Prospects to detect a $Z'$ with the LC

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Abstract

The search for a $Z'$ is one of the tasks of future colliders. I study the capability to detect the $Z'$ at a linear $e^+e^-$ collider operating below resonance production. Depending on $m_{Z'}$ and the collider parameters we will be able to discriminate between $Z'$ models.

1 Introduction

Despite the excellent agreement of Standard Model predictions with present experimental results many of us have no doubt that a more fundamental theory (GUT) describes all forces at high energy scales by only one gauge group. The symmetry breaking of a unifying gauge group may lead to new gauge bosons at a scale of order 1 TeV. Popular additional gauge bosons are the $Z'$ coming from an $E_6$ GUT or the $Z'=Z_R$ with $W^+_R$ arising from symmetry breaking in left-right models:

$$J^\mu_{Z'} = J^\mu_ch_6 + J^\mu_{\psi}\sin\Theta_6; \quad J^\mu_{Z'} = \frac{1}{2\alpha_{LR}}J^\mu_{3R} - \frac{1}{2\alpha_{LR}}J^\mu_{B-L}. \quad (1)$$

Specific cases are the $\chi$, $\psi$ and $\eta$ models ($\Theta_6 = 0; \pi/2; -\arctan\sqrt{5/3}$) and the leftright-models ($\sqrt{2/3} \leq \alpha_{LR} \leq \sqrt{\cot^2\theta_W - 1}$).

With $e^+e^-$ colliders the properties of a $Z'$ can be investigated. The determination of $Z'$ parameters is easy if the centre–of–mass energy of a collider is large enough to produce this boson. But even indirect measurements of $e^+e^- \rightarrow (\gamma, Z, Z') \rightarrow f\bar{f}$ below the $Z'$ production threshold gives information about the nature of the $Z'$.

Here, prospective measurements of $Z'$ parameters are presented. Besides the determination of the $Z'$ mass the identification of the $Z'$ model is reviewed analyzing fermion-pair production below a $Z'$ resonance.

I study the following collider scenario:

$$\sqrt{s} = 500\text{GeV}; \quad L_{int} = 50fb^{-1} \quad (2)$$

The electron beam is polarized, $P_{e^-} = 80\%$. The results may be extrapolated to the scenarios $\sqrt{s} = 800 \text{ GeV}, L_{int} = 200fb^{-1}$ and $\sqrt{s} = 1600 \text{ GeV}, L_{int} = 800fb^{-1}$. 

The total cross section, $\sigma_T$, the forward-backward asymmetry, $A_{FB}$, the left-right asymmetry, $A_{LR}$, and the forward-backward polarization asymmetry, $A_{FB}^{LR}$, can be measured with small statistical uncertainties. For leptonic and hadronic final states without discriminating between quark flavors small systematic errors are expected (see also [1]). The experience of SLD and LEP experiments has shown that good techniques of quark flavour identification with high efficiencies and purities are feasible. However, background reactions and misidentification of final state fermions can lead to relatively large systematic errors if $q\bar{q}$ final states are analysed. Hence in the following, the influence of systematic errors on the determination of $Z'$ parameters is considered.

An angular acceptance cut of $20^\circ$ to final state fermions is assumed. Further, the t-channel exchange in Bhabha scattering is neglected. By applying a cut on the energy of radiative photons, $\Delta = E_\gamma/E_{beam}$, the radiative return to the $Z$ peak can be suppressed. Here, $\Delta = 0.9$ is used. An uncertainty of 0.5\% is taken into account for the luminosity measurement. For numerical studies I use the program package ZEFIT/ZFITTER [2, 3].

2 Determination of $Z'$ Parameters

2.1 $Z'$ Mass

A crucial element of a $Z'$ search is the determination of its $Z'$ mass, $m_{Z'}$. Exclusion limits for $m_{Z'}$ have been determined for different collider types and various $Z'$ models. An overview can be found in [4].

Assuming the collider scenario (2), it is expected that an analysis of all leptonic and hadronic observables is sensitive to the $Z'$ mass as shown in Figure 1 (see also [5, 6]). here, the $Z'$ model is assumed to be known.

Let us try to determine the $Z'$ mass assuming the realization of an $E_6$ GUT but without any information about the model parameter $\Theta_6$ in [11]. Figure 2 demonstrates
the possibility to measure $m_{Z'}$ and $\Theta_6$ simultaneously if a $Z'$ in the $\chi$ model has a mass of 1 TeV or 1.5 TeV. If $m_{Z'} \approx 2 \sqrt{s}$ the $Z'$ model and the $Z'$ mass can be reproduced with a good precision. For $m_{Z'} \approx 3 \sqrt{s}$ the determination of the $Z'$ model becomes difficult. Having in mind that the $\chi$ model ($\Theta_6 = 0$) is identical with the left-right model for $\alpha_{LR} = \sqrt{2}/3$, a confusion between $Z'$ models remains. Figure 3 shows corresponding regions of confusion between $E_6$ and left-right models assuming $m_{Z'} = 1.5$ TeV and $L_{int} = 20$ fb$^{-1}$.

2.2 $Z'$ Couplings to Fermions

If deviations from the Standard Model predictions will be found the search for explanations will also include the possibility that a $Z'$ is the source of the disagreement. But, are we able to analyze the $Z'$ without any knowledge about its origin?

The measurements of 2-fermion final states below the $Z'$ resonance are sensitive to normalized $Z'$ couplings $a'^N_f$, $v'^N_f$ [7],

$$a'^N_f = a_f \sqrt{s}/(m^2_{Z'} - s),$$

$$v'^N_f = v_f \sqrt{s}/(m^2_{Z'} - s).$$

From (3), for a given $Z'$ mass the couplings $a'_f$ and $v'_f$ can be found and thus the $Z'$ model can be determined. First, let us assume that the $Z'$ is detected at LHC and the $Z'$ mass is known.

2.2.1 $Z'$ Couplings to Leptons

Assuming lepton universality the situation is quite clear: The couplings of the $Z'$ to the initial and final states are identical and can be determined with a good accuracy if
Figure 3: Confusion regions between $E_6$ and left-right models for $m_{Z'} = 1.5$ TeV, $\sqrt{s} = 500$ GeV, and $L_{int}=20$ fb$^{-1}$ based on $\sigma_t$, $A_{FB}^t$ and $A_{LR}^t$.

Figure 4: (a) 95% CL contours for $a_{l'}$ and $v_{l'}$. A $Z'$ is assumed in the $\chi$ model or in the LR model with a mass of $m_{Z'}=1$ TeV (hatched area) and $m_{Z'}=1.5$ TeV (shaded area). The dotted line limits the 95% CL bounds on $Z'll$ couplings if a $Z'$ with a mass $m_{Z'}=3$ TeV exists in the $\chi$ model. $L = 50$ fb$^{-1}$ and $\sqrt{s} = 500$ GeV. (b) Discrimination between $\chi$, $\psi$ and LR model based on 95% CL contours for $a_{b'}$ and $v_{b'}$ assuming $m_{Z'}=1$ TeV (hatched area). For comparison a $Z'$, $m_{Z'}=1.5$ TeV, is considered in the $\chi$ model, too (dashed line). Collider scenario (2) is taken into account.
the $Z'$ is not too heavy compared to the collider energy. The observables depend only on bilinear products of $a'_f$ and $v'_f$. Thus, a two-fold ambiguity in the signs of couplings remains.

Figure 4 shows the bounds on $Z'\ell\bar{\ell}$ couplings for different collider scenarios and various $Z'$ masses. Evidently, the sensitivity to the $Z'$ couplings is weakened with decreasing luminosity and with increasing $m_{Z'}$:

$$\frac{\Delta a'_1}{\Delta a'_2}, \frac{\Delta v'_1}{\Delta v'_2} \approx \left( \frac{m^2_{Z'1} - s}{m^2_{Z'2} - s} \right)^{1/2}$$

(4)

$$\frac{\Delta a'_1}{\Delta a'_2}, \frac{\Delta v'_1}{\Delta v'_2} \approx \left( \frac{L_2}{L_1} \right)^{1/4}$$

(5)

If $m_{Z'} \geq 5 \cdot \sqrt{s}$ the $Z'$ influences the observables only weakly and deviations from the Standard Model predictions cannot be safely observed. It is impossible to exclude the point $(a'_l, v'_l) = (0, 0)$ in Figure 4 with 95% CL, although the existence of a $Z' (\chi$ model) is assumed. Even the indirect detection of a $Z'$ is no longer possible. Nevertheless, upper limits on $Z'$ couplings can be derived.

2.2.2 $Z'$ Couplings to Quarks

The determination of $Z'$ couplings to quarks depends on the knowledge of the couplings to electrons. In particular, if the error range of $a'_e$ and $v'_e$ includes $a'_e = v'_e = 0$, a simultaneous fit to leptonic and quarkonic couplings will fail. In the following, we assume that an analysis of leptonic observables leads to non-vanishing $Z\ell\bar{\ell}$ couplings.

The identification of quark flavors is more complicated than lepton identification. Although very promising designs of a vertex detector for the LC let us expect efficiencies of more than 60% in b-tagging with purities of at least 98% (see [8]), the systematic error for the measurement of b-quark observables could be about 1% and dominate the statistical error. The systematic errors limit the accuracy of a $a'_q, v'_q$ determination substantially and could fully remove improvements due to a higher luminosity. The promising model identification power using the parameters,

$$P^l_V = \frac{v'_l}{a'_l}, \quad P^q_L = \frac{v'_q + a'_q}{a'_l}, \quad P^u,d_R = \frac{v'_u,d - a'_u,d}{a'_l + v'_l},$$

(6)

as suggested by [9] looses its charm if in addition to statistical errors realistic systematic errors are taken into account (see Table 2 of [5]).

In Figure 5 it is demonstrated for the $\chi$ model how systematic errors could complicate the determination of the $Z'q\bar{q}$ couplings. Otherwise, comparing Figures 4 and 5 it is obvious that the crucial quality for the determination of $Z'$ couplings is the difference $m_{Z'} - \sqrt{s}$.

2.3 $Z'$ Couplings without Information about the $Z'$ mass

If the $Z'$ mass is unknown the determination of $Z'$ couplings becomes difficult. This is demonstrated in Figure 6 assuming $m_{Z'} = 1$ TeV in the $\chi$ model and studying leptonic observables only. It is impossible to get upper limits on $Z'$ mass and couplings.
Figure 5: Influence of luminosity, \(Z'\) mass, and systematic error on contours of \(Z'b\overline{b}\) couplings. A \(Z'\) in the \(\chi\) model is assumed.

simultaneously. The mean axis of the \((a'_l, v'_l)\) contour in Figure 5 corresponds to the above mentioned parameter \(P_V = v'_l/a'_l\) and allows to some extent conclusions on the \(Z'\) model. Including \(q\overline{q}\) final states, this method – to extract information about the \(Z'\) model using the parameters \(P_V, P_R, P_L\) of Equ. (6) – fails due to possible infinite \(Z'\overline{\ell}\ell\) couplings.

The boundaries of the \((a'_l, m_{Z'})\) contour follow approximately the relation

\[
m_{Z'}^\pm(s) = \sqrt{\left[\frac{a_N^2}{(a_{11}^N + \Delta a_{11}^N)^2} + 1\right]} s. \tag{7}
\]

An additional measurement at a higher energy, \(s_2 > s_1\) resulting in \(m_{Z'}^\pm(s_2)\) can close the contours in Figure 5 if

\[
\left(\frac{s_1}{s_2}\right)^{1/2} = \frac{a_{12}^N - \Delta a_{12}^N}{a_{12}^N + \Delta a_{12}^N} \tag{8}
\]

A scanning strategy considering (8) will allow the simultaneous determination of \(Z'\) couplings and mass.

The success and failure of fitting \(Z'\) couplings and mass below a \(Z'\) peak is illustrated by Rizzo studying the model resolution for various distributions of luminosity on several energy points \([10]\).

3 Conclusions

If a \(Z'\) boson with a mass \(m_{Z'} < 5\sqrt{s}\) exists observables measured at LC differ from their Standard Model expectations. The interpretation of these deviations within special \(Z'\)
models gives the $Z'$ mass with a good accuracy or allows to determine lower bounds on the $Z'$ mass. More interesting is a model-independent analysis. With the determination of $Z'f\bar{f}$ couplings conclusions on the $Z'$ model are possible. If the $Z'$ mass is known and $m_{Z'} < 3\sqrt{s}$, $Z'$ models can be separated well considering lepton pair production only. In case of $q\bar{q}$ final states the accuracy of the $a'_{l}, v'_{l}$ coupling measurement is diminished by the uncertainty of $a'_{l}, v'_{l}$ and by systematic errors which could reach the magnitude of the statistical errors. A good model resolution is expected for $m_{Z'} < 2\sqrt{s}$ for the considered collider scenario. If the $Z'$ mass is unknown, only for energies $\sqrt{s}$ near the $Z'$ resonance a good indirect analysis of $Z'$ parameters is possible. To analyze the $Z'$ below the $Z'$ production threshold with a linear collider only, a special scanning strategy is essential.

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