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ANOMALOUS EFFECTS IN e^+e^- ANNIHILATION INTO BOSON PAIRS:

(II) $e^+e^- \rightarrow ZZ, \gamma Z, \gamma\gamma$

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A B S T R A C T

In application of the general procedure defined in I, we analyze various kinds of anomalous effects which could appear either in the leptonic or in the bosonic sector of the reactions $e^+e^- \rightarrow ZZ, \gamma Z$ and $\gamma\gamma$: excited electron, excited vector boson or isoscalar partner, anomalous three-neutral boson couplings, residual contact terms involving transverse or longitudinal Z-components. Results are given in view of SLC, LEP and future linear colliders.

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1. INTRODUCTION

Two-boson channels are well known to be the dedicated place to test the true nature of the intermediate bosons $W^\pm$ and Z^0 . The study of the reactions $e^+e^- \rightarrow VV'$ ($V, V'=W^\pm, Z^0, \gamma$) is an important part of the program of LEP 200¹⁾ and of the projects for high energy linear e^+e^- colliders²⁾. In a first paper³⁾ (hereby referred to as I) we have analyzed in detail the case of $e^+e^- \rightarrow W^+W^-$. We now present an analysis of the neutral cases $e^+e^- \rightarrow ZZ, \gamma Z$ and $\gamma\gamma$. This will obviously complete the study of the gauge boson sector. In addition there are specific tests of the neutral sector, which, in the standard picture, differ essentially from the charged one by the absence of Yang-Mills three-boson couplings. The reaction $e^+e^- \rightarrow \gamma\gamma$ has been since a long time recognized as a remarkable place for QED tests and searches for a possible electron substructure⁴⁾. Higher energies allow us to reach a deeper level in a possible anomaly in the leptonic sector. The reactions $e^+e^- \rightarrow ZZ$ and γZ will give similar tests with a new probe and different chiral structures. We study the effects of an excited electron exchange and of a residual interaction due for example to electron subconstituent rearrangements.

We then develop the tests in the bosonic sector. Anomalous three-neutral boson couplings $ZZZ, ZZ\gamma, Z\gamma\gamma$ can be constructed when at least one boson is off-shell⁵⁾. Contrarily to the case of a Z' gauge boson corresponding to any extension of the standard gauge group, an excited vector boson Z^* or an isoscalar partner Y can couple to ZZ and γZ . So with $e^+e^- \rightarrow ZZ$ and γZ we have an interesting possibility of testing the nature of any such new candidate. Finally if the Z^0 is non-standard, new interactions involving its longitudinal components can appear. For example, strong ZZ final state interactions (as the consequence of a strongly interacting bosonic sector⁶⁾) will especially affect the process $e^+e^- \rightarrow Z_L Z_L$. A comparison with the behaviour of $e^+e^- \rightarrow \gamma Z_L$ will then be certainly fruitful. Notice first that the reaction $e^+e^- \rightarrow \gamma Z$ is already accessible at SLC and LEP I and secondly that all three neutral processes are particularly easy to detect. Let us finally remark that all anomalous terms introduced in $e^+e^- \rightarrow \gamma Z$ would also modify the decay process $Z \rightarrow e^+e^-\gamma$. Some of them had already been discussed in connection with the first radiative events observed in 1983/84 by UA1 and UA2⁷⁾. A complete analysis could be done using our set of invariant amplitudes. The prospect of measuring an anomalous behaviour of $Z \rightarrow \mu^+\mu^-\gamma$ at LEP as compared to the standard bremsstrahlung has been done recently⁸⁾. The sensitivity seems to be limited to an anomalous

contribution to the branching ratio $B(Z \rightarrow \mu^+\mu^-\gamma)$ of the order of 10^{-5} . This corresponds to a typical scale of the order of 100 GeV. Assuming e - μ universality this means that $e^+e^- \rightarrow \gamma Z$ at LEP II will be much more powerful for the search of anomalous effects than $Z \rightarrow ee\gamma$ or $\mu\mu\gamma$ at the Z peak.

The kinematical techniques for analyzing the various amplitudes and computing the cross-sections and angular distributions for the different vector boson polarization states had already been given in I. In section 2, we just express the standard $e^+e^- \rightarrow ZZ$, γZ and $\gamma\gamma$ amplitudes in terms of our basic set of invariant forms. In section 3, we proceed to the analysis of the anomalous effects classified with respect to the sector from which they originate:

Class A: anomalous effects in the leptonic sector, keeping Z as a true gauge boson: excited electron (e^*), gauge invariant e^+e^-VV' residual interactions (transverse-transverse terms).

Class B: anomalous effects in the bosonic sector with three-neutral boson couplings, excited Z^* or isoscalar Y partner formation or non-gauge invariant e^+e^-VV' residual interactions involving one or two longitudinal components (in all cases we keep the photon as a true massless gauge particle).

Following the same procedure as that already used in I, we discuss the observability of these effects in terms of effective scales Λ , firstly at SLC and LEP and secondly at very high energy linear e^+e^- colliders in the TeV range.

2. STANDARD CONTRIBUTIONS TO $e^+e^- \rightarrow ZZ$, γZ AND $\gamma\gamma$

In these three reactions the standard amplitude is just the sum of electron exchange in the t- and in the u-channels. The resulting cross-section for $e^+e^- \rightarrow \gamma\gamma$ is known since a very long time⁹⁾. The ones for $e^+e^- \rightarrow ZZ$ and γZ have recently been expressed in various forms¹⁰⁾⁻¹²⁾. For the discussion of the effects of the various anomalous terms that we shall introduce in the next sections, it is very convenient to decompose these standard amplitudes on the set of invariant forms N_i defined in I. The result is:

$e^+e^- \rightarrow ZZ$

$$R = -\frac{e^2}{ut} \left\{ \frac{M_Z^2}{s} (u-t)(N_1+N_2-N_3-N_4) + u(N_2-N_3+N_5) + t(N_4-N_1-N_5) \right. \\ \left. + 2\left(1 - 2\frac{M_Z^2}{s}\right)(N_6-N_7) \right\} (a^Z + b^Z - 2a^Z b^Z \gamma^5) \quad (1)$$

$e^+e^- \rightarrow \gamma Z$

$$R = -\frac{e^2}{ut} \left\{ \frac{M_Z^2}{s} (u(N_2-N_4) + t(N_3-N_1)) + u(N_2-N_3+N_5) + t(N_4-N_1-N_5) \right. \\ \left. + 2\left(1 - \frac{M_Z^2}{s}\right)(N_6-N_7) \right\} (-a^Z + b^Z \gamma^5) \quad (2)$$

$e^+e^- \rightarrow \gamma\gamma$

$$R = -\frac{e^2}{ut} \left\{ u(N_2-N_3+N_5) + t(N_4-N_1-N_5) + 2(N_6-N_7) \right\} \quad (3)$$

where s, t, u are the usual Mandelstam variables and a^Z, b^Z are the standard Zee couplings:

$$a^Z = \frac{-1 + 4 \sin^2 \theta_W}{2 \sin 2 \theta_W}, \quad b^Z = \frac{-1}{2 \sin 2 \theta_W} \quad (4)$$

The Bose symmetry is apparent in the ZZ and $\gamma\gamma$ cases. We also check that the three above amplitudes are purely transverse-transverse (TT), in a rigorous way for $\gamma\gamma$ and in the ($M_Z^2/s \rightarrow 0$) limit for ZZ . We present in Figs 1a, 1b and 1c respectively the behaviour of the total cross-sections with energy and the angular distributions at $\sqrt{s} = 190$ GeV and $\sqrt{s} = 2$ TeV for the three reactions $e^+e^- \rightarrow ZZ, \gamma Z, \gamma\gamma$ and $e^+e^- \rightarrow W^+W^-$ for comparison. For $\gamma\gamma$ and γZ we have decided to cut the angular distribution at an angle $\theta_\gamma = 5^\circ$ with respect to the e^- -beam direction.

The four reactions obviously differ by their thresholds ($\sqrt{s} = 92.6$ GeV for γZ , $\sqrt{s} = 163.6$ GeV for W^+W^- and $\sqrt{s} = 185.2$ GeV for ZZ). Above these thresholds ($\sqrt{s} > 200$ GeV) we observe the following hierarchy: $\sigma(W^+W^-) > \sigma(\gamma\gamma) > \sigma(\gamma Z) > \sigma(ZZ)$. At $\sqrt{s} = 190$ GeV, angular distributions for $\gamma\gamma$ and γZ exhibit the typical forward peaking due to electron exchange and massless photons. At this energy the ZZ angular distribution is almost flat due to the vicinity of the threshold. At higher energy it will also exhibit a forward peaking although less pronounced than for $\gamma\gamma$ and γZ . All these distributions are symmetric in $\cos\theta$ due to Bose symmetry for $\gamma\gamma$ and ZZ and to CP invariance for γZ .

At SLC and LEP I only $e^+e^- \rightarrow \gamma\gamma$ and γZ are accessible. Because of the standard forward peaking, the search of anomalous terms in these reactions will

be easier in the central region ($\theta \approx 90^\circ$). At LEP II, the opening of the ZZ channel with a much smaller standard contribution will allow us to proceed to new tests which will be more sensitive to the presence of such terms in the whole angular domain.

3. ANOMALOUS $e^+e^- \rightarrow ZZ, \gamma Z$ AND $\gamma\gamma$ AMPLITUDES

We follow the procedure already used in the study of $e^+e^- \rightarrow W^+W^-$. We separate the anomalous terms into two classes corresponding to the existence of new phenomena either in the leptonic or in the bosonic sector.

3.1 Class A: Standard Z boson

The introduction of anomalous e^+ and e^- properties while keeping Z as a true gauge boson will lead to the appearance of new transverse-transverse terms in the $e^+e^- \rightarrow ZZ, \gamma Z$ and $\gamma\gamma$ amplitudes. For example an $e^\pm$ substructure through sub-constituent rearrangements controlled by a high compositeness scale can generate e^+e^- -two boson contact (or "sea-gull") terms we shall study below. One peculiar consequence of $e^\pm$ substructure is also the possible existence of excited e^* states with a mass much lower than the compositeness scale. The reactions $e^+e^- \rightarrow ee\gamma, ee\gamma\gamma$ and $\gamma\gamma$ studied at PEP and PETRA already exclude some limited domain in e^* mass and coupling¹³⁾. We first show how far these kinds of limits can be pushed with the help of the above reactions.

3.1.1 Excited electron

We use the gauge invariant $e^*e\gamma, e^*eZ$ couplings similar to the one first introduced by Low¹⁴⁾ and then extended with a more general chiral structure¹⁵⁾:

$$\mathcal{L} = \frac{g}{2\Lambda} \bar{\psi}_{e^*} \sigma^{\mu\nu} (c - d\gamma_5) \psi_e F_{\mu\nu} + h.c. \quad (5)$$

Summing the e^* exchange in t- and u-channels one obtains the amplitude:

$$\begin{aligned} \mathcal{R} = & \frac{g^2}{\Lambda^2 s} \left\{ \left[N_1 t(t-m_1^2) - N_4 t(t-m_2^2) - N_2 t(u-m_1^2) + N_3 t(u-m_2^2) - N_5 t s \right. \right. \\ & \left. \left. + N_6 (2t+4s) - 2tN_7 \right] (c_1 c_2^* + d_1 d_2^* - (c_1 d_2^* + d_1 c_2^*) \gamma^5) \right. \\ & \left. - m_{e^*} [stI_1 + 2(m_1^2 + m_2^2 - t)I_2 - 2tI_3 + 2(m_2^2 - t)I_4 + 2(m_1^2 - t)I_5 \right. \end{aligned}$$

$$\begin{aligned}
& + \frac{2}{m_1^2 m_2^2 - u t} \left(t(m_1^2 - t) I_6 + (2 m_1^2 m_2^2 - t(u + m_1^2)) I_7 - (2 m_1^2 m_2^2 - t(u + m_2^2)) I_8 \right. \\
& + t(t - m_2^2) I_9 \left. \right) (c_1 c_2^* - d_1 d_2^* + (c_1 d_2^* - d_1 c_2^*) \gamma^5) \left. \right\} \frac{1}{t - m_{e^*}^2} \\
& + \left\{ [N_3 u(u - m_2^2) - N_2 u(u - m_1^2) - N_4 u(t - m_2^2) + N_1 u(t - m_1^2) + N_5 u s \right. \\
& + 2 u N_6 - N_7 (2u + 4s)] (c_1^* c_2 + d_1^* d_2 - (c_1^* d_2 + d_1^* c_2) \gamma^5) \\
& - m_{e^*} [s u I_1 + 2(m_1^2 + m_2^2 - u) I_3 - 2u I_2 + 2(m_1^2 - u) I_4 + 2(m_2^2 - u) I_5 \\
& + \frac{2}{m_1^2 m_2^2 - u t} (u(u - m_2^2) I_8 - (2 m_1^2 m_2^2 - u(t + m_2^2)) I_9 + (2 m_1^2 m_2^2 - u(t + m_1^2)) I_6 \\
& - u(u - m_1^2) I_7 \left. \right] (c_1^* c_2 - d_1^* d_2 - (c_1^* d_2 - d_1^* c_2) \gamma^5) \left. \right\} \frac{1}{u - m_{e^*}^2} \quad (6)
\end{aligned}$$

This formula applies to any process $e^+e^- \rightarrow V_1 + V_2$ with vector bosons of masses m_1, m_2 and ee^*V_i couplings including the chirality factor $c_i - d_i \gamma^5$. In order to reduce the number of parameters for the following discussion we assume the same values $c - d \gamma^5$ for both $ee^*\gamma$ and ee^*Z couplings. In agreement with our general way of normalizing the scales defined in I we impose $g^2(c^2 + d^2) \equiv 4\pi$. In the above Eq. (6), assuming CP-invariance (i.e. c, d real), the chiral structures of the chirality-conserving and chirality-violating (m_{e^*}) parts are respectively: $c^2 + d^2 - 2cd\gamma^5$ and $c^2 - d^2$. In the illustrations we consider the extreme cases: vector ($c=1, d=0$) or axial ($c=0, d=1$), left ($c=d=1/\sqrt{2}$), right ($c=-d=1/\sqrt{2}$). We first leave unrelated the values of Λ and m_{e^*} and then develop the more usual assumption $\Lambda = m_{e^*}$. Figure 2 shows the separate influence of Λ and m_{e^*} on the total cross-section in the vector or axial case. We have drawn contour plots corresponding to deviations of 5% or 20% to the standard contribution for the three reactions. These choices of chirality are the ones which give the most important effects because the chirality violating parts in Eq. (6) only contribute through $c^2 - d^2$ and thus vanish in the left and right cases. Taking $\Lambda = m_{e^*}$ at the 5% level leads to the bounds (Table 1) $\Lambda = m_{e^*} \gtrsim 1200$ GeV (1000, 1100) in the ZZ ($\gamma Z, \gamma\gamma$) channels. In Fig. 3 we show the behaviour of the total cross-sections in the range $100 \text{ GeV} < \sqrt{s} < 240 \text{ GeV}$ for $\Lambda = m_{e^*} = 400$ and 1200 GeV. Angular distributions at $\sqrt{s} = 190 \text{ GeV}$ are visualized in the ZZ, γZ and $\gamma\gamma$ cases for $\Lambda = 800 \text{ GeV}$ and in the various chirality choices (Figs. 4a, 4b, 4c). Deviations to the standard model appear as expected (see Section 2) isotropically in $e^+e^- \rightarrow ZZ$ and only in the central region in $e^+e^- \rightarrow \gamma Z$ and $\gamma\gamma$. For higher energies we can hope to reach sensitivities on Λ from about 3 TeV (6, 12, 60) at $\sqrt{s} = 500 \text{ GeV}$ (1 TeV, 2 TeV, 10 TeV). A choice of

normalization $\Lambda = m_{e^*}/e$ would lead to curves similar in shape but to larger cross-sections for given values of Λ (see for example Fig. 2). We emphasize that the above bounds only result from considering a 5% deviation from the total cross-section. It is obvious that much higher bounds can be reached if high statistics angular distributions in the central region are available (as it is the case at PEP and PETRA¹³⁾). Throughout this paper we will stick to the above criteria in order to make a consistent comparison between the various sources of anomalous effects.

3.1.2 Gauge invariant contact terms

Using the general classification of contact terms given in I and restricting to chirality and CP-conserving amplitudes we find three basic forms for ZZ and $\gamma\gamma$ (which are Bose symmetric):

$$R'_{\tau\tau} = \frac{g^2}{\Lambda^6} (u-t) \left\{ \frac{s}{2} N_5 + N_6 + N_7 + N_8 + N_9 \right\} (c-d\gamma^5) \quad (7)$$

$$R^2_{\tau\tau} = \frac{g^2}{\Lambda^4} \left\{ \frac{m^2-t}{2} (N_1-N_4) + \frac{m^2-u}{2} (N_3-N_2) + \frac{u-t}{2} N_5 + N_6 - N_7 \right\} (c-d\gamma^5) \quad (8)$$

$$R^4_{\tau\tau} = \frac{g^2}{\Lambda^8} (u-t) \left\{ \frac{u-t}{2} \left(\frac{m^2-t}{2} (N_4-N_1) + \frac{m^2-u}{2} (N_2-N_3) \right) + \frac{(m^2-t)(m^2-u)}{2} N_5 \right. \\ \left. + \frac{s}{2} (N_8 + N_9) \right\} (c-d\gamma^5) \quad (9)$$

where $m \equiv M_Z(ZZ)$ or $0(\gamma\gamma)$, and two ones for γZ , $R^2_{\tau\tau}$ with $m \equiv 0$ and

$$R^3_{\tau\tau} = \frac{g^2}{\Lambda^4} \left\{ -\frac{t}{2} (N_1 + N_4) + \frac{u}{2} (N_2 + N_3) + N_8 - N_9 \right\} (c-d\gamma^5) \quad (10)$$

As in I we normalize the scales by imposing $g^2(c^2+d^2) = 4\pi$. The invariant form used for $Z \rightarrow e^+e^- \gamma$ in Ref. 16) is a special combination of $R^2_{\tau\tau}$ and $R^3_{\tau\tau}$.

The $R^1_{\tau\tau}$, $R^4_{\tau\tau}$ amplitudes are much less sensitive to Λ than $R^2_{\tau\tau}$ because of their additional factor $1/\Lambda^2$ and $1/\Lambda^4$. For this reason it will not be possible at LEP 200 with these amplitudes, $R^1_{\tau\tau}$ and $R^4_{\tau\tau}$, to reach values of Λ larger than 200 GeV in $e^+e^- \rightarrow ZZ$ and 300 GeV in $e^+e^- \rightarrow \gamma\gamma$ while with $R^2_{\tau\tau}$ one can reach 1 TeV. In $e^+e^- \rightarrow \gamma Z$, $R^2_{\tau\tau}$ and $R^3_{\tau\tau}$ have the same dimension in Λ , however, the combination of invariant forms in $R^2_{\tau\tau}$ appears to be similar to the standard one [see Eq. (2) in the $M_Z^2/s \rightarrow 0$ limit] and therefore gives larger interference effects, especially in the axial, left and right cases. This is also the reason for the spectacular interference effects observed with $R^2_{\tau\tau}$ in $e^+e^- \rightarrow ZZ$ and $\gamma\gamma$ for the vector, left and right cases. This is illustrated in Figs. 5a, 5b and 5c, where the effect of $R^2_{\tau\tau}$ on the total cross-section is shown versus Λ at $\sqrt{s} = 190$ GeV for the three reactions $e^+e^- \rightarrow ZZ$, γZ and $\gamma\gamma$. Figure 6 shows the

effect of R_{TT}^2 on the energy behaviour of the total cross-sections for various values of Λ .

Angular distributions are drawn in Figs. 7a, 7b and 7c in order to illustrate a few typical features. In the first one corresponding to the ZZ case, the R_{TT}^2 angular distribution is flat as in the standard model. Because of the (u-t) factor in the definition of R_{TT}^4 the differential cross-section is equal to the standard one at $\theta = 90^\circ$. The interferences are more and more constructive going from the axial to the vector case, the left and right ones lying in between. For the same reasons the R_{TT}^1 differential cross-section coincides with the standard one at $\theta = 90^\circ$ but also at $\theta = 0^\circ$ because it involves only N_i with $i > 5$ (cf. I) leading to a whale-shaped angular distribution. In addition this shape is independent of the chirality choice because this special N_i combination does not interfere with the standard amplitude. These properties of R_{TT}^1 and R_{TT}^4 apply as well to $e^+e^- \rightarrow \gamma\gamma$. Figures 7b and 7c show the effect of the various chirality factors in R_{TT}^2 for $e^+e^- \rightarrow \gamma Z$ and $\gamma\gamma$. It is worth noticing the spectacular behaviour of the angular distribution for the axial case in γZ and the vector case in $\gamma\gamma$ due to an appropriate choice of Λ which maximizes the interference effect.

Typical bounds for Λ are 700 GeV, 1.5 TeV, 3 TeV, 7 TeV, 35 TeV at $\sqrt{s} = 190$ GeV, 500 GeV, 1 TeV, 2 TeV and 10 TeV (cf. the Table).

3.2 Class B: Non-standard Z boson

We now assume that the anomalous effects only occur in the bosonic sector. The main manifestations of a non-standard Z boson in these reactions can be the existence of anomalous three-neutral boson couplings, of excited Z^* or isoscalar Y partners and of new kinds of residual interactions (contact terms) involving in particular longitudinal Z components.

3.2.1 Anomalous three-neutral boson couplings

In the standard case there are no three-neutral boson Yang-Mills couplings at all. When the boson is non-standard (for example a composite particle) such couplings are allowed on the basis of general invariance principles. Spin and statistics considerations (Yang's theorem) impose that many of these couplings vanish when all three bosons are on mass-shell¹¹⁾. This is apparent from the s or $s - m_Z^2$ factors present in the following examples. Imposing CP-conservation one can write^{5),11)} the following effective couplings:

$$Z_V ZZ \quad ie \xi_1 \frac{s-M_Z^2}{M_Z^2} \epsilon^{\mu\nu\sigma} \epsilon_{1\mu} \epsilon_{2\nu} (p_2-p_1)_\sigma \quad (11)$$

$$\gamma_V ZZ \quad ie \xi_2 \frac{s}{M_Z^2} \epsilon^{\mu\nu\sigma} \epsilon_{1\mu} \epsilon_{2\nu} (p_2-p_1)_\sigma \quad (12)$$

$$Z_V \gamma Z \quad -ie \xi_2 \frac{s-M_Z^2}{M_Z^2} \epsilon^{\mu\nu\sigma} \epsilon_{1\mu} \epsilon_{2\nu} p_{1\sigma} \quad (13)$$

$$ie \xi_3 \frac{s-M_Z^2}{M_Z^4} \left\{ p_1^\beta \epsilon^{\alpha\beta\mu\nu} p_{1\alpha} p_{2\beta} \epsilon_{1\mu} \epsilon_{2\nu} - \frac{s}{2} \epsilon^{\mu\nu\rho\alpha} \epsilon_{2\mu} \epsilon_{1\nu} p_{1\alpha} \right\} \quad (14)$$

$$\gamma_V \gamma Z \quad -ie^2 \xi_4 \frac{s}{M_Z^2} \epsilon^{\mu\nu\sigma} \epsilon_{1\mu} \epsilon_{2\nu} p_{1\sigma} \quad (15)$$

$$ie^2 \xi_5 \frac{s}{M_Z^4} \epsilon^{\mu\tau\sigma} \epsilon_{1\mu} p_{2\tau} p_{1\sigma} (\epsilon_2 \cdot p_1) \quad (16)$$

(in these last two cases ϵ_1 , p_1 and ϵ_2 , p_2 respectively refer to the final photon and Z boson).

These couplings constitute a complete set which satisfy CP-conservation, gauge invariance at the photon vertices and Bose statistics for identical particles. There is no possible effect in $e^+e^- \rightarrow \gamma\gamma$. In $e^+e^- \rightarrow ZZ$ and γZ , one obtains the resulting amplitudes:

$e^+e^- \rightarrow ZZ$

$$R = -\frac{4e^2}{sM_Z^2} \left\{ N_6 - N_7 + \frac{u-t}{4} (N_4 + N_3 - N_1 - N_2) \right\} (\xi_1 (a^2 \gamma^5 - b^2) - \xi_2 \gamma^5) \quad (17)$$

$e^+e^- \rightarrow \gamma Z$

$$\begin{aligned} R = & -\frac{2e^2}{sM_Z^2} \left\{ N_6 - N_7 - \frac{t}{2} (N_3 - N_1) + \frac{u}{2} (N_4 - N_2) \right\} (\xi_2 (a^2 \gamma^5 - b^2) - e \xi_4 \gamma^5) \\ & - \frac{e^2 \xi_3}{2M_Z^4} \left\{ (N_1 t - N_2 u) \frac{M_Z^2}{s} + N_3 (u - t (1 + \frac{M_Z^2}{s})) + N_4 (u (1 + \frac{M_Z^2}{s}) - t) + 2 (1 + \frac{M_Z^2}{s}) (N_6 - N_7) \right. \\ & \left. + 2 (N_8 - N_9) \right\} (a^2 \gamma^5 - b^2) + \frac{e^3 \xi_5}{M_Z^4} \left\{ N_6 + N_8 - N_7 - N_9 + \frac{u-t}{2} (N_3 + N_4) \right\} \gamma^5 \end{aligned} \quad (18)$$

For $e^+e^- \rightarrow ZZ$ contour plots in the ξ_1 , ξ_2 plane are drawn in Fig. 8a for 5% and 20% deviations from the standard cross-section at $\sqrt{s} = 190$ GeV. Typical upper bounds from a 5% deviation are $|\xi_1| < 2$ and $|\xi_2| < 3$.

In Fig. 8b we have plotted the individual effects of the four couplings which can occur in $e^+e^- \rightarrow \gamma Z$. The dominance of the effect of ξ_3 over that of ξ_2 is due to the extra s/M_Z^2 factor appearing in definition (14). Its effects is

also larger than that of ξ_4 and ξ_5 because of the normalization to e^2 appearing for the two-photon couplings in Eqs. (15) and (16). The smallest value of ξ_3 which can be detected at $\sqrt{s} = 190$ GeV is of the order of 0.2. Figure 9 describes the energy behaviour of the total cross-section for the two processes. For the $e^+e^- \rightarrow ZZ$ reaction the angular distribution presents a destructive interference in the $\theta = 90^\circ$ region and a constructive one in the forward direction (for positive values of ξ_1 and ξ_2), cf. Fig. 10a. In the case of $e^+e^- \rightarrow \gamma Z$ the effects are, like in the previous examples, essentially localized in the central region (Fig. 10b). At CLIC energies one becomes sensitive to very small values of the ξ parameters. It is then more convenient to rescale their definition as follows:

$$e \frac{\xi_{1,2}}{M_Z^2} \equiv \frac{\sqrt{4\pi}}{\Lambda^2}, \quad e \frac{\xi_3}{M_Z^4} \equiv \frac{\sqrt{4\pi}}{\Lambda^4}, \quad e^2 \frac{\xi_4}{M_Z^2} \equiv \frac{\sqrt{4\pi}}{\Lambda^2}, \quad e^2 \frac{\xi_5}{M_Z^4} \equiv \frac{\sqrt{4\pi}}{\Lambda^4} \quad (19)$$

We then get bounds on Λ of the order of 3 TeV (10 TeV, 30 TeV, 300 TeV) at $\sqrt{s} = 0.5, 1, 2, 10$ TeV (see the Table).

3.2.2 Excited vector bosons and other neutral partners of the Z^0

Let us call X any kind of (composite) higher neutral vector boson. It can, for example, represent either an excited Z^{*} boson or an isoscalar Y partner. Again we restrict to CP-conserving couplings and impose gauge invariance in the case of a photon and Bose statistics for identical particles. There is no possible $X\gamma\gamma$ coupling with two real photons, but one gets one XZZ coupling:

$$2ig_3^X \in \mathcal{P}^{\mu\nu\sigma} \epsilon_{1\mu} \epsilon_{2\nu} (p_2 - p_1)_\sigma \quad (20)$$

and two $X\gamma Z$ couplings (γ and Z are labelled as 1 and 2):

$$ie \frac{g_1^X}{M_X^2} \in \mathcal{P}^{\mu\alpha\beta} \epsilon_{1\mu} p_{2\alpha} p_{1\beta} (\epsilon_2 \cdot p_1) \quad (21)$$

$$-ie g_2^X \in \mathcal{P}^{\mu\nu\alpha} \epsilon_{1\mu} \epsilon_{2\nu} p_{1\alpha} \quad (22)$$

The resulting amplitudes read:

$e^+e^- \rightarrow ZZ$

$$\mathcal{R} = - \frac{8eg_3^X}{s D_X(s)} \left\{ N_6 - N_7 + \frac{u-t}{4} (N_4 + N_3 - N_1 - N_2) \right\} (a^X s^5 - b^X) \quad (23)$$

$e^+e^- \rightarrow \gamma Z$

$$R = \frac{e^2 g_1^X}{M_X^2 \mathcal{D}_X(s)} \left\{ \frac{u-t}{2} (N_3 + N_4) + N_6 - N_7 + N_8 - N_9 \right\} (a^X \gamma^5 - b^X) \\ - \frac{e^2 g_2^X}{s \mathcal{D}_X(s)} \left\{ 2(N_6 - N_7) - t(N_3 - N_1) + u(N_4 - N_2) \right\} (a^X \gamma^5 - b^X) \quad (24)$$

Again we normalize the couplings through $g_1^{X^2} [(a^X)^2 + (b^X)^2] = 4\pi$.

The observation of a peak either in $e^+e^- \rightarrow \gamma Z$ or in $e^+e^- \rightarrow ZZ$ would be a clear evidence for non-gauge boson partner of the Z^0 . A comparison of its rates and angular distributions in the three channels γZ , ZZ and W^+W^- would then allow to determine its isospin nature and the type of couplings.

Figure 11 shows the energy dependence of the total cross-sections in the channels ZZ and γZ . When the X mass is higher than the available c.m. energy, the interference with the standard amplitude is illustrated in Fig. 12a for $e^+e^- \rightarrow ZZ$. The vector coupling ($a^X=1$, $b^X=0$) interferes very little, the axial and left ones have positive interferences in the forward region and negative ones in the central region. The situation is opposite for the right case due to the change of sign in b^X . All these properties are the ones which can be expected from Eq. (23). The corresponding interference pattern for $e^+e^- \gamma Z$ is shown in Fig. 12b. The deviations appear in the central region in a way which depends on the nature of the coupling (g_1^X or g_2^X) and on the chiral structure (a^X , b^X). At LEP 200 one should detect excited boson effects up to $m_X = 400$ GeV. This value could be pushed to 6 TeV (20, 50, 600 TeV) at $\sqrt{s} = 0.5, 1, 2$ and 10 TeV (Table 1).

3.2.3 Longitudinal contact terms

If the Z boson is non-standard, residual interactions involving longitudinal Z components may appear. According to the classification given in I, in the case of $e^+e^- \rightarrow ZZ$ there are two chiral CP-conserving, Bose symmetric, transverse longitudinal contact terms:

$$R_{TL}^1 = \frac{g^2}{\Lambda^6} (u-t) \left\{ 2(N_6 + N_7 + N_8 + N_9) - \frac{s}{2} (N_1 + N_2 - N_3 - N_4) \right\} (c-d\gamma^5) \quad (25)$$

$$R_{TL}^2 = \frac{g^2}{\Lambda^4} \left\{ 2(N_6 - N_7) + \frac{t-u}{2} (N_1 + N_2 - N_3 - N_4) \right\} (c-d\gamma^5) \quad (26)$$

and one longitudinal-longitudinal:

$$R_{LL} = \frac{g^2}{\Lambda^6} (u-t) (N_6 + N_7 + N_8 + N_9) (c-d\gamma^5) \quad (27)$$

In the case of $e^+e^- \rightarrow \gamma Z$, the photon being necessarily transverse, one finds only one transverse-longitudinal contact term:

$$R_{TL}^3 = \frac{g^2}{\Lambda^4} \left\{ N_6 + N_8 - N_7 - N_9 + \frac{u-t}{2} (N_3 + N_4) \right\} (c-d\gamma^5) \quad (28)$$

Let us first notice that R_{TL}^2 and R_{TL}^3 have a factor $1/\Lambda^4$ whereas R_{TL}^1 and R_{LL} have $1/\Lambda^6$. The former will thus be the most sensitive to Λ as illustrated in Fig. 13. At $\sqrt{s} = 190$ GeV, we reach bounds on Λ of the order of 400 GeV with both reactions. We can appreciate the sensitivity at other energies from Fig. 14. Angular distributions are substantially different (Fig. 15) for the three amplitudes of $e^+e^- \rightarrow ZZ$. $R_{TL}^{1,2}$ show very strong interferences with the standard model especially in the forward region. The R_{TL}^1 distribution coincides with the standard one at $\theta = 90^\circ$ because of its $u-t$ factor. The LL distribution is whale-shaped as was the case for R_{TT}^1 . In $e^+e^- \rightarrow \gamma Z$, the angular distribution shows an interference pattern rather similar to previous ones (cf. for example Fig. 12b). The departure from the standard cross-section in the central region increases from the axial to the left, vector and right chirality combinations. At higher energies one should be able to reach values of Λ larger than in the transverse-transverse cases: 2.6 TeV (6, 13, 100 TeV) at $\sqrt{s} = 0.5, 1, 2, 10$ TeV (cf. the Table).

4 CONCLUSION

In this second part of our general study of anomalous effects in e^+e^- annihilation into boson pairs we have treated the cases of $e^+e^- \rightarrow ZZ$, $Z\gamma$ and $\gamma\gamma$. Working in the same spirit as in I we have separated the effects appearing in the leptonic sector (excited e^* , residual interactions with transverse Z components) from those of the bosonic sector (anomalous three-neutral boson couplings, excited vector boson or isoscalar partner, residual interactions with longitudinal Z components).

The reaction $e^+e^- \rightarrow \gamma\gamma$ will, as at PEP and PETRA, be a useful tool to test possible electron anomalous properties at high energy. Because of the strong forward peaking of the standard angular distribution any anomalous effect will mainly show up for large angle photons ($\theta \approx 90^\circ$). Limits on a high mass excited electron will be pushed up to 600 GeV at SLC or LEP I, 1100 GeV at LEP II and 12 TeV at CLIC, according to our conventions. Any new dynamics can be represented by an effective gauge invariant $e\bar{e}\gamma\gamma$ interaction with a scale Λ . The corresponding upper bounds will be 150 GeV at SLC/LEP I, 700 GeV at LEP II and 7 TeV at CLIC.

The reaction $e^+e^- \rightarrow \gamma Z$ already accessible at SLC/LEP I will give similar bounds on the leptonic sector. However, the presence of the Z boson with its vector and axial couplings will give a deeper insight on the structure of any new effect. This is also the first of the two-boson processes which can give information on the true nature of the Z boson. Four types of CP-conserving anomalous three-boson couplings can be considered. Converting the associated parameters into Λ -type bounds, we get Λ of order 800 GeV at LEP II and 24 TeV at CLIC. These particular terms are difficult to detect at lower energies because of the large standard cross-section. Excited vector boson formation can obviously be seen as a peak in $\sigma(e^+e^- \rightarrow \gamma Z)$ if its mass lies in the available energy domain. Higher mass vector bosons can indirectly be seen through interference with the standard amplitude up to 400 GeV at LEP II and 13 TeV at CLIC. Comparison with the reactions $e^+e^- \rightarrow W^+W^-$ and fermions pairs will allow us to disentangle the case of a new true gauge boson with a composite one. Contact terms involving the longitudinal Z component can also be studied with this reaction. The corresponding effective scales which can be probed are 500 GeV at LEP II and 10 TeV at CLIC.

So far we have only considered CP-conserving interactions. A large variety of CP-violating terms can be written^{3),17)}. In the reactions studied here the most striking effect will be the appearance of a forward-backward asymmetry in $e^+e^- \rightarrow \gamma Z$ (Fig. 16). This cannot appear in $\gamma\gamma$ and ZZ because of Bose statistics. In these processes CP-violation could only be found by looking at the final decay distributions.

The reaction $e^+e^- \rightarrow ZZ$ is characterized by a high threshold very close to LEP II energy giving thus an isotropic angular distribution. In addition, the standard cross-section is smaller than the W^+W^- by a factor 20 even at very high energy. As a consequence, most of the anomalous terms will lead to relatively larger effects than in the previous reactions, cf. the Table. Moreover, this

reaction allows to test some new types of effects like anomalous three Z boson couplings, excited vector boson decays into ZZ, new types of contact terms involving the longitudinal Z component and in particular the possibility of analyzing the very interesting $Z_L Z_L$ channel⁶⁾.

The bounds of the effective scales Λ appear to be of the same order of magnitude as the ones obtained in the W^+W^- channel³⁾. However, the information obtained from the neutral channel is complementary to the charged one. Owing to the large variety of possible anomalous effects, it is very likely that only a detailed comparison of the four reactions will allow to identify the origin of any new phenomenon.

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Anomalous effect	$\sqrt{s}$	Λ_{ZZ}	Λ_{YZ}	Λ_{YY}
e* exchange ($\Lambda \equiv m_{e^*}$) V-case	0.1	-	0.2	0.6
	0.19	1.2	1	1.1
	0.5	4.0	3	3.0
	1	7.6	6	6.0
	2	15	12	12.0
	10	80	60	60
Transverse- transverse contact terms	0.1	-	0.15 (R_{TT}^2) _A	0.15 (R_{TT}^2) _V
	0.19	1.0 (R_{TT}^2) _V	0.7 "	0.7 "
	0.5	2.3 "	1.5 "	1.8 "
	1	4.4 "	3 "	3.6 "
	2	8 "	7 "	7.2 "
	10	33 "	35 "	38 "
Anomalous three-boson couplings	0.19	0.23	0.8 (ξ_4)	
	0.5	4.2	2.4 "	
	1	13.0	8 "	
	2	33.0	24 "	
	10	400	280 "	
Excited bosons	0.19	0.38 (g_3) _R	0.4 (g_2) _A	
	0.5	6 "	1.7 "	
	1	20 "	5 "	
	2	48 "	13 "	
	10	600 "	150 "	
Longitudinal contact terms	0.19	0.35 (R_{TL}^2) _V	0.5 (R_{TL}^3) _V	
	0.5	2.6 "	1.9 "	
	1	6 "	4.5 "	
	2	13 "	10 "	
	10	100 "	85 "	

TABLE 1

Limiting values of effective scales (in TeV) obtained from a typical 5% departure to the standard cross-section. This is a conservative estimate since better bounds could in principle be derived using appropriate cuts on the angular distribution. The above values refer to the choice of chirality and specific invariant form (quoted in parentheses) which leads to the best bound.

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FIGURE CAPTIONS

- Fig. 1 Standard model cross-sections for e^+e^- into two gauge bosons:
a) Integrated cross-section versus the CM-energy;
b) Angular distributions at $\sqrt{s} = 190$ GeV;
c) Angular distributions at $\sqrt{s} = 2$ TeV.
- Fig. 2 Contour plot corresponding to e^* effect with vector coupling [5%, (20%) deviation for upper (lower) curves] on the integrated cross-sections at $\sqrt{s} = 190$ GeV; dashed curve: ZZ; dotted-dashed curve: γZ ; full curve: $\gamma\gamma$.
- Fig. 3 Integrated cross-sections versus the energy including the e^* -exchange with vector coupling for several values of $\Lambda = m_{e^*}$. From now on the thick curves always refer to the standard model predictions.
- Fig. 4 Angular distributions at $\sqrt{s} = 190$ GeV including the e^* -exchange with $\Lambda = m_{e^*} = 800$ GeV for various choices of chirality:
a) ZZ;
b) γZ ;
c) $\gamma\gamma$.
- Fig. 5 Integrated cross-sections at $\sqrt{s} = 190$ GeV versus Λ , including the R_{TT}^2 contact term for various choices of chirality:
a) ZZ;
b) γZ ;
c) $\gamma\gamma$.
- Fig. 6 Integrated cross-sections versus the energy, including R_{TT}^2 for various choices of Λ ; ZZ, vector case; γZ , right case; $\gamma\gamma$, vector case.
- Fig. 7 Angular distributions at $\sqrt{s} = 190$ GeV, including various transverse-transverse contact terms:
a) ZZ; full curve: R_{TT}^1 , any case of chirality, $\Lambda = 160$ GeV; dashed curve: R_{TT}^2 , axial coupling, $\Lambda = 400$ GeV; dotted-dashed curves: R_{TT}^4 , vector and axial couplings, $\Lambda = 170$ GeV;
b) γZ ; R_{TT}^2 with $\Lambda = 320$ GeV and for various choices of chirality;
c) $\gamma\gamma$; R_{TT}^2 with $\Lambda = 290$ GeV and for various choices of chirality.

Fig. 8 Effects of anomalous three-neutral boson couplings on the integrated cross-sections at $\sqrt{s} = 190$ GeV:

- a) ZZ; contour plot in the ξ_1, ξ_2 plane for 5% (full curve) and 20% (dashed curve) deviation;
- b) γZ ; individual effect of each of the four possible couplings taken between -1 and +1.

Fig. 9 Integrated cross-sections versus the energy, including individual effects of anomalous three-neutral boson couplings.

Fig. 10 Angular distributions at $\sqrt{s} = 190$ GeV, including individual effects ($\xi_i = 1$) of anomalous three-neutral boson couplings:

- a) ZZ;
- b) γZ .

Fig. 11 Integrated cross-sections versus the energy, including the effect of a new vector boson X. Deviations of the ZZ cross-section correspond to various choices of M_X , with pure vector coupling. Deviations of the γZ cross-section correspond to two choices of M_X , 150 GeV and 300 GeV and the two types of couplings g_1^X (dashed curves) and g_2^X (dotted-dashed curves).

Fig. 12 Angular distributions at $\sqrt{s} = 190$ GeV, including X-boson exchange with $M_X = 300$ GeV and various chiralities:

- a) ZZ;
- b) γZ ; dashed curves: g_1^X ; dotted-dashed curves: g_2^X .

Fig. 13 Integrated cross-sections at $\sqrt{s} = 190$ GeV versus Λ , including effects of transverse-longitudinal contact terms with pure vector coupling.

Fig. 14 Integrated cross-sections versus the energy, including effects of transverse-longitudinal and longitudinal-longitudinal contact terms. Deviations of the ZZ cross-section correspond to $\Lambda = 300$ GeV; dashed curves: R_{LL} ; dotted-dashed curves: R_{TL}^1 ; dotted-dotted-dashed curve: R_{TL}^2 . Deviations of the γZ cross-section correspond to R_{TL}^3 with vector coupling and various Λ .

Fig. 15 Angular distributions for ZZ at $\sqrt{s} = 190$ GeV, including R_{TL}^1 (dotted-dashed curves) and R_{TL}^2 (dotted-dotted-dashed curves) with $\Lambda = 200$ GeV.

Fig. 16 Angular distributions for γZ at $\sqrt{s} = 190$ GeV, including the effect of the CP-violating contact term R_{TT}^4 with axial coupling and two values of Λ .

Fig. 1a

Fig. 1b

Fig. 1c

Fig. 2

Fig. 3

Fig. 4a

Fig. 4b

Fig. 4c

Fig. 5a

Fig. 5b

Fig. 5c

Fig. 6

Fig. 7a

Fig. 7b

Fig. 7c

Fig. 8a

Fig. 8b

Fig. 9

Fig. 10a

Fig. 10b

Fig. 11

Fig. 12a

Fig. 12b

Fig. 13

Fig. 14

Fig. 15

Fig. 16