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Event shape discrimination of supersymmetry from large extra dimensions at a linear collider

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Abstract

The production of a charged lepton ($\ell = e, \mu$) pair with a large missing energy at a linear collider is discussed as a means of distinguishing the minimal supersymmetry (MSSM) scenario from that with large extra dimensions (ADD) for parameter ranges where the total cross-sections are comparable for both. Analyses in terms of event shape variables, specifically sphericity and thrust, are shown to enable a clear discrimination in this regard.

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1. Introduction

A general expectation in high energy physics today is that of physics beyond the standard model (BSM) emerging at TeV energies. Supersymmetry (SUSY) [1] and extra dimensions [2] are two alternative possibilities in this direction that are the most exciting. They both address the naturalness/gauge hierarchy problem, arising from quantum corrections to the Higgs parameters, via the introduction of new physics at the TeV scale. Moreover, their attractive phenomenological features, in particular their promise of new states a bit beyond the current experimental lower mass bounds, put them in the limelight among scenarios of BSM physics to be explored by search strategies presently being designed. The latter, in fact, constitute the major motivation for constructing the next generation of colliders. If either SUSY or an extra-dimensional scenario should manifest itself at sub-TeV to TeV energies, its signals ought to show up at the upcoming Large Hadron Collider (LHC) at CERN. It is widely accepted, nonetheless, that the precise nature of the BSM physics responsible for such signals may not always be easily gleaned from analyses of the corresponding data on account of the complexity of the hadronic environment in any LHC process. Indeed, in order to unambiguously identify the nature and detailed properties of any such new physics, a high energy and high-luminosity e^+e^- machine [3]—such as the proposed International Linear Collider (ILC) or the Compact Linear Collider (CLIC)—will be very useful.

We consider the signal comprising unlike-sign dielectrons/dimuons, produced in a linear collider together with a very high amount of missing energy, seeking to distinguish between SUSY and the Arkani-Hamed–Dimopoulos–Dvali (ADD) model [4] of large extra dimensions.[2,3] Such a process has already

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[2] Within the extra-dimensional paradigm, there are other scenarios such as warped (Randall–Sundrum) or universal extra dimensions, which we do not address here.

[3] Another process where the two scenarios have been compared is $e^+e^- \to \gamma_H \not{E}$, where γ_H is a hard photon. The reactions for the ADD and SUSY sce-

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been considered [7,8] in the context of the universal extra dimension (UED) scenario [9]. The mechanism for this reaction is somewhat similar in SUSY and UED: a two-body production of heavy entities, each of which then has a dominant two-body decay. But the spins of the primarily produced entities are different in the two cases, leading to [8] distinguishable angular distributions and asymmetries. There are also differences in the lepton energy spectrum. We find, however that these quantities are not very sensitive to a SUSY vs ADD discrimination. First of all, the difference in these between the two scenarios is more quantitative, being in detailed shape aspects, rather than being something qualitative; systematic uncertainties would tend to wash out such quantitative differences. Secondly (and more importantly), these quantities are quite ISR-sensitive so that ISR-corrections significantly reduce the sensitivity to such a discrimination.

Let us give an illustration to highlight the last point. The famous box-shaped lepton energy spectrum in the SUSY case has been found (as shown in Fig. 5 of [8]) to be squeezed in energy, looking more like a peak, after ISR corrections. When we compare this corrected spectrum with the peaked one for the ADD case, there does not seem a whole lot of difference. Similarly, the angular distributions are flat in either case for the bulk of the measurable range in the cosine of the angle between the two leptons. We do not include these plots here since that will detract from our central point which is the following. Distributions in event shape variables, such as sphericity and thrust, are known to be ISR-stable and are yet found to be sensitive to such a discrimination. They are *qualitatively* different between SUSY and ADD, having a peak in sphericity or break in thrust for the former and monotonic fall or rise for the latter. This is owing to differences in the mechanisms leading to the $\ell^+\ell^-\not{E}$ final state in the two cases. Of course, slepton pair-production for SUSY will have a distinct threshold in $\sqrt{s}$ unlike the generation of the corresponding ADD final state, the cross-section for which increases smoothly with $\sqrt{s}$. So a careful scan of the CM energy for a threshold will also help discriminate between the two. However, that will require a more detailed step-by-step analysis. It will be useful to have a discriminant just with the first set of data at a particular $\sqrt{s}$ (above the slepton pair production threshold) and this is what we provide.

We work within the minimal weak-scale R-parity conserving supersymmetric standard model (MSSM) which predicts the pair-production of charged sleptons [10], once the requisite energy threshold is reached, in an e^+e^- collider. Each produced slepton would perforce decay into a charged lepton and the lightest supersymmetric particle (LSP). The latter is normally taken to be the lightest neutralino $\tilde{\chi}^0_1$ which, being stable and interacting only weakly, escapes unobserved through the detector—carrying a considerable amount of missing energy. In contrast, the ADD model has d extra dimensions compactified on a d-torus. Together with time and the three spatial dimensions of our world, these constitute the bulk spacetime. The radius[4] R_c of compactification of the extra dimensions could be as large as a quarter of a millimetre [11]. However, the SM fields are confined to a thin (thickness not more than 10^{-17} cm [12]) D_3-brane, which is a soliton solution of the underlying string theory on which the ends of open strings are confined. A crucial feature of this model is that gravity, which is a property of spacetime itself, is free to propagate anywhere in the bulk. On compactification, a Kaluza–Klein tower of closely spaced gravitons appear in our spacetime, a large number of which (controlled by $\sqrt{s}$) are producible[5] in a collider process [13] but are then invisibly lost in the higher-dimensional bulk. To an observer on the brane, they would appear to be escaping unobserved with a large missing energy. This is a direct production of a three-body final state unlike the SUSY case where the decays of the heavy sleptons tend to generate more isotropic events.

2. Comparison of the two signals

Recall that our process is $e^+e^- \to \ell^+\ell^-\not{E}$ where ℓ sums over both e and μ. Charged slepton ($\tilde{e}_{L,R}$ or $\tilde{\mu}_{L,R}$) pair production in an e^+e^- collider with both unpolarised and polarised beams has been explored earlier [10]. Once produced, the sleptons decay into either a chargino–neutrino pair or into a neutralino–lepton pair. The partial decay widths are governed by both the mass and the composition of the charginos (neutralinos) as well as by the type (L or R) of slepton. We select the channels yielding the final state of a same-flavour unlike-sign dilepton associated with a missing energy,[6] namely

$$e^+e^- \to \tilde{\ell}^+_{L,R}\tilde{\ell}^-_{L,R} \to \ell^+\ell^-\tilde{\chi}^0_1\tilde{\chi}^0_1. \tag{1}$$

In our analysis, we do not adhere to any particular SUSY-breaking scenario and make no assumption related to any high scale physics other than adopting gauge coupling unification. Thus, whereas the slepton masses[7] $m_{\tilde{\ell}}$ are free parameters in our analysis, the neutralino masses and couplings are completely specified by the respective $SU(2)$ and $U(1)$ gaugino masses M_2 and M_1, the higgsino mass parameter μ and $\tan\beta$, which is the ratio [1] of the two Higgs vacuum expectation values arising in the MSSM.

The branching ratio for slepton decay into the lightest neutralino and the corresponding lepton depends on quite a few parameters: $m_{\tilde{\ell}}$, μ, $\tan\beta$ as well as the gaugino mass parameters M_1 and M_2. Of these, the dependence on $\tan\beta$ is the

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narios in standard notation are $e^+e^- \to G_n\gamma_H$ and $e^+e^- \to \tilde{G}\tilde{G}\gamma_H$ [5] or $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_1\gamma_H$ [6], respectively. The energy spectrum of the hard photon together with the scaling of the cross-section with CM energy and moment distributions of the transverse energy squared have been used for discrimination purposes. However, since there is only one observable particle in the final state, no event shape analysis is possible here.

[4] For simplicity, we take the same radius of compactification for each of the d dimensions.

[5] An alternative way of probing the ADD scenario is to consider virtual graviton exchange [13] in SM processes where a coherent sum over closely spaced gravitons is involved, leading to deviations from SM predictions.

[6] In case $m_{\tilde{\ell}} > M_{\tilde{\chi}^\pm}$, there is also the chain $e^+e^- \to \tilde{\ell}^+_{L,R}\tilde{\ell}^-_{L,R} \to \tilde{\chi}^+\tilde{\chi}^-\nu_\ell\bar{\nu}_\ell \to \ell^+\ell^-\tilde{\chi}^0_1\tilde{\chi}^0_1\nu_\ell\nu_\ell\bar{\nu}_\ell\bar{\nu}_\ell$. However, it makes a very small contribution, which we do take into account.

[7] Again, for simplicity, we take $m_{\tilde{\ell}_L} = m_{\tilde{\ell}_R} = m_{\tilde{\ell}}$.