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Probing universal extra dimension at the international linear collider*

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Abstract. We consider the UED scenario and study the detectability of the first KK electron–positron pair at the ILC. A few hundred GeV KK electron decays into a nearly degenerate KK photon, which carries away missing energy, and the standard electron. The mass splitting between the KK electron and KK photon is controlled by the bulk- and brane-induced radiative corrections. We look for the signal event e^+e^-+ large missing energy for $\sqrt{s} = 1$ TeV and observe that with a few hundred fb^{-1} luminosity the signal can be deciphered from the standard model background. We briefly outline how the UED signals may be distinguished from the supersymmetric signals.

Keywords. Extra dimension; Kaluza–Klein; linear collider.

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1. Introduction

We consider universal extra dimension (UED) models [2] with just one extra compactified dimension in the range $R^{-1} = 250$–450 GeV. This extra dimension is accessed by all the standard model (SM) fields. In this context, we examine production of the first Kaluza–Klein (KK) electron–positron pair ($E_1^+E_1^-$) in the e^+e^- international linear collider (ILC) [3]. The heavy modes $E_1^{\pm}$ would decay into the SM (zero modes) $e^{\pm}$ and the first KK photon (γ_1), the latter being stable escapes the detector giving rise to missing energy. The splitting between $E_1^{\pm}$ and γ_1 arises from the bulk and brane-localized radiative corrections. The cross-section of the final state e^+e^- plus missing energy is in the pb range and the SM background is tractable, so that even with a one year run of the upgraded ILC at $\sqrt{s} = 1$ TeV with approximately 300 fb^{-1}, enough evidence may be garnered to support the UED hypothesis. Angular distribution of the final electrons can be used to discriminate the KK leptons from the supersymmetric particles.

*This talk is based on a work the author did with Paramita Dey, Anirban Kundu and Amitava Raychaudhuri [1].

2. Simplest universal extra dimension

The extra dimension here is actually an orbifold S^1/Z_2. The orbifolding is necessary to generate zero mode chiral fermions. The tree-level mass of the nth KK state is given by $M_n^2 = M_0^2 + n^2/R^2$, where M_0 is the zero mode mass. The momentum along y, quantized as n/R, is a conserved quantity at all tree-level interactions. But what is conserved at all order is the KK parity defined as $(-1)^n$, and as a result even states mix with even states via loops, and odd mix with odd. Therefore, (i) the lightest Kaluza–Klein particle (LKP) is stable, and (ii) a single KK state (e.g. $n = 1$ state) cannot be produced by tree-level couplings. Thus KK parity is quite similar to R-parity in supersymmetry. Phenomenological constraints on the UED scenario (see ref. [1]) indicate that $R^{-1} \gtrsim 250$ GeV. So we consider only the first level $E_1^+E_1^-$ pair production and their subsequent decays. In the next section, we shall see how the degeneracy between $E_1^\pm$ and γ_1 is lifted by radiative corrections.

3. Radiative corrections and the spectrum

The above-mentioned degeneracy ($M_n = n/R$), barring zero mode masses, is only a tree-level result. Radiative corrections lift this degeneracy [4]. For intuitive understanding, we consider the kinetic term of a 5D scalar field as $L_{\rm kin} = Z\partial_\mu\phi\partial^\mu\phi - Z_5\partial_5\phi\partial^5\phi$, where Z and Z_5 are wave-function renormalizations. Recall, tree-level KK masses ($M_n = n/R$) originate from the kinetic term in the y-direction. If $Z = Z_5$, there is no correction to those KK masses. But this equality is lost due to Lorentz violation leading to $\Delta M_n \propto (Z - Z_5)$. One actually encounters two kinds of radiative corrections.

(a) *Bulk corrections*: These corrections are finite, and nonzero only for bosons. They arise when the internal loop lines wind around the compactified direction. The correction turns out to be $\Delta M_n^2 \propto \beta/16\pi^4 R^2$, where β is a symbolic representation of the collective β-function contributions of the gauge and matter KK fields floating inside the loop. Since the β-functions are different for particles in different representations, the KK degeneracy is lifted causing splitting around n/R. For the KK fermions this correction is zero.

(b) *Orbifold corrections*: Orbifolding breaks translational invariance in the y-direction, and generates interactions localized at the fixed points. These corrections are log divergent. Such boundary terms can be thought of as counterterms whose finite parts are *assumed* to vanish at some cut-off Λ. The correction is given by $\Delta M_n \sim M_n(\beta/16\pi^2)\ln(\Lambda^2/\mu^2)$, where μ is the low energy where we compute these corrections. The KK states are thus further split, now with an additional dependence on Λ. The orbifold corrections are numerically dominant (see table 1 for mass spectrum including both types of corrections).

4. Production and decay modes of KK leptons

The KK fermions are vector-like. The $SU(2)$ doublet KK states are $(\mathcal{N}_n, \mathcal{E}_n)^T_{\rm L,R}$, and $SU(2)$ singlets are $(\hat{\mathcal{E}}_n)_{\rm L,R}$, where n is the KK index. Below we denote $\mathcal{E}_1^\pm$ and $\hat{\mathcal{E}}_1^\pm$ collectively by $E_1^\pm$.

Table 1. $n = 1$ KK masses in GeV for different cases.

R^{-1}	ΛR	$M_{\hat{\mathcal{E}}_1}$	$M_{\mathcal{E}_1}$	M_{W_1}	M_{Z_1}	M_{γ_1}
250	20	252.7	257.5	276.5	278.1	251.6
	50	253.6	259.7	280.6	281.9	251.9
350	20	353.8	360.4	379.0	379.7	351.4
	50	355.0	363.6	384.9	385.4	351.5
450	20	454.9	463.4	482.9	483.3	451.1
	50	456.4	467.5	490.6	490.8	451.1

The process $e^+e^- \to E_1^+E_1^-$ proceeds through s- (γ/Z mediated) and t-channel (γ_1/Z_1) graphs. E_1 decays into e and γ_1. The splitting between E_1 and γ_1 masses is sufficient for the decay to occur within the detector with a 100% branching ratio (BR). It may be possible to observe even a displaced vertex (e.g., $\hat{\mathcal{E}}_1$ decays, with $R^{-1} = 250$ GeV). So in the final state we have $e^+e^- + 2\gamma_1$ ($\equiv$ missing energy). The same final states can be obtained from $e^+e^- \to W_1^+W_1^-$, but this will be BR suppressed.

SM background: The main background comes from $\gamma^*\gamma^* \to e^+e^-$ events, where γ^*s arise from the initial e^+e^- pair while the latter go undetected down the beam pipe [5]. The $\gamma^*\gamma^*$ production cross-section is $\sim 10^4$ pb. About half of these events go to final-state e^+e^- pair as visible particles. The background e^+e^- pairs are usually quite soft and coplanar with the beam axis. An acoplanarity cut significantly removes this background without much affecting the signal. For example, excluding events which deviate from coplanarity within 40 mrad reduces only 7% of the signal cross-section. For another strategy to handle backgrounds, see footnote 1 in [1]. Numerically much less significant backgrounds would come from $e^+e^- \to W^+W^-$, $e\nu W$, e^+e^-Z, followed by the appropriate leptonic decays of W and Z.

Collider parameters: The study is performed in the context of the ILC, running at $\sqrt{s} = 1$ TeV (upgraded option), and with a polarization efficiency of 80% for e^- and 50% for e^+ beams. We impose kinematic cuts on the lower and upper energies of the final-state electrons/positrons as 0.5 GeV (for identification) and 20 GeV (for reducing SM background) respectively. We also employ a rapidity cut rejecting all final-state electrons which are within 15° of the beam pipe.

Cross-sections: The cross-section for e^+e^- plus missing energy final state has been plotted in figure 1. Varying the beam polarizations does create a detectable difference. The cross-section enhances as we increase ΛR from 2 to 20; this is due to the change in θ_{W1} (the weak angle for $n = 1$ KK gauge bosons). The cuts tend to reduce the cross-section which is why the curve for $\Lambda R = 50$ lies between the ones for $\Lambda R = 2$ and 20.

Forward-backward (FB) asymmetries: The FB asymmetries of the final-state electrons, defined as $A_{\rm FB} = (\sigma_{\rm F} - \sigma_{\rm B})/(\sigma_{\rm F} + \sigma_{\rm B})$, are plotted in figure 2. The first-stage process $e^+e^- \to E_1^+E_1^-$ is forward-peaked, and for smaller $1/R$, i.e. lighter KK electrons, the final state $e^\pm$ are boosted more along the direction of the parent $E_1^\pm$. As $1/R$ increases the boost drops and the distribution loses its original

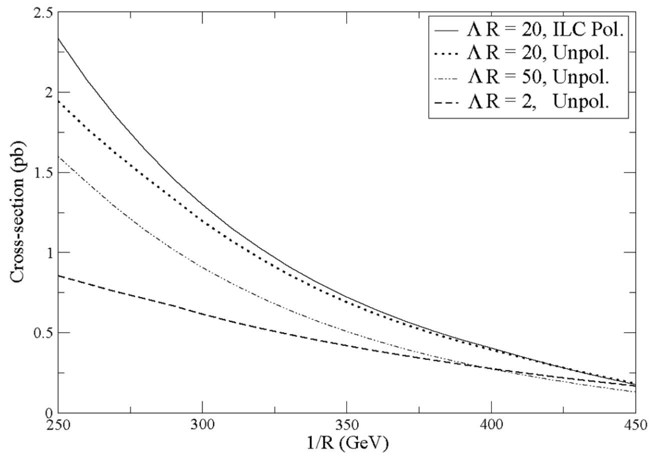

Figure 1. Cross-section vs. $1/R$ for the process $e^+e^- \to e^+e^- +$ missing energy.

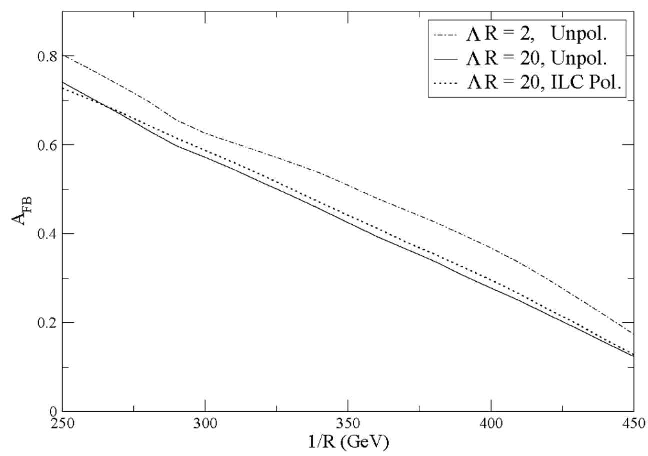

Figure 2. $A_{\rm FB}$ vs. $1/R$ for the same process as in figure 1.

forward-peaked nature. A point to note is that the electrons coming from the two-photon background will be FB symmetric.

5. Discriminating UED from other new physics

$n = 1$ KK spectrum [6] closely resembles supersymmetry spectrum if the latter is pretty degenerate. Still, even if the LSP weighs above 250 GeV and is almost degenerate with a selectron, the latter can be discriminated from a KK lepton from the decay angular distributions on account of their different spins. We demonstrate this with a simple toy scenario. Compare the pair production of (a) generic heavy fermions and (b) generic heavy scalars in an e^+e^- collider. Assume $\sqrt{s} \gg m$, where m is the mass of the heavy lepton/scalar, so that only the t-channel diagrams, with a heavy gauge boson in case (a) and a heavy fermion in case (b) as propagators, are dominant. The heavy states are produced with sufficient boost, and therefore the tagged leptons they decay into have roughly the same angular distributions as them. Then the cross-section ratio $\mathrm{d}\sigma/\mathrm{d}\cos\theta$ (case (a)$\div$ case (b)) $= (A + B\cos\theta + C\cos^2\theta) \div (\sin^2\theta)$, where A, B, C are parameter-dependent numbers, clearly indicates that angular distributions can discriminate the two cases. Moreover, the UED fermion pair production cross-section is about a factor of 4 to 5 larger than the scalar production cross-section for similar couplings and masses. While dealing with selectrons, one must take into account the detailed neutralino structure, but the above basic arguments go through.

6. LHC/ILC synergy and conclusions

For improved precision in the measurements of masses, decay widths, mixing angles, etc., ILC would be an ideal machine following the discovery runs at LHC. The accuracy of measuring the mass of a 200 GeV selectron is about 5 GeV at LHC, but it could be as low as 0.2 to 1 GeV at ILC [7]. Similar precisions may be expected for similar KK electron masses as well. A spin correlation study [8] to distinguish UED from supersymmetry at LHC concluded that spin assignments are extremely difficult if the observed spectrum turns out to be quasi-degenerate. A factor of 4 to 5 larger production cross-section for UED compared to supersymmetry will then be a better discriminator. The clinching evidence of UED would of course be the discovery of the single production of $n = 2$ KK modes (see [9] for details) which have no supersymmetry analog.

To conclude, ILC is important for precision studies in the post-LHC era. Studying the physics interplay between the LHC and ILC constitutes a very important particle physics research topic.

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