Direct Searches of New Physics at CLIC

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Abstract

The multi-TeV e^+e^- collider CLIC may allow for the direct study of new neutral gauge bosons or Kaluza-Klein states in the TeV range. We discuss some of the experimental aspects for the study of such resonances. Further we discuss briefly the effects of soft branes in scenarios with Large Extra Dimensions, and the production of Black Holes at CLIC.

1   Introduction

CLIC (Compact LInear Collider) is a concept for a linear e^+e^- collider with centre of mass (CMS) energies in the range of 3 to 5 TeV and a luminosity of 10^{35} cm^{-2}s^{-1}. The accelerating principle is based on two-beam acceleration [1], which is presently still in an experimental stage but has booked quite a few important successes in the last few years [2]. To reach such high luminosities CLIC operates in a high beamstrahlung environment, which distorts the luminosity spectrum and leads to important backgrounds, mostly $\gamma\gamma$ collisions, in the interaction region. Most studies

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in this paper were performed using tools which take into account these effects, as well as a detector response of a TESLA-like detector with slightly modified interaction and mask region [3].

Several different realisations of New Physics lead to new vector resonances and other phenomena for which the potential of CLIC has been studied. In this paper we discuss examples of direct searches for New Physics at CLIC: the observation of a new Z' like resonance, KK tower production, large extra dimensions with soft branes and the production of black holes. Results on indirect searches are discussed in [4]. Susy topics at CLIC are discussed in [5].

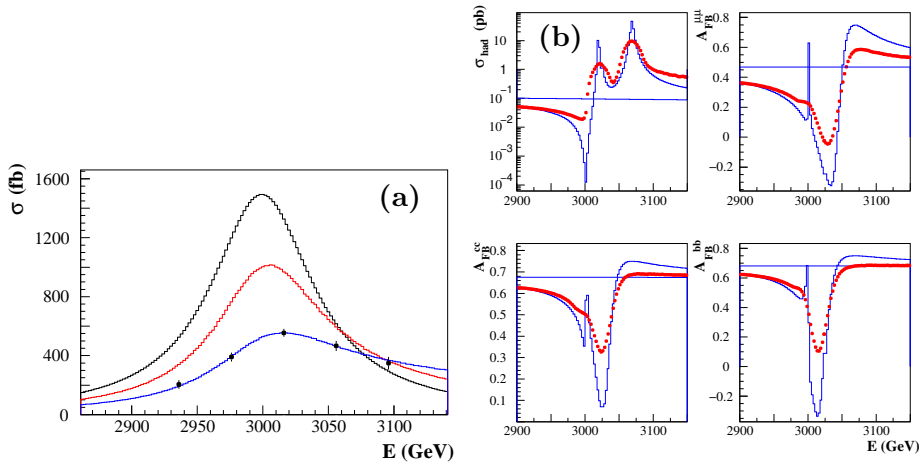## 2   Direct Production of New Gauge Bosons

Figure 1: (a) $Z'_{SSM} \rightarrow \ell^+\ell^-$ resonance profile obtained by energy scan. The Born production cross-section, the cross section with ISR included and that accounting for the CLIC luminosity spectrum (CLIC.01) and tagging criteria are shown. (b) Hadronic cross section (upper left) and $\mu^+\mu^-$ (upper right), $c\bar{c}$ (lower left) and $b\bar{b}$ (lower right) forward-backward asymmetries at energies around 3 TeV. The continuous lines represent the predictions for the D-BESS model with $M = 3$ TeV and $g/g'' = 0.15$, the flat lines the SM expectation and the dots the observable D-BESS signal after accounting for the CLIC.02 luminosity spectrum.

Observable	Breit Wigner	CLIC.01	CLIC.02
$M_{Z'}$ (GeV)	$3000 \pm .12$	$\pm .15$	$\pm .21$
$\Gamma_{Z'}/\Gamma_{Z^0}$	$1. \pm .001$	$\pm .003$	$\pm .004$
σ_{peak}^{eff} (fb)	1493 ± 2.0	564 ± 1.7	669 ± 2.9

Table 1: Results of the fits for the cross section scan of a Z'_{SSM} obtained by assuming no radiation and ISR with the effects of two different choices of the CLIC luminosity spectrum.

CLIC is an ideal collider to study the production of a new neutral gauge boson if its mass is within the kinematical reach. Similar to LEP, it will be able to make precision measurements of the boson properties. The results of a scan over a Z' resonance [6], assumed to have SM couplings, for one year of running and for two different assumptions for the luminosity spectra are given in Table. 1. The CLIC.01 is broader but delivers more integrated luminosity than the CLIC.02 spectrum. The pseudo data, shown in Fig. 1, are shared over 5 data points and $M_{Z'}$, $\Gamma_{Z'}/\Gamma_{Z^0}$ and σ_{peak} have been extracted from a χ^2 fit to the predicted cross section behaviour for different mass and width values. The relative statistical accuracies are found to be better than 10^{-4} on the mass and 5×10^{-3} on the width. In the case of wide resonances, there is an advantage in employing the broader luminosity spectrum, CLIC.01. Sources of systematics from the knowledge of the shape of the luminosity spectrum have also been estimated. In order to keep $\sigma_{syst} \leq \sigma_{stat}$ it is necessary to control N_γ to better than 5% and the fraction of collisions at $\sqrt{s} < 0.995\sqrt{s_0}$ to about 1%.

Models based on strong electro-weak symmetry breaking often predict several additional gauge bosons. Here we take as an example the degenerate BESS model [7] which introduces two new triples of gauge bosons $(L^\pm, L_3)$ and $(R^\pm, R_3)$ which are almost degenerate in mass.

The ability to identify the model distinctive features has been studied using the production cross section and the flavour dependent forward-backward asymmetries, for different values of g/g'', where g'' is the new gauge coupling constant. The resulting distributions are shown in Fig. 1 for the case of the narrower CLIC.02 beam parameters. A characteristic feature of the cross section distributions is the presence of a narrow dip, due to the interference of the L_3, R_3 resonances with the
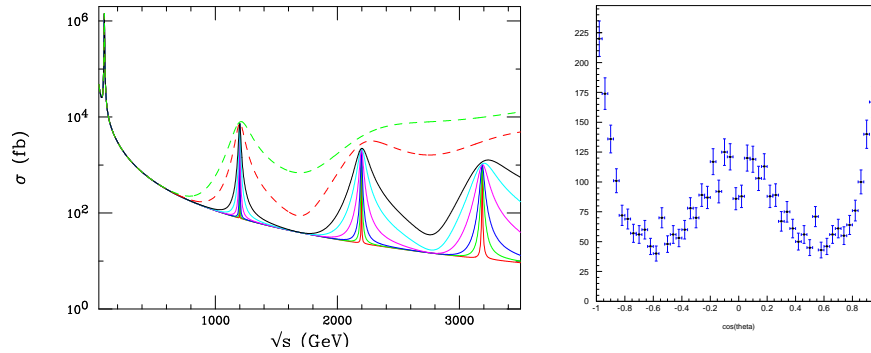
Figure 2: (Left) KK graviton excitations in the RS model produced in the process $e^+e^- \to \mu^+\mu^-$. From the most narrow to widest resonances the curves are for c in the range 0.01 to 0.2. (Right) Decay angle distribution of the muons from $G_3(3200\text{GeV}) \to \mu\mu$.

γ and Z^0 and to cancellations of the L_3, R_3 contributions. Figure 1 shows that the effect is still visible after the smearing from the luminosity spectrum. With realistic assumptions and 1 ab^{-1} of data, CLIC will be able to resolve the two narrow resonances for values of the coupling ratio $g/g'' > 0.08$, corresponding to a mass splitting $\Delta M = 13$ GeV for $M = 3$ TeV, and to determine ΔM with a statistical accuracy better than 100 MeV.

3 Extra Dimensions in the Randall-Sundrum Model

For the past few years the phenomenology of scenarios with extra dimensions has been explored at the TeV scale. These theories aim to solve the hierarchy problem by bringing the Gravity scale closer to the Electroweak scale.

In the extra-dimension scenario proposed by Randall-Sundrum(RS) [8] the hierarchy between the Planck and the Electroweak scale is generated by an exponential function called 'warp factor'. This model predicts Kaluza-Klein graviton resonances with both weak scale masses and couplings to matter in the TeV range.

An example of a spectrum for $e^+e^- \to \mu^+\mu^-$ is shown in Fig. 2, for different values of the parameter c which controls the effective coupling strength of the graviton and thus the width of the resonances. The cross sections are huge and the signal cannot be missed at a LC with sufficient CMS energy. The resonance spectrum was chosen such that the first resonance G_1 has a mass M around 1200 GeV, just outside the reach of a TeV class LC, and consequently the mass of the third resonance G_3 will be around 3200 GeV, as shown in Fig. 2. The CMS energy for the e^+e^- collisions of CLIC was taken to be 3.2 TeV in this study. Mainly the muon and photon decay modes of the graviton have been studied. The events used to reconstruct the G_3 resonance signal were selected either via two muons or two γ's with $E > 1200$ GeV and $|\cos\theta| < 0.97$. The background from overlaid two-photon events – on average four events per bunch crossing –is typically important only for angles below 120 mrad, i.e. outside the considered signal search region.

First we study the precision with which we can measure the shape, i.e. the c and M parameters, of the observed new resonance, similar to the Z', for an integrated luminosity of 1 ab^{-1}. The precision with which the cross sections are measured allows one to determine c to 0.2%, and M to better than 0.1%. Next we determine some key properties of the new resonance: the spin and the ratio of decay modes. The graviton is a spin-two object. Fig. 2 shows the decay angle of the fermions $G \to \mu\mu$ for the G_3 graviton, for 1 ab^{-1} of data, including CLIC machine background. The typical spin-two structure of the decay angle of the resonance is clearly visible. For gravitons as proposed in [9, 10] one expects $BR(G \to \gamma\gamma)/BR(G \to \mu\mu) = 2$. With the present detector simulation we get efficiencies in mass peak (± 200 GeV) of 84% and 97% for detecting the muon and photon decay modes, respectively. With cross sections of $O(pb)$, $\sigma_{\gamma\gamma}$ and $\sigma_{\mu\mu}$ can be determined to better than a per cent. Hence the ratio $BR(G \to \gamma\gamma)/BR(G \to \mu\mu)$ can be determined to an accuracy of 1% or better. Finally, if the CMS energy of the collider is large enough to produce the first three resonances states, one has the intriguing possibility to measure the graviton self-coupling via the $G_3 \to G_1 G_1$ decay [10]. The dominant decay mode will be $G_1 \to$ gluon-gluon or $q\bar{q} \to$ two jets. It has been shown [11] that four jet events can be used to reconstruct G_1 resonances in the G_3 decay with no significant distortion of the background.
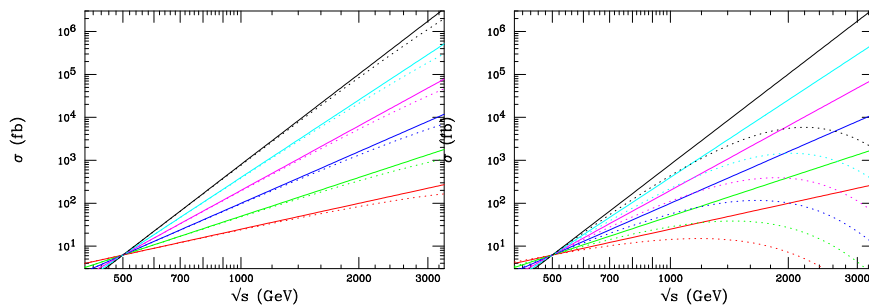
Figure 3: The cross section for $e^+e^- \to G\gamma$ with cuts as described in the text, for rigid (solid lines) and soft (dashed lines) branes. The different curves correspond, from bottom to top, to different number of extra dimensions $\delta = 2,3,4,5,6$ and 7. Left, for $\Delta = 4$ TeV, right for $\Delta = 1$ TeV.

4   Large Extra Dimensions with Soft Branes

Scenarios with large extra dimensions have been studied for TeV class linear colliders, e.g. TESLA [12] and are searched for typically in the channel $e^+e^- \to \gamma + G$. One of the acclaimed advantages of a LC w.r.t. the LHC is that by measuring the γG cross section at different center of mass energies one can disentangle the Planck scale and the number of extra dimensions δ simultaneously as is shown in Fig. 3 by the solid lines. The cross sections are calculated for cuts similar to corresponding to those in[12]: $\sin\theta_\gamma > 0.1$, $p_t^\gamma > 0.06E_{beam}$ and $x_\gamma < 0.65$. The cross sections are normalized such that for each value of δ, the scale, M_D, is chosen to give the same cross section at 500 GeV.

These predictions however assume the branes are rigid. Allowing for flexible branes instead [13] introduces a new dependence on a parameter Δ, the softening scale, which is related to the brane tension. The dashed lines in Fig. 3 shows the effect of Δ for values of 4 TeV and 1 TeV respectively.

For a brane tension of 4 TeV the effect on the cross section is rather small. A collider in the range of 0.5-1 TeV would not be sensitive to the effect and thus

M_D, and δ can be disentangled. However, at CLIC the cross sections are 30-40% lower than expected, allowing to observe the softness of the brane. For a brane with tension of 1 TeV the effect is more spectacular. For the example given here a lower energy LC when measuring cross sections only at 0.5 TeV and 1 TeV would get fooled and extract a wrong δ, M_D. Extending the range in the multi-TeV region again will allow this effect to be observed in its full drama. The cross section of the background channel $ee \to ee\gamma$ with the cuts as listed above is 16 fb at 3 TeV, which sets the scale for the detectability of a signal: for $\delta = 2$ or 3 the signal event rate at 3 TeV gets too small for such a soft brane scenario.

5 Black Holes

If the fundamental Planck scale is in the TeV range then a possible consequence would be that black holes (BH) could be produced in the multi-TeV range. The cross section is expected to be very large: $\sigma = \pi R_s^2 \sim 1$ TeV^{-2} $\sim O(100)$ pb, where R_S is the Schwarzschild Radius. If $\sqrt{s}_{e^+e^-} > M_{BH} > M_{\text{Planck}}$ then the collider becomes a black hole factory. The lifetime of such a black hole is of order $\sim 10^{-25} - 10^{-27}$ sec, and hence the black hole will evaporate before it could possibly 'attack' any detector material.

The decay of a black hole can be very complex and involve several stages [14, 15]. If the dominating mode is Hawking radiation then all particles (quarks, gluons, gauge bosons, leptons) are expected to be produced democratically, with e.g. a ratio 1/5 between leptonic and hadronic activity. The multiplicity is expected to be large. The production and decay process have been included in the PYTHIA generator[15]. Fig. 4a shows a black hole event produced in a detector at CLIC, leading to spectacular multi-jet and lepton/photon signals. Black holes will be easily detected at CLIC due to their energetic leptons and photons, and the more spherical event shape. As an example Fig. 4b shows, for 3 extra dimensions and a scale of 2 TeV, the sphericity of the events measured after detector simulation and addition of 5 bunch crossings of $\gamma\gamma$ background for black holes and annihilation events.

If this scenario is realized in Nature, black holes will be produced at high rates at the LHC. CLIC would be very instrumental in providing precise measurements. For example, it could be used to test Hawking radiation and extract the number of underlying extra dimensions. The large production cross section, low backgrounds

and little missing energy would make BH production and decay a perfect laboratory to study strings and quantum gravity in the lab.
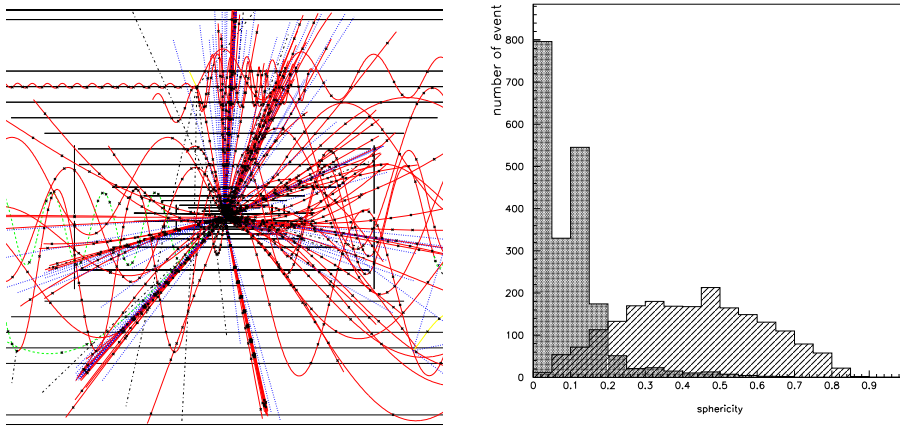

Figure 4: Black hole production in the CLIC detector. (Left) example of an event, (Right) sphericity distribution for 2 and 4 fermion events (full histogram) and black holes (hatched histogram).

6   Conclusions

The direct production of new gauge bosons and KK excitations in the TeV range was studied for CLIC. The expected backgrounds and the smeared luminosity spectrum of CLIC do not prevent to make precision measurements of the model parameters. In particular for the RS model it was shown that the key discriminating properties of these resonances can be reconstructed and the underlying model parameters can be determined precisely. Furthermore, CLIC will be very instrumental for the study of rigidness of branes in scenarios with large ED's, and the study of black holes if the Planck scale is below the CMS energy of the machine. Even though the LHC will likely detect most of such new phenomena, if these exist, CLIC data will be needed to fully understand their nature and properties.

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