Studies of s-channel Resonances at the CLIC Multi-TeV e^+e^- Collider

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Abstract. Several models predict the existence of new resonances in the multi-TeV region, which should be accessible in e^+e^- collisions by s-channel production. In this paper, we review the phenomenology of some specific models and we present a preliminary study of the potential of the future CLIC collider for the determination of their nature and properties.

I INTRODUCTION

While the core of the physics program of a 500 GeV linear collider can already be defined on the basis of the present data, signals from new physics that can be probed by a collider such as CLIC [1] at 1 TeV < \sqrt{s} < 5 TeV, belong to a significantly broader domain. Still, the most striking manifestation of new physics in the multi-TeV region will come from the sudden increase of the e^+e^- \rightarrow f\bar{f} cross section indicating the s-channel production of a new particle. There are several theories that predict the existence of such a resonance. A first class consists of models with extra gauge bosons such as a new neutral Z' gauge boson. This is common to both GUT-inspired E_6 models and to Left-Right symmetric models. They are discussed in Section II. Additional resonances are also predicted by recent theories of gravity with extra dimensions in the form of Kaluza-Klein graviton and gauge boson excitations [2]. Models of dynamical electroweak symmetry breaking also predict the existence of new resonances in the TeV region. In particular, we shall consider in Section III the degenerate BESS model, which predicts a pair of narrow and nearly degenerate vector and an axial-vector states [3]. The experimental study of such resonances at a multi-TeV collider will have to accurately measure their masses, widths, production and decay properties to determine their nature and identify which kind of new physics has been manifested.
II STUDY OF A $Z'$ BOSON AT CLIC

One of the simplest extensions of the SM is to introduce an additional $U(1)$ gauge symmetry, whose breaking scale is close to the Fermi scale. This extra symmetry is predicted in some grand unified theories and in other models. The extra $Z'$ associated to this symmetry naturally mixes with the SM $Z$ but the mixing angle is strongly constrained by precision electroweak data to be of the order of few mrad. Furthermore, direct searches for a new $Z'$ boson set a lower mass limit around 600 GeV. As a reference, an extra $Z'$ boson having the same couplings as the SM $Z^0$ boson ($Z'_\text{SM}$) is considered in the following. With an expected effective production cross section $\sigma(e^+e^- \rightarrow Z'_\text{SM}) \approx 15 \text{ pb}$, including the effects of ISR and luminosity spectrum, a $Z'$ resonance will tower over a $q\bar{q}$ continuum background of 0.13 pb. While the observation of such a signal is granted, the accuracy that can be reached in the study of its properties depends on the quality of the accelerator beam energy spectrum and on the detector response, accounting for the accelerator induced backgrounds. One of the main characteristics of the CLIC collider is the large luminosity, $L = 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ at $\sqrt{s_0} = 3 \text{ TeV}$, obtained in a regime of strong beamstrahlung effects ($\delta_B = 30\%$). The optimisation of the total luminosity and its fraction in the peak has been studied for the case of a resonance scan. The CLIC luminosity spectrum has been obtained with a dedicated beam simulation program [4] for the nominal parameters at $\sqrt{s_0} = 3 \text{ TeV}$. In order to study the systematics from the knowledge of this spectrum, the modified Yokoya-Chen parametrisation [5] has been adopted. The beam energy spectrum is described in terms of $N_\gamma$, the number of photons radiated per $e^\pm$ in the bunch, the beam energy spread in the linac $\sigma_p$ and the fraction $\mathcal{F}$ of events outside the 0.5% of the centre-of-mass energy. Two sets of parameters have been considered, obtained by modifying the beam size at the interaction point and therefore the total luminosity and its fraction in the highest energy region of the spectrum: CLIC.01 with $L=1.05 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ and $N_\gamma=2.2$; CLIC.02 with $L=0.40 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ and $N_\gamma=1.2$.

A $Z'$ Resonance Scan

The $Z'$ mass and width can be determined by performing either an energy scan, like the $Z^0$ scan performed at LEP/SLC and also foreseen for the $t\bar{t}$ threshold, or an auto-scan, by tuning the collision energy just above the top of the resonance and profiting of the long tail of the luminosity spectrum to probe the resonance peak. For the first method both di-jet and di-lepton final states can be considered, while for the auto-scan only $\mu^+\mu^-$ final states may provide with the necessary accuracy for the $Z'$ energy. $e^+e^- \rightarrow Z'$ events have been generated for $M_{Z'} = 3 \text{ TeV}$, including the effects of ISR, luminosity spectrum and $\gamma\gamma$ backgrounds, assuming SM-like couplings, corresponding to a total width $\Gamma_{Z'_\text{SM}} \approx 90 \text{ GeV}$ (see Figure 1).
A data set of 1000 fb$^{-1}$ has been assumed for the CLIC.01 beam parameters and of 400 fb$^{-1}$ for CLIC.02, corresponding to one year ($10^7$ s) of operation at nominal luminosity. This has been shared in a 3 to 7 points scan and $M_{Z'}$, $\Gamma(Z')/\Gamma_{SM}$ and $\sigma_{\text{peak}}$ have been extracted from a $\chi^2$ fit to the predicted cross section behaviour for different mass and width values. The dilution of the analysing power due to the beam energy spread is appreciable, as can be seen by comparing the statistical accuracy from a fit to the pure Born cross section to after including ISR and beamstrahlung effects. Still, the relative statistical accuracies are better than $10^{-4}$ on the mass and $5 \times 10^{-3}$ on the width. Sources of systematics from the knowledge of the shape of the luminosity spectrum have also been estimated. In order to keep $\sigma_{\text{ syst}} \leq \sigma_{\text{stat}}$ it is necessary to control $N_{\gamma}$ to better than 5% and the fraction $\mathcal{F}$ of collisions at $\sqrt{s} < 0.995 \sqrt{s_0}$ to about 1%.

**TABLE 1.** Results of the fits for the cross section scan of a $Z'_SM$ obtained by assuming no radiation and ISR with the effects of two different optimisation of the CLIC luminosity spectrum.

| Observable | Breit-Wigner | CLIC.01 | CLIC.02 |
|------------|--------------|---------|---------|
| $M_{Z'}$ (GeV) | 3000 ± .12 | ± .15 | ± .21 |
| $\Gamma(Z')/\Gamma_{SM}$ | 1. ± .001 | ± .003 | ± .004 |
| $\sigma_{\text{peak}}$ (fb) | 1493 ± 2.0 | 564 ± 1.7 | 669 ± 2.9 |
\section*{B \ Z' Decays}

The CLIC potential for the study of the couplings of a new resonance to fermions and of its possible decays to new particles has been tested for the case of the SM mode $Z' \to c\bar{c}, \ b\bar{b}$ and that of the exotic decay into pairs of right handed Majorana neutrinos. The large boost acquired by short-lived heavy hadrons from two fermion production at 3 TeV provides a very distinctive pattern of detached secondary vertices. A tagging technique based on charged multiplicity steps in the vertex tracker, independent on the track reconstruction efficiency in the highly collimated jets, provides a performance comparable to that achieved at LEP [7]. Therefore an accuracy on the partial decay widths $\Gamma_{c\bar{c}}$ and $\Gamma_{b\bar{b}}$ of the order of $10^{-3}$ can be obtained.

If the observed resonance is the neutral gauge boson $Z'_{LR}$ of the Left-Right symmetric model [8], the presence of right-handed Majorana neutrinos $N_e$ opens further decay channels. Their observability at CLIC was studied assuming their masses to be generated through the See-Saw mechanism [9]. Since $N_e$ is expected to decay promptly into $e^\pm$ and a $q_i\bar{q}_j$ pair, the typical signature consists of two electrons, with the same charge in half of the cases, and four hadronic jets. Their reconstructed energies and momenta need to be recalibrated to correct for the overlapping $\gamma\gamma \to$ hadrons events. The assignment of the two electrons, $e_{1,2}$, and the four hadronic jets $j_{a,b,c,d}$ to their correct $N_eN_e$ pair is performed by choosing the $(e_1j_aj_b;e_2j_cj_d)$ combination which minimizes the mass difference $|m(e_1j_aj_b) - m(e_2j_cj_d)|$. The invariant masses of these two selected systems and the resulting $Z'_{LR}$ boson mass spectrum are shown in Figure 2.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure2.png}
\caption{Reconstruction of the right-handed Majorana neutrino $N_e$ and the $Z'_{LR}$ boson. The spectra correspond to $M_{Z'} = 3$ TeV and $M_{N_e} = 1$ TeV ($L=1000$ fb$^{-1}$).}
\end{figure}
III STUDY OF THE DEGENERATE BESS MODEL

While the precise electroweak and LEP-2 data favour a realisation of the Higgs mechanism through a light elementary Higgs boson, it remains important to assess the sensitivity of a future multi-TeV collider to a strong electroweak symmetry breaking (SSB) scenario. SSB models are based on low energy effective lagrangians which provide a phenomenological description of the Goldstone boson dynamics. Possible new vector resonances produced by the strong interaction responsible for the electroweak symmetry breaking can be introduced in the formalism as the gauge bosons of a hidden symmetry. A description of a new triplet of vector resonances is obtained by considering an effective lagrangian based on the symmetry $SU(2)_L \otimes SU(2)_R \otimes SU(2)_{local}$ \cite{10}. The new vector fields are a gauge triplet of the $SU(2)_{local}$. These new fields acquire mass through the same mechanism which gives mass to the $W^\pm$ and the $Z^0$ bosons. By enlarging the symmetry group of the model, new vector and axial-vector resonances can be described.

The degenerate BESS model (D-BESS) \cite{3} is a realisation of dynamical electroweak symmetry breaking with decoupling. The D-BESS model introduces two new triplets of gauge bosons, which are almost degenerate in mass, $(L^\pm, L_3), (R^\pm, R_3)$. The extra parameters are a new gauge coupling constant $g''$ and a mass parameter $M$, related to the scale of the underlying symmetry breaking sector. In the charged sector the $R^\pm$ fields are not mixed and $M_{R^\pm} = M$, while $M_{L^\pm} \simeq M(1 + x^2)$ where $x = g/g''$ with $g$ the usual $SU(2)_W$ gauge coupling constant. The $L_3, R_3$ masses are given by $M_{L_3} \simeq M(1 + x^2), \ M_{R_3} \simeq M(1 + x^2 \tan^2 \theta)$ where $\tan \theta = s_\theta/c_\theta = g'/g$ and $g'$ is the usual $U(1)_Y$ gauge coupling constant. These resonances are narrow and almost degenerate in mass with $\Gamma_{L_3}/M \simeq 0.068 \ x^2$ and $\Gamma_{R_3}/M \simeq 0.01 \ x^2$, while the neutral mass splitting is: $\Delta M/M = (M_{L_3} - M_{R_3})/M \simeq (1 - \tan^2 \theta) \ x^2 \simeq 0.70 \ x^2$. This model respects the existing stringent bounds from electroweak precision data since the $S, T, U$ (or $\epsilon_1, \epsilon_2, \epsilon_3$) parameters vanish at the leading order due to an additional custodial symmetry. Therefore, the precision electroweak data only set loose bounds on the parameter space of the model as shown in Figure 3, comparable to those from the direct search at the Tevatron \cite{3}.

The behaviour of the resonance widths for this model as well as for other SM extensions with additional vector bosons is shown in Figure 3 as a function of the relevant model parameter. The $Z'_E$ and $Z'_{LR}$ widths are computed by assuming only decays into SM fermions and tend to be wider than the corresponding widths of the $L_3$ and $R_3$ states.

Future hadron colliders may be able to discover these new resonances which are produced through a $q\bar{q}$ annihilation and which decay in the leptonic channel $qq' \rightarrow L^\pm, W^\pm \rightarrow (e\nu_e)\mu\nu_\mu$ and $qq \rightarrow L_3, R_3, Z, \gamma \rightarrow (e^+e^-)\mu^+\mu^-$. The relevant observables are the di-lepton transverse and invariant masses. The main backgrounds, left to these channels after the lepton isolation cuts, are the Drell-Yan processes with SM gauge bosons exchange in the electron and muon channel. The study has been performed using a parametric detector simulation \cite{11}. Results are given in Table 2 for the combined electron and muon channels for $L = 100 \ fb^{-1}$. Results
TABLE 2. Sensitivity to $L_3$ and $R_3$ production at the LHC and CLIC for $L=100(500) \text{ fb}^{-1}$ with $M=1.2(3) \text{ TeV}$ at LHC and $L=1000 \text{ fb}^{-1}$ at CLIC.

| $g/g''$ | $M$ (GeV) | $\Gamma_{L_3}$ (GeV) | $\Gamma_{R_3}$ (GeV) | $S/\sqrt{S+B}$ LHC ($e+\mu$) | $S/\sqrt{S+B}$ CLIC (hadrons) | $\Delta M$ |
|--------|-----------|---------------------|---------------------|-----------------------------|-------------------------------|-----------|
| 0.1    | 1000      | 0.7                 | 0.1                 | 17.3                        |                               |           |
| 0.2    | 1000      | 2.8                 | 0.4                 | 44.7                        |                               |           |
| 0.1    | 2000      | 1.4                 | 0.2                 | 3.7                         |                               |           |
| 0.2    | 2000      | 5.6                 | 0.8                 | 8.8                         |                               |           |
| 0.1    | 3000      | 2.0                 | 0.3                 | (3.4)                       | 62                            | 23.20 ± 0.6 |
| 0.2    | 3000      | 8.2                 | 1.2                 | (6.6)                       | 152                           | 83.50 ± 0.2 |

are given for an integrated luminosity of 500 fb$^{-1}$ assuming $M=3 \text{ TeV}$.

The discovery limit at LHC with $L=100 \text{ fb}^{-1}$ is $M \sim 2 \text{ TeV}$ with $g/g'' = 0.1$. Beyond discovery, the possibility to disentangle the double peak structure depends strongly on $g/g''$ and smoothly on the mass [11]. A lower energy LC can also probe this multi-TeV region through the virtual effects in the cross-sections for $e^+e^- \rightarrow L_3, R_3, Z, \gamma \rightarrow f\bar{f}$. Due to the presence of new spin-one resonances the annihilation channel in $f\bar{f}$ and $W^+W^-$ is more efficient than the fusion channel.

In the case of D-BESS, the $L_3$ and $R_3$ states are not strongly coupled to $WW$

FIGURE 3. The left plot shows the widths of the new gauge vectors predicted in various new physics models as a function of the relevant parameters: $\theta_2$ for $Z'_{E_6}$ and $\lambda = g_L/g_R$ for $Z'_{LR}$ [6], $g/g''$ for D-BESS [3]. The right plot shows the 95% CL contour in the plane $(M, g/g'')$ from $e^+e^-\rightarrow\text{linear colliders}$ with $\sqrt{s} = 500(800) \text{ GeV}$. Also shown are the present bounds from LEP and SLC. The allowed regions are below the lines.

making the $f\bar{f}$ final states the most favourable channel for discovery. The analysis at $\sqrt{s} = 500 \text{ GeV}$ and $\sqrt{s} = 800 \text{ GeV}$ is based on the following observables: $\sigma^\mu$, $\sigma^A$, $A_{FB}^{e^+e^-\rightarrow\mu^+\mu^-}$, $A_{FB}^{e^+e^-\rightarrow\ell^+\ell^-}$, $A_{LR}^{e^+e^-\rightarrow\mu^+\mu^-}$, $A_{LR}^{e^+e^-\rightarrow\ell^+\ell^-}$, $A_{LR}^{e^+e^-\rightarrow\ell^+\ell^- had}$. The sensitivity contours obtained for $L = 1000 \text{ fb}^{-1}$ and $P(e^-) = 80\%$ are shown in Figure 3. The LC
indirect reach for $\sqrt{s} < M$ is lower or comparable to that of the LHC. However, the QCD background rejection essential for the LHC sensitivity still needs to be validated using full detector simulation and pile-up effects.

A Resonance Scan

Assuming a resonant signal to be seen at the LHC or at a lower energy LC, CLIC can measure its width, mass, and also investigate the existence of an almost degenerate structure [12]. This needs to be validated taking full account of the luminosity spectrum and accelerator induced backgrounds. The ability in identifying the model distinctive features has been studied using the production cross section and the flavour dependent forward-backward asymmetries, for different values of $g/g''$. The resulting distributions are shown in Figure 4 for the case of the CLIC.02 beam parameters. A characteristic feature of the cross section distributions is the presence of a narrow dip at energies around 3 TeV. This is due to the interference

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{The 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.}
\end{figure}
of the $L_3$, $R_3$ resonances with the $\gamma$ and $Z$ and to cancellations of the $L_3$, $R_3$ contributions. The effect becomes larger for decreasing $g/g''$. Similar considerations hold for the asymmetries. In the case shown in Figure 4, the effect is still visible after accounting for the CLIC.02 luminosity spectrum.

This study has demonstrated that with $1000 \text{ fb}^{-1}$ 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 $\Delta M = 13 \text{ GeV}$ for $M = 3 \text{ TeV}$, and to determine $\Delta M$ with a statistical accuracy better than $100 \text{ MeV}$ (see Table 2).

IV CONCLUSIONS

Two scenarios predicting new resonances in the multi-TeV region have been studied in relations to the discovery and study potential of the CLIC $e^+e^-$ linear collider. The profile of such a new resonance can be studied with high accuracy due to the large anticipated CLIC luminosity. This accuracy can be exploited to distinguish the nature of the resonance and the cases of an additional $Z'$ gauge boson and of nearly degenerate resonances from a strong symmetry breaking scenario have been discussed.

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