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COMPOSITE Z-BOSON IN THE $e^+e^- \to ZZ$ PROCESS*

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A detailed analysis is presented of two Z production in e^+e^- annihilation with arbitrary $ZZ\gamma^*$ and ZZZ^* couplings. Both *CP*-even and *CP*-odd anomalous couplings are taken into account. The unitarity bounds for the anomalous form factors are found.

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1. *Introduction*

Up to now the SU(2) ⊗ U(1) electroweak theory has proved very satisfactory (see e.g. Ref. [1]). However, there are parts of the model which still await experimental verification, hence it becomes justified to look beyond the standard model (SM). Over the last few years two main concepts have been formulated for this purpose. In the first, fermions and gauge bosons are still elementary but there are more of them (grand unification, supersymmetry, superstrings) (see Ref. [2] and Refs therein). The second concept proposes a search for deeper layers of constituents in the structure of matter (see Ref. [3]).

There are two versions of the model of such constituents. In the first only leptons and quarks are composite, but gauge bosons are elementary (see Ref. [3]), in the second $W^\pm$ and Z particles are also composite particles (see Refs [4, 5]).

If $W^\pm$ and Z are composite, then the three gauge boson couplings W^+W^-V, $Z\gamma V$ and ZZV, where V = Z or γ, are different from those which follow from the SM. The phenomenological consequences of such couplings should be observed in the next collider experiments (LEP I, LEP II, SSC, CLIC...). The observable consequences of general W^+W^-V ($V = Z, \gamma$) couplings in the $e^+e^- \to W^+W^-$ process has been checked by different groups

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[6, 7]. Similar studies have also been conducted for three neutral vector boson couplings (Refs [5, 8]).

Our aim in this paper is to present the observable consequences of the anomalous ZZV* couplings in the $e^+e^- \to ZZ$ process. The most general ZZV* coupling (where two identical Z's are on-shell) is described by two independent form factors [6], i.e. the *CP*-even and the *CP*-odd factors. Up to now only investigations on the *CP*-even form factor have been reported in the literature (Refs [5, 8]). Here we present the full spin analysis including also the *CP*-odd form factor. The reaction $e^+e^- \to ZZ$ has less physical meaning than the W pair and $Z\gamma$ pair production because of the smaller cross section but it needs to be studied because it provides an important background for high mass Higgs searches [9]. With planned luminosity for LEP II we can expect a production of 500–600 ZZ pairs per year. This number of events is too small for full polarization analysis but, as it will be shown, the effects of both anomalous couplings are also visible in the non-polarized cross sections.

In the next Section we present the helicity amplitudes for the reaction $e^+e^- \to ZZ$ with general anomalous couplings. In Section 3 the unitarity constraints for the form factors are found. Section 4 gives a discussion on the observable consequences of the anomalous ZZV* couplings and a final summary is given in Section 5.

2. *Helicity amplitudes for $e^+e^- \to ZZ$ with anomalous couplings*

The helicity amplitudes for the process

$$e^+(p_1, \bar{\sigma}) + e^-(p_4, \sigma) \to Z(-p_2, \lambda') + Z(-p_3, \lambda), \tag{2.1}$$

(notation as in Fig. 1) can be written as

$$M(\sigma, \bar{\sigma}; \lambda, \lambda') = \bar{v}(p_1, \bar{\sigma}) M^{\mu\nu} u(p_4, \sigma) \varepsilon_\mu^*(-p_2, \lambda') \varepsilon_\nu^*(-p_3, \lambda), \tag{2.2}$$

where $M^{\mu\nu}$ is a 4×4 matrix valued 2^{nd} rank tensor.

To construct the $M^{\mu\nu}$ tensor for a composite Z-boson we assume that the e^+e^-Z coupling is the same as in the standard model (Fig. 2a) but additionally virtual γ or Z can couple

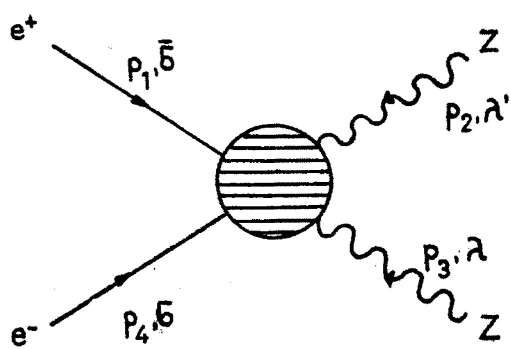

Fig. 1. Kinematic variables for the process $e^+e^- \to ZZ$. All momenta are incoming. Indices σ, $\bar{\sigma}$, λ and λ' denote helicities

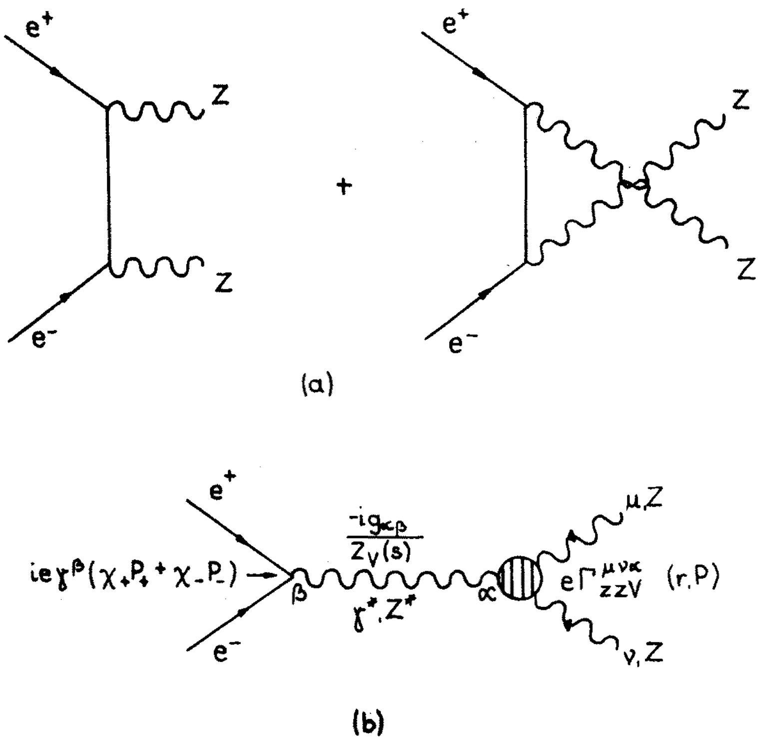

Fig. 2. Feynman diagrams for the process $e^+e^- \to ZZ$. a) Two diagrams which contribute to $e^+e^- \to ZZ$ in the standard model. b) The anomalous three gauge bosons contribution to $e^+e^- \to ZZ$ $\Big(\chi_\pm = 1$ for photons, $\chi_+ = -\dfrac{1}{\sin 2\theta_w} + \mathrm{tg}\,\theta_w$ and $\chi_- = \mathrm{tg}\,\theta_w$ for Z's, $P_\pm$ are projector chiral operator $P_\pm = \frac{1}{2}(1 \pm \gamma_5)$,

$$Z_\gamma(s) = s \text{ and } Z_Z(s) = s - M_Z^2 + M_Z\Gamma_Z\Big)$$

to subconstituents of Z. Then the $M^{\mu\nu}$ tensor is given by

$$M^{\mu\nu} = M^{\mu\nu}_{SM} + M^{\mu\nu}_{ANOM}, \tag{2.3}$$

where $M^{\mu\nu}_{TM}$ represents the known standard model $t-u$ part from Fig. 2a, and the anomalous part $M^{\mu\nu}_{ANOM}$ is equal to

$$M^{\mu\nu}_{ANOM} = M^{\mu\nu}_{\gamma *} + M^{\mu\nu}_{Z*}. \tag{2.4}$$

For virtual γ and Z the $M^{\mu\nu}_{V*}$ tensors are given by (see Fig. 2b)

$$M^{\mu\nu}_{V*} = \frac{e^2}{Z_V(s)} \Gamma^{\mu\nu\alpha}_{ZZV*}(r, P)\gamma_\alpha(\chi_+P_+ + \chi_-P_-), \tag{2.5}$$

where the neutral gauge boson coupling $\Gamma^{\mu\nu\alpha}_{ZZV^*}$ for on-shell Z's ($r = p_2 - p_3$, $P = p_2 - p_3$) is equal to (compare Ref. [6])

$$\Gamma^{\mu\nu\alpha}_{ZZV^*}(r, P) = \frac{P^2 - M_V^2}{M_Z^2} \{f_1(P^\mu g^{\nu\alpha} + P^\nu g^{\mu\alpha}) + f_2(\varepsilon^{\mu\nu\alpha\gamma} r_\gamma)\}. \tag{2.6}$$

Generally the coupling between three spin-one particles is described by 20 form factors. If, however, two particles are on-shell and the third couples to massless fermions, then only 7 form factors survive. If we also assume that two on-shell particles are identical, Bose symmetry allows only two couplings. The $P^2 - M_V^2$ factor in Eq. (2.6) follows from gauge invariance for V = γ and Bose symmetry for V = Z. The coupling $f_1^V(f_2^V)$ is CP-odd (even).

If we neglect the electron mass, only two initial helicity configurations $\Delta\sigma = 1/2$ $(\sigma - \bar{\sigma}) = \pm 1$ are allowed. Using the helicity convention as in Ref. [10] we obtain the helicity amplitudes (2.2) for the process $e^+e^- \to ZZ$

$$M(\Delta\sigma; \lambda, \lambda') = \frac{-ise^2}{\sqrt{2}\, M_Z^2} \tilde{M}(\Delta\sigma, \lambda, \lambda') d^{J_0}_{\Delta\sigma,\Delta\lambda}(\theta), \tag{2.7}$$

where $\Delta\lambda = \lambda' - \lambda$, $J_0 = \max(|\Delta\sigma|, |\Delta\lambda|)$, $d^{J_0}_{\Delta\sigma,\Delta\lambda}(\theta)$ are ordinary $d^j_{mm'}$ Wigner functions and θ is the scattering angle in the CM system between the electron and one of the Z's. The reduced amplitudes $\tilde{M}(\Delta\sigma, \lambda, \lambda')$ are given by

$$\tilde{M}(\Delta\sigma, \lambda, \lambda') = \frac{\chi_{\Delta\sigma}}{4\beta^2\gamma^2 \sin^2\theta + \gamma^{-2}} M_\perp(\Delta\sigma, \lambda, \lambda') + \sum_{i=1}^{2} (f_i^\gamma + \chi_{\Delta\sigma} f_i^Z) M_{s_i}(\lambda, \lambda') \tag{2.8}$$

and the $t-u$ channel (M_T) and s-channel amplitude M_{s_i} are given in Table I $\left(\gamma = \frac{\sqrt{s}}{2M_Z},\right.$ $\left.\beta = \left(1 - \frac{4M_Z^2}{s}\right)^{1/2}\right)$. All polarized cross sections can now be calculated from the formula ($\alpha = e^2/4\pi$).

$$\frac{d\sigma(\Delta\sigma, \lambda\lambda')}{d\cos\theta} = \frac{4\pi\alpha^2}{M_Z^2} \beta\gamma^2 |\tilde{M}(\Delta\sigma, \lambda, \lambda') d^{J_0}_{\Delta\sigma,\Delta\lambda}(\theta)|^2. \tag{2.9}$$

TABLE I

Reduced t-u channel M_T and s channel M_{s_i} ($i = 1, 2$) amplitudes (see Eq. (2.8))

$\Delta\lambda$	$\lambda'\ \lambda$	M_T	M_{s_1}	M_{s_2}
± 2	$\pm\ \mp$	$-2^{1/2}(1+\beta^2)$	0	
± 1	$0\ \pm$ $\pm\ 0$	$\gamma^{-1}[\Delta\sigma\Delta\lambda(1+\beta^2) - 2\cos\theta]$	$-i\gamma\beta$ $i\beta\gamma$	$\Delta\lambda\gamma\beta^2$
0	$\pm\ \pm$ $0\ 0$	$-\gamma^{-2}\cos\theta$ $-2\gamma^{-2}\cos\theta$	0	0

3. *Unitarity constraints for anomalous form factors*

Tree level unitarity does not allow any constant anomalous couplings between three neutral gauge bosons. If, however, the Z bosons are composite objects then the form factors are functions of the virtual mass of the off-shell particle $M_V^2 = s$, $f_i^V = f_i^V(s)$ which vanish for $s \to \infty$. To find the unitarity bounds for the energy dependent form factors $f_i^V(s)$ we shall analyse unitarity constraints for partial waves amplitudes in the process $f\bar{f} \to ZZ$. Each anomalous coupling will give a contribution to the $J = 1$ partial wave. For high energy the SM part may be neglected and the unitarity condition for $J = 1$ partial wave will give the bounds for $f_i^V(s)$. Using a calculation procedure similar to that presented in Ref. [11] we found the following bounds for Z

$$\{(f_1^Z)^2 + \beta^2 (f_2^Z)^2\}^{1/2} \leqslant \frac{\sqrt{3}\sin\theta_W \cos\theta_W}{\sqrt{10}\,\alpha\beta^{3/2}\gamma^3} = L_Z \tag{3.1}$$

and for γ

$$\{(f_1^\gamma)^2 + \beta^2 (f_2^\gamma)^2\}^{1/2} \leqslant \frac{\sqrt{3}\,(3 - 6\sin^2\theta_W + 8\sin^4\theta_W)^{1/2}}{4\sqrt{5}\,\alpha\beta^{3/2}\gamma^3} = L_\gamma. \tag{3.2}$$

Assuming that no cancellation occurs between different anomalous couplings, we can now find unitarity bounds for each f_i^V

$$|f_1^V| \leqslant L_V, \quad |f_2^V| \leqslant \frac{L_V}{\beta} \quad \text{for} \quad V = Z \text{ and } \gamma. \tag{3.3}$$

For LEP II energies ($\sqrt{s} = 200$ GeV) with the parameters $\alpha^{-1} = 137.03604$, $M_Z = 93$ GeV and $\sin^2\theta_W = 0.226$ we find the following unitarity bounds

$$|f_1^Z| \leqslant 113, \quad |f_2^Z| \leqslant 308, \quad |f_1^\gamma| \leqslant 137, \quad |f_2^\gamma| \leqslant 373. \tag{3.4}$$

For a large value of s which will be probed at future colliders (LHC, SSC, CLIC), the bounds are stronger, e.g. for CLIC energy, $\sqrt{s} = 2000$ we have

$$|f_1^Z| \text{ and } |f_2^Z| < 0.025, \quad |f_1^\gamma| \text{ and } |f_2^\gamma| < 0.031. \tag{3.5}$$

4. *Observable consequences of the anomalous ZZV* couplings*

In the SM frame the total cross sections σ ($e^+e^- \to ZZ$) $\cong$ 1.1 pb for $\sqrt{s} = 200$ GeV. We expect LEP II to collect an integrated luminosity ~ 500 pb^{-1} [9] so one should be able to detect about 550 ZZ pairs per one year of LEP II running. Detailed investigation of the Z's production and decay thus appears to have poor statistics, so we will give only the results for non-polarized cross sections and beam differential polarization asymmetry. First of all, in Fig. 3 we present the total cross section in the SM and with the highest anomalous couplings in agreement with the unitarity bounds (3.3). If the Z boson is composite the measured total cross section should be somewhere between the two lines. The dashed

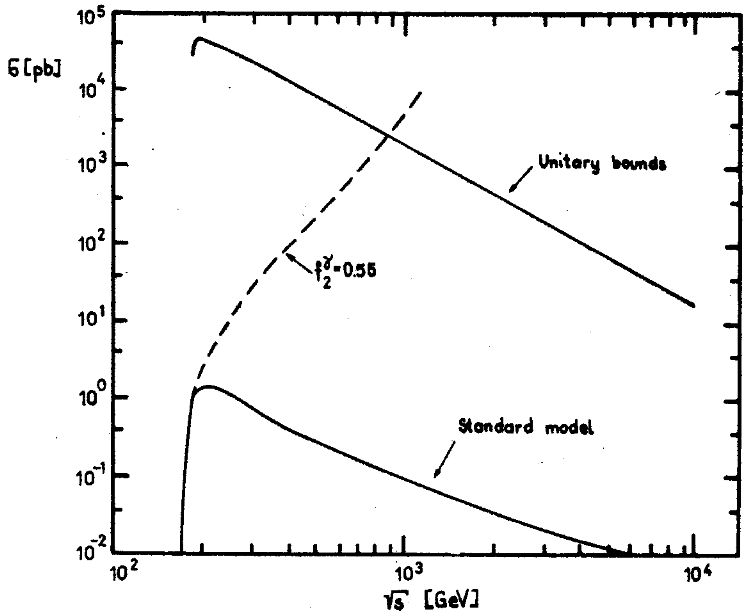

Fig. 3. Total cross section for $e^+e^- \to ZZ$ in the standard model and with the anomalous form factor in agreement with the unitarity bounds. Dashed line gives σ_{total} with constant form factors $f_2^\gamma = 0.55$, $f_1^\gamma = 0$, $f_i^Z = 0$

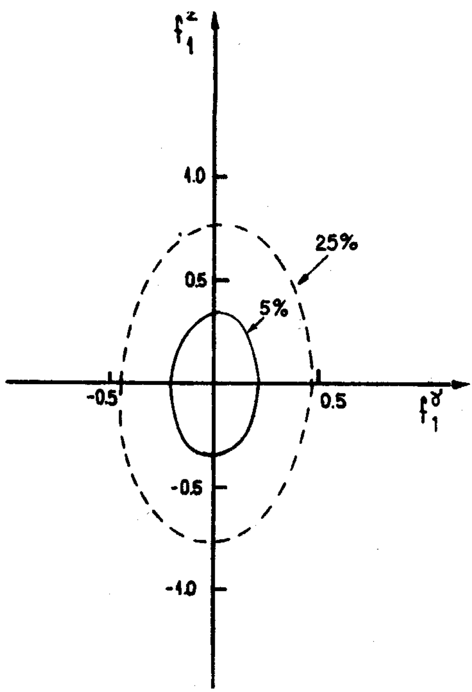

Fig. 4. Effects of anomalous three-neutral-boson couplings on the integrated cross section. The contour plot in the *CP*-odd form factors f_2^γ and f_i^Z plane for 5% (solid line) and 25% (dashed line) deviation from the standard model

line gives the cross section which for LEP II energy differs from the SM value by 5%. For this constant form factors unitarity is broken for $\sqrt{s} \approx 850$ GeV.

In Fig. 4 we present the contour plots in the f_1^γ, f_1^Z plane where the total cross section for $\sqrt{s} = 200$ GeV differs from the SM cross section by 5% (solid line) and 25% (dashed line). Typical values are $|f_1^\gamma| < 0.2$ and $|f_1^Z| < 0.35$ for 5% ($|f_1^\gamma| < 0.45$ $|f_1^Z| < 0.75$ for 25%). Similar ellipse-type curves in the f_2^γ, f_2^Z plane are presented in Fig. 5. Because of the additional β factor in the M_{s_2} reduced amplitudes (see Table I) the typical values are now larger, i.e. $|f_2^\gamma| < 0.55$, $|f_2^Z| < 1$ for 5% and $|f_2^\gamma| < 1.2$, $|f_2^Z| < 2$ for 25%.

In Fig. 6a we depict the non-polarized differential cross section for the various values of the f_i^V form factors taking the 5% deviation from the standard cross section at $\sqrt{s} = 200$ GeV. The CP-even form factors interfere with the standard Born amplitudes

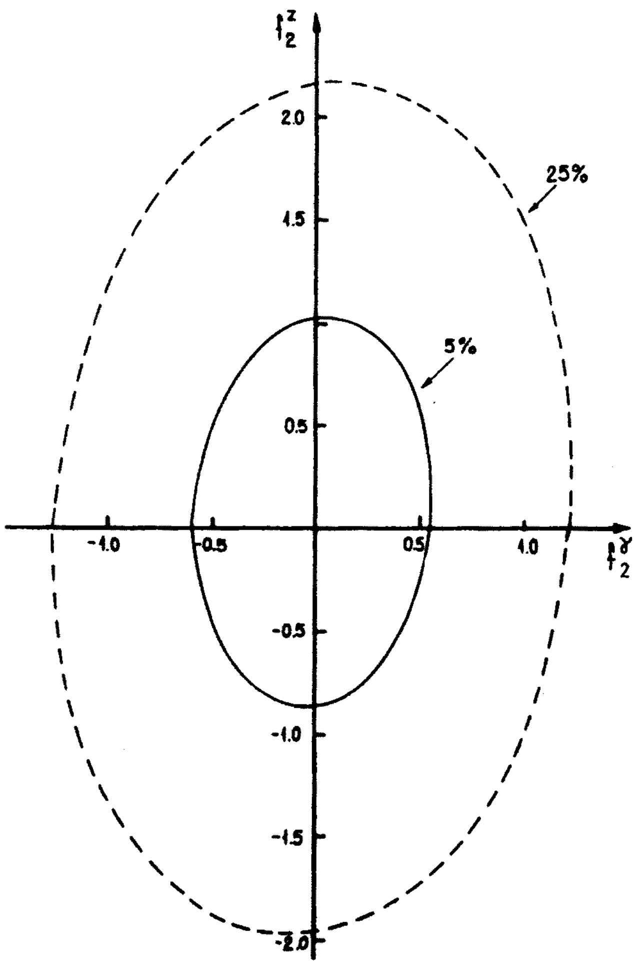

Fig. 5. Effects of the anomalous CP-even $ZZ\gamma$ couplings on the integrated cross section. The contour plot in the f_2^γ and f_2^Z plane for 5% (solid line) and 25% (dashed line) deviation from the standard model

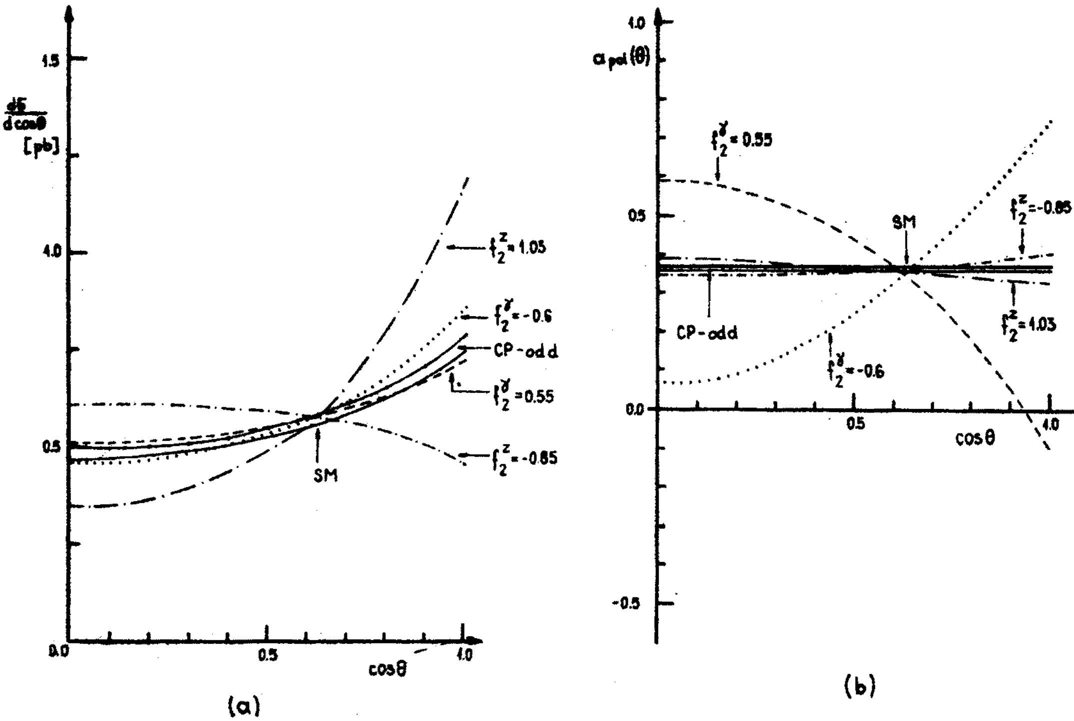

Fig. 6. Differential cross section (Fig. 6a) and differential polarization asymmetry (Fig. 6b) for various anomalous couplings as indicated in Fig. 4 which give 5% deviation from the standard model

and $\dfrac{d\sigma}{d\cos\theta}$ is markedly dependent on the f_2^V values. For $f_2^Z = 1.03, f_2^\gamma = 0$, $\dfrac{d\sigma}{d\cos\theta}$ has a much higher peak in the forward direction (in comparison with the SM), but for $f_1^\gamma = 0, f_2^Z = -0.85$. there is a minimum in the forward direction. The *CP*-odd form factors do not interfere with the Born amplitudes (Table I) and the differential cross section $\dfrac{d\sigma}{d\cos\theta}$ is virtually independent of the f_1^V values, while its shape is the same as in the SM.

In Fig. 6b the differential polarization asymmetry defined by

$$a_{pol}(\theta) = \frac{\sum\limits_{\lambda\lambda'}\left(\dfrac{d\sigma(+;\lambda\lambda')}{d\cos\theta} - \dfrac{d\sigma(-;\lambda\lambda')}{d\cos\theta}\right)}{\dfrac{d\sigma}{d\cos\theta}} \tag{4.1}$$

is plotted. This quantity is of particular interest because at energy a little above the ZZ production threshold it is independent of the radiative corrections [12].

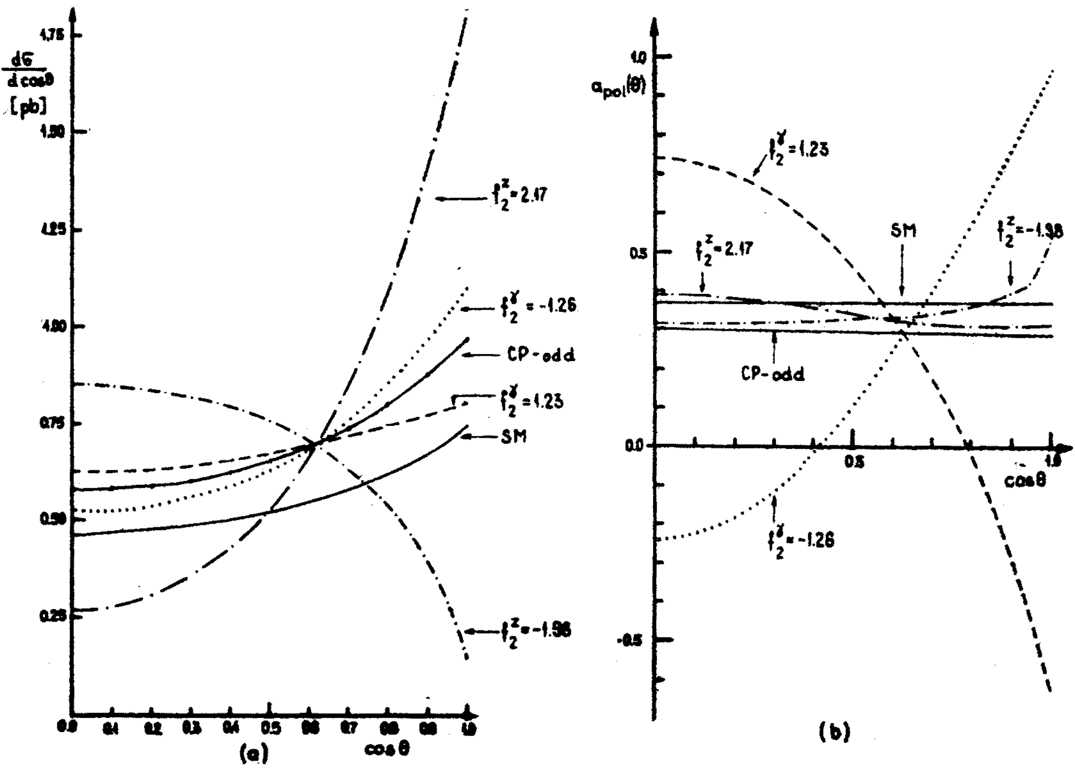

Fig. 7. Differential cross section (Fig. 7a) and differential polarization asymmetry (Fig. 7b) for various anomalous couplings as indicated in Fig. 5 which give 25% deviation from the SM

In the SM Born approximation the polarization asymmetry (4.1) is constant, i.e.

$$a_{\rm pol}^{\rm Born}(\theta) = \frac{\chi_+^4 - \chi_-^4}{\chi_+^4 + \chi_-^4}, \tag{4.2}$$

and any angular dependence of the $a_{\rm pol}(\theta)$ will be caused by anomalous form factors. From Fig. 6b we see that even for small photon form factors $a_{\rm pol}(\theta)$ markedly depends on θ. For the same form factors f_i^γ the deviation from the SM in the differential cross section (Fig. 6a) is small. The *CP*-odd form factors do not have any visible effect on the polarization asymmetry. Similar curves for the 25% deviation from the SM are depicted in Fig. 7a, b.

Without beam polarization we are unable to distinquish γ and Z anomalous couplings (compare Ref. [13]). The polarized cross sections depend only on the combination

$$|f_i^\gamma + \chi_{\Delta\sigma} f_i^Z| = \begin{cases} |f_i^\gamma - 0.655 f_i^Z| & \text{for} \quad \Delta\sigma = +1 \\ |f_i^\gamma + 0.540 f_i^Z| & \text{for} \quad \Delta\sigma = -1, \end{cases} \tag{4.3}$$

therefore to find f_i^γ and f_i^Z we have to measure both combinations in (4.3) separately.

5. Conclusions

A study was made of the experimental consequences of the assumption that in the process $e^+e^- \to ZZ$, Z bo-on are composite particles. Taking the standard model as a guideline we add the assumption that there is a direct coupling between three neutral gauge bosons ZZV* (V = Z or γ). We have taken the couplings ZZV* in the most general form allowed by relativistic invariance and Bose symmetry. We have found all the helicity amplitudes for the $e^+e^- \to ZZ$ process with general ZZV* couplings. They are functions of two *CP*-even (f_2^γ, f_2^Z) and two *CP*-odd (f_1^γ, f_1^Z) form factors. As the number of ZZ pairs produced in LEP II experiments does not allow full polarization analysis, we discuss non-polarized cross sections. We also found that the measurment of differential polarization asymmetry for e^+e^- beams can give valuable information on the photon *CP*-even anomalous form factor. The shape of the differential cross section $\frac{d\sigma}{d\cos\theta}$ markedly depends on the *CP*-even form factors f_2^V. The *CP*-odd form factors f_1^V have a weaker influence on $\frac{d\sigma}{d\cos\theta}$ and can cause only an overall increase in the cross section without changing its shape.

We have also found the unitarity bounds for $f_i^V(s)$ as a function of energy s which follows from unitarity condition for partial wave amplitudes. There is a large difference between the standard model cross section and the one limited by unitarity, allowing much space for compositness.

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