Tests of anomalous quartic couplings at the Next Linear Collider

O. J. P. Éboli*

Instituto de Física Teórica, Universidade Estadual Paulista, Rua Pamplona, 145, 01405-900 São Paulo, Brazil

M. C. Gonzalez-Garcia†

*Instituto de Física Teórica, Universidade Estadual Paulista, Rua Pamplona, 145, 01405-900 São Paulo, Brazil
and Instituto de Física Corpuscular–IFIC/CSIC, Departament de Física Teòrica, Universitat de València,
46100 Burjassot, València, Spain*

J. K. Mizukoshi‡

Instituto de Física, Universidade de São Paulo, C. P. 66.318, 05315-970 São Paulo, SP, Brazil

We analyze the potential of the Next Linear e^+e^- Collider to study anomalous quartic vector-boson interactions through the processes $e^+e^- \to W^+W^-Z$ and ZZZ. In the framework of $SU(2)_L \otimes U(1)_Y$ chiral Lagrangians, we examine all effective operators of order p^4 that lead to four-gauge-boson interactions but do not induce anomalous trilinear vertices. In our analysis, we take into account the decay of the vector bosons to fermions and evaluate the efficiency in their reconstruction. We obtain the bounds that can be placed on the anomalous quartic interactions and we study the strategies to distinguish the possible couplings. [S0556-2821(98)01515-X]

I. INTRODUCTION

The impressive agreement of the standard model (SM) predictions for the fermion-vector boson couplings with the experimental results has been a striking confirmation of the $SU_L(2) \times U_Y(1)$ gauge structure of the model in that sector [1]. However, we still lack the same accuracy tests for the structure of the bosonic sector. If the gauge and symmetry breaking sectors are invariant under the $SU_L(2) \times U_Y(1)$ gauge group, the structure of the triple and quartic vector boson is completely determined. Thus a detailed study of these interactions can either confirm the local gauge invariance of the theory or indicate the existence of new physics beyond the SM.

Presently, we have only started to probe directly the triple gauge-boson couplings at the Fermilab Tevatron [2,3] and CERN e^+e^- collider LEP [4] through the production of pairs of vector bosons. Notwithstanding, the constraints on these couplings are still very loose. Future hadron [5] and e^+e^-, $e\gamma$, and $\gamma\gamma$ [6] colliders will provide further information on these couplings and improve significantly our knowledge of possible anomalous gauge-boson interactions.

If the $SU(2)_L \otimes U(1)_Y$ symmetry of the model is to be linearly realized, these studies of the triple gauge-boson couplings will be able to furnish information on the gauge-boson four-point functions provided that dimension 8 and higher anomalous operators are suppressed. This is the case when the breaking of the $SU(2)_L \otimes U(1)_Y$ symmetry takes place via the Higgs mechanism with a relatively light elementary Higgs boson. If, on the other hand, no fundamental light Higgs particle is present in the theory, one is led to consider

the most general effective Lagrangian which employs a nonlinear representation of the broken $SU(2)_L \otimes U(1)_Y$ gauge symmetry. In this case the relation between the structure of the three- and four-point functions of the gauge bosons does not hold already at p^4 order, leaving open the question of the structure of the quartic vector-boson interactions.

At present the only information on quartic gauge-boson interactions is obtained *indirectly* as they modify the gauge-boson two-point functions at one loop [7]. The precise electroweak measurements both at low energy and at the Z pole, constrains the quartic anomalous couplings to be smaller than 10^{-3}–10^{-1} depending on the coupling.

Direct studies of quartic vector-boson interactions cannot be performed at the present colliders since the available center-of-mass energy is not high enough for multiple vector-boson production. This crucial test of the gauge structure of the SM will only be possible at the CERN Large Hadron Collider (LHC) through the reaction $pp \to V_L V_L X$ [8–10] or at the Next Linear Collider (NLC) through the processes $e^+e^- \to VVV$ [11,12], $e^+e^- \to FFVV$ [13], $e^-e^- \to FFVV$ [14], $e\gamma \to VVF$ [15], $\gamma\gamma \to VV$ [16], and $\gamma\gamma \to VVV$ [17], where $V = Z$, $W^\pm$, or γ and $F = e$ or ν_e.

In this work we analyze in detail the processes $e^+e^- \to W^+W^-Z$ and ZZZ in order to assess the potential of the NLC, with and without polarized beams, to study anomalous quartic couplings of vector bosons. These reactions will be the most important processes to study the quartic gauge couplings at the NLC up to energies of the order of 1 TeV, where the processes $e^+e^- \to VVFF$ start to become important [18]. We work in the framework of chiral Lagrangians, and we study all p^4 operators that lead to genuine quartic gauge interactions, i.e., these operators do not give rise to triple gauge-boson vertices, and consequently are not bounded by the study of the production of gauge-boson pairs. We extend the analysis of Ref. [11] for the custodial $SU(2)_C$ conserving operators taking into account realistic

_____

*Email address: eboli@ift.unesp.br
†Email address: concha@axp.ift.unesp.br
‡Email address: mizuka@fma.if.usp.br

58 034008-1

cuts and detection efficiencies. Moreover, we also study the nonconserving $SU(2)_C$ interactions.

II. THEORETICAL FRAMEWORK

If the electroweak symmetry breaking is due to a heavy (strongly interacting) Higgs boson, which can be effectively removed from the physical low-energy spectrum, or to no fundamental Higgs scalar at all, one is led to consider the most general effective Lagrangian which employs a nonlinear representation of the broken $SU(2)_L \otimes U(1)_Y$ gauge symmetry [19]. The resulting chiral Lagrangian is a nonrenormalizable nonlinear σ model coupled in a gauge-invariant way to the Yang-Mills theory. This model independent approach incorporates by construction the low-energy theorems [20], that predict the general behavior of Goldstone boson amplitudes irrespectively of the details of the symmetry breaking mechanism. Notwithstanding, unitarity implies that this low-energy effective theory should be valid up to some energy scale smaller than $4\pi v \simeq 3$ TeV [21], where new physics would come into play.

To specify the low-energy effective Lagrangian one must first fix the symmetry breaking pattern. We consider that the system presents a global $SU(2)_L \otimes SU(2)_R$ symmetry that is broken to $SU(2)_C$. With this choice, the building block of the chiral Lagrangian, in the notation of Ref. [19], is the dimensionless unimodular matrix field $\Sigma(x)$, which transforms under $SU(2)_L \otimes SU(2)_R$ as (2,2):

$$\Sigma(x) = \exp\left(i\frac{\varphi^a(x)\tau^a}{v}\right). \tag{1}$$

The φ^a fields are the would-be Goldstone fields and τ^a ($a = 1,2,3$) are the Pauli matrices. The $SU(2)_L \otimes U(1)_Y$ covariant derivative of Σ is defined as

$$D_\mu \Sigma \equiv \partial_\mu \Sigma + ig\frac{\tau^a}{2}W^a_\mu \Sigma - ig'\Sigma\frac{\tau^3}{2}B_\mu. \tag{2}$$

The lowest-order terms in the derivative expansion of the effective Lagrangian are

$$\mathcal{L}^{(2)} = \frac{v^2}{4}\text{Tr}[(D_\mu\Sigma)^\dagger(D^\mu\Sigma)] + \beta_1 g'^2\frac{v^2}{4}(\text{Tr}[TV_\mu])^2, \tag{3}$$

where we have introduced the auxiliary quantities $T \equiv \Sigma\tau^3\Sigma^\dagger$ and $V_\mu \equiv (D_\mu\Sigma)\Sigma^\dagger$ which are $SU(2)_L$ covariant and $U(1)_Y$ invariant. Notice that T is not invariant under $SU(2)_C$ custodial due to the presence of τ^3.

The first term in Eq. (3) is responsible for giving mass to the $W^\pm$ and Z gauge bosons for $v = (\sqrt{2}G_F)^{-1}$. The second term violates the custodial $SU(2)_C$ symmetry and contributes to $\Delta\rho$ at tree level, being strongly constrained by the low-energy data. This term can be understood as the low-energy remnant of a high-energy custodial symmetry breaking physics, which has been integrated out above a certain scale Λ. Moreover, at the one-loop level, this term is also required in order to cancel the divergences in $\Delta\rho$, arising from diagrams containing a hypercharge boson in the loop.

This subtraction renders $\Delta\rho$ finite, although dependent on the renormalization scale [19].

At the next order in the derivative expansion, $D = 4$, several operators can be written down [19]. We shall restrict ourselves to those containing genuine quartic vector-boson interactions, which are

$$\mathcal{L}_4^{(4)} = \alpha_4[\text{Tr}(V_\mu V_\nu)]^2, \tag{4}$$

$$\mathcal{L}_5^{(4)} = \alpha_5[\text{Tr}(V_\mu V^\mu)]^2, \tag{5}$$

$$\mathcal{L}_6^{(4)} = \alpha_6\text{Tr}(V_\mu V_\nu)\text{Tr}(TV^\mu)\text{Tr}(TV^\nu), \tag{6}$$

$$\mathcal{L}_7^{(4)} = \alpha_7\text{Tr}(V_\mu V^\mu)[\text{Tr}(TV^\nu)]^2, \tag{7}$$

$$\mathcal{L}_{10}^{(4)} = \alpha_{10}[\text{Tr}(TV_\mu)\text{Tr}(TV_\nu)]^2. \tag{8}$$

In an arbitrary gauge, these Lagrangian densities lead to quartic vertices involving gauge bosons and/or Goldstone bosons. In the unitary gauge, these effective operators give rise to anomalous $ZZZZ$ (all operators), W^+W^-ZZ (all operators except $\mathcal{L}_{10}^{(4)}$), and $W^+W^-W^+W^-$ ($\mathcal{L}_4^{(4)}$ and $\mathcal{L}_5^{(4)}$) interactions. Moreover, the interaction Lagrangians $\mathcal{L}_6^{(4)}$, $\mathcal{L}_7^{(4)}$, and $\mathcal{L}_{10}^{(4)}$ violate the $SU(2)_C$ custodial symmetry due to the presence of T in their definitions. Notice that quartic couplings involving photons remain untouched by the genuinely quartic anomalous interactions at the order $D = 4$. The Feynman rules for the quartic couplings generated by these operators can be found in the last article of Ref. [19].

In chiral perturbation theory, the p^4 contribution to the processes $e^+e^- \rightarrow W^+W^-Z$ and ZZZ arises from the tree level insertion of p^4 operators, as well as from one-loop corrections due to the p^2 interactions, which renormalize the p^4 operators [19]. However, the loop corrections to the scattering amplitudes are negligible in comparison to the p^4 contributions for the range of values of the couplings and center-of-mass energies considered in this paper. Therefore, numerically, our analysis is consistent even though we neglected the loop corrections and kept only the tree-level p^4 contributions.

III. LIMITS ON QUARTIC COUPLINGS

In order to study the quartic couplings of vector bosons we analyzed the processes

$$e^+e^- \rightarrow W^+W^-Z, \tag{9}$$

$$e^+e^- \rightarrow ZZZ, \tag{10}$$

which may receive contributions from anomalous $WWZZ$ and $ZZZZ$ interactions. For unpolarized beams and a center-of-mass energy of 0.5 (1) TeV, the SM cross section for the production of W^+W^-Z, in heavy Higgs limit and before cuts, is 43 (64) fb, while the one for ZZZ is 1.1 (0.97) fb, which is in agreement with Ref. [11]. In our calculations, we included all SM and anomalous contributions that lead to these final states, taking into account all interferences between the anomalous and SM amplitudes. The scattering amplitudes were generated using Madgraph [22] in the framework of Helas [23], with the anomalous couplings arising from the Lagrangians (4)–(8) being implemented as FORTRAN routines.
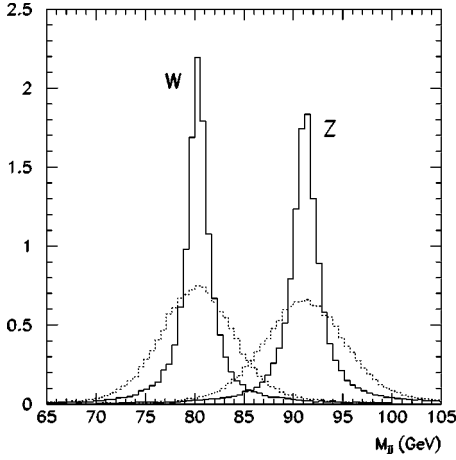
FIG. 1. Reconstructed invariant mass distribution for a jet pair from W and Z decays. The full line only includes the effect of the finite width while the dashed line contains also the effect of the smearing due to the experimental resolution.

In our analyses, we decayed the W's and Z's taking into account the gauge boson widths, spin structures, and correlations of the scattering amplitudes. However, we neglected SM nonresonance diagrams whose contributions are small due to our tight reconstruction cuts given below [24]. We required the visible final state fermions to be in the rapidity region

$$|\eta| < 3$$

and separated by

$$\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} > 0.7.$$

Furthermore, we also folded in the experimental resolution factors associated to the electromagnetic and hadronic calorimetry:

$$\left.\frac{\delta E}{E}\right|_{\text{em}} = \frac{0.12}{\sqrt{E}} \oplus 0.01 \, \text{eletromagnetic}, \qquad (11)$$

$$\left.\frac{\delta E}{E}\right|_{\text{had}} = \frac{0.25}{\sqrt{E}} \oplus 0.02 \, \text{hadronic}. \qquad (12)$$

The momentum carried out by neutrinos was obtained using energy-momentum conservation after smearing the momenta of final state quarks and charged leptons. As an illustration, we show in Fig. 1 the effect of smearing on reconstructed dijet invariant masses from hadronic W and Z decays.

Difermion final states (jj, $\ell^+\ell^-$, $\ell^\pm\nu$, and $\nu\nu$; with $\ell = e, \mu$) were identified, in a statistical basis, as being a W or a Z provided their invariant masses after the smearing were in the range [25], respectively,

$$\left[0.85 M_W, \; \frac{1}{2}(M_W + M_Z)\right], \quad \left[\frac{1}{2}(M_W + M_Z), \; 1.15 M_Z\right].$$

$$(13)$$

In what follows we present our results for two different center-of-mass energies, 500 GeV and 1 TeV, assuming an integrated luminosity of 100 fb^{-1} for both energies. We also study the impact of a 80% left-handed and 80% right-handed polarized electron beam while keeping the positron beam unpolarized.

A. $e^+e^- \to W^+W^-Z$

We identified W^+W^-Z events through the topologies $6j$, $4j+2\ell$, $4j+2\nu$, and $4j+\ell+\nu_\ell$, requiring two difermion systems with invariant masses compatible with the W mass — see Eq. (13) — and one difermion system with an invariant mass (or missing mass) consistent with it being a Z. These requirements together with the kinematical cuts described in the previous section are enough to reduce some of the backgrounds, such as the $e^+e^- \to W^+W^-e^+e^-$ background to the $4j+2\nu$ topology well below the W^+W^-Z signal [11].

Nonetheless, the above requirements are not enough to isolate the events from W^+W^-Z production for the topologies $6j$ and $4j+\ell+\nu_\ell$ since there is a severe background arising from the creation of top-quark pairs. In this case, the decays of top quarks lead to $b\bar{b}$ pairs which can be mistaken by a W or Z in our identification procedure:

$$e^+e^- \to t\bar{t} \to W^+W^-b\bar{b}.$$

This process has a large cross section of 600 (200) fb for unpolarized beams and a center-of-mass energy of 500 (1000) GeV. In order to analyze this background we generate the full final state topologies by allowing the W bosons to decay and imposing the cuts described above for the signal. Applying just the identification cuts reduces this background to the level of the SM contribution for W^+W^-Z production. In order to further suppress it, we introduced a b-tag veto, rejecting all events which exhibit one or more tagged b's.

TABLE I. Cross section in fb for $t\bar{t}$ events reconstructed as WWZ. The pol $-$ (pol $+$) lines correspond to 80% left-handed (right-handed) electron beam polarization.

Topology		$\sqrt{s} = 0.5$ TeV
$6j$	unpol	0.24
	pol $-$	0.32
	pol $+$	0.16
$4j+\ell+\nu_\ell$	unpol	0.07
	pol $-$	0.09
	pol $+$	0.05

TABLE II. Fraction of WWZ events that are reconstructed as WWZ and ZZZ for several topologies and center-of-mass energies of 0.5/1 TeV.

Topology	$F_{WWZ}\%$	$F_{ZZZ}\%$
$6j$	50.0/41.0	0.63/0.95
$4j+2\ell$	66.0/55.0	0.8/1.2
$4j+2\nu$	28.0/8.0	0.2/0.2
$4j+\ell\ \nu_\ell$	16.0/3.9	0.0/0.0

TABLE III. Values for the standard model, pure anomalous, and interference cross sections [see Eq. (14)] for the W^+W^-Z production and several center-of-mass energies and e^- polarizations. The pol $-$ (pol $+$) lines correspond to 80% left-handed (right-handed) electron beam polarization.

Topology		σ_{sm} (fb)	$-\sigma_{int}^{\alpha_4}$ (fb)	$\sigma_{ano}^{\alpha_4\alpha_4}$ (fb)	$\sigma_{int}^{\alpha_5}$ (fb)	$\sigma_{ano}^{\alpha_5\alpha_5}$ (fb)	$\sigma_{ano}^{\alpha_4\alpha_5}$ (fb)
	$\sqrt{s}$/TeV	0.5 (1)	0.5 (1)	0.5 (1)	0.5 (1)	0.5 (1)	0.5 (1)
	unpol	3.94 (3.32)	0.06 (0.05)	1.21 (2.58)	0.235 (0.07)	2.26 (6.10)	0.59 (-1.93)
$6j$	pol $-$	7.02 (5.99)	0.0 (0.0)	1.40 (3.03)	0.285 (0.)	2.63 (7.12)	0.685 (-2.26)
	pol $+$	0.97 (0.66)	0.11 (0.10)	1.00 (2.13)	0.17 (0.16)	1.88 (5.08)	0.49 (-1.61)
	unpol	0.49 (0.44)	0.007 (0.005)	0.16 (0.035)	0.026 (0.01)	0.30 (0.81)	0.08 (-0.26)
$4j+2\ell$	pol $-$	0.87 (0.79)	0.0 (0.0)	0.18 (0.40)	0.03 (0.0)	0.34 (0.95)	0.09 (-0.29)
	pol $+$	0.10 (0.09)	0.015 (0.012)	0.13 (0.27)	0.02 (0.02)	0.25 (0.68)	0.007 (-0.21)
	unpol	0.86 (0.23)	0.003 (0.007)	0.26 (0.29)	0.06 (0.013)	0.58 (0.55)	0.18 (-0.22)
$4j+2\nu$	pol $-$	1.52 (0.41)	0.0 (0.004)	0.30 (0.34)	0.08 (0.01)	0.68 (0.64)	0.21 (-0.26)
	pol $+$	0.18 (0.05)	0.017 (0.012)	0.22 (0.25)	0.04 (0.01)	0.49 (0.46)	0.15 (-0.18)
	unpol	1.02 (0.25)	0.02 (0.004)	0.31 (0.28)	0.06 (0.019)	0.55 (0.77)	0.16 (-0.14)
$4j+\ell\ \nu_\ell$	pol $-$	1.79 (0.45)	0.0 (0.0)	0.37 (0.33)	0.08 (0.017)	0.64 (0.90)	0.18 (-0.17)
	pol $+$	0.25 (0.05)	0.03 (0.01)	0.26 (0.24)	0.04 (0.022)	0.46 (0.64)	0.13 (-0.12)

Assuming the b-tagging probability to be 80% at the NLC, this background is considerably reduced for the center-of-mass energy of 500 GeV, see Table I, and it disappears completely at 1 TeV. For right-handed polarization of the electron beam, despite the large suppression due to b vetoing, $t\bar{t}$ production still accounts for about 20% of the SM contributions to the $6j$ and $4j+\ell+\nu_\ell$ topologies.

We show in Table II the fraction of true WWZ events passing the $|\eta|$, ΔR, and b-veto cuts that are reconstructed statistically as WWZ and ZZZ for center-of-mass energies of 0.5 and 1 TeV. We explicitly verified that the reconstruction probabilities are basically independent of the e^- polarization and that the overall efficiency for reconstructing WWZ events is around 14% at a center-of-mass energy of 500 GeV, when we take into account the effect of the $|\eta|$, ΔR, and b-veto cuts. Furthermore, despite been very unlikely the misidentification of WWZ events as ZZZ, this is still very serious once it generates a background for the study of anomalous couplings in ZZZ production, whose cross section is much smaller than the W^+W^-Z one.

In general, the cross section for W^+W^-Z (or ZZZ) is a quadratic function of the anomalous couplings α_i, i.e.,

$$\sigma_{tot} = \sigma_{SM} + \sum_i \alpha_i \sigma_{int}^{\alpha_i} + \sum_{ij} \alpha_i \alpha_j \sigma_{ano}^{\alpha_i\alpha_j}, \quad (14)$$

where σ_{SM} stands for the SM cross section, including the $t\bar{t}$ events reconstructed as WWZ, and $\sigma_{int}^{\alpha_i}$ ($\sigma_{ano}^{\alpha_i\alpha_j}$) is the interference (pure anomalous) contribution. In Table III, we present our results after applying all cuts and the W and Z identification efficiencies as well. Since there are only two independent Lorentz invariant structures for the $WWZZ$ vertices at p^4 order, the couplings α_5 and α_7 (α_4 and α_6) give rise to identical contributions to $\sigma_{int}^{\alpha_i}$ and $\sigma_{ano}^{\alpha_i\alpha_j}$ in W^+W^-Z production. From this table we can witness that the SM contributions are slowly varying functions of the center-of-mass energy, while the anomalous contributions grow rapidly, as

one could naively expect. Moreover, the SM background can be efficiently reduced using right-handed electrons as this polarization eliminates almost completely the contribution where the W^- couples directly to the e^- fermion line.

In order to quantify the effect of the new couplings, we defined the statistical significance S of the anomalous signal

$$S = \frac{|\sigma_{tot} - \sigma_{SM}|}{\sqrt{\sigma_{SM}}}\sqrt{\mathcal{L}}, \quad (15)$$

which can be easily evaluated using the parametrization (14) with the coefficients given in Table III.

Table IV contains the values of the quartic anomalous couplings that lead to changes in the number of reconstructed W^+W^-Z events smaller than 3σ, assuming an integrated luminosity of 100 fb^{-1} and that only one anomalous coupling is nonvanishing. These limits were obtained combining events reconstructed as W^+W^-Z from all the topologies. It is interesting to notice that having right-handed polarized electrons improves the bounds in 20–30 % with respected to the results for unpolarized beams, while the use of left-handed electrons weakens the limits. This result is in agreement with Ref. [11]. Moreover, the bounds improve as the center-of-mass energy increases since the anomalous contributions grow with energy. In general, more than one anoma-

TABLE IV. 3σ allowed values of the quartic anomalous couplings obtained from the reaction $e^+e^- \rightarrow W^+W^-Z$.

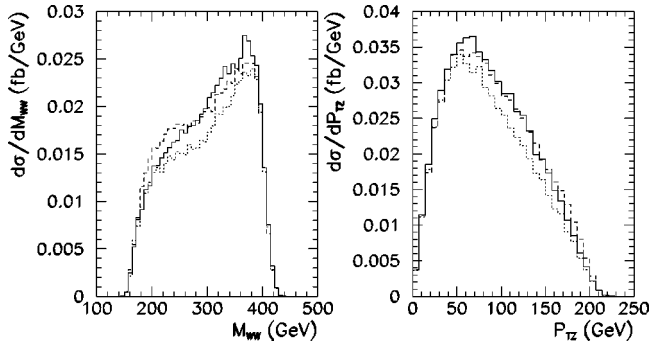| $\sqrt{s}$ GeV	e^- polarization (%)	$\alpha_{4,6}$	$\alpha_{5,7}$
500	0	($-0.60,0.65$)	($-0.51, 0.41$)
500	-80	($-0.67,0.67$)	($-0.54,0.43$)
500	80	($-0.43,0.53$)	($-0.39,0.30$)
1000	0	($-0.43,0.45$)	($-0.28,0.27$)
1000	-80	($-0.45,0.45$)	($-0.29,0.29$)
1000	80	($-0.29,0.33$)	($-0.22,0.19$)

FIG. 2. W^+W^- invariant mass and p_{TZ} distributions for unpolarized W^+W^-Z production at $\sqrt{s}=500$ GeV. The dotted line stands for the SM result, while the solid (dashed) line represent the case $\alpha_5=0.38$ ($\alpha_4=0.65$).

lous coupling might be nonvanishing. In this case the correlation among the anomalous couplings can be easily taken into account using the full expression of Eq. (14) and Table III.

In order to discriminate between the different couplings we studied the kinematical distributions of the final gauge bosons. Figure 2 displays the W^+W^- invariant mass spectrum and the p_T distribution of the Z in the W^+W^-Z production with unpolarized beams at $\sqrt{s}=500$ GeV. We plotted in this figure the standard model prediction (dotted line) as well as the predictions for $\alpha_4=0.65$ (dashed line) and $\alpha_5=0.38$ (solid line), which are the values that lead to a 3σ signal in the total number of events for unpolarized beams. As we can see, the W^+W^- invariant mass distribution for α_4 presents a larger contribution at small values of the W^+W^- invariant mass, while α_5 gives rise to more events with larger invariant masses. In principle we can use this distribution not only to distinguish the anomalous couplings, but also to increase the sensitivity to the signal. However, this can only be accomplished with a higher integrated luminosity. On the other hand the p_T distributions of the Z are very similar in the SM and in presence of the anomalous couplings, being the only difference the larger number of events in the latter case.

B. $e^+e^-\rightarrow ZZZ$

The production cross section for ZZZ final states is rather small and consequently just a few fermionic topologies can be used to identify these events. We considered only the final states $6j$, $4j+2\ell$, and $4j+2\nu$. Moreover, since the cross sections for the production of W^+W^-Z and $t\bar{t}$ are much larger then the one for ZZZ, misidentified events constitute the bulk of the reconstructed $6j$ events as ZZZ. In fact the cross section for $t\bar{t}$ events identified as ZZZ in the $6j$ topology is 0.080 (0.107, 0.055) fb for unpolarized (80% left-handed, 80% right-handed polarized) electron beam at 500 GeV. Analogously to the W^+W^-Z case, the importance of the $t\bar{t}$ diminishes as the center-of-mass energy increases, becoming negligible at 1 TeV. We present in Table V the efficiency for the reconstruction of the ZZZ events passing the rapidity, ΔR, and b-veto cuts for the above topologies and

TABLE V. Fraction of ZZZ events that are reconstructed as ZZZ for several topologies and center-of-mass energies of 0.5/1 TeV.

Topology	$F_{ZZZ}\%$
$6j$	29.0/27.0
$4j+2\ell$	390/36.0
$4j+2\nu$	16.0/4.4

center-of-mass energies of 0.5 and 1.0 TeV. Once again, these efficiencies are independent of the polarization of the e^-.

Table VI contains the values of σ_{SM}, $\sigma_{int}^{\alpha_i}$, and $\sigma_{ano}^{\alpha_i\alpha_j}$ for ZZZ production, taking into account the η, ΔR, and b-veto cuts, as well as the reconstruction efficiencies. We included in σ_{SM}, the $t\bar{t}$ and W^+W^-Z backgrounds, which add to approximately 75% of the $6j$ cross section. At p^4 order in chiral perturbation theory, all anomalous interactions are proportional to each other since there is only one possible Lorentz structure for the vertex which is multiplied by $\alpha_4+\alpha_5+2(\alpha_6+\alpha_7+\alpha_{10})$. Therefore, we only present the results for α_4, being straightforward the generalization to the other cases. From this table we can see that most of the reconstructed ZZZ events will be observed in the $6j$ and $4j+2\nu$ topologies. Furthermore, the largest anomalous contribution comes from $\sigma_{ano}^{\alpha_i\alpha_j}$, being the interference with the SM of the same order of the SM contribution but with the opposite sign. Analogously to W^+W^-Z production, the anomalous contributions grow substantially with the increase of the center-of-mass energy, while the SM cross section decreases.

We present in Table VII the 3σ allowed range for genuinely quartic couplings that can be obtained from the nonobservation of deviations at this level from the SM in ZZZ production. Despite the reduced number of events in the ZZZ channel, the bounds on the quartic couplings are at least a factor of 2 better than the ones drawn from the W^+W^-Z channel due to the smaller size of the background. On the other hand, contrary to the W^+W^-Z channel, beam polariza-

TABLE VI. Values for the standard model, pure anomalous, and interference cross sections [see Eq. (14)] for the ZZZ production and several center-of-mass energies and e^- polarizations.

Topology		σ_{sm} (fb)	$-\sigma_{int}^{\alpha_4}$ (fb)	$\sigma_{ano}^{\alpha_4\alpha_4}$ (fb)
	$\sqrt{s}$/TeV	0.5 (1)	0.5 (1)	0.5 (1)
	unpol	0.174 (0.118)	0.049 (0.032)	0.821 (2.25)
$6j$	pol $-$	0.259 (0.198)	0.065 (0.043)	0.963 (2.64)
	pol $+$	0.091 (0.038)	0.032 (0.022)	0.690 (1.88)
	unpol	0.025 (0.025)	0.017 (0.012)	0.330 (0.896)
$4j+2\ell$	pol $-$	0.038 (0.040)	0.022 (0.017)	0.384 (1.04)
	pol $+$	0.011 (0.011)	0.012 (0.008)	0.277 (0.749)
	unpol	0.039 (0.012)	0.031 (0.005)	0.587 (0.625)
$4j+2\nu$	pol $-$	0.058 (0.019)	0.043 (0.007)	0.686 (0.726)
	pol $+$	0.019 (0.004)	0.020 (0.003)	0.493 (0.519)

TABLE VII. 3σ allowed values of the quartic anomalous couplings obtained from the reaction $e^+ e^- \to ZZZ$.

$\sqrt{s}$ GeV	e^- polarization (%)	$\alpha_{4,5}$	$\alpha_{6,7,10}$
500	0	$(-0.26, 0.32)$	$(-0.13, 0.16)$
500	-80	$(-0.26, 0.33)$	$(-0.13, 0.16)$
500	80	$(-0.25, 0.29)$	$(-0.12, 0.14)$
1000	0	$(-0.17, 0.18)$	$(-0.08, 0.09)$
1000	-80	$(-0.18, 0.19)$	$(-0.09, 0.10)$
1000	80	$(-0.14, 0.15)$	$(-0.07, 0.08)$

tion does not lead to a substantial improvement on the attainable limits.

We display in Fig. 3 the pseudorapidity and transverse momentum distribution of the Z's in unpolarized ZZZ production at $\sqrt{s} = 500$ GeV. As we can see, the anomalous quartic interactions leads to more centrally produced Z's (smaller $\langle \eta_z \rangle$) which have a slightly harder p_T spectrum. However, the number of reconstructed events is not large enough to allow the use of cuts to enhance the anomalous contributions.

IV. DISCUSSION AND CONCLUSIONS

$W^+ W^- Z$ and ZZZ are the best channels for direct study of quartic gauge-boson couplings in $e^+ e^-$ colliders with center-of-mass energies up to 1 TeV. At higher energies $e^+ e^- \to W^+ W^- f\bar{f}$ becomes the most important process [13]. We showed in this work that the NLC will be able to uncover the existence of anomalous quartic couplings of the order $\mathcal{O}(10^{-1})$ for center-of-mass energies up to 1 TeV and an integrated luminosity of 100 fb^{-1}; see Tables IV and VII. Despite these limits being weaker or of the order of the present indirect bounds [7], the above processes will provide a *direct* test of the quartic interactions among the electroweak gauge bosons. We have also shown that the use of a right-handed polarized electron beam leads to better limits on the anomalous interactions from the $W^+ W^- Z$ production due to a large reduction of the SM backgrounds, even for the conservative values of the e^- polarization that we assumed.

It is also important to devise a strategy to disentangle the anomalous couplings in case a departure from the SM prediction is observed. In $W^+ W^- Z$ production, the analysis of the $W^+ W^-$ invariant mass distribution, see Fig. 2, can be used to distinguish between the two possible structures for the $WWZZ$ vertex, one associated to $\alpha_{4,6}$ and the other re-
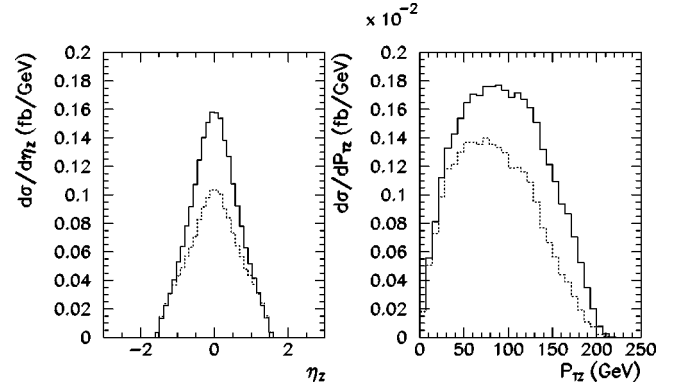

FIG. 3. Pseudorapidity and transverse momentum Z distributions in unpolarized ZZZ production at $\sqrt{s} = 500$ GeV. The dotted line stands for the SM result, while the solid line represent the case $\alpha_4 = 0.32$.

lated to $\alpha_{5,7}$. However, we are still left with two possibilities in both cases. At this point it is important to use the information from the ZZZ reaction, because the $SU(2)_C$ violating interactions leads to a much larger excess of events for the same value of the anomalous coupling, due to the coupling structure $\alpha_4 + \alpha_5 + 2(\alpha_6 + \alpha_7 + \alpha_{10})$. Therefore, the combination of the $W^+ W^-$ distribution and the total number of events in both reactions is a powerful tool to separate the effects of the different anomalous couplings provided there is enough statistics. Moreover, the comparison between the $W^+ W^- Z$ event rates for different polarizations can also be used to further distinguish between the couplings $\alpha_{4,6}$ and $\alpha_{5,7}$, since the latter are less sensitive to the electron polarization. Finally the anomalous coupling α_{10} has the distinguished characteristics of modifying only the ZZZ production.

Note added. During the write up of this work we became aware of a similar study performed by T. Han, H.-J. He, and C.-P. Yuan [26].

[1] The LEP Collaborations ALEPH, DELPHI, L3, OPAL, and the LEP Electroweak Working Group, contributions to the 28th International Conference on High-energy Physics (ICHEP 96), Warsaw, Poland, 1996, Report No. CERN-PPE/96-183, 1996.

[2] UA2 Collaboration, J. Alitti *et al.*, Phys. Lett. B **277**, 194 (1992); U. Baur and E. Berger, Phys. Rev. D **41**, 1476 (1990);

D0 Collaboration, S. Abachi *et al.*, Phys. Rev. Lett. **75**, 1028 (1995); D0 Collaboration, S. Abachi *et al.*, *ibid.* **75**, 1034 (1995).

[3] F. de Campos, M. C. Gonzalez-Garcia, and S. F. Novaes, Phys. Rev. Lett. **79**, 5210 (1997).

[4] OPAL Collaboration, K. Ackerstaff *et al.*, Phys. Lett. B **397**, 147 (1997); DELPHI Collaboration, P. Abreu *et al.*, *ibid.* **397**,

158 (1997); L3 Collaboration, M. Acciarri *et al.*, *ibid.* **398**, 223 (1997).

[5] See for instance H. Kuijf *et al.*, in *Proceedings of the ECFA Large Hadron Collider Workshop*, Aachen, Germany, 1990, edited by G. Jarlskog and D. Rein (CERN Report No. 90-10, Geneva, Switzerland, 1990).

[6] See, for instance, W. Beenaker *et al.*, in *Proceedings of the Workshop on e^+e^- Collisions at 500 GeV: The Physics Potential*, Munich-Annecy-Hamburg, 1993 (unpublished).

[7] A. Brunstein, O. J. P. Éboli, and M. C. Gonzalez-Garcia, Phys. Lett. B **375**, 233 (1996); S. Alam, S. Dawson, and R. Szalapski, Phys. Rev. D **57**, 1577 (1998).

[8] A. Dobado, D. Espriu, and M. J. Herrero, Z. Phys. C **50**, 205 (1991).

[9] J. Bagger, S. Dawson, and G. Valencia, Nucl. Phys. **B399**, 364 (1993).

[10] A. Dobado and M. T. Urdiales, Z. Phys. C **71**, 659 (1996); A. Dobado, M. J. Herrero, J. R. Peláez, E. Ruiz Morales, and M. T. Urdiales, Phys. Lett. B **352**, 400 (1995).

[11] G. Bélanger and F. Boudjema, Phys. Lett. B **288**, 201 (1992); S. Dawson *et al.*, *Proceedings of the 1996 DPF/DPB Summer Study on New Directions for High Energy Physics*, Snowmass, Colorado, 1996, hep-ph/9610299; A. Miyamoto, in *Proceedings of the Workshop on Physics and Experiments with Linear Colliders*, edited by A. Miyamoto *et al.* (World Scientific, Singapore, 1996).

[12] G. A. Leil and W. J. Stirling, J. Phys. G **21**, 517 (1995).

[13] E. Boos *et al.*, Phys. Rev. D **57**, 1553 (1998).

[14] F. Cuypers and K. Kolodziej, Phys. Lett. B **344**, 365 (1995).

[15] O. J. P. Éboli, M. C. Gonzalez-Garcia, and S. F. Novaes, Nucl. Phys. **B411**, 381 (1994).

[16] G. Bélanger and F. Boudjema, Phys. Lett. B **288**, 210 (1992).

[17] O. J. P. Éboli, M. B. Magro, P. G. Mercadante, and S. F. Novaes, Phys. Rev. D **52**, 15 (1995).

[18] See, for instance, F. Boudjema, in *Proceedings of the Workshop on Physics and Experiments with Linear Colliders*, edited by A. Miyamoto *et al.* (World Scientific, Singapore, 1996), hep-ph/9701409.

[19] T. Appelquist and C. Bernard, Phys. Rev. D **22**, 200 (1980); A. Longhitano, *ibid.* **22**, 1166 (1980); Nucl. Phys. **B188**, 118 (1981).

[20] M. S. Chanowitz, M. Golden, and H. Georgi, Phys. Rev. D **36**, 1490 (1987).

[21] B. W. Lee, C. Quigg, and H. B. Thacker, Phys. Rev. D **16**, 1519 (1977).

[22] W. Long and T. Steltzer, Comput. Phys. Commun. **81**, 357 (1994).

[23] H. Murayama, I. Watanabe, and K. Hagiwara, KEK Report No. 91-11 (unpublished).

[24] E. Accomando, A. Ballestrero, and M. Pizzio, in the Proceedings of Joint ECFA/DESY study: Physics and Detectors for a Linear Collider, Frascati, Italy, 1996, Report No. DFTT 52/97, hep-ph/9709277.

[25] V. Barger *et al.*, Phys. Rev. D **52**, 3815 (1995).

[26] T. Han, H.-J. He, and C.-P. Yuan, Phys. Lett. B **422**, 294 (1998).