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Probing universal extra dimension at the International Linear Collider

Gautam Bhattacharyya [a], Paramita Dey [a], Anirban Kundu [b], Amitava Raychaudhuri [b]

[a] *Saha Institute of Nuclear Physics, 1/AF Bidhan Nagar, Kolkata 700064, India*
[b] *Department of Physics, University of Calcutta, 92 A.P.C. Road, Kolkata 700009, India*

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Abstract

In the context of an universal extra-dimensional scenario, we consider production of the first Kaluza–Klein electron positron pair in an e^+e^- collider as a case-study for the future International Linear Collider. The Kaluza–Klein electron decays into a nearly degenerate Kaluza–Klein photon and a standard electron, the former carrying away missing energy. The Kaluza–Klein electron and photon states are heavy with their masses around the inverse radius of compactification, and their splitting is controlled by radiative corrections originating from bulk and brane-localised interactions. 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 will be readily detectable over the standard model background. We comment on how this signal may be distinguished from similar events from other new physics.
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1. Introduction

If extra-dimensional models in a few hundred GeV scale [1] are realised in nature, one cannot only undertake their precision studies at the proposed International Linear Collider (ILC) [2] but also can distinguish them from other new physics. In this Letter, we consider such models with one extra dimension having inverse radius of compactification in the range $R^{-1} =$ 250–450 GeV. We examine production of the first Kaluza–Klein (KK) electron positron pair ($E_1^+ E_1^-$) in a linear e^+e^- collider operating at $\sqrt{s} = 1$ TeV. The heavy modes $E_1^\pm$ would decay into the standard (zero modes) $e^\pm$ and the first KK photon (γ_1), the latter carrying away missing energy. The splitting between $E_1^\pm$ and γ_1 comes from the bulk and brane-localised radiative corrections. The cross section of the final

E-mail address: gautam@mail.cern.ch (G. Bhattacharyya).

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state e^+e^- plus missing energy is quite large and the Standard Model (SM) background is tractable, so that even with a one year run of ILC at $\sqrt{s} = 1$ TeV with approximately 300 fb^{-1} enough statistics would accumulate. Forward–backward asymmetry of the final state electron mildly depends on the initial polarisations. Even though the mass spectrum of KK excitations of different SM particles may resemble the supersymmetric pattern, angular distribution of the final electrons can be used to discriminate the intermediate KK electrons from selectrons or other new physics scalars.

2. Simplest universal extra dimension

We consider the simplest realisation of the universal extra dimension (UED) scenario in which there is only one extra dimension which is accessed by all SM particles [3]. The extra dimension (y) is compactified on a circle of radius R along with a Z_2 orbifolding which renders all matter and gauge fields, viewed from a 4-dimensional (4d) perspective, depend on y either as $\cos(ny/R)$ (even states) or $\sin(ny/R)$ (odd states), where n is the KK index. The tree level mass of the nth state of a particular field is given by $M_n^2 = M_0^2 + n^2/R^2$, where M_0 is the zero mode mass of that field. Clearly, excepting the top quark, Higgs, W, and Z, the KK states of all other SM particles with the same n are nearly mass degenerate at n/R. Now, with all the fields propagating in the bulk, the momentum along the fifth direction, quantised as n/R, remains a conserved quantity. A closer scrutiny however reveals that a remnant Z_2 symmetry (different from the previous Z_2) in the effective 4d Lagrangian dictates that what actually remains conserved is the KK parity defined as $(-1)^n$. As a result, level mixings may occur which admit even states mix only with even states, and odd 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. These two criteria are reminiscent of supersymmetry with conserved R-parity where the lightest supersymmetric particle (LSP) is stable, and superparticles can only be pair produced. If produced, the heavier KK modes can cascade decay to lighter ones, eventually to soft SM particles plus LKP carrying away missing energy. But low energy constraints on the UED scenario from $g - 2$ of the muon [4], flavour changing neutral currents [5–7], $Z \to b\bar{b}$ decay [8], the ρ parameter [3], other electroweak precision tests [9] and implications from hadron collider studies [10], all indicate that $R^{-1} \gtrsim$ a few hundred GeV. As a result, even the second KK state having mass $2/R$ will be beyond the pair-production reach of at least the first phase of the planned linear collider. So, as mentioned in the introduction, we consider the production of first KK electron positron pair and their subsequent decays into first KK photon plus the standard leptons; the degeneracy between $E_1^{\pm}$ and γ_1 being lifted by radiative corrections which we shall briefly touch upon below.

3. Radiative corrections and the spectrum

Barring zero mode masses, the degeneracy (n/R) at a given KK level is only a tree level result. Radiative corrections lift this degeneracy [11–14]. For intuitive understanding, we consider the kinetic term of a scalar field as [11] $L_{\rm kin} = Z\partial_\mu\phi\partial^\mu\phi - Z_5\partial_5\phi\partial^5\phi$ ($\mu = 0, 1, 2, 3$), where Z and Z_5 are renormalisation constants. 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 a consequence of Lorentz invariance. When a direction is compactified, Lorentz invariance is lost, so also is lost the equality between Z and Z_5, leading to $\Delta M_n \propto (Z - Z_5)$. One actually encounters two kinds of radiative corrections.

(a) *Bulk corrections*: These corrections are finite. Moreover, they are nonzero only for bosons. They arise when the internal loop lines wind around the compactified direction, sensing that compactification has actually occured, leading to the breaking of Lorentz invariance. The correction to the KK mass M_n works out to be independent of n and goes like $\Delta M_n^2 \propto \beta/16\pi^4 R^2$, 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 function contributions are different for particles in different representation, the KK degeneracy is lifted. One can understand the decoupling of the correction as inverse power of R by noting that the

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