Universal Extra Dimensions at the $e^-e^-$ Colliders

Hsin-Chia Cheng

Enrico Fermi Institute, The University of Chicago, Chicago, IL 60637, USA

Abstract

Universal Extra Dimensions (UEDs) with compactification radius near the TeV scale provide interesting phenomenology at future colliders. The collider signals of the first Kaluza-Klein (KK) level are very similar to those of a supersymmetric model with a nearly degenerate superpartner spectrum. The heavier first level KK states cascade decay to the lightest KK particles (LKP), which is neutral and stable because of KK-parity. The signatures involve missing energy and relatively soft jets and leptons which can be difficult for detection. The KK electron signal in $e^-e^-$ collisions is free from the problematic two photon background therefore provides a unique opportunity for a detailed studies of the KK electrons in the Universal Extra Dimension scenario.
1 Introduction

Large extra dimensions have recently attracted a lot of interest. They provide many new theoretical ideas to explore questions in particle physics. Most excitingly, they also predict signals which will be tested at the upcoming collider experiments.

In this talk we focus on the scenario of Universal Extra Dimensions (UEDs) [1]. In UEDs, all standard model (SM) fields propagates in extra dimensions of size $R \sim \text{TeV}^{-1}$. There are many theoretical motivations for this scenario, such as electroweak symmetry breaking [2], proton decay [3], the number of generations [4], neutrino masses [5], etc. The current experimental bounds allow Kaluza-Klein (KK) states in UEDs to be as light as a few hundred GeV [1, 6, 7]. Such light KK states can be copiously produced at the current or future colliders with center of mass energies $\gtrsim \text{TeV}$. It is therefore interesting to study their collider phenomenology, and one might expect that it would be easy to discover these KK states. However, although their production cross section can be very large, their subsequent detection is non-trivial because they decay nearly invisibly. The phenomenology of UEDs shows interesting parallels to supersymmetry. Every Standard Model field has KK partners. The lowest level KK partners carry a conserved quantum number, KK parity, which guarantees that the lightest KK particle (LKP) is stable. Heavier KK modes cascade decay to the LKP by emitting soft Standard Model particles. The LKP escapes detection, resulting in missing energy signals.

Given that the signals are very similar to supersymmetry (SUSY), it is important to distinguish them by studying the properties of the new states produced in colliders in details. Linear colliders often provide a clean environment for such kind of studies. However, in $e^+e^-$ collisions, the signals will be plagued by the huge two photon backgrounds due to the softness of the observable decay products. On the other hand, the $e^-e^-$ mode, as we will see, stands as a unique opportunity for a detailed study of the KK excitations of the electrons. This talk was based on work in collaboration with Konstantin T. Matchev and Martin Schmaltz [8, 9].

2 Minimal Universal Extra Dimensions

Let us first describe the model. The simplest UED scenario has all of the Standard Model fields (no supersymmetry) propagating in a single extra dimension. In 4+1 dimensions, the fermions $[Q_i, u_i, d_i, L_i, e_i, i = 1, 2, 3$, where upper (lower) case letters represent $SU(2)$ doublets (singlets)] are four-component and contain both chiralities when reduced to 3+1 dimensions. To produce a chiral 4d spectrum, we compactify the extra dimension on an $S_1/Z_2$ orbifold. Fields
which are odd under the $Z_2$ orbifold symmetry do not have zero modes, hence the unwanted fields (zero modes of fermions with the wrong chiralities and the 5th component of the gauge fields) can be projected out. The remaining zero modes are just the Standard Model particles in 3+1 dimensions.

The full Lagrangian of the theory comprises both bulk and boundary interactions. Gauge and Yukawa couplings and the Higgs potential are contained in the bulk Lagrangian in one-to-one correspondence with the couplings of the Standard Model. The boundary Lagrangian interactions are localized at the orbifold fixed points and do not respect five dimensional Lorentz invariance.

Ignoring the localized terms for the moment, the tree-level mass of the $n$-th KK mode is

$$m_n^2 = \frac{n^2}{R^2} + m_0^2,$$

(1)

where $R$ is the radius of the compact dimension, and $m_0$ is the zero mode mass. The spectrum at each KK level is highly degenerate except for particles with large zero mode masses ($t, W, Z, h$). The bulk interactions preserve the 5th dimensional momentum (KK number). The corresponding coupling constants among KK modes are simply equal to the SM couplings (up to normalization factors such as $\sqrt{2}$). The Feynman rules for the KK modes can easily be derived (e.g., see Ref. [10, 11]).

In contrast, the coefficients of the boundary terms are not fixed by Standard Model couplings and correspond to new free parameters. In fact, they are renormalized by the bulk interactions and hence are scale dependent [12, 8]. One might worry that this implies that all predictive power is lost. However, since the wave functions of Standard Model fields and KK modes are spread out over the extra dimension and the new couplings only exist on the boundaries, their effects are volume suppressed. We can get an estimate for the size of these volume suppressed corrections with naive dimensional analysis by assuming strong coupling at the cut-off. The result is that the mass shifts to KK modes from boundary terms are numerically equal to corrections from loops $\delta m_n^2/m_n^2 \sim g^2/16\pi^2$.

We will assume a symmetry which exchanges the two orbifold fixed points. The boundary terms on the two fixed points are equal under this symmetry. It is anomaly free and preserved by the radiative corrections of the bulk interactions. Most relevant to the phenomenology are localized kinetic terms for the SM fields, such as

$$\frac{\delta(x_5) + \delta(x_5 - \pi R)}{\Lambda} \left[ G_4 (F_{\mu\nu})^2 + F_4 \overline{\Psi} i\gamma_5 \partial_\mu \Psi + F_5 \overline{\Psi} \gamma_5 \partial_5 \Psi \right],$$

(2)

where the dimensionless coefficients $G_4$ and $F_i$ are arbitrary and not universal for the different Standard Model fields. These terms are important phenomenologically for several reasons:
Figure 1: One-loop corrected mass spectrum of the first KK level in MUEDs for $R^{-1} = 500$ GeV, $\Lambda R = 20$ and $m_h = 120$ GeV.

$(i)$ they split the near-degeneracy of KK modes at each level, $(ii)$ they break KK number conservation down to a KK parity (due to the symmetry between the two fixed points,) under which modes with odd KK numbers are charged, $(iii)$ they may introduce new flavor violations.

For simplicity and definiteness, we will concentrate on the Minimal Universal Extra Dimensions (MUEDs) \cite{9}, where all boundary terms are assumed to vanish at some cutoff scale $\Lambda > R^{-1}$. At a lower scale, they will be generated by radiative corrections from the bulk interactions which are calculable. This is analogous to the case of the Minimal Supersymmetric Standard Model (MSSM) where one has to choose a set of soft supersymmetry breaking parameters at some high scale in order to study its phenomenology. In some sense, our choice of the boundary terms may be viewed as analogous to the simplest minimal supergravity boundary condition — universal scalar and gaugino masses.

Given this choice of the boundary condition, we can calculate the corrections to the KK spectrum, which depends on the boundary terms at low scales. Since the corrections are small one can use the one-loop leading log approximation. In addition to the boundary terms, the KK spectrum also receives corrections from pure bulk effects. Loops wrapping around the compact extra dimension with nonzero net winding numbers break the 5-dimensional Lorentz invariance and therefore also correct the KK mass formula \cite{11}. The bulk corrections are finite and exactly calculable due to their non-local nature. All these corrections, including both bulk and boundary contributions, were computed at one-loop in Ref. \cite{8}. 

3
An example of the spectrum for the first level KK modes is shown in Fig. 1. Typically, the corrections for KK modes with strong interactions are > 10% while those for states with only electroweak interactions are a few percent. We find that the corrections to the masses are such that $m_{g_n} > m_{Q_n} > m_{q_n} > m_{w_n} \sim m_{z_n} > m_{L_n} > m_{e_n} > m_{\gamma_n}$. The lightest KK particle $\gamma_1$, is a mixture of the first KK mode $B_1$ of the $U(1)_Y$ gauge boson $B$ and the first KK mode $W_1^0$ of the $SU(2)_W W^3$ gauge boson. We will usually denote this state by $\gamma_1$. However, note that the corresponding “Weinberg” angle $\theta_1$ is much smaller than the Weinberg angle $\theta_W$ of the Standard Model \cite{weinberg}, so that the $\gamma_1$ LKP is mostly $B_1$ and $Z_1$ is mostly $W_1^0$. The mass splittings among the level 1 KK modes are large enough for the prompt decay of a heavier level 1 KK mode to a lighter level 1 KK mode. But since the spectrum is still quite degenerate, the ordinary SM particles emitted from these decays will be soft, posing a challenge for collider searches.

The terms localized at the orbifold fixed points also violate the KK number by even units. However, assuming that no explicit KK-parity violating effects are put in by hand, KK parity remains an exact symmetry. The boundary terms allow higher \((n > 1)\) KK modes to decay to lower KK modes, and even level states can be singly produced (with smaller cross sections because the boundary couplings are volume suppressed). Thus KK number violating boundary terms are important for higher KK mode searches.

### 3 Collider Phenomenology

Once the radiative corrections are included, the KK mass degeneracy at each level is lifted and the KK modes decay promptly. The collider phenomenology of the first KK level is therefore very similar to a supersymmetric scenario in which the superpartners are relatively close in mass — all squeezed within a mass window of 100-200 GeV (depending on the exact value of $R$). Each level 1 KK particle has an exact analogue in supersymmetry: $B_1 \leftrightarrow \text{bino}$, $g_1 \leftrightarrow \text{gluino}$, $Q_1(q_1) \leftrightarrow \text{left-handed (right-handed) squark}$, etc. The decay cascades of the level 1 KK modes will terminate in the $\gamma_1$ LKP (Fig. 2). Just like the neutralino LSP is stable in $R$-parity conserving supersymmetry, the $\gamma_1$ LKP in MUEDs is stable due to KK parity conservation and its production at colliders results in generic missing energy signals.

At hadron colliders, the largest cross sections for KK states come from strongly interacting KK quarks and gluons because of the approximately degenerate KK spectrum. The level 1 KK states have to be pair produced due to KK parity conservation. Their cross sections at the Tevatron Run II and the LHC can be found in Ref. \cite{kk_cross_sections} and \cite{mued_cross_sections}. In MUEDs, the heaviest KK state at level 1 is the KK gluon $g_1$. It decays to a KK quark and an ordinary quark. The
SU(2) singlet KK quarks will decay to $\gamma_1$ directly. The signature is jets+$E_T$, similar to the traditional squark and gluino searches [14]. Using the existing studies of the analogous SUSY studies, one might expect that Run II can probe $R^{-1} \sim 300$ GeV while the LHC reach for $R^{-1}$ can be $\sim 1$ TeV [15, 16]. However, the jets will be relatively soft in the case of MUEDs due to the approximate degeneracy of the KK initial and final states, and the measured missing energy is correlated with the energy of the soft recoiling jets hence also small, even though the total missing mass is large. They may cause more difficulties in triggering and separation of backgrounds. Further studies in the context of MUEDs are needed to obtain a better estimate of the reaches with the jetty signatures. The SU(2) doublet KK quarks will mostly decay to KK $W$ and $Z$ bosons, then subsequently decay to KK leptons and $\gamma_1$. They give rise to the much cleaner signatures with multi-leptons. Using the very clean 4 lepton channel in Ref. [9] we estimate that Run IIb can go slightly beyond the current indirect bounds ($R^{-1} > 300$ GeV) from precision data, and LHC can extend the reach to $R^{-1} \sim 1.5$ TeV.

Although LHC will be able to extend the reach much beyond the current bounds, to identify the extra-dimensional nature of the new physics once some signals are found will be rather challenging. All signals from level 1 KK states look very much like supersymmetry — all SM particles have “partners” with similar couplings. Of course, the spins of these SM particle partners are different in SUSY and UEDs, but this difference will most likely escape detection at a hadron collider. In addition, all the observed jets, leptons, and $E_T$
are relatively soft. It would be difficult to know exactly the mass scale of these KK states. Additional experimental information will be needed to identify which scenario of new physics is realized and the mass scale associated with it.

Linear colliders provide a clean environment for precise studies of particle properties. Taking the slepton production in supersymmetry as an example, one can get a precise measurement of the slepton mass and the LSP mass from the end points of the final state lepton energy distribution \[17, 18\]. The flat energy distribution between the end points will also tell the scalar nature of the sleptons produced. Therefore, a linear collider can be a great tool to distinguish UEDs from SUSY. Given the bounds on the masses of the level 1 KK modes, the required energy for pair producing them is probably too high for the first stage of the next generation linear colliders, but may be reachable with energy upgrades or at CLIC. However, in \( e^+ e^- \) collisions there are huge backgrounds from the two photon processes for very soft final state leptons or jet (Fig. 3). Soft leptons or jets are produced by the collisions of the two soft photons from the initial state radiation, while the initial \( e^+ \) and \( e^- \) go down the beam pipe, resulting in large missing energies. The two photon background for slepton search at a 500 GeV linear collider is studied in details in Ref. [19]. It was shown that for very soft final state leptons (\( \lesssim 10\% \times E_{\text{beam}} \)), the two photon background is still several order magnitude larger than the signal even after the cuts. In the case of MUEDs, the mass splittings between the KK leptons and \( \gamma_1 \) are only about 1–3\%. Therefore the leptons coming from decays of the KK leptons will be completely buried in the two photon background. KK quarks receive larger mass corrections and the jets coming from their decay would be harder. Their detection in the \( e^+ e^- \) collisions is more promising.

On the other hand, only KK electrons can be produced in the \( e^- e^- \) collisions (if there is no flavor violation from the boundary terms). The signal will be two soft electrons of the
same charge plus large missing energy, while the two photon processes produce fermions of the opposite charges. By charge identification one can remove the problematic two photon background. Therefore, the $e^-e^-$ mode of a linear collider stands as a unique opportunity for KK electron studies. All particle properties of the KK electrons should be able to be measured unambiguously, providing valuable information for identifying the corresponding new physics. It would also be useful to study possible lepton flavor violations if they are present as in the case of supersymmetry \[20\].

4 Conclusions

Universal extra dimensions with compactification radius near the TeV scale promise exciting phenomenology for future colliders. All Standard Model particles have KK partners which can be produced with enormous cross sections at the LHC. However, the subsequent decays produce very soft Standard Model particles which can be difficult to see above the backgrounds, hence their detection and identification are rather non-trivial. The $e^+e^-$ collider has one more piece of information as the total missing energy can be measured, but also suffers from the huge two photon background if the SM particles from the decays of the KK states are too soft. The $e^-e^-$ collider provide a unique clean environment for the detailed studies of the KK electrons. As different possible new physics scenarios often give rise to complicated but sometimes similar collider phenomenologies, it is essential to have as many tools as possible to provide enough experimental information for our understanding of any new physics.

Acknowledgements

I would like to thank K. T. Matchev and M. Schmaltz for collaboration on this work. I also thank N. Arkani-Hamed, M. Chertok, A. Cohen, B. Dobrescu and B. Schumm for useful discussions. This work is supported by the Department of Energy grant DE-FG02-90ER-40560.

References

[1] T. Appelquist, H.-C. Cheng and B. A. Dobrescu, Phys. Rev. D 64, 035002 (2001), [hep-ph/0012100].
[2] N. Arkani-Hamed, H.-C. Cheng, B. A. Dobrescu and L. J. Hall, Phys. Rev. D 62, 096006 (2000), hep-ph/0006238.

[3] T. Appelquist, B. A. Dobrescu, E. Ponton and H. U. Yee, Phys. Rev. Lett. 87, 181802 (2001), hep-ph/0107056.

[4] B. A. Dobrescu and E. Poppitz, Phys. Rev. Lett. 87, 031801 (2001), hep-ph/0102010.

[5] T. Appelquist, B. A. Dobrescu, E. Ponton and H. U. Yee, hep-ph/0201131.

[6] K. Agashe, N. G. Deshpande and G. H. Wu, Phys. Lett. B 514, 309 (2001), hep-ph/0105084.

[7] T. Appelquist and B. A. Dobrescu, Phys. Lett. B 516, 85 (2001), hep-ph/0106140.

[8] H.-C. Cheng, K. T. Matchev and M. Schmaltz, hep-ph/0204342.

[9] H.-C. Cheng, K. T. Matchev and M. Schmaltz, hep-ph/0205314.

[10] C. Macesanu, C. D. McMullen and S. Nandi, hep-ph/0201300.

[11] D. A. Dicus, C. D. McMullen and S. Nandi, Phys. Rev. D 65, 076007 (2002), hep-ph/0012259.

[12] H. Georgi, A. K. Grant and G. Hailu, Phys. Lett. B 506, 207 (2001), hep-ph/0012379.

[13] T. G. Rizzo, Phys. Rev. D 64, 095010 (2001), hep-ph/0106330.

[14] B. Abbott et al. [D0 Collaboration], Phys. Rev. Lett. 83, 4937 (1999), hep-ex/9902013; T. Affolder et al. [CDF Collaboration], Phys. Rev. Lett. 88, 041801 (2002), hep-ex/0106001.

[15] S. Abel et al. [SUGRA Working Group Collaboration], hep-ph/0003154.

[16] S. I. Bityukov and N. V. Krasnikov, Phys. Lett. B 469, 149 (1999), hep-ph/9907257.

[17] T. Tsukamoto, K. Fujii, H. Murayama, M. Yamaguchi and Y. Okada, Phys. Rev. D 51, 3153 (1995).

[18] T. Abe et al. [American Linear Collider Working Group Collaboration], in Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001) ed. R. Davidson and C. Quigg, hep-ex/0106056.
[19] N. Danielson and L. Goodman, “Point 2 Selections and the Standard Model Background,” University of Colorado, COLO-HEP-422 (1998); N. Danielson, “Search for Supersymmetry and the Two Photon Background,” University of Colorado, COLO-HEP-423 (1998), http://hep-www.colorado.edu/SUSY.

[20] N. Arkani-Hamed, H.-C. Cheng, J. L. Feng and L. J. Hall, Phys. Rev. Lett. 77, 1937 (1996), hep-ph/9603431.