

Study of Z' Couplings to Leptons and Quarks at NLC

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ABSTRACT

The discovery of a Z' and the measurement of Z' couplings to fermions are main tasks of future colliders. Here, the possibilities to measure $Z' f \bar{f}$ couplings at an NLC operating below a Z' resonance are studied. In dependence on the mass of the Z' and the collider parameters one will be able to discriminate between Z' models.

I. INTRODUCTION

The Standard Model is the powerful theory to describe processes observed at existing colliders. But, most physicists are thoroughly convinced that beyond the Standard Model surprises are ahead. A Z' is an extension of the Standard Model with clear possibilities of detection and interpretation. If the centre-of-mass energy of an NLC is large enough to produce Z' bosons the study of their properties will be easy. But even indirect measurements of $e^+ e^- \rightarrow f \bar{f}$ below the Z' production threshold may give information about its nature. Besides information about the mass the knowledge of Z' couplings to fermions is important for a study of the symmetry breaking expected at an energy of 1 TeV.

As long as the Z' mass is unknown, a precise and model-independent measurement of $Z' f \bar{f}$ couplings, a'_f , v'_f is difficult. One has to analyze directly cross sections and asymmetries [1]. Nevertheless, all observables are sensitive to normalized Z' couplings a'_f, v'_f ; e.g. $a'_f = a'_f \sqrt{s/(m_{Z'}^2 - s)}$ (see [2]). Only if the centre-of-mass energy is near the production threshold Z' mass and $Z' f \bar{f}$ couplings can be determined with good accuracy and the identification of Z' models becomes possible (see [3, 4]).

Here, prospective measurements of Z' couplings to fermions at NLC are studied assuming that the Z' mass is known from a discovery at LHC.

In preparation of the design for an NLC different scenarios of basic parameters are suggested (see [5]):

- (a) $\sqrt{s} = 500 \text{ GeV} : 50 fb^{-1}$
- (b) $\sqrt{s} = 1000 \text{ GeV} : 100 fb^{-1}$
- (c) $\sqrt{s} = 1500 \text{ GeV} : 100 fb^{-1}$

The electron beam will be polarized, $P_e = 80 \%$, the positron beam is assumed to be unpolarized. Here, case (1 a) and (1 c) are taken into account. Expectations for (1 b) or other scenarios can be extrapolated.

A collider with the parameters (1) allows the measurement of total cross section, σ_T , forward-backward asymmetry, A_{FB} , left-right asymmetry, A_{LR} and forward-backward polarization asymmetry, A_{LR}^{FB} with small statistical uncertainties. The experience of LEP and SLD experiments encourages to expect good techniques of quark flavour identification with high efficiencies and purities [6]. Nevertheless, background reactions and

misidentification of final state fermions can lead to relatively large systematic errors especially if $q\bar{q}$ final states are analysed. The systematic errors can dominate and weaken the results for the $Z' f \bar{f}$ couplings (see also [3, 4]) The influence of systematic errors on Z' coupling measurements is considered.

In the following, the measurements of $Z' l \bar{l}$ couplings and $Z' q \bar{q}$ couplings are studied separately.

Cuts are applied to approach a realistic situation of measurements. In case of leptonic final states an angular acceptance cut of 20° is taken into account. Further, the t-channel exchange in Bhabha scattering is neglected. If quark flavours are tagged the fiducial volume depends on the design of the vertex detector. Prospective designs foresee a selection of at least two tracks within $25^\circ < \theta < 155^\circ$. For completeness, the influence of different angular ranges on the accuracy of the $Z' f \bar{f}$ coupling measurement is also considered.

In order to reach the full sensitivity to Z' effects, a cut on the energy of photons emitted in the initial state, $\Delta = 1 - s'_{min}/s$, is applied. At $\sqrt{s} = 500 \text{ GeV}$ a radiative return to the Z peak is avoided choosing e.g. $\Delta = 0.9$. An uncertainty of 0.5% is taken into account for the luminosity measurement. For numerical studies the program package ZEFIT/ZFITTER [7, 8] is used.

II. Z' COUPLINGS TO LEPTONS

Assuming lepton universality Z' couplings to the initial and final state are equal. This clean scenario allows the determination of Z' couplings to leptons with a good accuracy if the difference between centre-of-mass energy and Z' mass is not too large. Taking into account a systematic error of 0.5% for all leptonic observables and an efficiency of lepton identification of 95% the Z' couplings can be identified as demonstrated in figure 1. It is assumed that a Z' exists either in the χ model or in the LR model. Different Z' masses are assumed.

The observables depend only on products or squares of a'_f and v'_f . Thus, an ambiguity in the signs of couplings remains.

The sensitivity to Z' effects in $e^+ e^-$ annihilation is reduced if the Z' mass is larger. A scaling law describes this (see [2]):

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

If $m_{Z'} \geq 6 \cdot \sqrt{s}$ the Z' contributions influence the observables only weakly. The point $(a'_1, v'_1) = (0, 0)$ in figure 1 cannot be excluded with 95% CL, although the existence of a Z' (χ model) is assumed. A discrimination between models, even the indirect detection of a Z' is no longer possible. Only upper limits on Z' parameters can be derived.

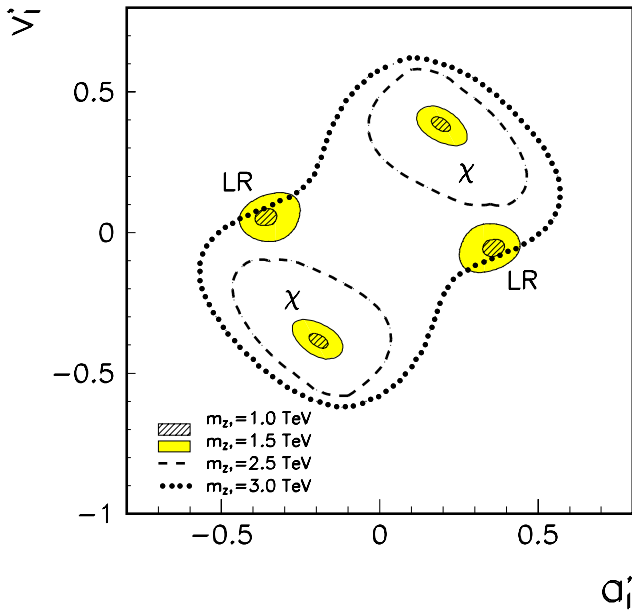


Figure 1: 95% CL contours for a'_1 and v'_1 . A Z' is assumed in the χ model or in the LR model with a mass of $m_{Z'}=1$ TeV (hatched area) and $m_{Z'}=1.5$ TeV (shaded area). The dashed (dotted) line limits the 95% CL bounds on $Z'\ell\ell$ couplings if a Z' with a mass $m_{Z'}=2.5$ TeV ($m_{Z'}=3$ TeV) exists in the χ model; $\mathcal{L} = 50 \text{ fb}^{-1}$ and $\sqrt{s} = 500 \text{ GeV}$.

With a higher luminosity the loss of sensitivity may be compensated,

$$\frac{\Delta a'_1}{\Delta a'_2}, \frac{\Delta v'_1}{\Delta v'_2} \approx \left(\frac{\mathcal{L}_2}{\mathcal{L}_1} \right)^{1/4} \quad (3)$$

Relation (3) shows that an increase of luminosity improves the accuracy of the Z' coupling measurement only slowly. If possible, it is better to go to higher centre-of-mass energies. An NLC operating at $\sqrt{s} = 1.5 \text{ TeV}$ with a luminosity of 100 fb^{-1} allows a clear distinction between Z' models up to $m_{Z'} = 3 \text{ TeV}$ analyzing leptonic observables. This is shown in figure 2. The Z' mass is assumed to be known.

Systematic errors of leptonic observables as assumed above influence the results for a_1 and v_1 only weakly.

III. Z' COUPLINGS TO QUARKS

At NLC the derivation 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 fails. In the following we assume that an analysis of leptonic observables leads to non-vanishing $Z'e\bar{e}$ couplings.

The identification of quark flavors is more complicated than lepton identification. Although designs of a vertex detector for the NLC let expect efficiencies of 60% in b-tagging with a purity of 80% [6], the systematic error of b-quark observables will not be less than 1%. This is suggested from extrapolating the present experience of the SLD collaboration with roughly 150 k

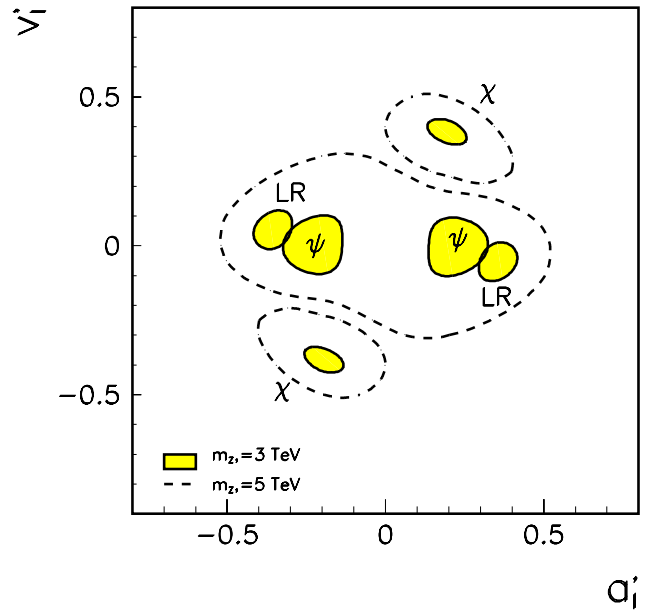


Figure 2: Discrimination between χ , ψ and LR model based on 95% CL contours for a'_1 and v'_1 for $m_{Z'}=3 \text{ TeV}$ (shaded area). For $m_{Z'} = 5 \text{ TeV}$ (dashed line) χ and LR model can be still distinguished; $\mathcal{L} = 100 \text{ fb}^{-1}$ and $\sqrt{s} = 1.5 \text{ TeV}$.

hadronic Z^0 events [9] up to the collider performance given in (1). The systematic errors limit the accuracy of a a'_q, v'_q determination substantially. Improvements due to a higher luminosity can be fully removed by an imperfect flavor identification. Figure 3 and 4 demonstrate the influence of integrated luminosity, Z' mass and systematic errors on the contours for $Z'q\bar{q}$ couplings. An efficiency of 40% is assumed for the determination of $Z'c\bar{c}$ couplings in agreement with [6]. Both figure 3 and 4 demonstrate that the magnitude of the systematic errors is important for $Z'q\bar{q}$ coupling measurements.

In figure 5 expected results for $Z'b\bar{b}$ couplings are shown for different fiducial volumes of the vertex detector. An ideal vertex detector leads to only slightly better results.

IV. MODEL IDENTIFICATION

Figures 6, 7 and 8, 9 show the expected results for $Z'b\bar{b}$ and $Z'c\bar{c}$ couplings for the two different collider scenarios (1 a) and (1 c) assuming $m_{Z'} = 1 \text{ TeV}$ and $m_{Z'} = 3 \text{ TeV}$, respectively. It is assumed that a Z' in the χ , ψ , or LR model exists. Systematic errors of 1% for b-quark observables and 1.5% for c-quark observables are taken into account. The figures demonstrate that a Z' model can be separated although the collider operates below a Z' resonance – but only to some extent. The crucial point is the ratio of Z' mass and centre-of-mass energy, $R = m_{Z'}/\sqrt{s}$. If $R > 2$ the distinction between most of the models becomes nearly impossible if quark final states are analyzed. (see also [2, 4]). An increase of luminosity cannot improve this substantially (see figures 3 and 4) and the systematic errors must not be neglected. The detection limits are reached.

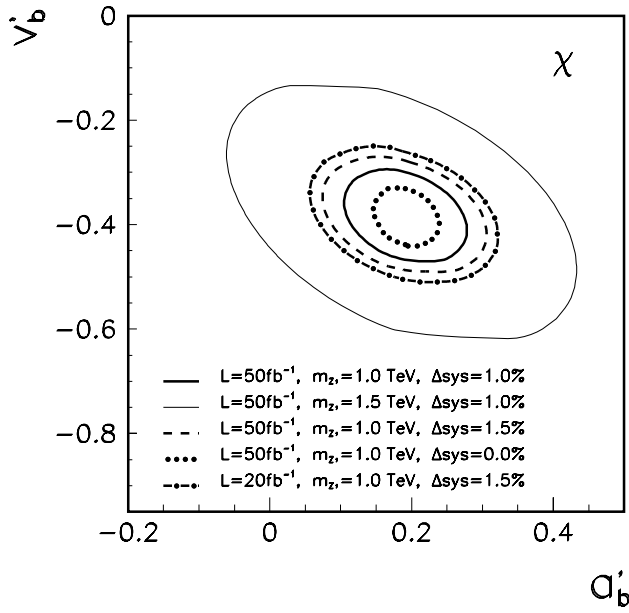


Figure 3: Influence of luminosity, Z' mass, and systematic error on contours of $Z' b \bar{b}$ couplings. A Z' in the χ model is assumed; $\sqrt{s} = 500$ GeV.

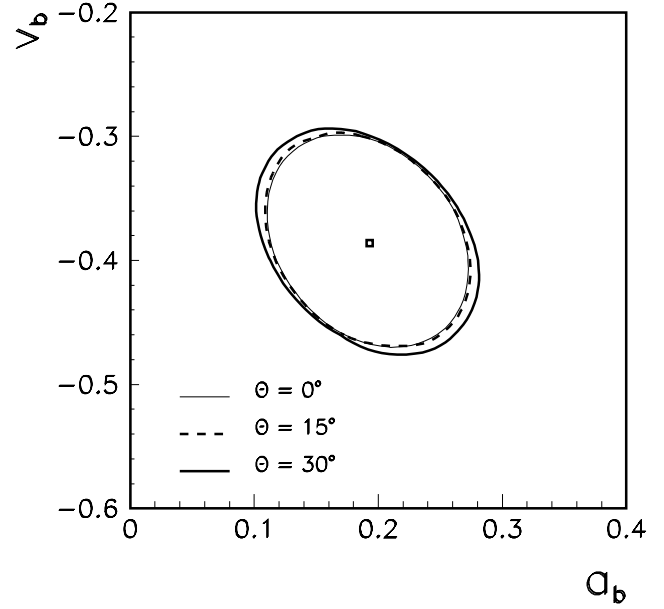


Figure 5: 95% CL contours of Z' couplings to b -quarks in dependence on the fiducial volume of the vertex detector. An ideal 4π detector (thin solid line) is compared with $\cos \theta < 0.96$ (dashed line) and $\cos \theta < 0.87$ (solid line). A systematic error of 1% for all b -quark observables is taken into account.

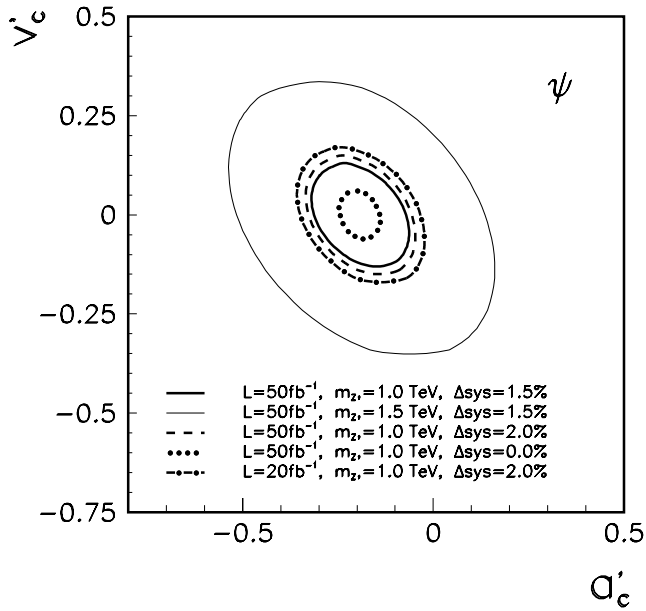


Figure 4: Influence of luminosity, Z' mass, systematic error on contours of $Z' c \bar{c}$ couplings. A Z' in the χ model is assumed; $\sqrt{s} = 500$ GeV.

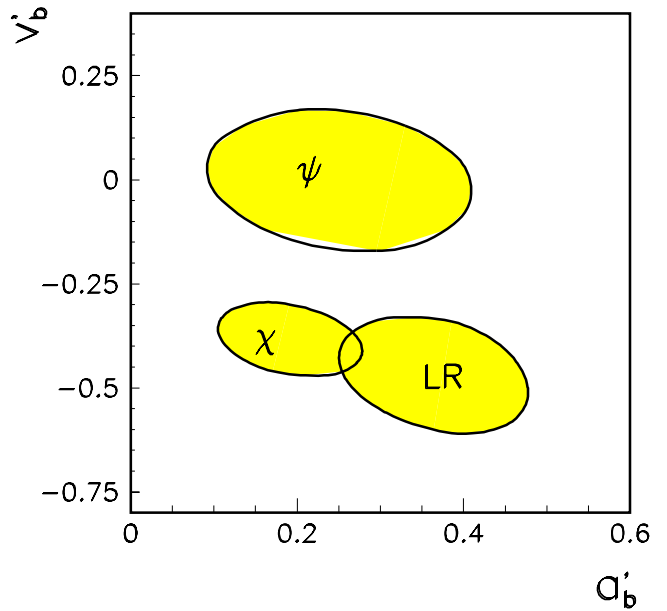


Figure 6: Model discrimination for $m_{Z'} = 1$ TeV studying $e^+ e^- \rightarrow b \bar{b}$ at $\sqrt{s} = 0.5$ TeV with $\mathcal{L} = 50 \text{ fb}^{-1}$. A systematic error of 1% for all b -quark observables is taken into account.

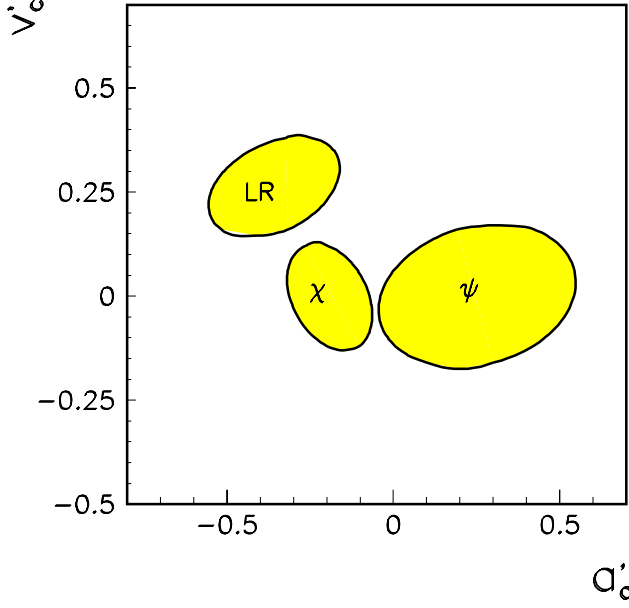


Figure 7: Model discrimination for $m_{Z'} = 1$ TeV studying $e^+e^- \rightarrow c\bar{c}$ at $\sqrt{s} = 0.5$ TeV with $\mathcal{L} = 50 \text{ fb}^{-1}$. A systematic error of 1.5% for all c-quark observables is taken into account.

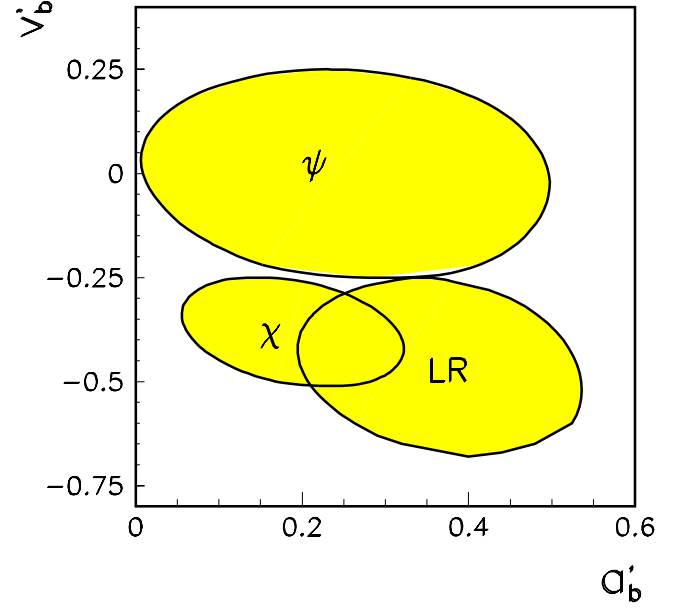


Figure 8: Model discrimination for $m_{Z'} = 3$ TeV studying $e^+e^- \rightarrow b\bar{b}$ at $\sqrt{s} = 1.5$ TeV with $\mathcal{L} = 100 \text{ fb}^{-1}$. A systematic error of 1% for all b-quark observables is taken into account.

The situation becomes still worse if the Z' mass is unknown. In order to perform a simultaneous fit of Z' mass and couplings the available luminosity should be distributed on different of centre-of-mass energies since the contributions $\sigma_{\gamma Z'}$, $\sigma_{ZZ'}$ and $\sigma_{Z'Z'}$ to the observables vary as a function of $\sqrt{s}$ and $m_{Z'}$. This could guarantee a sufficient number of data points and a well-defined χ^2 . But the distribution of luminosity on several centre-of-mass points and the uncertainty of $m_{Z'}$ enlarges the allowed range for Z' couplings. Furthermore, if the difference between centre-of-mass energy and Z' mass is large, the sensitivity for model-independent searches can be lost. More details on a simultaneous determination of $m_{Z'}$, a'_f and v'_f can be found in [3].

V. CONCLUSIONS

If a Z' boson with a mass $m_{Z'} < 6 \times \sqrt{s}$ exists observables measured at NLC deviate from their Standard Model expectations. The interpretation of these deviations within special Z' models gives the Z' mass. More interesting is a model-independent analysis. With the determination of $Z'f\bar{f}$ couplings conclusions on the Z' model become possible. If the Z' mass is known a good discrimination between Z' models is possible for $m_{Z'} < 3 \times \sqrt{s}$ from lepton pair production. In case of quarkonic final states the accuracy of the $Z'q\bar{q}$ coupling measurement is diminished by systematic errors which could reach the magnitude of the statistical errors. A good model resolution is expected for $m_{Z'} < 2 \times \sqrt{s}$ for the considered collider scenarios.

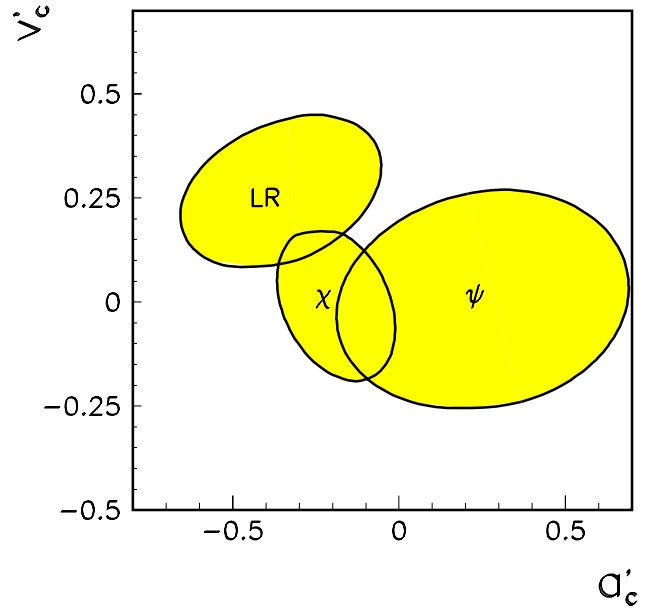


Figure 9: Model discrimination for $m_{Z'} = 3$ TeV studying $e^+e^- \rightarrow c\bar{c}$ at $\sqrt{s} = 1.5$ TeV with $\mathcal{L} = 100 \text{ fb}^{-1}$. A systematic error of 1.5% for all c-quark observables is taken into account.

VI. ACKNOWLEDGEMENT

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VII. REFERENCES

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