

The International Linear Collider as a Kaluza-Klein Factory

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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. We also touch upon the potential of the $\gamma\gamma$ mode of the collider to study the production and the decay of an intermediate mass Higgs boson and its KK excitations.

Keywords: Universal Extra Dimension, Electron-Positron Collider

I Introduction

The possibility of a compactified extra dimension was first discussed by Kaluza and Klein [1], and such extra dimensional models were later revived by the necessity of a consistent formulation of string theories. There are a number of such models, and they differ mainly in two ways: first, the number of extra dimensions, the geometry of space-time, and the compactification manifold, and second, which particles can go into the extra dimensions (hereafter called bulk) and which cannot.

We will focus on the so-called Universal Extra Dimension (UED) model proposed by Appelquist, Cheng, and Dobrescu [2]. In this model, all SM particles can go into the bulk. In the simplest UED scenario, there is only one extra dimension, denoted by y , compactified on a circle (S_1) of radius R . The model predictions remain essentially unchanged if there are more than one extra dimension, with a hierarchical radii of compactification. Our discussion will be on the simplest scenario only.

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

$$m_n^2 = m_0^2 + \frac{n^2}{R^2}. \quad (1)$$

This is a tree-level relationship and gets modified once we take into account the radiative corrections.

Another important feature of the UED scenario is the conservation of the KK number. This is simply a reflection of the fact that all particles can go into the fifth dimension and so the momentum along the fifth dimension must be conserved. Also, 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 [3, 4, 5, 6].

Radiative corrections to the masses of the KK particles have been computed in [7, 8, 9]. These papers, in particular [8], show that the almost mass-degenerate spectrum for any KK level, resulting from eq. (1), 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 letter.

The low-energy phenomenology has been discussed in [2, 10, 11, 12, 13, 14, 15], and the high-energy collider signatures in [16, 17, 18, 19, 20, 21, 22]. The limit on $1/R$ from precision data is about 250-300 GeV, while the limit estimated from dark matter search [3] is about a factor of two higher. The loop corrections are quite insensitive to the precise values of the radiative corrections. With the proposed reach of ILC in mind, we will be interested in the range $300 \text{ GeV} < R^{-1} < 500 \text{ GeV}$. (The role of linear colliders in precision study of TeV-scale extra dimension models has been emphasized in, *e.g.*, [23].)

One of the reasons that UED has been considered seriously for the next generation collider experiments is the fact that in a certain region of the parameter space, supersymmetric models can mimic the UED signals. In this parameter space, sleptons are almost degenerate with electroweak gauginos and the lightest neutralino is only slightly separated from the lighter chargino (analogous to the anomaly-mediated supersymmetric models). If one only observes the $n = 1$ states, such a discrimination is difficult in LHC, though how the spin of the excited state can be determined has been discussed in the literature [24, 25]. At ILC or CLIC, the discrimination is simpler; even if one looks for the production of $n = 1$ electron [19] or muon [20] pair, the angular distribution of the ultimate soft leptons will be a good discriminator; this is just based on the simple fact that the decay distribution from a spin-0 object is different from a spin-1/2 one, whether or not there is a t -channel contribution.

Let us mention here that though the main focus is on the ILC, an identical study may be performed for CLIC, the proposed multi-TeV e^+e^- machine, with an optimised $\sqrt{s} = 3 \text{ TeV}$ (and may be upgraded to 5 TeV), and luminosity of $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$. The electron beam at CLIC may be polarised upto 80%, and the positron beam upto 60-80%, from Compton scattering off a high power laser beam [26]. Clearly, the reach of CLIC will be much higher.

It has been pointed out [21] 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 [20, 22]. These will be narrow peaks, closely spaced, and probably not resolvable at LHC. (In fact, as we will show later, due to the decay pattern of γ_2 , almost entirely to two jets plus no missing energy, it will be very difficult to locate this resonance 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.

- 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 ($2 \rightarrow 2 - 0, 1 - 1$, 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 [8] and hence both KK conserving and KK violating decays are to be taken into account.

In this letter we will discuss the role that ILC may play in studying this resonance physics. We will also mention how the production and the decay of the Standard Model (SM) Higgs boson as well as its excitations can be

studied in the $\gamma\gamma$ mode of the collider. In particular we will focus on the intermediate mass Higgs boson ($115 \text{ GeV} < m_h < 160 \text{ GeV}$) case. The decay that is most seriously affected is $h \rightarrow gg$, the decay to a gluon pair. (Obviously, the SM Higgs production in the gluon-gluon fusion channel at LHC will also show a marked change; this has been discussed in [27].) The reason for such a change is the higher n particles running in the loop, but unlike the SM, the effect is decoupling in nature, at least if there is only one extra dimension; otherwise the result is divergent and one is forced to use some hard truncation. The $h \rightarrow \gamma\gamma$ and $h \rightarrow \gamma Z$ vertices are comparably less affected.

II The KK number violating interactions

A consistent formulation of UED needs the inclusion of interaction terms that exist only at the fixed points [7, 8]. These terms can in principle be non-universal (just like non-universal soft mass terms in supersymmetry) and hence can affect the FCNC processes, but in the simplest UED model, they 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 as shown later.)

The excited fermions are vectorial. For SU(2) doublets, the left-handed components are \mathcal{Z}_2 -even and right-handed components are \mathcal{Z}_2 -odd, and the opposite is true for SU(2) singlets. The Yukawa terms in the fermion mass matrices may mix the doublet and the singlet states; however, this is numerically significant only for the top quark. The first four components of the gauge bosons are \mathcal{Z}_2 -even, while the fifth one is a \mathcal{Z}_2 -odd scalar. A combination of this and the excitation of the zero-mode charged Goldstone boson is absorbed by the excited gauge boson, and the orthogonal combination remains in the spectrum as a physical charged Higgs. The Higgs spectrum is nearly degenerate, with $m_{h_1} > m_{A_1} > m_{h_{1\pm}}$. To a very good approximation, the charged Higgs is the excitation of the zero-mode Goldstone. A complete set of Feynman rules is given by [12].

The excited states of Z and photon are obtained by diagonalising the mass matrix of W_3 and B . It has been shown in [8] 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 [8]

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

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 [8]. They are proportional to the renormalisation-group (RG) β -functions times $\ln(\Lambda^2/\mu^2)$, where the regularisation scale μ may be taken to be $2/R$ in this case. Clearly, in the fine-tuned case $\Lambda R = 2$, all KK number violating couplings are identically zero.

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. (2). In figure 1, we show how the function X_{Vf} , defined as

$$X_{Vf} = \frac{\sqrt{2}}{2} \left(\frac{\bar{\delta}(m_{V_2}^2)}{m_2^2} - 2 \frac{\bar{\delta}(m_{f_2})}{m_2} \right), \quad (3)$$

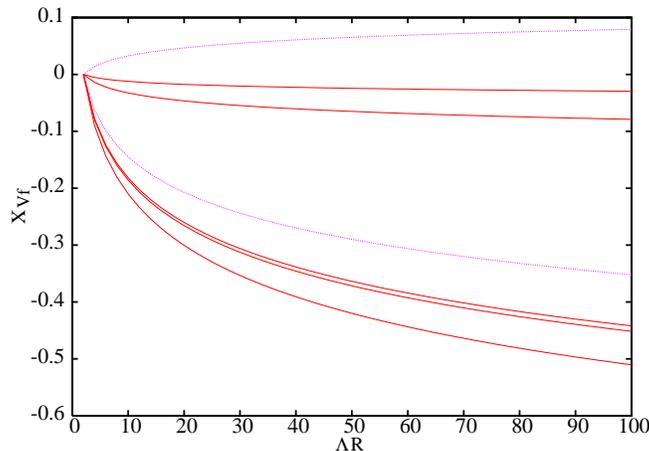


Figure 1: X_{Vf} , the KK number violating couplings, as a function of ΛR , for $R^{-1} = 300$ GeV (the values are independent of R). From top to bottom, the curves are for X_{ZL} , $X_{\gamma e}$, $X_{\gamma L}$, X_{ZQ} , $X_{\gamma d}$, $X_{\gamma u}$, and $X_{\gamma Q}$ respectively. For their definitions, see text.

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.

One may ask whether γ_2 can decay into KK-number conserving three- or four-body channels, *e.g.* $\gamma_2 \rightarrow e_1^+ e_1^{-*} \rightarrow e_1^+ e_0^- \gamma_1$. The answer is *no*, in particular for the minimal UED model. The reason is that KK-number conserving decays must result in two LKPs in the final state, and $2m_{\gamma_1} > m_{\gamma_2}$ over the entire parameter space. This we have checked both analytically and numerically; in fact, an analytical check is easy if one looks at the mass corrections and $W_3 - B$ mixing effects [8].

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 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 [19, 20]. 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.

Since KK parity is conserved, the s -channel Feynman diagrams have only the gauge bosons (\mathcal{Z}_2 -even) as mediators, not the \mathcal{Z}_2 -odd scalar which is the fifth component of the gauge boson. This statement is, of course, independent of the gauge choice. Similarly, the final state particles must be both KK even or both KK odd. However, we have just shown that only \mathcal{Z}_2 -even states will be produced in the final state.

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 τ s 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.

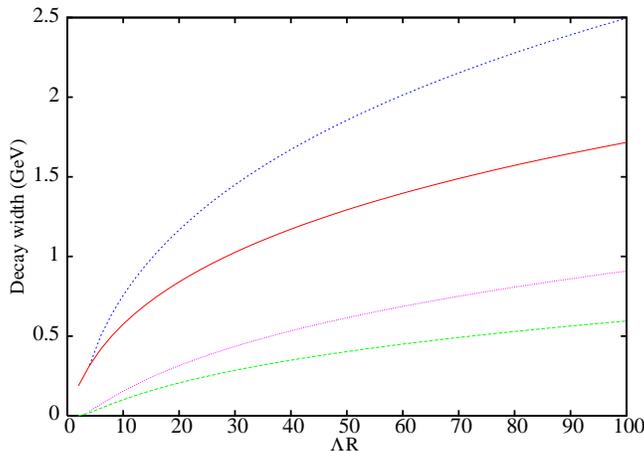


Figure 2: Decay widths of Z_2 (upper pair) and γ_2 (lower pair) as a function of ΛR , for $R^{-1} = 450$ GeV and 300 GeV (upper and lower curves in a pair).

III 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 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:

- On the Z_2 peak, \mathcal{R} , the ratio of e^+e^- to two jets to $e^+e^- \rightarrow \mu^+\mu^-$ 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.
- The cross-section would show a kink between the two peaks; this is the position where the KK-number conserving channels open up.
- 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. The reason is that the hypercharge gauge boson B couples to both R and L fermions, and though $Y_{e_R} = 2Y_{e_L}$, the ratio $X_{\gamma L}/X_{\gamma e}$ (see eq. (3)) overcompensates it.

- As we have pointed out earlier, γ_2 cannot have a KK-number conserving decay channel. This is true only in the minimal UED model. In a nonminimal version, there may be two possible corrections. First, due to nonuniversal boundary terms, γ_2 may become a little more massive, which will open the KK-number conserving windows. There is a chance that this will spoil the nice feature of having the LKP as a viable dark matter candidate. The second point, which is more probable, is to have asymmetric boundary terms (different for $y = 0$ and $y = \pi R$). This will break the KK-parity, and will result in decay modes like $\gamma_2 \rightarrow e_1^+ e_0^-$. Even if such couplings are suppressed, a precision study at ILC may discriminate between different models of UED.

Let us also note that the SM background, coming from the continuum, is less than 10 pb for $\sqrt{s} = 600\text{-}900$ GeV [28], and may be further reduced by suitable cuts.

IV Production and decay of the Higgs boson and its excitations

We focus on the production channel $\gamma\gamma \rightarrow h$, assuming that ILC will have a $\gamma\gamma$ option. The importance of this channel has been emphasized in the literature, particularly for intermediate mass Higgs. The reason is that the production is loop-mediated, and the excited states can run in the loop, without the need of a KK-number violating vertex. (This is analogous to the case of R-parity conserving supersymmetry.) Again, we assume the Higgs to be in the intermediate mass range, $115 \text{ GeV} < m_h < 160 \text{ GeV}$.

In the SM, the process $\gamma\gamma \rightarrow h$ proceeds mainly through the top quark and the W -boson loops. The leading order expressions are to be found in [29, 30]. The UED case, for a larger range of m_h and R^{-1} than we discuss, has been treated in detail in [27], and we agree with the findings. Let us try to see the result in a physically more transparent way.

- There are higher n excitations in the loop. Only three loops are of relevance: those of the top quark, the W boson and the charged Higgs. Though the masses of other fermionic excitations are large too, their contributions get suppressed from their couplings with Higgs, which is proportional to their zero-mode masses m_f . Moreover, in the fermionic loops, there is one more chirality flip, which brings in another factor of m_f . Note that the vectorial mass term cannot come since \mathcal{Z}_2 -parity of the virtual fermion cannot change inside the loop. Also, unlike SM, the W -loop and the top quark loop interfere constructively.
- For the W loop and the charged Higgs loop, the mass suppression in the vertex exists, but there is no question of a chirality flip. On the other hand, if one wishes to normalise the result with the same prefactor of G_F as in the SM, this brings another factor of m_W/m_{W_1} , thus making the effective suppression quadratic in vR , where v is the vacuum expectation value of the SM Higgs field. (Note that $G_F \propto v^{-2}$). In the unitary gauge, the fifth component of W^+ does not appear. The top quark loop is also quadratically suppressed in vR , but there are two such loops, due to the vectorial nature of the excitation.
- With these modifications, one may use the standard expressions (leading order is sufficient) for these loops, with a suitable scaling of the mass of the loop particle. Note that all the amplitudes must be coherently added.

The result is in conformity with [27]: the $\gamma\gamma \rightarrow h$ cross-section drops by 25-30% for $R^{-1} = 300$ GeV, and by a smaller amount for higher values of R^{-1} . The SM W -loop contribution is large and negative, but the UED bosonic loops are positive. However, because of the quadratic suppression, they can only partly offset the SM contribution. The intermediate mass Higgs decays dominantly to $b\bar{b}$, or to three-body final states through

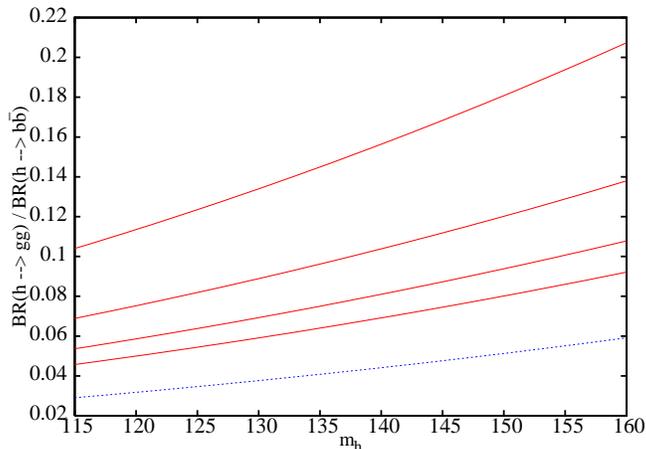


Figure 3: The relative enhancement of $h \rightarrow gg$ decay width for $R^{-1} = 300, 400, 500,$ and 600 GeV (top to bottom). The SM expectation is the blue line at the bottom.

virtual gauge bosons [31]. Such tree-level modes will hardly feel the effect of UED. But the loop-induced decay $h \rightarrow gg$, a pair of gluons (second in importance in the intermediate mass range), will be enhanced by UED (only the top quark loop is relevant here). In figure 3 we show how the relative importance of this mode changes with the dominant mode $h \rightarrow b\bar{b}$. The result is convergent for one extra dimension. We note that in the clean atmosphere of ILC, such an enhancement will be easily detectable. A similar calculation, performed in the context of LHC for the production of Higgs through gluon-gluon fusion, shows an identical effect [27].

ILC is not the ideal machine to produce the excited neutral Higgses. The best channel is the fusion of a W_0 and a W_1 , accompanied by a ν_0 and a ν_1 . The signal will be a soft τ pair, with a huge amount of missing energy (ν_1 decays to ν_0 and LKP, and hence acts as a virtual LKP). The charged Higgs may be pair produced in the $\gamma\gamma$ mode with a large cross-section. In the minimal UED model, $\bar{m}_h^2 = 0$, h_1^+ can decay to a right-handed τ_1 and a zero-mode ν_τ , and the former will again give a soft τ . If it is too soft, even the charged Higgs may decay invisibly. Anyway, it is important to have a high soft- τ detection efficiency (preferably < 1 GeV) in the ILC detector. It will be even better if one can measure the polarisation of the τ . The excited Higgs sector will be discussed in detail in a subsequent publication.

V Summary

ILC can act as a Kaluza-Klein factory if R^{-1} happen to be on the lower side so that one is able to pair produce $n = 1$ states of the minimal UED (otherwise we have to turn to CLIC). ILC can make a precision study of the two peaks, Z_2 and γ_2 , including precise measurements of their positions and widths. The peaks are well over the continuum background, and if the machine can be tuned properly, it can repeat the LEP-I story. Precision study of these peaks will not only discriminate this model from any supersymmetric scenarios that may mimic UED at the LHC, but also be able to determine the model parameters R and Λ , and hence can potentially test the minimality of the UED version. The only parameter that the resonance study may not be able to fix is \bar{m}_h^2 , which in turn may be determined through the study of the Higgs sector. The $h \rightarrow gg$ mode should show a marked enhancement. On the other hand, the excited Higgses will mostly decay to soft τ s, and it is of utmost importance to have a high soft- τ detection efficiency.

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References

- [1] T. Kaluza, Preuss.Akad.Wiss., Berlin, Math. Phys. K1 (1921) 966; O. Klein, Z. Phys. 37 (1926) 895.
- [2] T. Appelquist, H.C. Cheng, and B.A. Dobrescu, Phys. Rev. D 64 (035002) 2001.
- [3] G. Servant and T.M.P. Tait, Nucl. Phys. B650 (2003) 391.
- [4] D. Majumdar, Phys. Rev. D 67 (2003) 095010.
- [5] M. Byrne, Phys. Lett. B583 (2004) 309.
- [6] M. Kakizaki, S. Matsumoto, Y. Sato, and M. Senami, hep-ph/0502059.
- [7] H. Georgi, A.K. Grant and G. Hailu, Phys. Lett. B506 (2001) 207.
- [8] H.C. Cheng, K.T. Matchev, and M. Schmaltz, Phys. Rev. D 66 (2002) 036005.
- [9] M. Puchwein and Z. Kunszt, Annals Phys. 311 (2004) 288.
- [10] K. Agashe, N.G. Deshpande, and G.H. Wu, Phys. Lett. B514 (2001) 309.
- [11] D. Chakraverty, K. Huitu, and A. Kundu, Phys. Lett. B558 (2003) 173.
- [12] A.J. Buras, M. Spranger, and A. Weiler, Nucl. Phys. B660 (2003) 225;
A.J. Buras, A. Poschenrieder, M. Spranger, and A. Weiler, Nucl. Phys. B678 (2004) 455.
- [13] J.F. Oliver, J. Papavassiliou, and A. Santamaria, Phys. Rev. D 67 (2003) 056002.
- [14] J.F. Oliver, arXiv:hep-ph/0403095.
- [15] T.G. Rizzo and J.D. Wells, Phys. Rev. D 61 (2000) 016007; A. Strumia, Phys. Lett. B466 (1999) 107; C.D. Carone, Phys. Rev. D 61 (2000) 015008.
- [16] T. Rizzo, Phys. Rev. D 64 (2001) 095010.
- [17] C. Macesanu, C.D. McMullen, and S. Nandi, Phys. Rev. D 66 (2002) 015009.
- [18] C. Macesanu, C.D. McMullen, and S. Nandi, Phys. Lett. B546 (2002) 253;
H.C. Cheng, Int. J. Mod. Phys. A18 (2003) 2779;
A. Muck, A. Pilaftsis, and R. Rückl, Nucl. Phys. B687 (2004) 55.
- [19] G. Bhattacharyya, P. Dey, A. Kundu, and A. Raychaudhuri, hep-ph/0502031.
- [20] M. Battaglia, A. Datta, A. De Roeck, K. Kong and K.T. Matchev, J. High Energy Physics 0507 (2005) 033.
- [21] H.C. Cheng, K.T. Matchev and M. Schmaltz, Phys. Rev. D 66 (2002) 056006.
- [22] S. Riemann, hep-ph/0508136.
- [23] I. Antoniadis, Phys. Lett. B246 (1990) 377.
- [24] A.J. Barr, Phys. Lett. B596 (2004) 205.
- [25] J.M. Smillie and B.R. Webber, hep-ph/0507170.
- [26] Physics at the CLIC multi-TeV linear collider, hep-ph/0412251, ed. M. Battaglia, A. De Roeck, J. Ellis, D. Schulte.
- [27] F.J. Petriello, J. High Energy Physics 0205 (2002) 003.
- [28] K. Abe *et al.* [ACFA Linear Collider Working Group], hep-ph/0109166.

- [29] A.I. Vainshtein, M.B. Voloshin, V.I. Sakharov, and M.A. Shifman, *Sov. J. Nucl. Phys.* 30 (1979) 711.
- [30] M. Spira, A. Djouadi, D. Graudenz and P.M. Zerwas, *Nucl. Phys.* B453 (1995) 17.
- [31] M. Carena and H.E. Haber, hep-ph/0208209.