Z' Constraints from $e^+e^- \rightarrow f\bar{f}$ at NLC

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Abstract
Constraints on extra neutral gauge bosons are obtained from $e^+e^- \rightarrow f\bar{f}$ at NLC energies. Model independent limits on the $Z'f\bar{f}$ couplings and lower limits on the $Z'$ mass are discussed. Typical GUTs with $M_{Z'}$ up to $(3 – 6)\sqrt{s}$ can be excluded. A distinction between different GUT scenarios is possible if $M_{Z'} \leq 3\sqrt{s}$. Radiative corrections give only small changes to the $Z'$ exclusion limits provided that appropriate cuts are applied.

1 Introduction

The search for extra neutral gauge bosons is an important task of the physics programme of all present and future colliders. Up to now, no $Z'$ signals are found. These experimental results are usually reported as lower limits on excluded $Z'$ masses or as upper limits on the $ZZ'$ mixing angle for selected $Z'$ models. With future colliders one can find a $Z'$ or put much stronger constraints, see [1, 2, 3].

In this paper and in a more detailed analysis [4], we examine the $Z'$ constraints which can be obtained from $e^+e^- \rightarrow f\bar{f}$ at c.m. energies $\sqrt{s} = 500\text{GeV}$ with $L_{\text{int}} = 20fb^{-1}$ (NLC500) or $\sqrt{s} = 2\text{TeV}$ with $L_{\text{int}} = 320fb^{-1}$ (NLC2000) and $P = 80\%$ polarization of the $e^-$ beam in both scenarios. In comparison to [1, 2, 3], we take into account all available QED, electroweak and QCD corrections and apply kinematical cuts in order to approach a more realistic description.

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of future detectors. Including more observables into our analysis, we go beyond [4, 5]. In contrast to [3], we additionally include the expected systematic errors.

We set the $Z'Z'$ mixing angle zero in accordance with present experimental constraints [5-7]. CDF data indicate that NLC500 will operate below a $Z'$ peak [8]. Similarly, LHC will be able to exclude a $Z'$ which could be produced at NLC2000 on resonance. We assume that NLC2000 will operate below the $Z'$ peak, too. Throughout we presume universality of generations. Theories including extra neutral gauge bosons usually predict new fermions [9-10]. Their effects are neglected here.

We consider $Z'$ models which are described by the following effective Lagrangian at low energies,

$$\mathcal{L} = eA_\beta J_\gamma^\beta + g_1 \gamma Z_\gamma J_\gamma^\beta + g_2 \gamma Z'_\gamma J'_\gamma^\beta.$$  \hspace{1cm} (1)

The term proportional to $g_2$ contains the new interactions of the $Z'$ with Standard Model fermions.

Although we mainly focus on model independent $Z'$ limits, we will also refer to some special models predicted in an $E_6$ GUT [10, 11] and in a Left-Right Model [11, 12],

$$J^\mu_\gamma = \frac{\alpha_{LR}}{2\alpha_{LR}} J^\mu_\gamma - J^\mu_\gamma,$$  \hspace{1cm} (2)

Some completely specified cases are $Z' = \chi$, $\psi$ and $\eta$ ($\beta = -\arctan \sqrt{5/3}$) in the $E_6$ GUT. Special cases in the Left-Right Model are obtained for $\alpha_{LR}$ equal to $\sqrt{2/3}$ and $\sqrt{\cot^2 \theta_W - 1}$. The first value of $\alpha_{LR}$ gives again the $\chi$ model, while the second number gives the Left-Right Symmetric Model (LR). The Sequential Standard Model (SSM) is also considered. It contains a heavy $Z'$ with exactly the same couplings to fermions as the Standard $Z$ boson.

The presence of an extra neutral gauge boson leads to an additional amplitude of fermion pair production at the Born level,

$$\mathcal{M}(Z') = \frac{g_2^2}{s - m^2_{Z'}} \bar{u}_e \gamma_5 a'_e \left[ \gamma \gamma_5 a'_e + v'_e \right] u_e \bar{u}_f \gamma_5 \bar{u}_f \gamma_5 \left[ \gamma \gamma_5 a'_e + v'_e \right] u_f$$  \hspace{1cm} (3)

$$= \left[ \frac{4\pi}{s} \left[ \bar{u}_e \gamma_5 a'_e + v'_e \right] \bar{u}_f \gamma_5 \left[ \gamma \gamma_5 a'_e + v'_e \right] u_f \right]$$

with $a'_N = a'_f = g^2_2 \frac{s}{4\pi m^2_{Z'} - s}$, $v'_f = \sqrt{\frac{g^2_2}{4\pi m^2_{Z'} - s}}$, and $m^2_{Z'} = M^2_{Z'} - i\Gamma_{Z'} M_{Z'}$. \hspace{1cm} (4)

Equations (3) and (4) show that far below the resonance the effect of a $Z'$ is described by the two parameters $a'_N$ and $v'_f$ and not by $a'_f$, $v'_f$ and $m_{Z'}$ separately. The fermionic couplings of some $Z'$ define a point in the $(a'_N, v'_f)$ planes ($f = \nu, l, u, d$). Various observables can detect a $Z'$ in different regions of the $(a'_N, v'_f)$ planes.

The $e^+e^-$ colliders provide several observables depending on couplings to only leptons as

$$\sigma_{t}^l, A_{FB}^l, A_{LR}^l, A_{pol}^l, A_{pol,FB}^l \text{ and } A_{LR,FB}^l.$$  \hspace{1cm} (5)

Therefore, the $Z'$ couplings to leptons $(a'_N, v'_f)$ can be constrained independently of the quarkonic $Z'$ couplings. The index $l$ stands for electrons and muons the final state. Only the $s$
channel is considered for electrons in the final state. Neglecting fermion masses, the last four leptonic observables in (5) are related at the Born level,
\[ A_{LR}^l = A_{pol}^l = \frac{4}{3} A_{pol,FB}^l = \frac{4}{3} A_{LR,FB}^l. \]  
Therefore, they are equivalent for a \( Z' \) search. Without loss of generality, we will consider only \( A_{LR} \) as a representative. It is expected to have the smallest error compared to the other three observables.

The hadronic observables can be divided into three groups: Observables containing in addition to the obligatory \( Z' \) couplings the \( Z' b \bar{b} \) couplings only, as
\[ R_b = \sigma_b^b/\sigma_t^b, \quad A_b^b, \quad A_{LR}^b, \]  
the \( Z' c \bar{c} \) couplings only, and all couplings of the \( Z' \) to quarks. The analysis of the first two groups is very similar. However, we will not consider the second group because \( c \)-quark flavour identification leads to systematic errors which are considerably larger than those from \( b \)-quark identification. The third group has the smallest errors because it doesn’t require flavour identification. We consider
\[ R_{\text{had}} = \sigma_{\text{had}}^t/\sigma_t^t = \sigma_{\text{had}}^{u+d+s+c+b}/\sigma_t^t \]  
and \( A_{\text{had}}^l = A_{LR}^{u+d+s+c+b}. \)  

The statistical errors of all observables for \( N \) detected events are
\[ \frac{\Delta \sigma_t}{\sigma_t} = \frac{1}{\sqrt{N}}, \quad \Delta A_{FB} = \sqrt{\frac{1 - A^2}{N}}, \quad \Delta A_{LR} = \sqrt{\frac{1 - (P A_{LR})^2}{NP^2}}. \]  

We assume a systematic error of the luminosity measurement of 0.5%. Further, we include a systematic error of 0.5% for the measurement of each observable. We assume 1% systematic error due to \( b \)-quark identification and take into account the efficiency of quark tagging. Statistical and systematic errors are added in quadrature. The resulting combined errors are equal for NLC500 and NLC2000:
\[ \Delta \sigma_t^l/\sigma_t^l = 1\%, \quad \Delta A_{FB}^l = 1\%, \quad \Delta A_{LR}^l = 1.2\%, \]  
\[ \Delta R_b = 2.2\%, \quad \Delta A_{FB}^b = 2.0\%, \quad \Delta A_{LR}^b = 1.5\%, \quad \Delta R_{\text{had}} = 0.9\%, \quad \Delta A_{LR}^{\text{had}} = 0.7\%. \]  

To obtain confidence levels for different sets of parameters, we calculate the prediction for all observables in the Standard Model \( O_i^{(\text{SM})} \) and in a theory including a \( Z' \) \( O_i^{(\text{SM}, v_N, a_N)} \) and consider the deviation of
\[ \chi^2 = \sum_{O_i} \left[ \frac{O_i^{(\text{SM})} - O_i^{(\text{SM}, v_N, a_N)}}{\Delta O_i} \right]^2 \]  
from the minimum.

With our assumptions, the \( Z' \) can be detected only through small deviations of observables from their Standard Model predictions. It is known that radiative corrections have to be included to meet the expected experimental precision. For all energies considered here, the QED corrections are numerically most important. The energy spectrum of the radiated photons has a huge peak for energies \( E_\gamma/E_{\text{beam}} \approx 1 - M_Z^2/s \). This is due to the radiative return to the \( Z \) resonance. Such events do not contain information about new heavy particles. They may be eliminated by a cut on hard photons. This can be realized by a cut on the photon energy, \( E_\gamma/E_{\text{beam}} < \Delta < 1 - M_Z^2/s \), or by a cut on the acollinearity angle of the two outgoing fermions. Satisfying these conditions, the analysis is much less sensitive to further cuts.
Fig. 1: Areas in the $(\alpha_l^N, \nu_l^N)$ plane indistinguishable from the SM at NLC500 (95% C.L.). $\sigma_l^N$ cannot distinguish models inside the shaded ellipse. $A_{FB}^l$ ($A_{LR}^l$) are blind to models inside the hatched areas with falling (rising) lines. The region from all observables combined is also shown (thick line).

Fig. 2: Resolution power of NLC500 (95% C.L.) by all leptonic observables combined for different models and $M_{Z'} = 3\sqrt{s} = 1.5\, TeV$.

2 Model independent $Z'$ limits

Our analysis is performed by the code ZEFIT [7] which works together with ZFITTER [13]. All Standard Model corrections and all possibilities to apply kinematical cuts available in ZFITTER are made operative. The code ZEFIT contains the additional $Z'$ contributions. It was already applied to LEP 1 data to set bounds to the $ZZ'$ mixing angle [6] and is now adapted to a model independent $Z'$ analysis. QED corrections to the new $Z'$ interferences are applied to the same order as to the SM cross section. In our fits, we used the full one-loop electroweak corrections, the QCD corrections and soft photon exponentiation for photons in the initial and final states. The initial state radiation was taken at two-loops. We forbid hard photons taking $\Delta = 0.9$ for NLC500 and $\Delta = 0.98$ for NLC2000. As a simple simulation of the detector acceptance, we demand that the angle between the outgoing leptons and the beam axis is larger than 20°. We apply no angular restrictions to outgoing quarks. Possible correlations between the errors of different observables are neglected.

Figure 1 shows our model independent discovery limits on the couplings of the $Z'$ to leptons from different observables. The corresponding figures for NLC500 and NLC2000 are almost identical because we expect the same number of events for both collider scenarios and $\alpha_l^N$ and $\nu_l^N$ are normalized. We see that $\sigma_l^N$ constrains both the vector and the axial vector couplings, while $A_{FB}^l$ constrains mainly the axial vector couplings. $A_{LR}^l$ gives only a minor improvement to the discovery limits. The region obtained by all leptonic observables in combination is also shown. The changes of figure 1 for experimental errors different from our assumptions are described by the Born formulae given in ref. [2].
Assuming the existence of a $Z'$, one can distinguish between different models at NLC500. This is shown in figure 2 for $M_{Z'} = 3\sqrt{s}$. The corresponding figure for NLC2000 does not differ from figure 2. In contrast to figure 1, $A_{LR}^l$ is a really important input because it is sensitive to the sign of the $Z'$ couplings. Note that a simultaneous change of the sign of both leptonic $Z'$ couplings can never be detected by the reaction $e^+e^- \to f\bar{f}$.

The constraints on $a_l^N$ and $v_l^N$ by the three leptonic observables could in principle lead to contradicting results. This could happen, if an area allowed by two observables, e.g. $\sigma^l_t$ and $A_{LE}^l$ is excluded by a third observable (e.g. $A_{LR}^l$). Such a case would be an indication for new physics beyond a $Z'$. Non-zero $Z'$ couplings to leptons are necessary for a $Z'$ signal in the hadronic observables. To be definite, we assume that the $Z'$ is described by one of the models $\chi$, LR or SSM considered in figure 2. As in the leptonic case, different $b$-quark observables are blind in different directions. Polarized beams give a large improvement to the measurement of $Z'b\bar{b}$ couplings. If combined, all $b$-quark observables define a closed region in the $(a_b^N, v_b^N)$ plane. Figure 3 shows that for all three models one can detect a non-zero $Z'$ signal also in the $Z'b\bar{b}$ couplings. However, one cannot discriminate between $\chi$ and LR as it was possible in the leptonic sector. We refer to [4] for more details.

### 3 Model dependent $Z'$ limits

We now discuss the results of several one parameter fits with and without systematic errors. The lower limits (95% C.L.) on the $Z'$ mass, $M_{Z'}^{lim}$, for different $Z'$ models are given in table 1. The observables $R^{had}$ and $A_{LR}^{had}$ give an important input to these fits. Table 1 shows three rows for every collider. The first row contains the limits from leptonic observables only. The second row includes leptonic and hadronic observables. The third row includes all observables as the second row but without systematic errors. Comparing the first two rows of a certain collider, we see that the hadronic observables improve the mass limits between 5% and

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**Fig. 3:** Resolution power of NLC500 in the $(a_b^N, v_b^N)$ plane (95% C.L.) by all $b$-quark observables combined. Different $Z'$ models with $M_{Z'} = 1.5 \text{TeV}$ are assumed.
10%. Therefore, both the leptonic and hadronic observables are important for measurements of $M_{Z'}^{\text{lim}}$. The difference between the numbers of the second and third row is about 10%. Hence, the mass limits obtained for a particular $Z'$ model are rather insensitive to the assumptions about systematic errors.

The errors of hadronic observables are dominated by systematic uncertainties. Thus, the relatively large vector and axialvector couplings of the $Z'$ in the SSM cause a larger sensitivity of $M_{Z'}^{\text{lim}}$ to systematic errors.

As a result, $e^+e^-$ colliders can exclude a $Z'$ with a mass lighter than $M_{Z'}^{\text{lim}} \sim 3$ to $6\sqrt{s}$ for popular GUT’s and $M_{Z'}^{\text{lim}} \sim 8\sqrt{s}$ for the SSM.

To summarize, we investigated the limits on extra neutral gauge bosons which can be achieved at future linear $e^+e^-$ colliders. We included radiative corrections, kinematical cuts and systematic errors in our analysis. The influence of radiative corrections on the $Z'$ mass limits is small after applying appropriate cuts. Systematic errors have a moderate influence on the $Z'$ mass limits but they are important to distinct models.

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