Signals of Universal Extra Dimension at the ILC

Biplob Bhattacherjee [1]

Department of Physics, Calcutta University, 92 A.P.C. Road, Kolkata - 700009, India

Abstract

In the minimal Universal Extra Dimension model, single production of $n = 2$ gauge bosons provides a unique discriminating feature from supersymmetry. We discuss how the proposed International Linear Collider can act as a $n = 2$ factory, much in the same vein as LEP.

1   Introduction

In the simplest Universal Extra Dimension (UED) model proposed by Appelquist, Cheng, and Dobrescu [1], there is only one extra dimension, denoted by y, compactified on a circle (S_1) of radius R. All SM particles can access this dimension. To get chiral fermions at low-energy, one must impose a further $\mathcal{Z}_2$ symmetry ($y \leftrightarrow -y$), so that finally we have an $S_1/\mathcal{Z}_2$ orbifold. As is well-known, a higher dimension theory is nonrenormalisable and should be treated in the spirit of an effective theory valid upto a scale $\Lambda > R^{-1}$. All fields have five space-time components; when brought down to four dimensions, for each low-mass (zero-mode) Standard Model (SM) particle of mass m_0, we get an associated Kaluza-Klein (KK) tower, the n-th level (this n is the KK number of the particle) of which has a mass given by $m_n^2 = m_0^2 + \frac{n^2}{R^2}$. This is a tree-level relationship and gets modified once we take into account the radiative corrections. The KK-number is conserved in the tree-level theory; this means that the lowest-mass $n = 1$ particle, which turns out to be the $n = 1$ photon, is absolutely stable. Such a lightest KK particle (LKP), just like the lightest supersymmetric particle (LSP), is an excellent candidate for dark matter.

Radiative corrections to the masses of the KK particles have been computed in [2, 3, 4]. These papers, in particular [3], show that the almost mass-degenerate spectrum for any KK level splits up due to such correction terms. There are two types of correction; the first one, which results just from the compactification of the extra dimension, is in general small (zero for fermions) and is constant for all n levels. This we will call the bulk correction. The second one, which we will call boundary correction, is comparatively large (goes as $\ln \Lambda^2$ and hence, in principle, can be divergent), and plays the major role in determining the exact spectrum and possible decay modes. The boundary correction terms are related with the interactions present only at the fixed points $y = 0$ and $y = \pi R$. If the interaction is symmetric under the exchange of these fixed points (this is another $\mathcal{Z}_2$ symmetry, but not the $\mathcal{Z}_2$ of $y \leftrightarrow -y$), the conservation of KK number breaks down to the conservation of KK parity, defined as $(-1)^n$. Thus, LKP is still stable, but it is possible to produce an $n = 2$ state from two $n = 0$ states. This particular feature will be of central interest to this talk. With the proposed reach of ILC in mind, we will focus on the range 300 GeV $< R^{-1} <$ 500 GeV. A more detailed discussion and relevant references can be found in [5, 6].

Let us mention here that though the main focus is on the ILC, an identical study may be performed for CLIC. Clearly, the reach of CLIC will be much higher.

It has been pointed out [7] that a 'smoking gun' signal of UED would be the production of $n = 2$ states. Pair production of such states is difficult even at the LHC energy, and is surely out of reach for ILC. However, one can produce a single γ_2 or Z_2. These will be narrow peaks, closely spaced, and probably not resolvable at LHC. Here ILC will perform a much better job, and if it can sit on these resonances, it may even repeat the LEP-I story. Such precision measurements will definitely determine the model parameters, even if it is not the simplest UED model. There are a couple of points that the reader should note.

---

[1]Presented at the Linear Collider Workshop (LCWS06), Bangalore, India, March 2006

- If a collider is energetic enough to pair produce $n = 1$ excitations, single production of $n = 2$ states is also possible. Since it is not possible to produce only one $n = 1$ UED state, it is a none-or-both situation.

- Decay of a $n = 2$ state to two $n = 0$ states is allowed by KK parity conservation, but this is suppressed by boundary-to-bulk ratio. However, there is no phase space suppression, not even if the final state is a $t\bar{t}$ pair. On the other hand, the coupling is large for the KK number conserving decays ($2 \to 2 - 0, 1 - 1$, where the numbers are for the generic KK levels), but there is a heavy kinematic suppression. Ultimately it turns out that both suppressions are of equal importance [3] and hence both KK conserving and KK violating decays are to be taken into account.

In this talk we will discuss the role that ILC may play in studying this resonance physics.

2   The KK number violating interactions

A consistent formulation of UED needs the inclusion of interaction terms that exist only at the fixed points [2, 3]. In the simplest UED model, these terms are taken to be universal, symmetric about the fixed points, and vanishing for energy $\Lambda \gg R^{-1}$. This introduces only two new parameters in the model, Λ and R^{-1}, and ensures the conservation of KK parity. (In fact, there is a third parameter, $\bar{m}_h^2$, the Higgs mass term induced on the fixed points. In the minimal UED model this is assumed to be zero, but its precise value may be probed through a precision study [6].)

The excited states of Z and photon are obtained by diagonalising the mass matrix of W_3 and B. It has been shown in [3] that for all practical purpose, the $n = 2$ excitation of Z is almost W_3 (so that it is a pure SU(2) triplet and couples only to the left-handed fermions) while the $n = 2$ excitation for photon is almost a pure B (so that it couples with different strengths to left- and right-handed fermions).

We will be interested in the coupling of $n = 2$ gauge bosons with an $n = 0$ fermion-antifermion pair. This coupling is given by [3]

$$(-ig\gamma^\mu T_a P_+) \frac{\sqrt{2}}{2} \left(\frac{\bar{\delta}(m_{V_2}^2)}{m_2^2} - 2\frac{\bar{\delta}(m_{f_2})}{m_2} \right), \tag{1}$$

where g is the generic gauge coupling, T_a is the group generator (third component of isospin, or hypercharge), and P_+ is the $\mathcal{Z}_2$-even projection operator, which is $P_L = (1 - \gamma_5)/2$ for Z_2, but can be both P_L or P_R for γ_2. V can be either Z or γ. The expressions for the boundary corrections, $\bar{\delta}$, can be found in [3].

It is easy to check that for any level, the excitation of the photon, γ_n, is the lowest-lying particle. Thus, γ_2 cannot decay into a pair of $n = 0$ and $n = 2$ fermions. In fact, the decay to an $n = 1$ pair is also kinematically forbidden, for all choices of Λ and R. Thus, the only possible way to decay is to an $n = 0$ fermion-antifermion pair. Here, both right- and left-handed pairs (of quarks and leptons, including neutrinos) are included, albeit with different strengths, as obtained from eq. (1). In figure 1, we show how the function X_{Vf}, defined as

$$X_{Vf} = \frac{\sqrt{2}}{2} \left(\frac{\bar{\delta}(m_{V_2}^2)}{m_2^2} - 2\frac{\bar{\delta}(m_{f_2})}{m_2} \right), \tag{2}$$

varies for $V = \gamma, Z$ and $f = u_i, d_i, e_i$ (SU(2) singlet states) and L_i, Q_i (SU(2) doublet states), where i is the generation index. It is obvious that γ_2 should decay almost entirely to a $q\bar{q}$ pair, because of the larger splitting between γ_2 and $n = 2$ quarks. Altogether, there are 45 channels, including the colour degrees of freedom.

The decay pattern of Z_2 is more complicated. It is an almost pure $(W_3)_2$, so it couples only to left-handed doublet fermions. Kinematically, decay to an $n = 1$ pair of lepton doublet ($\mathcal{Z}_2$-even) is allowed, except for very low values of Λ ($\Lambda R < 3$). There are 6 such channels, including
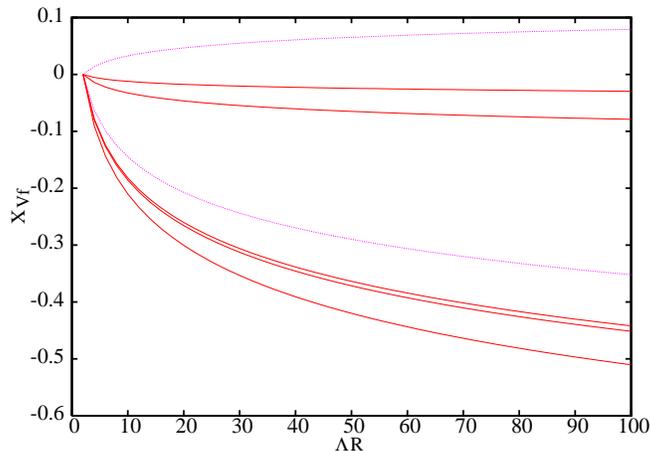
Figure 1: X_{Vf}, the KK number violating couplings, as a function of ΛR, for $R^{-1} = 300$ GeV (the values are independent of R). From top to bottom, the curves are for X_{ZL}, $X_{\gamma e}$, $X_{\gamma L}$, X_{ZQ}, $X_{\gamma d}$, $X_{\gamma u}$, and $X_{\gamma Q}$ respectively. For their definitions, see text.

neutrinos. These states will ultimately decay to the corresponding $n = 0$ leptons, plus γ_1, the LKP, (even the $n = 1$ neutrino can decay in this channel), so that the signature will be a pair of soft leptons (for charged lepton channels) plus a huge missing energy (excited neutrinos, of course, will go undetected). Fortunately, these final soft leptons should be detectable [8, 9]. Similarly, Z_2 can decay to a pair of $n = 2$ and $n = 0$ doublet leptons. Again, there are 6 channels, plus 6 CP-conjugate ones. Both these modes are KK-number conserving, but there is an important difference: while the coupling is the usual g for the latter channels, it is $g/\sqrt{2}$ for the former ones. This can be checked by integrating the trigonometric terms dependent on the fifth coordinate y.

Just like γ_2, Z_2 has its own share of KK-number violating modes, but it can only decay to a left-handed pair. Since the lower limit on R^{-1} is about 300 GeV, both these gauge bosons can decay even to the $n = 0$ $t\bar{t}$ pair. However, KK-number conserving Z_2 decays to electroweak bosons are forbidden from kinematic considerations.

In the minimal UED model, $\bar{m}_h^2 = 0$, Z_2 cannot decay through the Bjorken channel to $Z_1 h_1$, purely from kinematic considerations. (The three-body channels, with a virtual Z_1 or h_1, will be even more suppressed.) However, if $\bar{m}_h^2 < 0$, all the Higgs masses will be lowered, and one can just be able to produce a neutral CP-even Higgs excitation through this channel. The decay channel of h_1 is dominantly a right-handed τ pair (assuming the mixing in the $n = 1$ level to be small) plus LKP, and if the τs are soft enough, they may escape detection, leading to an invisible decay mode of h_1. Of course, the vertex $Z_2 W_1^\pm h_1^\mp$ does not exist.

3   Production and decay of n = 2 neutral gauge bosons

The gauge bosons are produced as s-channel resonances in e^+e^- collision through KK-number violating couplings. This suppression brings down the peak cross-section to an otherwise expected nanobarn level to about 35-45 pb for Z_2 and about 63 pb for γ_2 (for $R^{-1} = 300$ GeV, and the variation is due to that of Λ). For $R^{-1} = 450$ GeV, these numbers drop to 16-21 pb and 28 pb, respectively. The reason for a higher production cross-section for γ_2 is its narrower width compared to Z_2. However, it will be almost impossible to detect γ_2 at LHC since it decays almost entirely to two jets which will be swamped by the QCD background, and moreover the resonance is quite narrow. Z_2 has a better chance, since there are a number of hadronically quiet channels, and soft leptons with energy greater than 2 GeV should be detectable. But for a precision study of these resonances we must turn to ILC (or CLIC). These machines should be able to measure precisely the positions and the widths of these two peaks, and hence entirely determine the spectrum, since
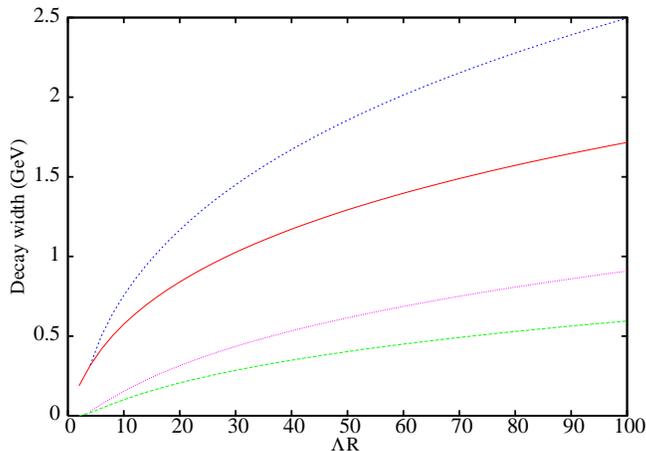
3

Figure 2: Decay widths of Z_2 (upper pair) and γ_2 (lower pair) as a function of ΛR, for $R^{-1} = 450$ GeV and 300 GeV (upper and lower curves in a pair).

there are only two unknown parameters (hopefully the Higgs mass will already be measured by LHC). These measurements, in conjunction with the precise determination of $n = 1$ levels, should be able to discriminate, not only between UED and supersymmetry, but even the minimal version of UED from its variants.

In figure 2 we show the decay widths of Z_2 and γ_2, plotted for two different values of R^{-1} and as a function of ΛR. They increase logarithmically, because of the $\log \Lambda^2$ dependence of the couplings, but no new channel opens up. For small values of ΛR (2-3), the KK-number conserving channels for Z_2 are still closed, and Z_2 can be very long-lived, even to leave a displaced vertex. (As discussed earlier, for $\Lambda R = 2$, a somewhat fine-tuned value, Z_2 is almost stable, and the peak is correspondingly narrow and hence difficult to detect.)

We emphasize that this study will be meaningful only if LHC finds some signal of new physics, which may look like UED, and for which the pair production of $n = 1$ states is not beyond the reach of ILC. In that case a careful scan about $\sqrt{s} = 2/R$ should reveal these two peaks. The points that one would like to verify are:

(i) On the Z_2 peak, $\mathcal{R}$, the ratio of e^+e^- to two jets to $e^+e^- \to \mu^+\mu^-$ would show a sharp dip, in particular if we include the missing energy events. The reason is that the Z_2-width is dominated by the channel to a pair of $n = 1$ leptons, and quarks can appear only from KK-number violating interactions. On the other hand, $\mathcal{R}$ should show a sharp peak on the γ_2 resonance.

(ii) The cross-section would show a kink between the two peaks; this is the position where the KK-number conserving channels open up.

(iii) With the polarised beam option, the behaviour of the two peaks will be quite different. Since Z_2 couples only to the left-handed fermions, with suitable polarisation the peak may vanish altogether, or may get enhanced by a factor of 3 (assuming 80% e^- polarisation and 60-70% e^+ polarisation). The γ_2 peak will get enhanced by about a factor of 2 with left-polarised e^- beam, but will never vanish altogether.

Let us also note that the SM background, coming from the continuum, is less than 10 pb for $\sqrt{s} = 600\text{-}900$ GeV [10], and may be further reduced by suitable cuts.

References

[1] T. Appelquist, H.C. Cheng, and B.A. Dobrescu, Phys. Rev. D **64**, 2001 (035002).

[2] H. Georgi, A.K. Grant and G. Hailu, Phys. Lett. **B506**, 207 (2001).

[3] H.C. Cheng, K.T. Matchev, and M. Schmaltz, Phys. Rev. D **66**, 036005 (2002).

[4] M. Puchwein and Z. Kunszt, Annals Phys. 311 (2004) 288.

[5] B. Bhattacherjee and A. Kundu, Phys. Lett. **B627**, 137 (2005).

[6] B. Bhattacherjee and A. Kundu, hep-ph/0605118.

[7] H.C. Cheng, K.T. Matchev and M. Schmaltz, Phys. Rev. D **66**, 056006 (2002).

[8] G. Bhattacharyya *et al.*, Phys. Lett. **B628**, 141 (2005).

[9] M. Battaglia *et al.*, J. High Energy Physics **0507**, 033 (2005).

[10] K. Abe *et al.* [ACFA Linear Collider Working Group], hep-ph/0109166.