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Probing UED at the ILC/LHC

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Summary. — We study the possibility of detecting the first KK electron-positron pair in the UED scenario at the ILC. A few hundred GeV KK electron decays into a KK photon (which carries away missing energy) and the standard electron. We look for the signal event e^+e^-+ large missing energy for $\sqrt{s} = 1\,\text{TeV}$ and notice that with a luminosity of few hundred fb^{-1} the signal can be deciphered from the SM background. We briefly outline the methods of distinguishing UED signals from supersymmetry. In a separate analysis we show that UED KK states upto 700–800 GeV can be probed at the LHC with an integrated luminosity of 100–300 fb^{-1}.

PACS `12.60.-i` – Models beyond the standard model.
PACS `14.60.Hi` – Other charged heavy leptons.

1. – Introduction

This write-up is based on two analyses on Kaluza-Klein (KK) particle search at colliders—one in the context of the ILC [1] and the other in the context of the LHC [2].

We consider Universal Extra Dimension (UED) models [3] where the single extra dimension is compactified on an orbifold S^1/Z_2. The inverse radius of compactification (R^{-1}) is in the range 250–450 GeV. This extra dimension is accessed by all the Standard Model (SM) states. In the context of the International Linear Collider (ILC), we examine production of the first KK electron positron pair ($E_1^+E_1^-$). The heavy modes $E_1^\pm$ would decay into the zero mode state ($e^\pm$) and the first KK photon (γ_1). The KK photon is stable and escapes the detector giving rise to missing energy. The splitting between $E_1^\pm$ and γ_1 is induced from the bulk and brane-localized radiative corrections. The cross-section of the final state e^+e^- + missing energy is in the pb range and the SM background is tractable. With just one year run of the upgraded ILC at $\sqrt{s} = 1\,\text{TeV}$ with an integrated luminosity of $300\,\text{fb}^{-1}$, it is possible to gather enough evidence to support the UED hypothesis [1]. In the context of the LHC, with 100–300 fb^{-1} integrated luminosity, it would be possible to probe R^{-1} upto 700–800 GeV in the single jet + missing p_T + multi-lepton channels [2].

TABLE I. – $n = 1$ *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

2. – UED model

For generating *chiral* zero mode fermions we compactify the extra dimension on an orbifold S^1/Z_2. 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 the extra space coordinate y, quantized as n/R, is a conserved quantity at all tree level vertices but not at higher orders. But KK parity, defined as $(-1)^n$, is conserved at all order, and as a result even states mix with even states 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 very similar to R-parity in supersymmetry. Phenomenological constraints on the UED scenario (see references cited in [1]) indicate that $R^{-1} \gtrsim 250\,\mathrm{GeV}$.

3. – Radiative corrections and the spectrum

The degeneracy of KK states ($M_n = n/R$), *modulo* 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: $L_{\rm kin} = Z\partial_\mu\phi\partial^\mu\phi - Z_5\partial_5\phi\partial^5\phi$, where Z and Z_5 are wave function renormalizations. 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 compactification leads to violation of Lorentz symmetry and as a result the equality between Z and Z_5 is lost. This gives rise to mass splitting: $\Delta M_n \propto (Z - Z_5)$. There are two kinds of radiative corrections.

a) *Bulk corrections*: These corrections are finite, and nonzero *only* for bosons. 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 beta-function contributions of the gauge and matter KK fields floating inside the loop. Since the beta-functions are different for different particles, the KK degeneracy is lifted.

b) *Orbifold corrections*: Orbifolding breaks translational invariance in the y-direction and generates log divergent interactions localized at the fixed points. The finite parts of such boundary terms are *assumed* to vanish at some cutoff 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 orbifold corrections are numerically more dominant than bulk corrections. (See table I for mass spectrum including both types of corrections.)

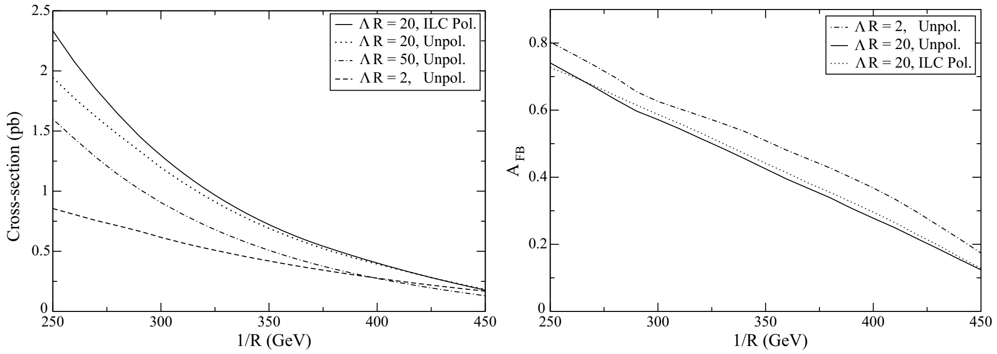

Fig. 1. – Cross-section and A_{FB} *vs.* $1/R$ for the process $e^+e^- \rightarrow e^+e^-+$ missing energy [1].

4. – Production and decay modes of KK leptons

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

The process $e^+e^- \rightarrow E_1^+E_1^-$ 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 the masses of E_1 and γ_1 is sufficient for the decay to take place 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, for $R^{-1} = 250\,\mathrm{GeV}$). Thus in the final state we have $e^+e^- + 2\gamma_1$ ($\equiv$ missing energy). The same final states can be obtained from $e^+e^- \rightarrow W_1^+W_1^-$, but this will be BR suppressed.

SM background: The main background comes from $\gamma^*\gamma^* \rightarrow e^+e^-$ events, where γ^*s arise from the initial e^+e^- pair while the latter go undetected down the beam pipe. The $\gamma^*\gamma^*$ production cross-section is $\sim 10^4\,\mathrm{pb}$. About half of these events goes 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 of 40 mrad reduces only 7% of the signal cross-section but almost entirely removes the background. Numerically much less significant backgrounds would come from $e^+e^- \rightarrow W^+W^-$, $e\nu W$, e^+e^-Z, followed by the appropriate leptonic decays of the W and Z.

Collider parameters: The study is performed in the context of the upgraded ILC at $\sqrt{s} = 1\,\mathrm{TeV}$, 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° from the beam pipe.

Cross-sections: The cross-section for e^+e^- + missing energy final state has been plotted in the left panel of fig. 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 mixing angle for $n = 1$ KK gauge bosons).

Forward-backward asymmetries: The asymmetry of the final state electrons, defined as $A_{\mathrm{FB}} = (\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}})/(\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}})$, is plotted in the right panel of fig. 1. The first stage process $e^+e^- \rightarrow E_1^+E_1^-$ is forward-peaked, and for smaller $1/R$ the final states $e^\pm$ 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 forward-peaked nature. We should remember that the electrons coming from the two-photon background will be FB symmetric.

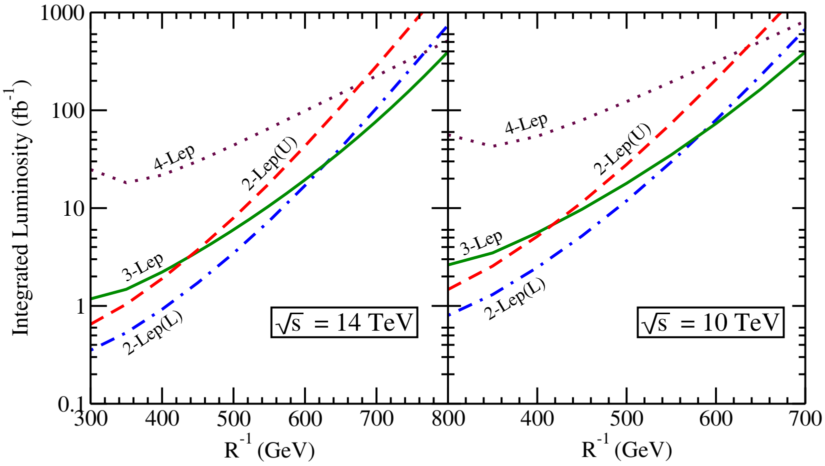

Fig. 2. – The required integrated luminosity at the LHC running at $\sqrt{s} = 14\,\text{TeV}$ (left panel) and 10 TeV (right panel) for a 5σ signal in the multi-lepton + 1 jet + missing p_T channels as a function of R^{-1}. Results are shown for 2-, 3-, and 4-leptons. "U" and "L" correspond to unlike- and like-lepton flavors [2].

5. – Discriminating UED from supersymmetry at ILC

$n = 1$ KK spectrum closely resembles supersymmetry spectrum *if* the latter turns out to be pretty degenerate. Still a selectron can be distinguished, in principle, from a KK electron as their spins are different. Consider the following toy scenario: Compare the pair production of a) heavy leptons and b) heavy scalars in an e^+e^- collider. Assume $\sqrt{s} \gg m$, where m is the mass of the heavy lepton or the scalar, so that only the t-channel diagrams are dominant. The t-channel will involve a heavy gauge boson in case (a), and a heavy fermion in case (b), as propagators. The lepton or scalar states are produced with sufficient boost. Hence the tagged leptons they decay into have roughly the same angular distributions as them. The ratio of differential cross-sections in the two cases is $\mathrm{d}\sigma/\mathrm{d}\cos\theta$ (case (a) $\div$ case (b)) $= (A + B\cos\theta + C\cos^2\theta) \div (\sin^2\theta)$, where A, B, C are model-dependent quantities. Clearly, exploiting the angular distributions the two cases can be discriminated. *Very importantly*, the UED fermion pair production cross-section is about a factor of 4 to 5 larger than the sfermion production cross-section in supersymmetry for similar couplings and masses [5].

6. – LHC analysis

We briefly describe an LHC-based analysis done in [2]. For optimization of signal-to-background ratio we considered the production of an $n = 1$ electroweak gauge boson in association with an $n = 1$ quark. The KK gauge boson decay yields ordinary leptons and missing p_T (from the undetected γ_1) and the KK quark decay produces a jet, missing p_T and *possibly* leptons. Thus the signal is a jet, several leptons and missing p_T. The SM background for such topologies is overwhelmingly large, but with suitable kinematic cuts, including an isolation of the jet from all leptons, it is possible to win over the background. The general conclusion is that it will be possible to probe R^{-1} upto 700–800 GeV with an accumulated luminosity of (100–300) fb^{-1} at $\sqrt{s} = 14\,\text{TeV}$ (see fig. 2).

7. – LHC/ILC synergy and conclusions

While the LHC is a discovery machine, for improved precision in the measurements of masses, decay widths, mixing angles, etc., the ILC is an ideal machine to follow. 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 [6]. Similar precisions may be expected for KK electron masses as well. Spin assignments are extremely difficult if the observed spectrum turns out to be quasi-degenerate. But a better discriminator between UED and supersymmetry will be an accurate measurement of the total cross-section [5] as mentioned above. A more serious evidence of UED would of course be the discovery of the single production of $n = 2$ KK modes [7] which has no supersymmetric analog.

In conclusion, ILC is crucial for precision studies in the post-LHC era. The LHC/ILC physics interplay needs to be further explored.

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