Extra Dimensional Signatures at CLIC

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A brief overview is presented of the signatures for several different models with extra dimensions at CLIC, an e^+e^- linear collider with a center of mass energy of 3-5 TeV and an integrated luminosity of order 1 ab^{-1}. In all cases the search reach for the resulting new physics signatures is found to be in the range of $\simeq$15-80 TeV.

1. Introduction

Many models predict the existence of additional spatial dimensions that lead to new and distinct phenomenological signatures for future colliders which have center of mass energies in the TeV range and above. Most of the models in the literature fall into one of the three following classes: (i) the large extra dimensions scenario of Arkani-Hamed, Dvali and Dimopoulos(ADD)[1]. This model predicts the emission and exchange of large Kaluza-Klein(KK) towers of gravitons that are finely-spaced in mass. The emitted gravitons appear as missing energy while the KK tower exchange leads to contact interaction-like dimension-8 operators. (ii) A second possibility are models where the extra dimensions are of TeV scale in size. In these scenarios there are KK excitations of the SM gauge (and possibly other SM) fields with masses of order a TeV which can appear as resonances at colliders. (iii) A last class of models are those with warped extra dimensions, such as the Randall-Sundrum Model(RS)[3], which predict graviton resonances with both weak scale masses and couplings to matter. High energy lepton colliders in the multi-TeV range with sufficient luminosity, such as CLIC, will be able to both directly and indirectly search for and/or make detailed studies of models in all three classes. The case of direct searches is rather straightforward as we are producing the new physics, such as a KK resonance, directly. Indirect searches are more subtle but the capability of making high precision measurements at lepton colliders allows us to probe mass scales far in excess of the collider center of mass energy, in some cases by more than an order of magnitude. For most models of type (i) or (iii) which deal with the hierarchy problem, if no signal is observed by the time the mass scales probed by CLIC are reached, the motivation behind these particular models will be greatly weakened if not entirely removed. In what follows, for simplicity, we will only focus on searches involving the process $e^+e^- \to f\bar{f}$. From studies performed for both NLC/TESLA and LEP we know that this channel provides an excellent probe of the parameter spaces of extra-dimensional models and we expect that this will continue to be true at even higher energies.

2. Signatures

The first model we consider is ADD; we will limit our discussion to the case of graviton tower exchange in $e^+e^- \to f\bar{f}$. The effect of summing the KK gravitons is to produce a set of effective dimension-8 operators of the form $\sim \lambda T^{\mu\nu}T_{\mu\nu}/M_s^4$, where $T_{\mu\nu}$ is the stress-energy tensor of the SM matter exchanging the tower[4]. This approximation only applies in the limit that the center of mass energy of the collision process lies sufficiently below the cut-off scale, M_s, which is of order the size of the Planck scale in the extra dimensional space. In the convention used by Hewett[4] and adopted here, the contribution of the spin-2 exchanges can be universally expressed in terms of the scale, M_s, and a sign, λ. Current experimental constraints from LEP and the Tevatron[5]

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tell us that $M_s \geq 1$ TeV for either sign of λ; values for M_s as large as the low 10's of TeV may be contemplated in this scenario.

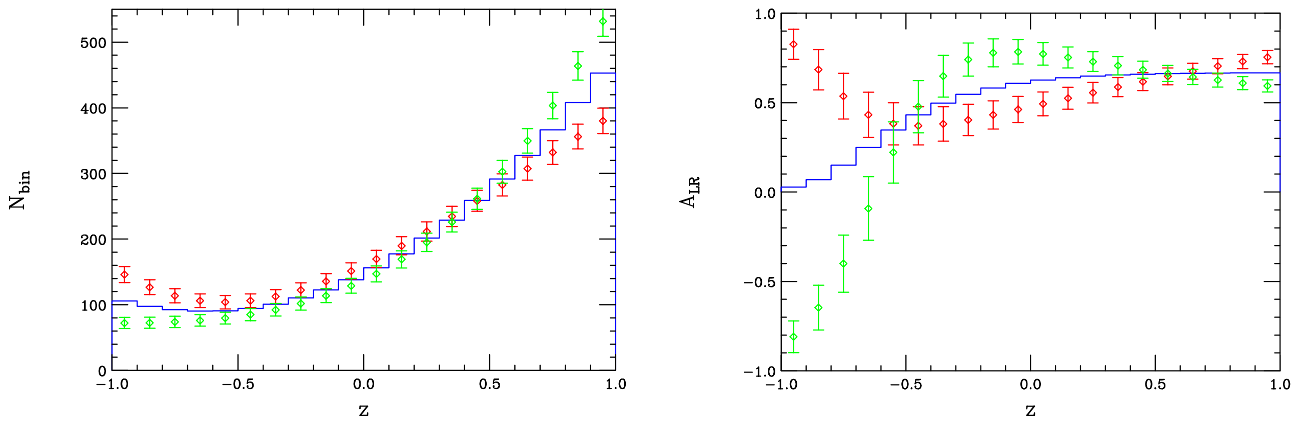

Figure 1: Deviations in the cross section for μ-pairs(left) and A_{LR} for b-quarks(right) at $\sqrt{s}$=5 TeV for M_s = 15 TeV in the ADD model for an integrated luminosity of 1 ab^{-1}. The SM is represented by the histogram while the red and green data points show the ADD predictions with $\lambda = \pm 1$. In both plots $z = \cos\theta$.

In the case of $e^+e^- \to f\bar{f}$, the addition of KK tower exchange leads to significant deviations in differential cross sections and polarization asymmetries from their SM values which are strongly dependent on both the sign of λ and the ratio s/M_s^2. Such shifts are observable in final states of all flavors. In addition, the shape of these deviations from the SM with varying energy and scattering angle, as shown by Hewett[4], tells us that the underlying physics arises due to dimension-8 operators and not, for example, Z' exchange. Fig. 1 shows an example of how such deviations from the SM might appear at a 5 TeV CLIC in the case that M_s=15 TeV for either sign of λ. The indirect search reach for the scale M_s can be obtained by combining the data for several of the fermion final states(μ, τ, c, b, t, etc) in a single overall fit. The result of this analysis for CLIC is the λ independent bound shown in Fig. 2 as a function of the integrated luminosity for $\sqrt{s}$=3 or 5 TeV. For an integrated luminosity of 1 ab^{-1} we see that the reach is $M_s \simeq 6\sqrt{s}$ which is consistent with analyses at lower energy machines[4].

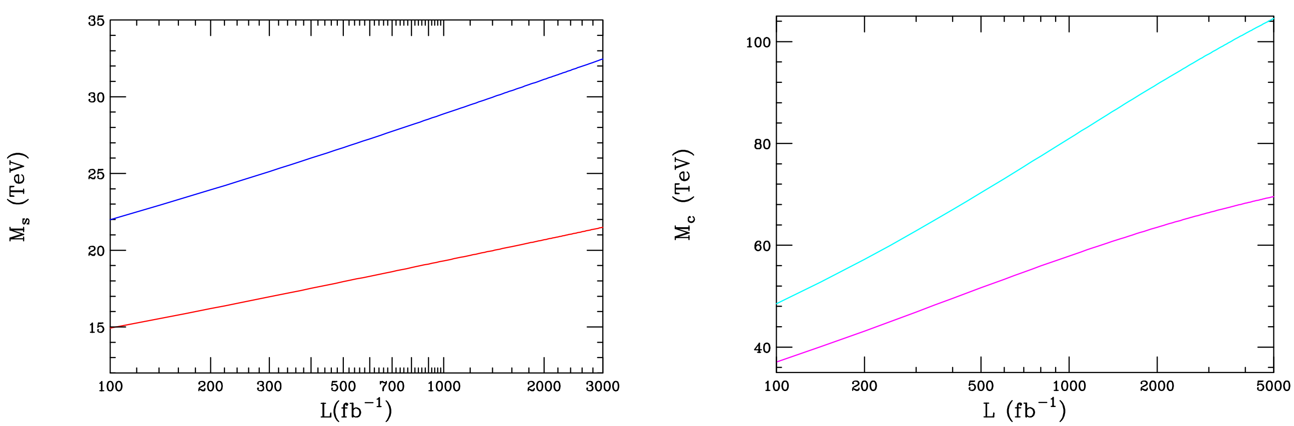

Figure 2: (Left) Search reach for the ADD model scale M_s at CLIC as a function of the integrated luminosity from the set of processes $e^+e^- \to f\bar{f}$ assuming $\sqrt{s}$ = 3(red) or 5(blue) TeV. Here $f = \mu, \tau, b, c$, t, etc. (Right) Corresponding reach for the compactification scale of the KK gauge bosons in the case of one extra dimension and all fermions localized at the same orbifold fixed point.

Next we turn to models with TeV scale extra dimensions. In the simplest versions of these theories, only the SM gauge fields are in the bulk whereas the fermions remain at one of the two orbifold fixed points; Higgs fields may lie at the fixed points or propagate in the bulk. (More complicated scenarios with very different phenomenology are possible.) It is possible that, *i.e.*, quarks and leptons may lie at *different* fixed points in which case they would be separated by a distance $D = \pi R_c$, where R_c is the compactification radius. In the case with only one extra dimension it has been shown that the current high precision electroweak data can place a lower bound on the mass of the first KK excited gauge boson in excess of $\simeq 4$ TeV[6]. In such a model, to a good approximation, the masses of the KK tower states are given by $M_n = nM_c$, where $M_c = R_c^{-1}$ is the compactification scale. For this one extra dimensional example all of the excited KK states have identical couplings to the SM fermions, apart from possible overall signs. In this case, only the first KK state may be observable at the LHC since KK modes with masses in excess of $\simeq 7$ TeV will be too massive to be produced. High energy e^+e^- colliders can search for SM gauge boson excitations in exactly the same way as described above for ADD graviton tower exchange but with a significantly higher search reach, as shown in Fig. 2, since the shifts in SM observables are now due to effective dimension-6 (instead of dimension-8) operators. Note that the search reach in this case can be as large as $\sim 15\sqrt{s}$. A very high energy CLIC may be even more useful if the number of extra dimensions is greater than one; in this case, still keeping the fermions at the orbifold fixed points, the bounds from precision data are expected to be stricter than in the one-dimensional case but are less quantitatively precise since the naive evaluation of the relevant sums over KK states are divergent. One now finds that the masses and couplings of KK excitations become both level and compactification-scheme dependent thus leading to a rather complex KK spectrum. Some sample KK excitation spectra for several different TeV-scale models with more than one extra dimension are shown in Fig. 3. Note that the measurements of the locations of the peaks and their relative heights and widths can be used to uniquely identify a given extra-dimensional model.

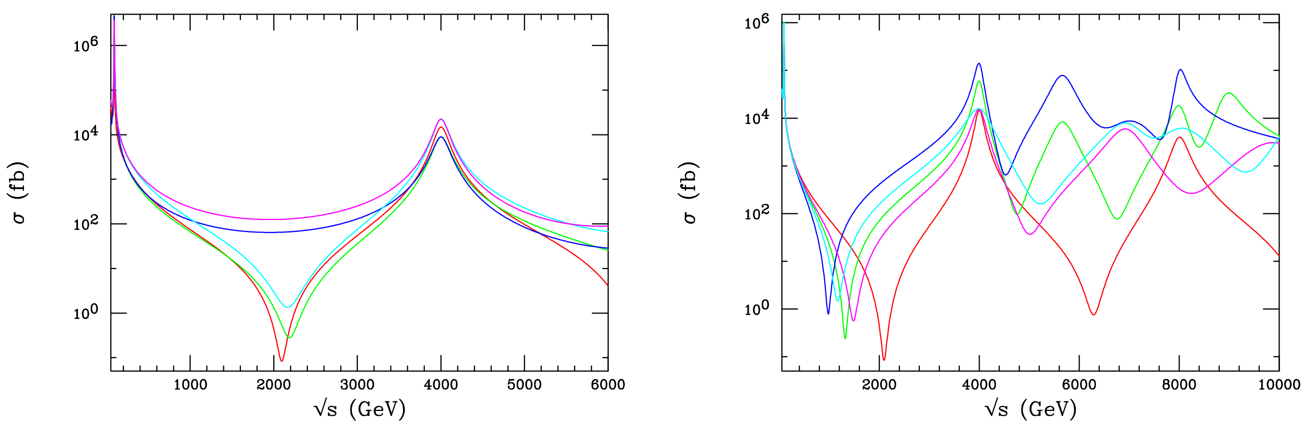

Figure 3: (Left) Comparison of $e^+e^- \to f\bar{f}$ cross sections in the case of one extra dimension when $M_c = 4$ TeV. The red curve is for the case $f = \mu$ while the green(blue) and cyan(magenta) curves are for the cases $f = b, c$, respectively when $D = 0(\pi R_c)$. (Right) $e^+e^- \to \mu^+\mu^-$ cross sections for several different models with one or more extra dimensions assuming $M_c = 4$ TeV.

The last case we consider is the RS model wherein, as discussed above, we expect to produce TeV-scale graviton resonances in many channels[7] including $e^+e^- \to f\bar{f}$. In its simplest version, with two branes, one extra dimension, and with all of the SM fields remaining on the TeV-brane, this model has only two fundamental parameters: the mass of the first KK state (from which all the others can be determined) and an additional parameter, $c = k/\overline{M}_{Pl}$, which we expect to be smaller than but not too far from unity. This parameter essentially controls the effective coupling strength of the gravitons(when expressed in terms of the mass of the lowest lying KK state) and thus also the widths of the corresponding resonances. Below the mass of the lightest resonance linear colliders can still search indirectly for the contributions of RS graviton exchange in a manner similar to that described above; the results of such an analysis are shown in Fig. 4. On top of the resonances as in Fig. 4 the decay angular distribution can be easily determined allowing us to demonstrate that a spin-2 particle is being produced while measurements of the branching fractions to various decay modes, shown in Fig. 5, would prove that we are producing gravitons. If several resonances are produced the ratios of their masses can be used verify the RS scenario since their masses are in the ratios of the roots of the J_1 Bessel function. It also seems likely that CLIC will be able to perform a detailed study of some of the more exotic decays of the

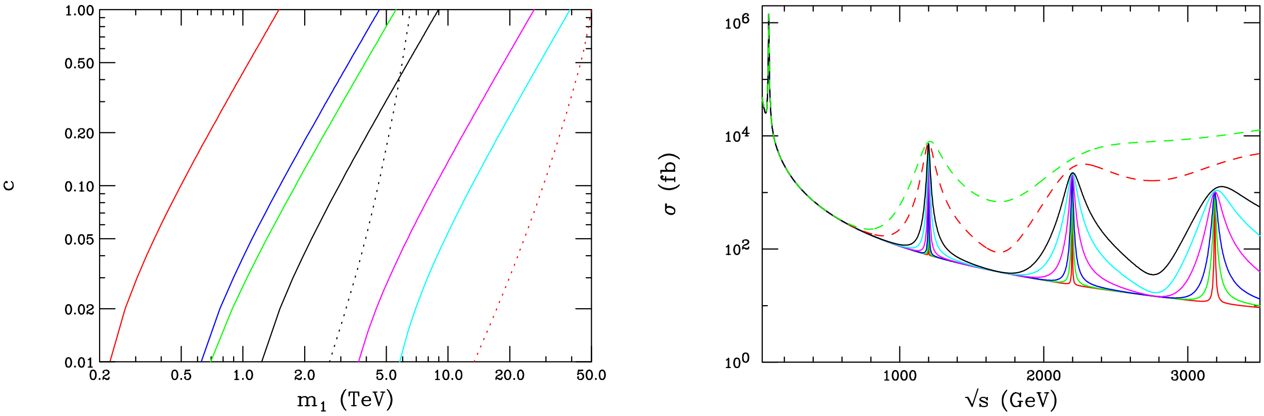

Figure 4: (Left) Indirect constraints from e^+e^- colliders on the RS model parameter space with $c = k/\overline{M}_{Pl}$; the excluded region is to the left of the curves. From left to right the solid curves correspond to bounds from LEP II, a 500 GeV LC with 75 or 500 fb^{-1} luminosity, a TeV machine with 200 fb^{-1}, and a 3 or 5 TeV CLIC with 1 ab^{-1}. The dotted lines are the corresponding LHC (100 fb^{-1}) and $\sqrt{s} = 175$ TeV VLHC(200 fb^{-}) direct search reaches. (Right) KK graviton excitations in the RS model produced in the process $e^+e^- \to \mu^+\mu^-$. From the most narrow to widest resonances the curves are for c in the range 0.01 to 0.2.

heavier graviton states[8] that may occur in this model. Fig. 5 shows the current bounds on the RS parameter space from both precision measurements and Tevatron searches. Also shown are the constraints from naturalness on Λ_π and on c from the requirement of stability under quantum corrections. For the tighter set of constants the LHC can cover all of the model space whereas if these theoretical constraints are allowed to be somewhat weakened then the whole space will be essentially covered by CLIC.

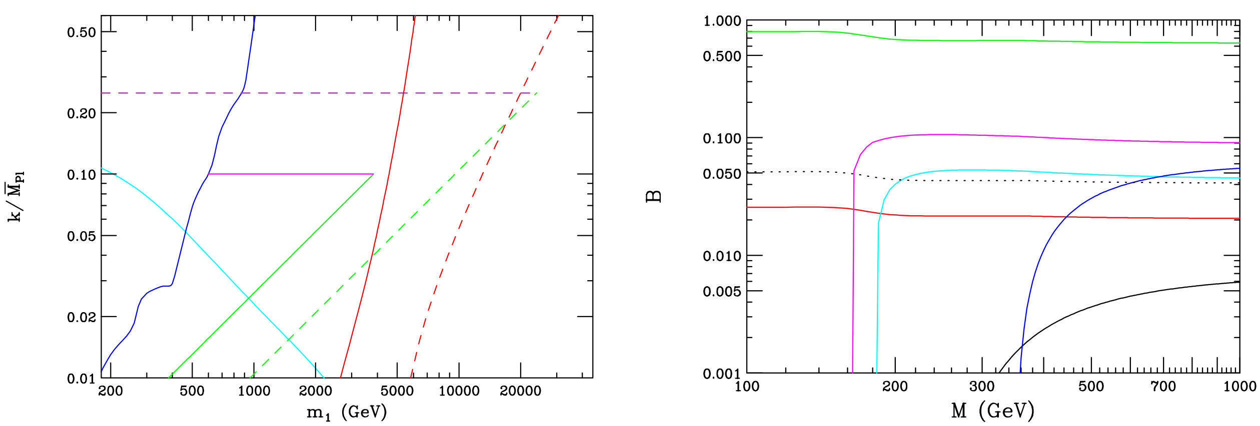

Figure 5: (Left) Allowed regions of the RS model parameter space. Current Tevatron(blue) and precision measurements(cyan) forbid regions to the left of their specific curves. The horizontal magenta solid(dashed) lines form the upper bound of the region when $c = 0.10(0.25)$ while the solid(dashed) green curve is the corresponding lower bound when $\Lambda_\pi = 10(25)$ TeV. The solid(dashed) red curve is the reach of the LHC(CLIC) with 100 fb^{-1} ($\sqrt{s} = 5$ TeV with 1 ab^{-1}). (Right) Branching fractions for the lightest RS KK graviton; from top to bottom on the right-hand side the curves are for 2 jets, W^+W^-, $t\bar{t}$, $2Z$, 2γ, e^+e^- and $2h$, respectively.

3. Discussion and Conclusion

From the discussion above it is clear that the high center of mass energy of CLIC offers a great opportunity to study many different models with extra dimensions.

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