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The Polarization Asymmetry in γe Collisions at the NLC and Triple Gauge Boson Couplings

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ABSTRACT

The capability of the NLC in the γe collider mode to probe the CP-conserving γWW and γZZ anomalous couplings through the use of the polarization asymmetry is examined. When combined with other measurements, very strong constraints on both varieties of anomalous couplings can be obtained. We show that these bounds are complementary to those that can be extracted from data taken at the LHC.

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1 Introduction

As confirmed by the discovery of the top quark, the Standard Model(SM) continues to do an excellent job at describing essentially all existing data[1, 2]. In addition to unravelling the source of symmetry breaking, one of the most crucial remaining set of tests of the structure of the SM will occur at future colliders when precision measurements of the various triple gauge boson vertices(TGVs) become available[3]. Such analyses are in their infancy today at both the Tevatron and LEP. If new physics arises at or near the TeV scale, then on rather general grounds one expects that the deviation of the TGVs from their canonical SM values, *i.e.*, the anomalous couplings, to be *at most* $\mathcal{O}(10^{-3}-10^{-2})$ with the smaller end of this range of values being the most likely. To get to this level of precision and beyond, for all of the TGVs, a number of different yet complementary reactions need to be studied using as wide a variety of observables as possible.

In the present analysis we concentrate on the CP-conserving γWW and γZZ anomalous couplings that can be probed in the reactions $\gamma e \to W\nu, Ze$ at the NLC using polarized electrons and polarized backscattered laser photons[4]. In the γWW case, the anomalous couplings modify the magnitude and structure of the already existing SM tree level vertex. No corresponding tree level γZZ vertex exists in the SM, although it will appear at the one-loop level. One immediate advantage of the $\gamma e \to W\nu$ process over, *e.g.*, $e^+e^- \to W^+W^-$ is that the γWW vertex can be trivially isolated from the corresponding ones for the ZWW vertex, thus allowing us to probe this particular vertex in a model-independent fashion. In addition, the $\gamma e \to W\nu$ process probes the TGVs for on-shell photons whereas $e^+e^- \to W^+W^-$ probes the couplings at $q^2 \geq 4M_W^2$. To set the notation for what follows, we recall that the $CP-$conserving γWW and γZZ anomalous couplings are traditionally denoted by $\Delta\kappa$, λ and $h^0_{3,4}$[3], respectively. We will assume that the γWW and γZZ anomalous couplings are unrelated; the full details of our analysis can be found in Ref.[4].

2 Analysis

The use of both polarized electron and photon beams available at the NLC allows one to construct a polarization asymmetry, A_{pol}. As we will see, this asymmetry provides a new handle on possibly anomalous TGVs of both the W and Z. In general the $\gamma e \to W\nu, Ze$ (differential or total) cross sections can be written schematically as

$$\sigma = (1+A_0P)\sigma_{un} + \xi(P+A_0)\sigma_{pol}\,, \tag{1}$$

where P is the electron's polarization(which we take to be > 0 for left-handed beam polarization), $-1 \leq \xi \leq 1$ is the Stoke's parameter for the circularly polarized photon, and A_0 describes the electron's coupling to the relevant gauge boson[$A_0 = 2va/(v^2+a^2) = 1$ for W's and $\simeq 0.150$ for Z's, with v, a being the vector and axial-vector coupling of the electron]. $\sigma_{pol}(\sigma_{un})$ represents the polarization (in)dependent contribution to the cross section, both of which are functions of only a single dimensionless variable at the tree level after angular integration, *i.e.*, $x = y^2 = s_{\gamma e}/M_{W,Z}^2$, where $\sqrt{s_{\gamma e}}$ is the $\gamma - e$ center of mass energy. Taking the ratio of the ξ-dependent to ξ-independent terms in the expression for σ above gives us the asymmetry A_{pol}.

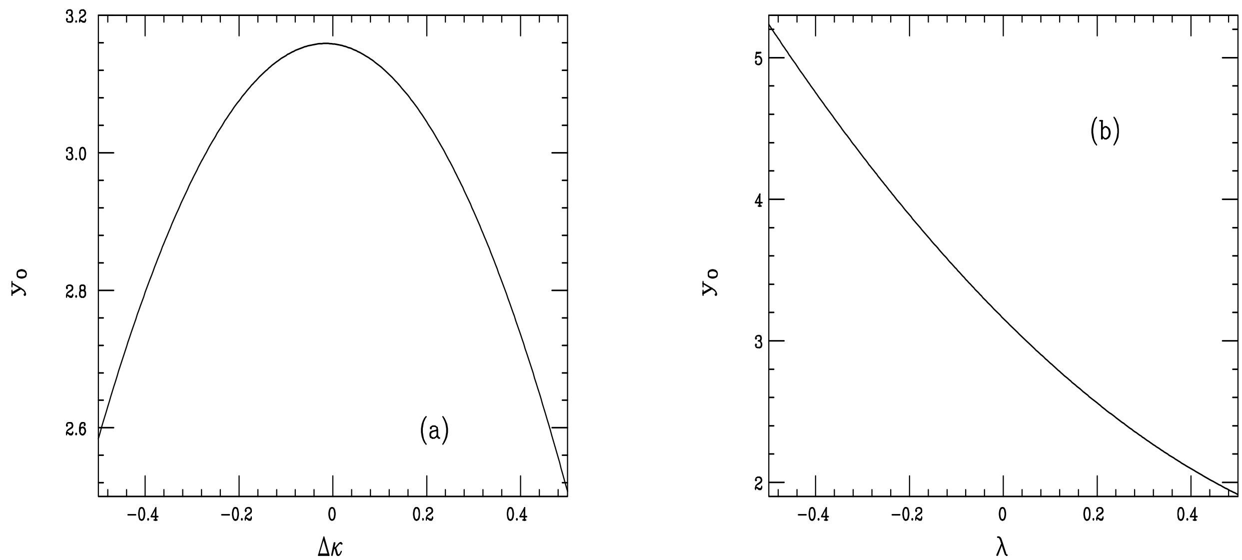

Figure 1: Separate $\Delta\kappa$ and λ dependence of the value of y_0, the zero position for the process $\gamma e \rightarrow W\nu$.

One reason to believe *a priori* that A_{pol}, or σ_{pol} itself, might be sensitive to modifications in the TGVs due to the presence of the anomalous couplings is the Drell-Hearn Gerasimov(DHG) Sum Rule[5]. In its $\gamma e \rightarrow W\nu, Ze$ manifestation, the DHG sum rule implies that

$$\int_1^\infty \frac{\sigma_{pol}(x)}{x} dx = 0\,, \tag{2}$$

for the tree level SM cross section when the couplings of all the particles involved in the process are 'canonical', *i.e.*, gauge invariant. That this integral is zero results from (i) the fact that σ_{pol} is well behaved at large x and (ii) a delicate cancellation occurs between the two regions where the integrand takes on opposite signs. This observation is directly correlated with the existence of a single, unique value of x(or y), *i.e.*, $x_0(y_0)$, where σ_{pol}(and, hence, A_{pol}) vanishes. For this reason A_{pol} is sometimes referred to as A_{DHG}. For the $W(Z)$ case this asymmetry 'zero' occurs at approximately $\sqrt{s_{\gamma e}} \simeq 254(150)$ GeV, both of which correspond to energies which are easily accessible at the NLC. In the Z boson case the SM position of the zero can be obtained analytically as a function of the cut on the angle of the outgoing electron. In the corresponding W case, the exact position of the zero can only be determined numerically.

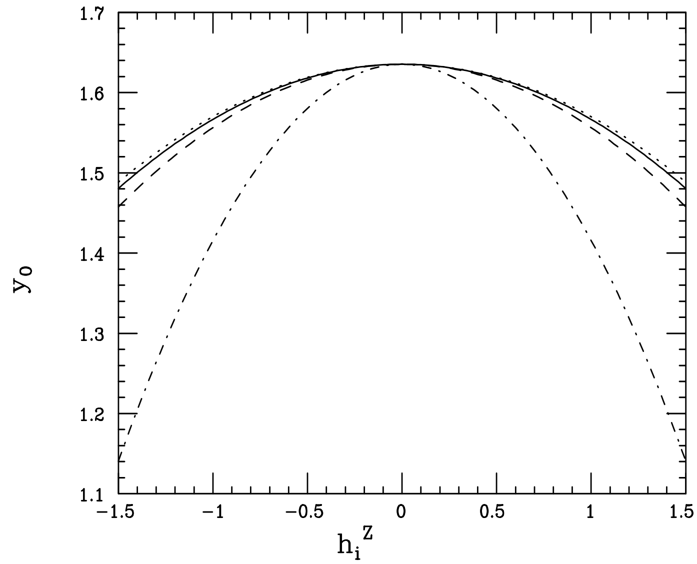

Figure 2: Position of the SM polarization asymmetry zero in $\gamma e \to Ze$ as a function of $h^0_{3,4}$ for $P = 90\%$ with a 10° angular cut. The dotted(dashed, dash-dotted, solid) curve corresponds to the case $h^0_4 = 0(h^0_3 = 0,\ h^0_3 = h^0_4,\ h^0_3 = -h^0_4)$.

As discussed in detail in Ref. [4], the inclusion of anomalous couplings not only moves the position of the zero but also forces the integral to become non-vanishing and, in most cases, *logarithmically divergent*. In fact, the integral is only finite when $\Delta\kappa + \lambda = 0$, the same condition necessary for the existence of the radiation amplitude zero[6]. The reason for the divergence stems from the fact that the most divergent terms in σ_{pol} proportional to the anomalous couplings become constants in the large x limit; see Ref. [4] for complete expressions. It is interesting that the anomalous couplings do not induce additional zeros or extinguish the zero completely. Unfortunately, since we cannot go to infinite energies we cannot test the DHG Sum Rule directly but we *are* left with the position of the zero, or more generally, the asymmetry itself as a probe of TGVs. In the W case the zero position, y_0, is found to be far more sensitive to modifications in the TGVs than is the zero position in in the Z case. The zero position as a function of $\Delta\kappa$ and λ for the $\gamma e \to W\nu$ process is shown in Fig.1 whereas the corresponding Z case is shown in Fig.2. In either situation, the position of the zero *alone* does not offer sufficient sensitivity to the existence of anomalous couplings for us to obtain useful constraints.(See Ref. [4].)

Our analysis begins by examining the energy, *i.e.*, y dependence of A_{pol} for the two processes of interest; we consider the W case first. For a 500(1000) GeV collider, we see that only the range $1 \leq y \leq 5.4(10.4)$ is kinematically accessible since the laser photon energy

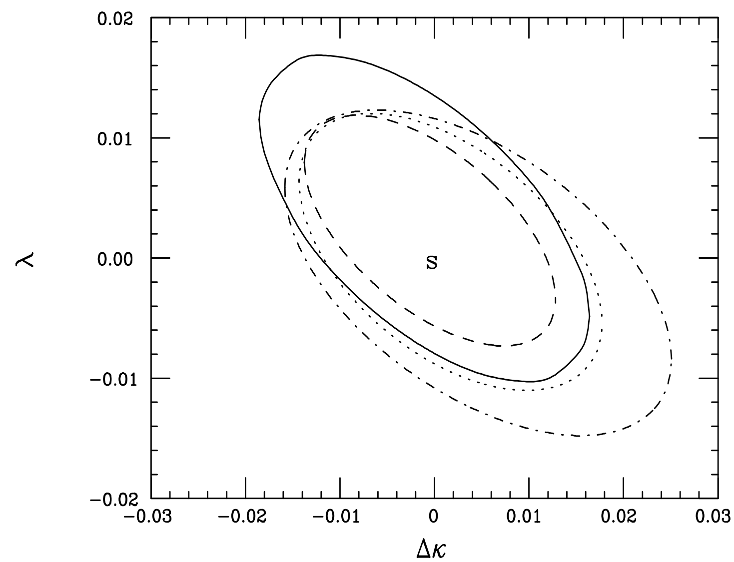

Figure 3: 95 % CL bounds on the W anomalous couplings from the polarization asymmetry. The solid(dashed, dash-dotted) curves are for a 500 GeV NLC assuming complete y coverage using 22(22, 44) bins and an integrated luminosity per bin of 2.5(5, 1.25)fb^{-1}, respectively. The corresponding bins widths are Δy =0.2(0.2, 0.1). The dotted curve corresponds to a 1 TeV NLC using 47 $\Delta y = 0.2$ bins with 2.5 fb^{-1}/bin. 's' labels the SM prediction.

maximum is $\simeq 0.84E_e$. Since we are interested in bounds on the anomalous couplings, we will assume that the SM is valid and generate a set of binned A_{pol} data samples via Monte Carlo taking only the statistical errors into account. We further assume that the electrons are 90% left-handed polarized as right-handed electrons do not interact through the W charged current couplings. Our bin width will be assumed to be Δy =0.1 or 0.2. We then fit the resulting distribution to the $\Delta\kappa$- and λ-dependent functional form of $A_{pol}(y)$ and subsequently extract the 95% CL allowed ranges for the anomalous couplings. The results of this procedure are shown in Fig. 3, where we see that reasonable constraints are obtained although only a single observable has been used in the fit.

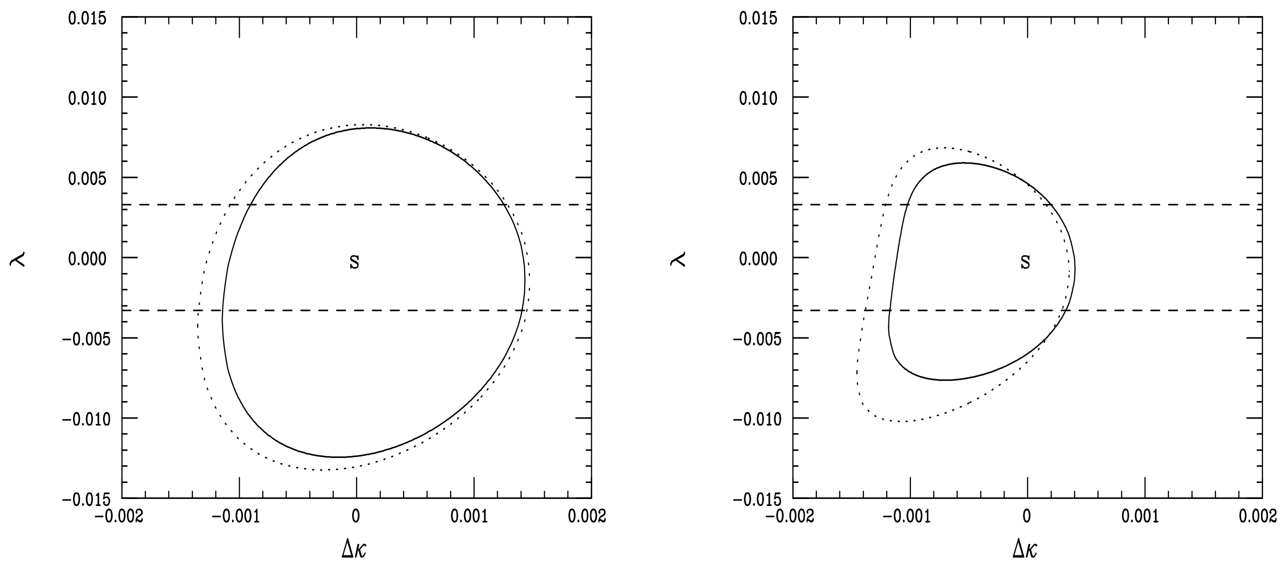

Figure 4: Same as the previous figure, but now for a (0.5)1 TeV NLC on the left(right) and combined with data on the total cross section and angular distribution in a simultaneous fit. The dotted(solid) curve uses the polarization asymmetry and total cross section(all) data. Only statistical errors are included. The dashed lines are the corresponding bounds from the LHC from the $pp \to W\gamma + X$ process with an integrated luminosity of 100 fb^{-1}.

Clearly, to obtain stronger limits we need to make a combined fit with other observables, such as the energy dependence of the total cross section, the W angular distribution, or the net W polarization. As an example we show in Fig. 4 from the results of our Monte Carlo study that the size of the 95% CL allowed region shrinks drastically in the both the 0.5 and 1 TeV cases when the W angular distribution and energy-dependent total cross section data are included in a simultaneous fit together with the polarization asymmetry. For this analysis the angular distribution was placed into 10 bins and energy averaged over the accessible kinematic region. The total cross section data was binned in exactly the same way as was the polarization asymmetry. Note that the constraints obtained by this analysis are superior to that of the LHC[3] with an integrated luminosity of 100 fb^{-1}. (The LHC constraints on $\Delta\kappa$ are rather poor whereas the λ bounds are somewhat better.) As is well known, both the total cross section and the W angular distributions are highly sensitive to $\Delta\kappa$ and thus the allowed region is highly compressed in that direction. At 500 GeV(1 TeV), we find that $\Delta\kappa$ is bounded to the range $-1.2\cdot 10^{-3} \leq \Delta\kappa \leq 1.4(0.4)\cdot 10^{-3}$ while the allowed λ range is still rather large. Further improvements in these limits will result from data taken at a 1.5 TeV NLC.

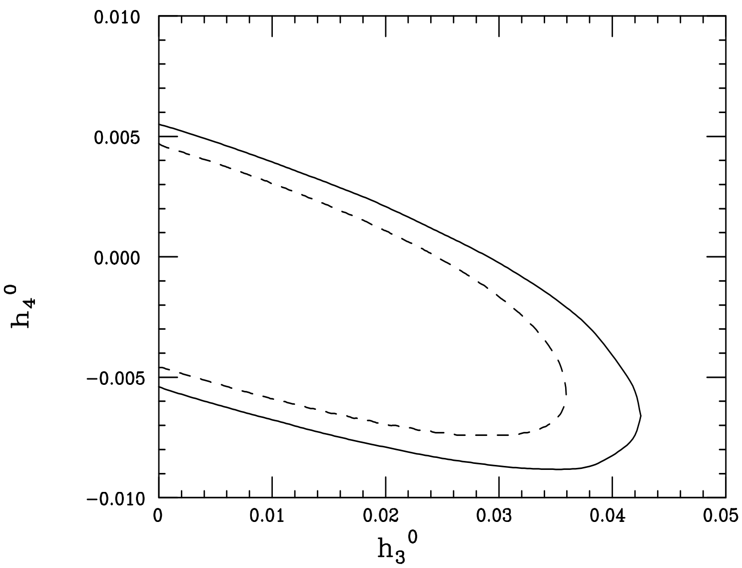

Figure 5: 95%CL allowed region for the anomalous coupling parameters h_3^0 and h_4^0 from a combined fit to the energy dependencies of the total cross section and polarization asymmetry at a 500 GeV NLC assuming $P = 90\%$ and an integrated luminosity of $3(6) fb^{-1}$/bin corresponding to the solid (dashed) curve. 18 bins of width Δy=0.2 were chosen to cover the y range $1 \leq y \leq 4.6$. The corresponding bounds for negative values of h_3^0 are obtainable by remembering the invariance of the polarization dependent cross section under the reflection $h_{3,4}^0 \to -h_{3,4}^0$.

With this experience in mind, in the Z case we will follow a similar approach but we will simultaneously fit both the energy dependence of A_{pol} as well as that of the total cross section. (Later, we will also include the Z boson's angular distribution into the fit.) In this Z analysis we make a 10° angular cut on the outgoing electron and keep a finite form factor scale, $\Lambda = 1.5$ TeV, so that we may more readily compare with other existing analyses. (The angular cut also gives us a finite cross section in the massless electron limit; this cut is not required in the case of the W production process.) We again assume that $P = 90\%$ so that data taking for this analysis can take place simultaneously with that for the W. The accessible y ranges are now $1 \leq y \leq 4.6(9.4)$ for a 500(1000) GeV collider. Fig.5 shows our results for the 500 GeV NLC while Fig.6 shows the corresponding 1 TeV case. For a given energy and fixed total integrated luminosity we learn from these figures that it is best to take as much data as possible at the highest possible values of y. Generally, one finds that increased sensitivity to the existence of anomalous couplings occurs at the highest possible collision energies.

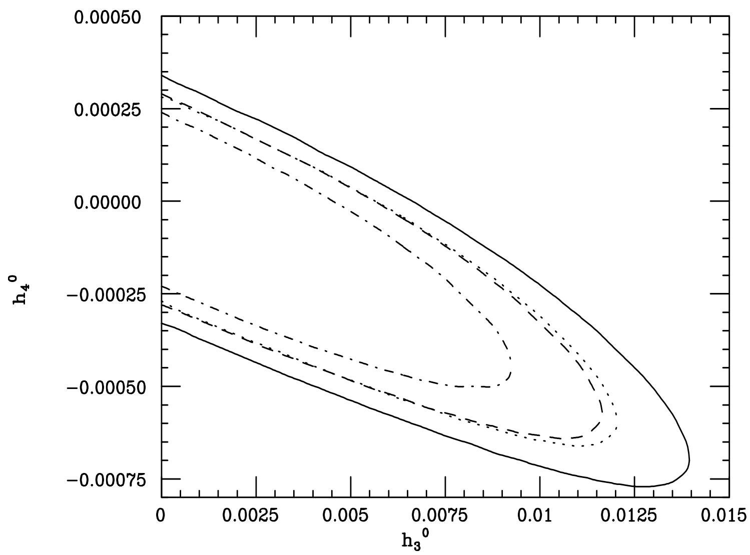

Figure 6: Same as Fig. 5 but for a 1 TeV NLC. The solid(dashed) curve corresponds to a luminosity of $4(8) fb^{-1}$/bin for 42 bins of width Δy=0.2 which covered the range $1 \leq y \leq 9.4$. The dotted curve corresponds to a luminosity of $8 fb^{-1}$/bin but only for the last 21 bins. The dash-dotted curve corresponds to the case of $16.8 fb^{-1}$/bin in only the last 10 bins.

Even these anomalous coupling bounds can be significantly improved by including the Z boson angular information in the fit. To be concrete we examine the case of a 1 TeV NLC with $16.8 fb^{-1}$/bin of integrated luminosity taken in the last 10 Δy bins(corresponding to the dash-dotted curve in Fig.6). Deconvoluting the angular integration and performing instead the integration over the 10 Δy bins we obtain the energy-averaged angular distribution. Placing this distribution into 10 (almost) equal sized $cos\theta$ bins while still employing our 10° cut, we can use this additional data in performing our overall simultaneous χ^2 fit. The result of this procedure is shown in Fig.7 together with the anticipated result from the LHC using the $Z\gamma$ production mode. Note that the additional angular distribution data has reduced the size of the 95% CL allowed region by almost a factor of two. Clearly both machines are complementary in their abilities to probe small values of the γZZ anomalous couplings. As in the W case, if the NLC and LHC results were to be combined, an exceptionally small allowed region would remain. The NLC results themselves may be further improved by considering measurements of the polarization of the final state Z as well as by an examination of, *e.g.*, the complementary $e^+e^- \to Z\gamma$ process.

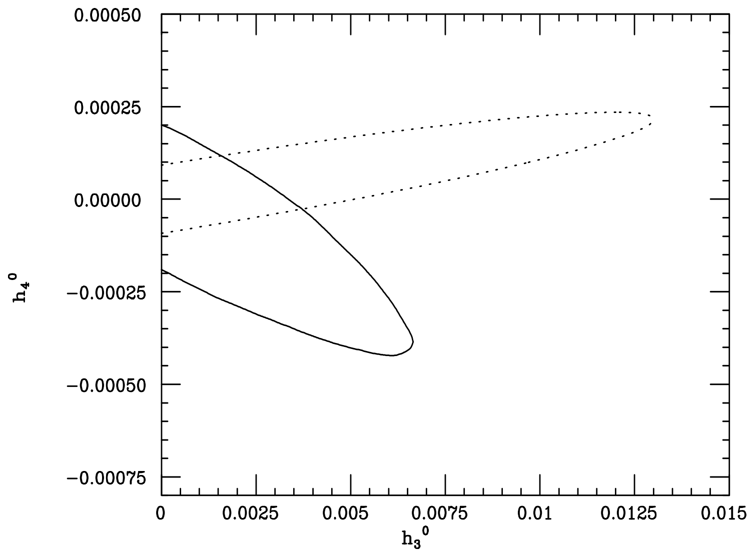

Figure 7: The solid curve is the same as dash-dotted curve in Fig. 6, but now including in the fit the Z boson angular distribution obtained from the highest 10 bins in energy. The corresponding result for the 14 TeV LHC with $100 fb^{-1}$ of integrated luminosity from the process $pp \to Z\gamma + X$ is shown as the dotted curve.

3 Discussion and Conclusions

The collision of polarized electron and photon beams at the NLC offers an exciting opportunity to probe for anomalous gauge couplings of both the W and the Z through the use of the polarization asymmetry. In the case of $\gamma e \to W\nu$ we can cleanly isolate the γWW vertex in a model independent fashion. When combined with other observables, extraordinary sensitivities to such couplings for W's are achievable at the NLC in the γe mode. These are found to be quite complementary to those obtainable in e^+e^- collisions as well as at the LHC. In the case of the γZZ anomalous couplings, we found constraints comparable to those which can be obtained at the LHC.

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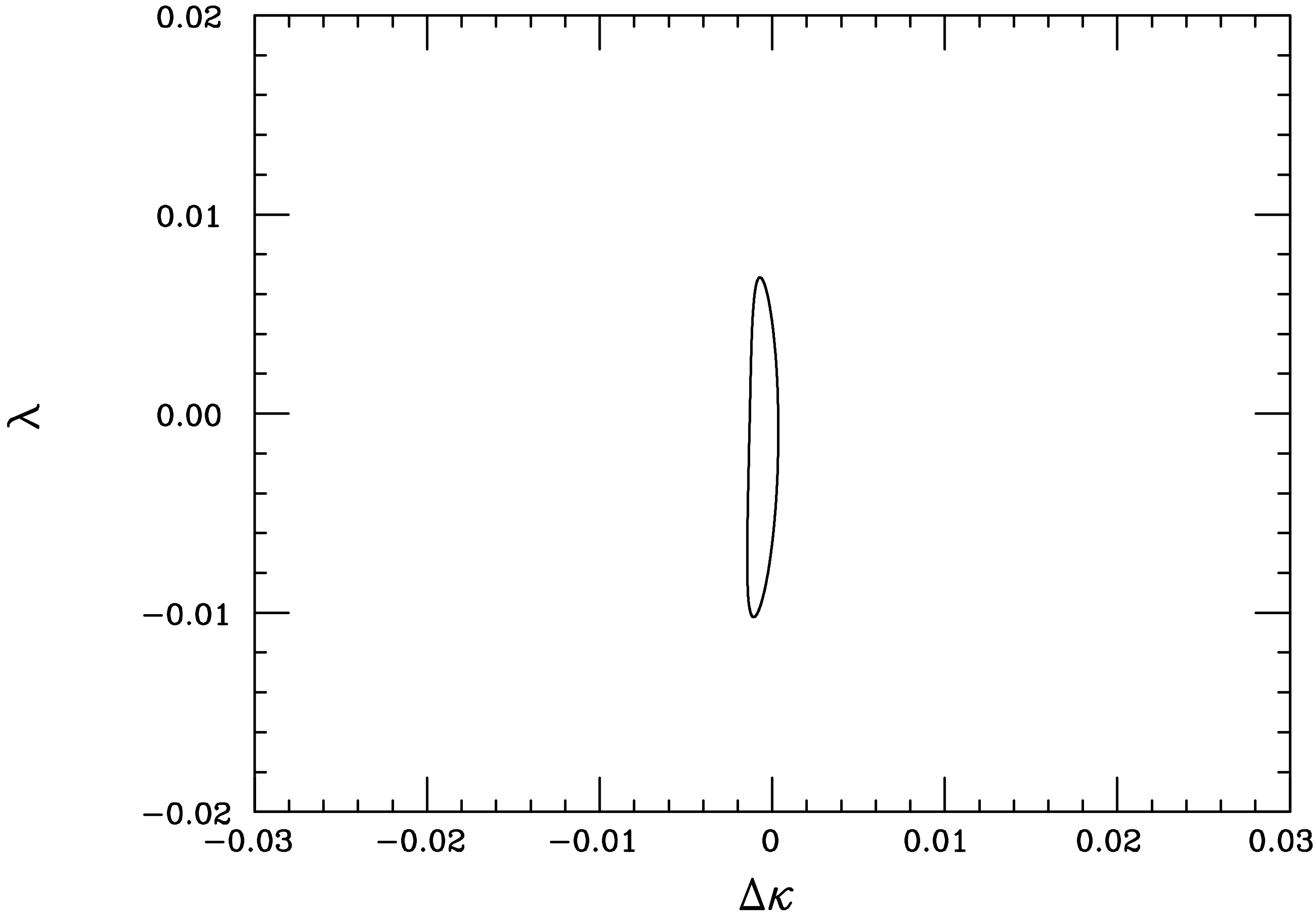
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