Study of a New Z' Boson Decaying into Right-Handed Majorana Neutrinos at CLIC

A. Ferrari*
Department of Radiation Sciences, Uppsala University, Sweden

In the framework of the Left-Right Symmetric Model and the See-Saw mechanism, we report on the study of the production of a new Z' boson decaying into right-handed Majorana neutrinos in e^+e^- collisions at 3 TeV. Final states with two electrons and four hadronic jets are considered to reconstruct these particles, and an accurate measurement of their masses is performed with a resonance scan.

1. Introduction

Despite its remarkable agreement with the current data, the Standard Model cannot be considered as a complete theory. For instance, parity violation in the weak interactions is introduced by hand and neutrinos are massless, despite the fact that they are elementary matter particles. However, in accordance with experimental data in the field of neutrino oscillations, neutrinos should have very small masses. The Left-Right Symmetric Model [1] is an alternative theory which restores the parity symmetry at high energy by extending the $SU(2)_L \otimes U(1)_Y$ gauge group of the Standard Model to $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ and by introducing three new heavy gauge bosons: W_R^+, W_R^- and Z'. If neutrinos are Majorana particles, the Left-Right Symmetric Model, together with the See-Saw mechanism [2], may provide an explanation for the lightness of the three left-handed neutrinos by introducing three heavy right-handed neutrinos (N_l's).

A detailed study of $pp \to W_R \to eN_e$, which is the most promising channel at LHC, was reported in reference [3]. With an integrated luminosity of 300 fb^{-1}, the right-handed Majorana neutrinos can be discovered together with the W_R boson, if m_{N_e} and m_{W_R} remain smaller than 4 and 6 TeV respectively. The production of the Z' boson at LHC and its decay into two right-handed Majorana neutrinos was discussed in reference [4]. With an integrated luminosity of 300 fb^{-1}, $pp \to Z' \to N_eN_e$ can be observed if m_{N_e} and $m_{Z'}$ are smaller than 1.2 and 4.3 TeV respectively.

In the following, we study the production of the Z' boson and its decay into a N_eN_e pair at the Compact Linear Collider (CLIC) operating at an energy of 3 TeV and a luminosity of 10^{35} cm^{-2}.s^{-1} (we assume that Z' and N_e are already discovered when CLIC starts operation). In our study, the right-handed fermions have exactly the same couplings as the left-handed fermions and Z' does not decay into W^+W^-. The default version of PYTHIA 6.1 [5] has been modified in order to include the right-handed Majorana neutrinos. N_l decays into a charged lepton $l^\pm$ and an off-shell W_R^*, which leads to the production of a $q_i\bar{q}_j$ pair, or a $l'N_{l'}$ pair if $m_{N_{l'}} < m_{N_l}$. However, it appears that the $N_l \to l^\pm l'^\mp N_{l'}$ decays have small branching ratios. They can thus be neglected in the following. This is easily done by assuming $m_{N_e} = m_{N_\mu} = m_{N_\tau}$ which also allows restriction of the number of additional parameters. The influence of high energy beam-beam effects on the production cross section and on the reconstruction of Z' and N_e are discussed, and we show that a resonance scan allows to measure $m_{Z'}$ and m_{N_e} with a high degree of precision.

*ferrari@tsl.uu.se

2. Production cross section for $e^+e^- \to Z' \to N_e N_e$ at CLIC

When calculating the cross section for $e^+e^- \to Z' \to N_e N_e$ at CLIC, one must take into account the initial state radiation of photons (ISR), but also high energy beam-beam effects, such as beamstrahlung and coherent pair production [6]. Figure 1 shows that, even with these high energy beam-beam effects, the cross section for $e^+e^- \to Z' \to N_e N_e$ (calculated here with $m_{Z'} = 3$ TeV and for various values of the ratio $r_Z = m_{N_e}/m_{Z'}$) remains two orders of magnitude higher than the cross section for $pp \to Z' \to N_e N_e$ at LHC. Since the luminosity considered here should be 10 times higher than the nominal luminosity at LHC, one expects the number of $Z' \to N_e N_e$ events to be three orders of magnitude higher at CLIC than at LHC, allowing thus precision measurements.

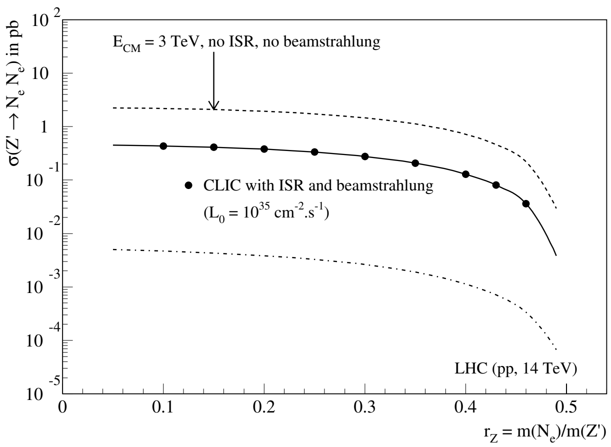

Figure 1: Production cross section for a Z' boson with a mass of 3 TeV, decaying into two right-handed Majorana neutrinos at CLIC (full line) and at LHC (dashed line at the bottom of the figure). We assume that $m_{N_e} = m_{N_\mu} = m_{N_\tau}$.

3. Detection and reconstruction of Z' and N_e

Following the generation of $e^+e^- \to Z' \to N_e N_e$ events, a fast detector simulation is performed by using the SIMDET code [7] with its default parametrizations for CLIC. Since N_e promptly decays into $e^\pm$ and a $q_i\bar{q}_j$ pair, one expects two electrons and four quarks in the final state. In order to have a very high signal purity, one requires to detect two same-sign electrons having $E_T \geq 50$ GeV. Then, a cluster analysis method based on particle momenta is used to reconstruct hadronic jets. Their multiplicity depends on the distance scale d_{join} above which two clusters may not be joined in the PYCLUS subroutine of PYTHIA. If no hadronic background is included and if only the $Z' \to N_e N_e$ decays that lead to four light quarks are selected, the fraction of events with exactly four jets is maximal if $d_{join} = 75$ GeV, for the set of masses that we consider here. At CLIC, high energy $\gamma\gamma$ collisions lead to the production of additional hadrons with a small transverse energy. With a nominal energy of 3 TeV, one expects four hadronic events per bunch crossing. Since bunch crossings occur every 0.67 ns, one should integrate the contribution of the hadronic background over N_{bc} bunch crossings. Most of the hadrons from the $\gamma\gamma$ collisions form jets with a small transverse energy. However, the hadrons which are close to the quarks from the Majorana neutrinos can be merged with high-p_T jets, which leads to a shift of the Z' and N_e peaks towards higher masses. The larger N_{bc}, the more significant this shift.

The following procedure is used to reconstruct the Z' boson and the Majorana neutrinos. In a first step, the assignment of the two electrons and the four leading jets to the correct $N_e N_e$ pair is done by choosing the $(e_1 j_a j_b\,; e_2 j_c j_d)$ combination which minimizes $|m(e_1 j_a j_b) - m(e_2 j_c j_d)|$. The invariant masses of the two selected systems are then plotted on the same histogram to reconstruct N_e. The Z' boson is reconstructed by calculating the invariant mass of the two electrons and the four leading jets. In order to reduce the combinatorial background and the effect of $\gamma\gamma \rightarrow$ hadrons, a second reconstruction procedure is performed. This time, the assignment of the two electrons and the four leading jets is done such that the invariant masses of both (ejj) systems are as close to the reconstructed value of m_{N_e} as possible (because of the hadronic background, it is larger than the real mass of N_e). Then, a kinematical fit is applied with the following constraints:

- the two N_e candidates have the same mass,
- the system consisting of the two electrons and the four leading jets has p_x and p_y equal to zero,
- the momentum and energy conservation at $\sqrt{s} = 3$ TeV (assuming neither ISR nor beamstrahlung losses) is applied to an imaginary system consisting of the two electrons, the four leading jets and a light neutrino with a zero transverse momentum.

These corrections allow a good reconstruction of the Z' boson and of the right-handed Majorana neutrino N_e, as shown in Figure 2. For the sake of simplicity, we consider here the case where the hadronic background is integrated over one bunch crossing only. However, this procedure could be used for other values of N_{bc} without dramatically changing our conclusions (only the width of the Z' and N_e mass peaks tends to increase with N_{bc}).

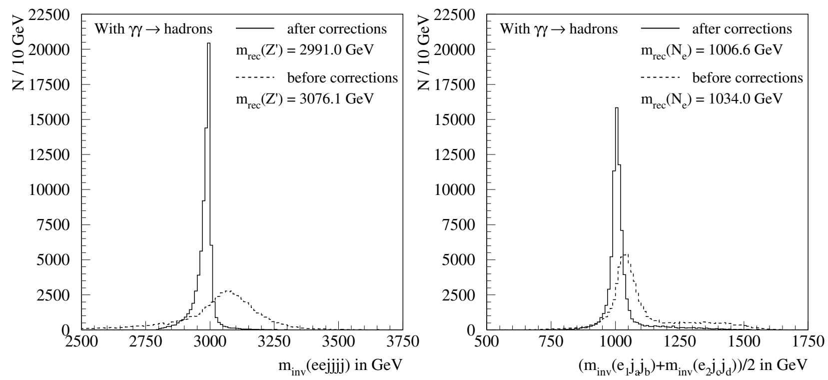

Figure 2: Reconstruction of Z' and N_e before and after the reduction of the combinatorial and hadronic backgrounds ($N_{bc} = 1$). Here, $m_{Z'} = 3$ TeV and $m_{N_e} = 1$ TeV. The integrated luminosity is 1000 fb^{-1}.

4. Resonance scan

Let us choose five values of $\sqrt{s}$: 2980, 3000, 3020, 3040 and 3060 GeV. For each of them, a "real" Z' of 3 TeV and a "real" N_e of 1 TeV are reconstructed with the method described previously (the integrated luminosity is 200 fb^{-1} for each value of $\sqrt{s}$). Only the events for which the reconstructed Z' and N_e are respectively in the 2.8-3.1 TeV and 0.9-1.1 TeV mass windows are kept (the corresponding total efficiency is 30%). For each value of $\sqrt{s}$, some "simulated" Z' and N_e are reconstructed as well, but with slightly different masses. Let $N_r(i)$ and $N_s(i)$ respectively be the number of "real" and "simulated" events that one obtains at the end of the reconstruction procedure for an energy $\sqrt{s}(i)$. For each "simulated" combination of $(m_{Z'}; m_{N_e})$, one calculates:

$$\chi^2 = \sum_{i=1}^{5} \frac{(N_r(i) - N_s(i))^2}{N_r(i)}.$$

Four masses were considered for the "simulated" Z'. For each of them, four values of $r_Z = m_{N_e}/m_{Z'}$ were chosen, the corresponding values of χ^2 were calculated and the minimal value of χ^2 was derived from a parabolic fit. Knowing how Min(χ^2) depends on the mass of the "simulated"

Z', it is possible to derive the mass for which $\mathrm{Min}(\chi^2)$ is the smallest with a parabolic fit: we found $m_{Z'} = 3000.0 \pm 0.3$ GeV. If this value is chosen for the mass of the "simulated" Z', then χ^2 becomes minimal when $m_{N_e} = 1000.1 \pm 1.9$ GeV.

5. Conclusion

The production of a 3 TeV Z' boson decaying into Majorana neutrinos was discussed in this paper. The hadronic background from high energy $\gamma\gamma$ collisions can deteriorate the reconstruction of the mass peaks, but it can be reduced with a kinematical fit. The large number of $Z' \to N_e N_e$ events allows to determine the masses of these new particles with an accuracy of 0.01% for Z' and 0.19% for N_e. CLIC seems to be the appropriate machine to provide details on the Left-Right Symmetric Model and the See-Saw mechanism.

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