamma_\alpha m_\alpha)(s - m_\beta^2 - i\Gamma_\beta m_\beta)}, \quad (1)$$

where the labels  $\alpha, \beta$  stand for the different neutral vector bosons  $\gamma, Z$ , and their KK excitations with coupling constants  $g_\alpha$  and masses  $m_\alpha$  given by

$$m_n^2 = m_0^2 + \frac{\vec{n}^2}{R^2}. \quad (2)$$

Here,  $R$  denotes the common radius for  $D$  large (TeV) dimensions and  $m_0$  is a  $(D + 4)$ -dimensional mass which, for instance, can appear through an ordinary Higgs mechanism, such as that responsible for the electroweak symmetry breaking. The widths  $\Gamma_\alpha$  are decay rates into standard model fermions  $f$ :

$$\Gamma(X_n \rightarrow f\bar{f}) = g_\alpha^2 \frac{m_n}{12\pi} C_f (v_f^2 + a_f^2) \quad (3)$$

and their scalar superpartners

$$\Gamma(X_n \rightarrow \tilde{f}_{(R,L)} \tilde{f}_{(R,L)}^*) = g_\alpha^2 \frac{m_n}{48\pi} C_f (v_f \pm a_f)^2, \quad (4)$$

where  $C_f = 1$  (3) for colour singlets (triplets) and  $v_f, a_f$  are the standard model vector and axial couplings. The precise value of the width is not important in most of our analysis based on virtual effects. It is however important in the case of on-shell production of KK excitations. In our studies we use the standard model particles as the only accessible final states. If instead one includes also their superpartners, then the widths of KK excitations of the photon and  $Z$  are multiplied by a factor  $3/2$ . As a result the resonances are wider.

We expect, in experiments to be held at energies far below the resonance peaks, that interference terms will be the main source of any observable effects. As the latter are small, they must be computed with the highest possible accuracy. In our analysis we include radiative corrections, and in particular the bremsstrahlung effects on the initial electron and positron [22]. These are described by the convolution of (1) with radiator functions, which describe the probability of having a fractional energy loss,  $x$ , due to the initial-state radiation:

$$\sigma_T(s) = \int_0^{x_{\max}} dx \sigma_T^0(s') r_T(x), \quad s' = s(1 - x) \quad (5)$$

In the above equation,  $x_{\max}$  represents an experimental cut off for the energy of emitted soft photons in bremsstrahlung processes. The radiator function is given by [22]:

$$r_T(x) = (1 + X)yx^{y-1} + H_T(x) , \quad (6)$$

with:

$$\begin{aligned} X &= \frac{e^2(\sqrt{s})}{4\pi^2} \left[ \frac{\pi^2}{3} - \frac{1}{2} + \frac{3}{2} \left( \log \frac{s}{m_e^2} - 1 \right) \right] \\ y &= \frac{2e^2(\sqrt{s})}{4\pi^2} \left( \log \frac{s}{m_e^2} - 1 \right) \\ H_T &= \frac{e^2(\sqrt{s})}{4\pi^2} \left[ \frac{1 + (1-x)^2}{x} \left( \log \frac{s}{m_e^2} - 1 \right) \right] - \frac{y}{x} , \end{aligned} \quad (7)$$

where  $m_e$  is the electron mass.

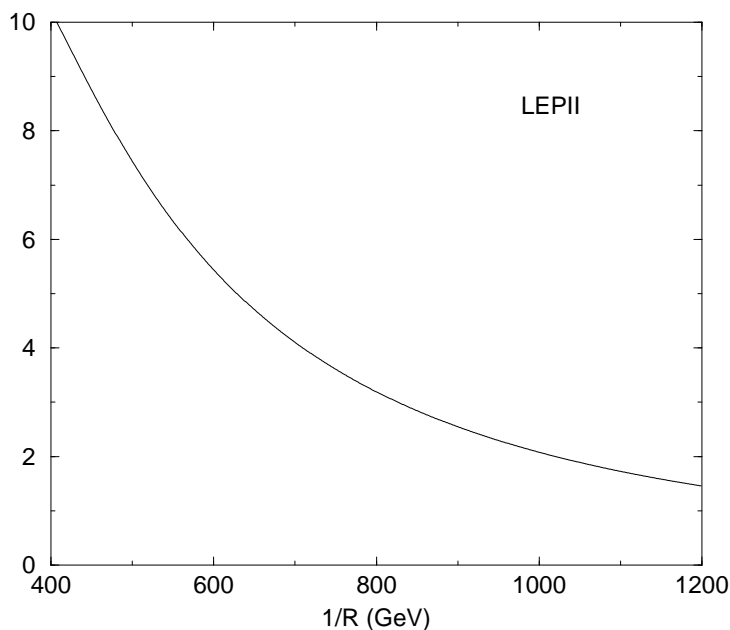


Figure 1: Ratio  $\left| \frac{N_T(s) - N_T^{\text{SM}}(s)}{\sqrt{N_T^{\text{SM}}(s)}} \right|$  from the total cross section at LEP II. We assumed a luminosity times efficiency of  $200 \text{ pb}^{-1}$ .

We use  $\sqrt{s} = 189 \text{ GeV}$  for LEP II,  $500 \text{ GeV}$  for NLC-500 and  $1 \text{ TeV}$  for NLC-1000, together with the numerical values for the experimental cuts:

$$\begin{aligned} x_{\text{max}}(\text{LEP II}) &= 0.77, \\ x_{\text{max}}(\text{NLC-500}) &= 0.967, \\ x_{\text{max}}(\text{NLC-1000}) &= 0.992, \end{aligned} \quad (8)$$

coming from the condition of removing the  $Z$ -boson tail, which amounts to imposing the cut  $s' \geq M_Z^2$ .

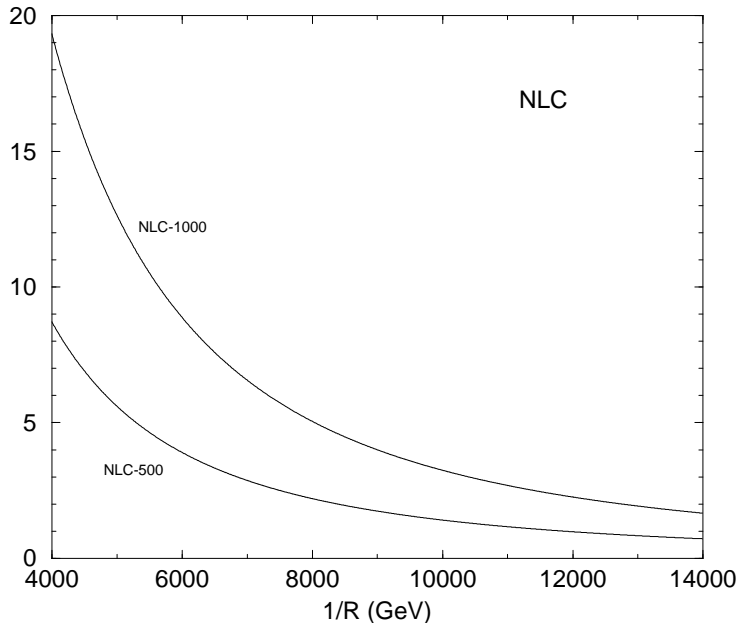


Figure 2: Ratio  $\left| \frac{N_T(s) - N_T^{\text{SM}}(s)}{\sqrt{N_T^{\text{SM}}(s)}} \right|$  from the total cross section at NLC-500 and NLC-1000. We assumed a luminosity times efficiency of  $75 \text{ fb}^{-1}$  and  $200 \text{ fb}^{-1}$ , respectively.

We first consider the case of one extra dimension ( $D = 1$ ). The sum over KK modes in (1) converges rapidly and it is dominated by the lowest modes. We then use the approximation where the couplings of all  $n > 0$  modes are equal<sup>3</sup>. In Fig. 1 we plot, for LEP-II, the ratio

$$\Delta_T = \left| \frac{N_T(s) - N_T^{\text{SM}}(s)}{\sqrt{N_T^{\text{SM}}(s)}} \right| \quad (9)$$

where  $N_T(s)$  is the total number of events while  $N_T^{\text{SM}}(s)$  is the corresponding quantity expected from the standard model. This quantity gives an estimate of the deviation from the background fluctuation in the case of a large number of events. The corresponding plots for NLC-500 and NLC-1000 are given in Fig. 2.

We can see from Fig. 1 that a measurement of the total number of events (from which one extracts  $\sigma_T(s)$ ) puts a limit of 1 TeV (95% c.l.) from LEP-II<sup>4</sup>. Future experiments at

<sup>3</sup>Summing modes with  $n$  positive, the coupling of  $n \neq 0$  modes is enhanced by a factor  $\sqrt{2}$  [11].

<sup>4</sup>Combining data from the four LEP experiments would lead to a corresponding bound of  $\sim 1.9$  TeV.

the NLC with centre-of-mass energies of 500 GeV and 1 TeV, and luminosities of  $75 \text{ fb}^{-1}$  and  $200 \text{ fb}^{-1}$ , will allow us to probe sizes of the order of 8 TeV and 13 TeV, respectively, as can be seen from Fig. 2.

## Production at hadron colliders

At hadron colliders, the KK excitations might be directly produced in Drell–Yan processes  $pp \rightarrow l^+l^-X$  at the LHC, or  $p\bar{p} \rightarrow l^+l^-X$  at the Tevatron, with  $l = e, \mu, \tau$ . This is due to the fact that the lepton pairs are produced via the subprocess  $q\bar{q} \rightarrow l^+l^-X$  of centre-of-mass energy  $M$ . We will follow here the method of Ref. [23] where a similar analysis was performed for the production of  $Z'$  vector bosons from  $E_6$  string-inspired models.

The two colliding partons take a fraction

$$x_a = \frac{M}{\sqrt{s}} e^y \quad \text{and} \quad x_b = \frac{M}{\sqrt{s}} e^{-y} \quad (10)$$

of the momentum of the initial proton ( $a$ ) and (anti)proton ( $b$ ), with a probability described by the quark or antiquark distribution functions  $f_{q,\bar{q}}^{(a)}(x_a, M^2)$  and  $f_{q,\bar{q}}^{(b)}(x_b, M^2)$ .

The total cross section, due to the production is given by:

$$\sigma = \sum_{q=\text{quarks}} \int_0^{\sqrt{s}} dM \int_{\ln(M/\sqrt{s})}^{\ln(\sqrt{s}/M)} dy g_q(y, M) S_q(y, M) , \quad (11)$$

where

$$g_q(y, M) = \frac{M}{18\pi} x_a x_b [f_q^{(a)}(x_a, M^2) f_{\bar{q}}^{(b)}(x_b, M^2) + f_{\bar{q}}^{(a)}(x_a, M^2) f_q^{(b)}(x_b, M^2)] , \quad (12)$$

and

$$S_q(y, M) = \sum_{\alpha, \beta \gamma, Z, KK} g_\alpha^2(M) g_\beta^2(M) \frac{(v_e^\alpha v_e^\beta + a_e^\alpha a_e^\beta)(v_l^\alpha v_l^\beta + a_l^\alpha a_l^\beta)}{(s - m_\alpha^2 + i\Gamma_\alpha m_\alpha)(s - m_\beta^2 - i\Gamma_\beta m_\beta)} . \quad (13)$$

In our computations we used leading-order approximations (set 3 of CTEQ parton distribution functions [24]) and we included a multiplicative  $K$ -factor [25]. We take  $K = 1.3$  for the Tevatron and  $K = 1.1$  for the LHC.

## One extra dimension

Let us first consider, as we did for the case of  $e^+e^-$ -colliders, the simplest case of one extra dimension. At the Tevatron, the CDF collaboration has collected an integrated luminosity

$\int \mathcal{L} dt = 110 \text{ pb}^{-1}$  during the 1992-95 running period. From the non-existence of candidate events at  $e^+e^-$  invariant mass above 400 GeV a lower bound on the size of the extra dimension can be derived. In Fig. 3 we plot the number of expected events assuming efficiency (times acceptance) of  $\sim 50\%$  in this region. This leads to a limit of  $R^{-1} \gtrsim 900 \text{ GeV}$  with a 95% confidence level. An efficiency of  $\sim 90\%$  would have led to  $R^{-1} \gtrsim 940 \text{ GeV}$ . In Fig. 3 we

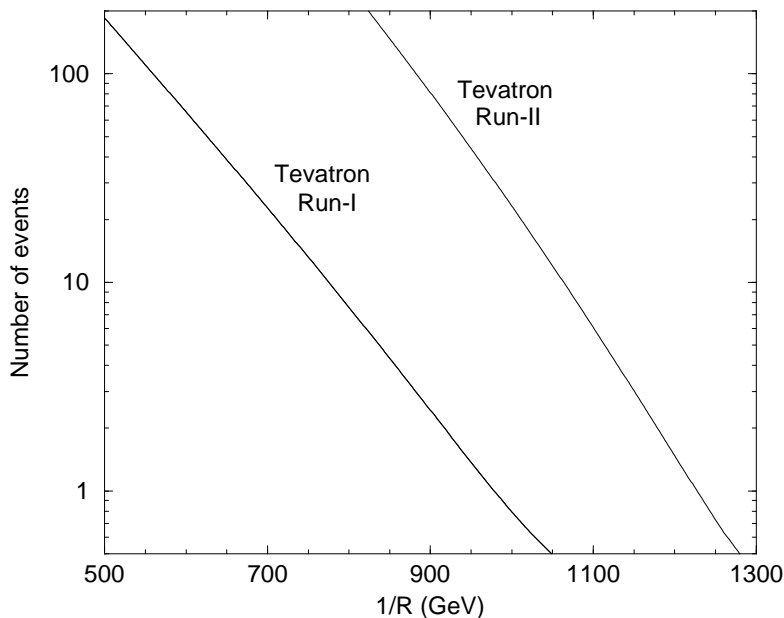


Figure 3: Number of  $l^+l^-$ -pair events with centre-of-mass energy above 400 GeV (600 GeV) expected at the Tevatron run-I (run-II) with integrated luminosity  $\int \mathcal{L} dt = 110 \text{ pb}^{-1}$  ( $\int \mathcal{L} dt = 2 \text{ fb}^{-1}$ ) and efficiency times acceptance of  $\sim 50\%$ , as a function of  $R^{-1}$ .

also plot the expected number of events in the run-II of the Tevatron with a centre-of-mass energy  $\sqrt{s} = 2 \text{ TeV}$ . We use an integrated luminosity  $\int \mathcal{L} dt = 2 \text{ fb}^{-1}$  with an efficiency of  $\sim 50\%$ . The non-observation of any candidates would translate to a limit of  $R^{-1} \gtrsim 1.2 \text{ TeV}$ .

Certainly more promising for probing TeV-scale extra-dimensions are the LHC future experiments at  $\sqrt{s} = 14 \text{ TeV}$ . In Fig. 4 we plot the deviation from the standard model prediction of the total number of lepton pairs with center of mass energy above 400 GeV. Non-observation of such deviations would translate into a lower bound for  $R^{-1}$  of 6.7 TeV (95% c.l.). One could instead cut off the lepton pairs with centre-of-mass energy at a scale  $\sim 2.5 \text{ TeV}$ , above which no event is expected from standard model interactions. A 4.8 TeV



limit (95% c.l.) on the scale of compactification is obtained from not having at least three candidate events above 2.5 TeV.

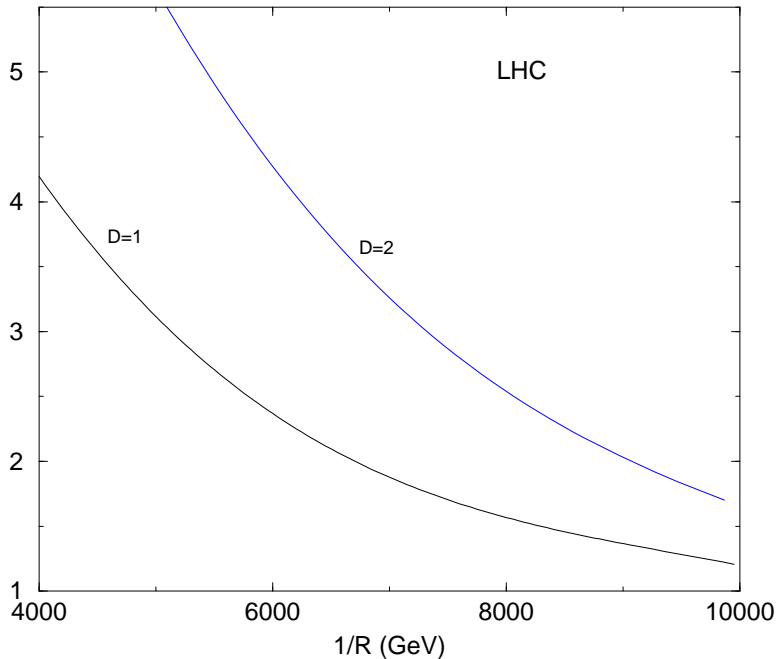


Figure 4: Ratio  $\left| \frac{N_T(s) - N_T^{\text{SM}}(s)}{\sqrt{N_T^{\text{SM}}(s)}} \right|$  from the total cross section at the LHC for dilepton-invariant mass above 400 GeV as a function of  $R^{-1}$ . We assumed a luminosity (times acceptance) times efficiency of  $5 \text{ fb}^{-1}$ .

Within this range of TeV values, the two KK excitations of the photon and  $Z$ -boson are very close to each other and would be difficult to separate. Moreover the second, and higher, peaks are very small and likely to be missed by the first round of the experiment. In Fig. 5 we plot the expected shape of a resonance that could be discovered for an extra dimension of 3 TeV.

## More than one extra dimensions

In this section we generalize the previous results concerning the production of KK excitations at large hadron colliders to the case of more than one large extra dimensions.

For simplicity, in our numerical analysis, we take the large longitudinal dimensions to

have a common compactification radius  $R$ . Our computation involves the sum:

$$\sum_{|\vec{n}|} \frac{g^2(|\vec{n}|)}{|\vec{n}|^2} \quad (14)$$

coming from interference terms between the exchange of the photon and  $Z$ -boson and their KK excitations, where  $g^2(|\vec{n}|)$  are the KK-mode couplings.

In the case of one extra-dimension the sum in (14) converges rapidly. Only the first few terms contribute and it is legitimate to assume that all the KK modes have the same couplings to the boundary fields. This is not the case for two or more dimensions as (14) is divergent and needs to be regularized. The tree-level dependence of  $g(|\vec{n}|)$  on  $|\vec{n}|$  can be computed in a string framework and leads to an exponential drop-off [3, 26]:

$$g(|\vec{n}|) \sim g a_{(|\vec{n}|)} e^{\frac{-c|\vec{n}|^2}{2R^2 M_s^2}}, \quad (15)$$

where  $M_s$  is the string scale,  $c$  is a constant and  $a_{(|\vec{n}|)}$  takes into account the normalization of the gauge kinetic term, as only the even combination couples to the boundary. For the case of two extra-dimensions  $a_{(0,0)} = 1$ ,  $a_{(0,p)} = a_{(q,0)} = \sqrt{2}$  and  $a_{(q,p)} = 2$  with  $(p, q)$  positive ( $> 0$ ) integers. Possible higher-order (loop) corrections to KK-mode couplings are assumed to be small.

The behaviour of the cross-sections in the case of more dimensions have some peculiarities that we would like to mention. When the number of extra dimensions increases, there is an increasing degeneracy of states within each mass level that leads to bigger resonances. Moreover, the spacing between the mass levels decreases, which means that more resonances could be reached by a given hadronic machine. There is an enhancement of the effects of KK states, which allows us to probe smaller values of the radius. Another difference with the one-dimensional case is the sensitivity to the value of the string scale as the latter determines where the divergent sum is cut off. In the case of non-degenerate radii, a corresponding number of resonances due to the first KK excitation along each direction can be observed with no regular spacing patterns.

In Fig. 4 we plot the deviation from the standard model prediction of the total number of lepton pairs with centre-of-mass energy above 400 GeV for the case of two extra dimensions of degenerate radii. Non-observation of such deviations would translate into a lower bound of 9 TeV (95% c.l.). In Fig. 5 we plot the expected shape of resonances that could be discovered for two extra dimensions of 3 TeV. In our examples we arbitrarily choose  $M_s \sim 6/R$  and we include only standard model particles in the computation of the width.

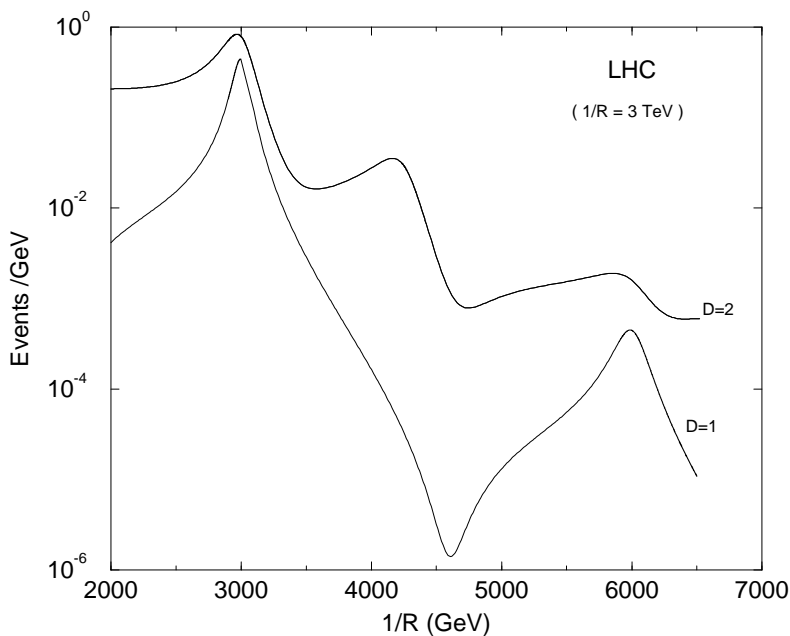


Figure 5: *First resonances in the LHC experiment due to a KK state for one and two extra dimensions at 3 TeV.*

## Conclusions

In theories with low string scale, there may exist longitudinal dimensions (seen by the gauge interactions) in the TeV range. This possibility is also favoured by supersymmetry breaking via the compactification, in four-dimensional string theories. In the models discussed here quarks and leptons are localized at particular points of the internal space. In contrast gauge bosons have KK excitations.

In this paper we have studied the production, decays and signatures of these KK-excitations at present (LEP-II and Tevatron run-I) and future (NLC, Tevatron run-II and LHC) colliders. In some of them (LEP, NLC and Tevatron) the energy is not high enough to produce on-shell KK modes and one should look at the deficit, induced by them, of cross-sections with respect to the standard model ones. This indirect search would lead, in the case of no deviations, to lower bounds on the compactification scale that can be as high as  $\sim 1.9$  TeV for the case of LEP-II and  $\sim 8$  TeV and 13 TeV for NLC-500 and NLC-1000, respectively. On the other hand, the LHC can probe values of the order of 6.7 TeV (9 TeV) for one (two) large extra dimensions. These bounds (summarized in Table 1) are very sim-

ilar to those obtained for the quantum gravity scale [9] in the case of two large transverse dimensions.

Collider	LEP II	NLC-500	NLC-1000	TeV-I	TeV-II	LHC
$R^{-1}(\text{TeV}) \lesssim$	1.9	8	13	0.9	1.2	6.7

Table 1: *Compactification scales that can be probed with 95% confidence level at present and future colliders for one large extra dimension.*

At the LHC the energy can be high enough to produce the photon and  $Z$  KK modes, leading to a characteristic signal of resonances in the differential cross-section with respect to the invariant dilepton mass, which is the golden signature for direct detection of these states. Although for large value of the compactification scale, one sees only the first KK-excitation resonance, this scenario can be differentiated from  $Z'$  models by the observation of excitations of the  $W$  boson in  $pp \rightarrow WX$  processes.

On top of these longitudinal dimensions with gauge interactions and their direct production at high-energy colliders, there can exist transverse directions, as large as (sub)millimeter, feeling only gravitational interactions. They would indirectly contribute to the processes we have studied in this paper (by exchange of towers of KK-excitations of gravitons and moduli fields) and provide independent signatures and bounds on low string scales, which could be combined with ours.

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