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## Possible Nonstandard Effects in $Z\gamma$ Events at LEP2

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### Abstract

We point out that the so-called 'radiative return' events  $e^+e^- \rightarrow Z\gamma$  are suited to the study of nonstandard physics, particularly if the vector bosons are emitted into the central detector region. An effective vertex is constructed which contains the most general gauge invariant  $e^+e^-Z\gamma$  interaction and its phenomenological consequences are examined. Low Energy Constraints on the effective vertex are discussed as well.

## 1. Introduction

In the last decade a huge number of  $Z$ 's has been produced by the LEP1 experiment working on the  $Z$ -pole and the data obtained has been used for high precision tests of the Standard Model and to establish stringent bounds on physics beyond the Standard Model. Subsequently, the LEP2 experiment has started data taking at higher energy with the primary aim of determining the mass and selfinteractions of the  $W$ -bosons. Unfortunately, only a few thousand  $W$ -pairs will be available for this study, because cross sections at LEP2 are generally much smaller than at LEP1, and the bounds on new physics will be correspondingly weak [1].

On the other hand, LEP2 is collecting a relatively large number of events with a very hard photon and an on-shell  $Z$  in the final state which in the Standard Model are produced by Bremsstrahlung of the photon from the  $e^+e^-$  legs. From the experimental point of view the production of  $Z$ 's together with a hard prompt photon is a very clear and pronounced signature. Nevertheless, this class of events is usually not considered very interesting [1], because they seem to lead back to LEP1 physics ('radiative return' to on-shell  $Z$  production). However, it is expected [2] that (very roughly) about 10000  $Z\gamma$  events will be collected until the end of LEP2, with an angle  $\theta$  of the photon larger than 5 degrees with respect to the  $e^+e^-$  beam direction. There will be less of such events in the central region  $\theta > 30^\circ$  of the detector, but still about 1000 of them will be available to the analysis. The primary motivation for the present study is whether at all there is a possibility to use these events in a nonstandard physics discussion.

In our approach we shall use an effective vertex for the  $e^+e^-Z\gamma$  interaction which contains the Standard Model part plus a small admixture of a new contribution. The new contribution will be presented in its most general form, i.e. as a sum of independent spinor and tensor structures. The approach comprises contributions from operators of arbitrary high dimensions. It can also be considered to effectively describe the exchange of new heavy particles or some other exotic mechanism for  $\gamma Z$  production like  $e^+e^- \rightarrow Z^* \rightarrow Z\gamma$  [3].

The new contribution is supposed to be small, of the order of some small coupling constant  $\delta \ll 1$ . Therefore, we will be mainly interested in interference terms between the Standard Model and the new vertices. More precisely, if  $\sigma_{SM}$  is the Standard Model contribution to any differential cross

section and  $\delta\sigma_{NEW}$  is the interference contribution, we shall consider the ratio  $\delta\sigma_{NEW}/\sigma_{SM}$ . To a first approximation it is sufficient to use the lowest order Standard Model result  $\sigma_{LOSM}$  with an on-shell  $Z$  in the calculation of that ratio. We assume that the Standard Model Radiative Corrections are sufficiently small so that only the interference amplitude between the Standard Model Contribution and the Radiative Corrections are relevant. This interference amplitude can be recast in terms of form factors we will introduce later on. New Physics can appear as form factors which do not arise in the Standard Model interference amplitude or as unexpected values for form factors which do arise in the Standard Model interference amplitude.

## 2. Construction of the $e^+e^-Z\gamma$ vertex

The process  $e^+(p_+)e^-(p_-) \rightarrow \gamma(k)Z(p_Z)$  is depicted as a Feynman diagram in Fig. 1a and in a kinematic view in Fig. 1b. The polarization indices of the photon and of the  $Z$  are denoted by  $\alpha$  and  $\mu$ , respectively. We parametrize the momenta as being  $p_{\pm} = \frac{\sqrt{s}}{2}(1, 0, 0, \pm 1)$ ,  $k = E_{\gamma}(1, 0, \sin\theta, \cos\theta)$  and  $p_Z = p_+ + p_- - k$ . For an on-shell  $Z$  ( $p_Z^2 = m_Z^2$ ) one obtains a hard monochromatic photon of (normalized) energy

$$x_{\gamma} \equiv \frac{E_{\gamma}}{\sqrt{s}/2} = 1 - \frac{m_Z^2}{s} \quad (1)$$

which is about  $x_{\gamma} = 0.75-0.8$  at LEP2 energies and goes up to almost 0.97 at an  $e^+e^-$  collider with  $\sqrt{s} = 500$  GeV. As discussed above, an on-shell  $Z$  is a reasonable approximation to study nonstandard effects.  $E_{\gamma}$  being constant, the process' real kinematical variable is the production angle  $\theta$  of the photon. There are essentially 2 regions for photon detection, depending on the polar angle,

- The region collinear to the beam with large bremsstrahlung contributions is dominated by the Standard Model amplitude which has poles at  $(k - p_{\pm})^2 = m_e^2$ .
- The central region of the detector, where the Standard Model cross section has its minimum value, so that one may be sensitive to non-standard physics.

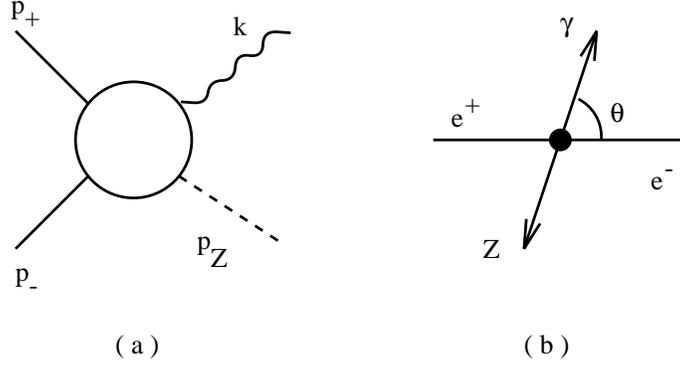


Figure 1:

The amplitude for  $Z\gamma$  production has the general form  $\Gamma_{\mu\alpha}\epsilon_{\mu}^Z\epsilon_{\alpha}^{\gamma}$  where  $\epsilon_{\mu}^Z$  is the polarization vector of the  $Z$  and  $\epsilon_{\alpha}^{\gamma}$  is the polarization vector of the photon. The vertex  $\Gamma_{\mu\alpha}$  may be decomposed as

$$\Gamma_{\mu\alpha} = \Gamma_{\mu\alpha}^{SM} + \delta\Gamma_{\mu\alpha} \quad (2)$$

The first term in this expression is the Standard Model contribution to the vertex

$$\Gamma_{\mu\alpha}^{SM} = -ie^2Q_l\left\{\gamma_{\alpha}\frac{\not{k} - \not{p}_+}{(k - p_+)^2 - m_e^2}\gamma_{\mu}(v_l + a_l\gamma_5) - \gamma_{\mu}(v_l + a_l\gamma_5)\frac{\not{k} - \not{p}_-}{(k - p_-)^2 - m_e^2}\gamma_{\alpha}\right\} \quad (3)$$

where  $a_l = \frac{1}{4s_Wc_W} \approx 0.594$  and  $v_l = -\frac{1}{4s_Wc_W} + \frac{s_W}{c_W} \approx -0.05$  are the vector and axial couplings of the electron to the  $Z$ . Note that the numerical value of  $v_l$  is small as compared to  $a_l$ . This will be important later on, when interference terms between  $\Gamma_{\mu\alpha}^{SM}$  and  $\delta\Gamma_{\mu\alpha}$  will be discussed and terms of the order  $v_l\delta$  will be neglected as compared to terms of order  $a_l\delta$ . The second term in Eq.

(2) has the general form

$$\begin{aligned}
\delta\Gamma_{\mu\alpha} = & ie\left\{\frac{1}{s}f_1\not{k}\gamma_\alpha\gamma_\mu\right. \\
& +\frac{1}{s}f_2(\gamma_\alpha k_\mu - \not{k}g_{\alpha\mu}) \\
& +\frac{1}{s^2}f_3\gamma_\mu(p_{+,\alpha}k p_- - p_{-,\alpha}k p_+) \\
& +\frac{1}{s^2}f_4p_{-,\mu}(\gamma_\alpha k p_+ - p_{+,\alpha}\not{k}) + \frac{1}{s^2}f_5p_{+,\mu}(\gamma_\alpha k p_+ - p_{+,\alpha}\not{k}) \\
& \left. +\frac{1}{s^2}f_6p_{-,\mu}(\gamma_\alpha k p_- - p_{-,\alpha}\not{k}) + \frac{1}{s^2}f_7p_{+,\mu}(\gamma_\alpha k p_- - p_{-,\alpha}\not{k})\right\} \quad (4)
\end{aligned}$$

where  $f_i \ll 1$  are dimensionless coupling constants whose strength cannot be predicted within our approach. One factor of  $e$  has been introduced in the definition of the vertex (4) for convenience. In writing down this formula several requirements are taken care of:

- The requirement of electromagnetic gauge invariance is fulfilled by forming in Eq. (4) suitable combinations such that  $k^\alpha\delta\Gamma_{\mu\alpha} = 0$ . under infinitesimal gauge transformations.
- Eq. (4) is not explicitly  $SU(2)_L$  invariant. The point is that in our approach the new interactions are not necessarily tied to very high energies but could in principle be related to energies below 1 TeV. Therefore we have refrained from make Eq. (4) explicitly  $SU(2)_L$  invariant. However, if desired, one can enforce global  $SU(2)_L$  by adding a similar correction to the  $e\nu\gamma W$  vertex. This will enforce additional low-energy constraints on the new vertex to be discussed in section 4.

It should be noted that our vertex is trivially invariant under those local  $SU(2)_L$  gauge variations which transform the  $Z$  into itself, because these are given by  $\delta\epsilon_Z^\mu \sim p_Z^\mu$  and thus one needs to have  $p_Z^\mu\delta\Gamma_{\mu\alpha} = 0$ . Although this condition is not explicitly fulfilled by Eq. (4), the situation is automatically cured, because one can replace all 4-vectors  $q = p_-, p_+, k$  by  $q_\mu - \frac{qp_Z}{m_Z^2}p_{Z,\mu}$  and  $g_{\alpha\mu}$  by  $g_{\alpha\mu} - \frac{p_{Z,\mu}p_{Z,\alpha}}{m_Z^2}$ , and this replacement does not change the cross section, because terms  $\sim p_{Z,\mu}$  give  $O(m_e)$  when sandwiched between the lepton spinors.

- The 'coupling constants'  $f_i$  are really form factors  $f_i = f_i(x_\gamma, \cos\theta)$ . Powers of  $s$  have been introduced in Eq. (4) in such a way as to make the  $f_i$  dimensionless. The new contribution would have the same overall energy dependence as the Standard Model contribution, if one would assume the  $f_i$  to first approximation to be constant in energy  $x_\gamma = 1 - m_Z^2/s$ . However, this would be a rather unpleasant feature, because it would induce effects already at the lowest energies (see the discussion of low energy constraints in section 4). Therefore, it is a good idea to assume that the form factors behave like some negative power of  $1 - x_\gamma$  in order to cut away the low energy constraints. Physically, such a behavior arises, for example, if the new physics is induced at some scale  $\Lambda \sim 1$  TeV which forces the form factors to behave like a power of  $s/\Lambda^2$ . Furthermore, such behaviour is also desirable for the purpose of satisfying constraints from unitarity at high energies.
- The coupling constants  $f_i$  are of the general form  $f_i = v_i + a_i\gamma_5$  and are really form factors  $f_i = f_i(x_\gamma, \cos\theta)$ .
- Terms which give contributions of order  $m_e/\sqrt{s}$  when the interference with the Standard Model is formed, have not been included in Eq. (4). Such terms consist of a product of an even number of  $\gamma$  matrices.
- The interactions in Eq. (4) conserve CP. Using complex form factors one could also undertake a search for CP violating interactions – in analogy to what has been done in ref. [4] concerning the  $bb\gamma Z$  vertex.

### 3. Quantitative Phenomenological Consequences

With the vertex (4) at hand one can calculate the cross section  $d\sigma/d\cos\theta$  where  $\theta$  is the production angle of the photon.  $d\sigma/d\cos\theta$  consists of a Standard Model term  $d\sigma_{SM}/d\cos\theta$  which is proportional to  $v_l^2 + a_l^2$  and an interference term  $d\sigma_{NEW}/d\cos\theta$ . These interference contributions between  $\Gamma_{\mu\alpha}^{SM}$  and  $\delta\Gamma_{\mu\alpha}$  are  $\sim v_l v_i - a_l a_i$ . For convenience the numerical analysis will be done only for the form factors  $f_{1,2,3,4}$  but not for  $f_{5,6,7}$ . Due to the fact that the Standard Model coupling  $v_l$  almost vanishes it turns out that the  $v_i$  practically do not contribute to the interference term and that the ratio of

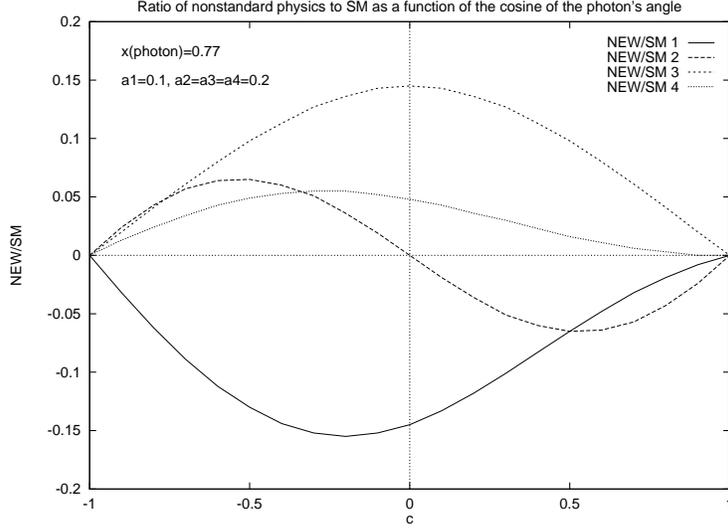


Figure 2:

$d\sigma_{NEW}/d\cos\theta$  and  $d\sigma_{SM}/d\cos\theta$  is proportional to  $a_i/a_l$ . Explicitly one has

$$\frac{d\sigma_{NEW}/d\cos\theta}{d\sigma_{SM}/d\cos\theta} = \frac{1}{v_l^2 + a_l^2} \frac{1}{4(x_\gamma^2 + 2 - 2x_\gamma)/\sin^2\theta - 2} \{ (v_l v_1 - a_l a_1)(2 - x_\gamma(1 + \cos\theta)) + (v_l v_2 - a_l a_2)x_\gamma \cos\theta + (v_l v_3 - a_l a_3)(2x_\gamma - 1) + (v_l v_4 - a_l a_4)x_\gamma(\cos\theta - 1) + \dots \} \quad (5)$$

where  $x_\gamma = 1 - m_Z^2/s$  as before and the dots stand for similar terms stemming from the other formfactors  $i > 4$ . Note that  $d\sigma_{SM}/d\cos\theta$  becomes very large in the collinear regions  $\cos\theta \approx \pm 1$  and stays roughly constant and small in the central region  $\cos\theta \approx 0$ . Fig. 2 shows the ratio (5) as a function of  $\cos\theta$  for form factors with numerical values  $a_1 = 0.1$ ,  $a_2 = 0.2$ ,  $a_3 = 0.2$  and  $a_4 = 0.2$  at  $x_\gamma = 0.77$  (corresponding to  $\sqrt{s} = 190$  GeV). It is nicely seen that the different form factors contribute quite differently to the  $\theta$  distribution. The knots at  $\cos\theta = \pm 1$  are due to the fact that the new contributions

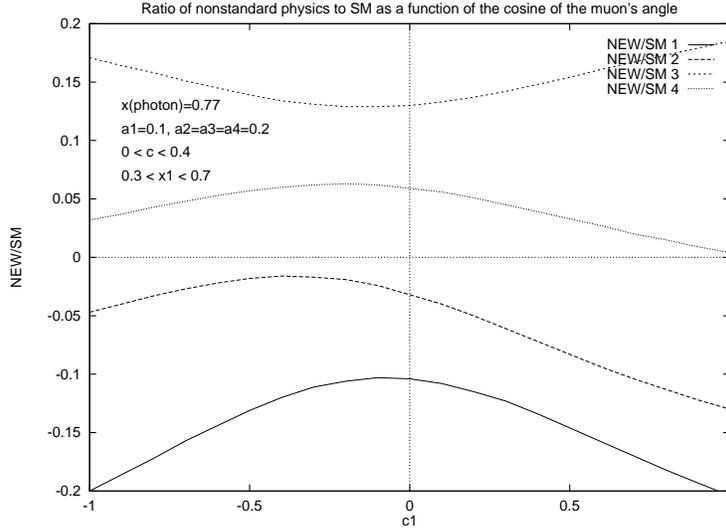


Figure 3:

remain regular at this point whereas the Standard Model cross section is large. Note that the result is linear in the  $a_i$  and that the order of magnitude of the result is roughly the same as the magnitude of the  $a_i$ .

One can learn more about the nature of the process  $e^+e^- \rightarrow \gamma Z$  if one analyzes correlations with the decay products of the  $Z$ , e.g. muons. One should not, however, give up the condition of an on-shell  $Z$ . This is because otherwise a lot of other Standard Model processes like  $e^+e^- \rightarrow Z^* \rightarrow \mu^+\mu^-\gamma$  would contribute and complicate the analysis. Experimentally, it is straightforward to isolate a sample with on-shell  $Z$ 's by cutting in the  $x_\gamma$  distribution, because the  $x_\gamma$  distribution reflects the  $Z$  resonance. If one restricts to a bin in the neighbourhood of the pole at  $x_\gamma = 1 - m_Z^2/s$ , there are only small irrelevant off-shell corrections as discussed in detail in the introduction.

A second important issue is that the  $Z \rightarrow \mu^+\mu^-$  vertex is assumed to be that of the Standard Model. This assumption is justified as any deviation is constrained from Lep-1 data to be small. Therefore, from  $Z$  decay one has factors of the form  $v_m^2 + a_m^2$  or  $v_m a_m$  in all terms of the complete matrix elements, where  $v_m$  and  $a_m$  are vector and axial-vector coupling of the  $Z$  to its

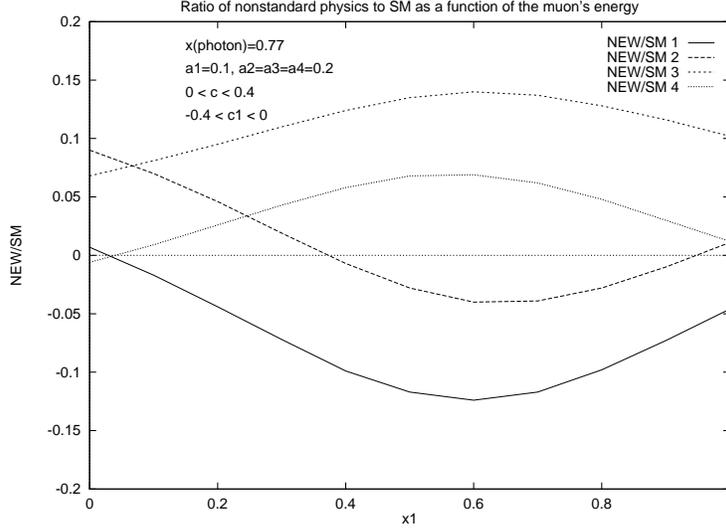


Figure 4:

decay product (lepton or quark).

Let us now discuss in detail some distributions of  $Z$  decay products, assuming first that the  $Z$  decays leptonically. As without  $Z$ -decay, all ratios  $d\sigma_{NEW}/d\sigma_{SM}$  behave like  $a_i/a_l$  to a good approximation. The reason for that is mainly due to  $v_m \approx 0$  for leptons. The Standard Model terms either go with  $(v_l^2 + a_l^2)(v_m^2 + a_m^2) \approx a_l^4$  or with  $(v_l a_l)(v_m a_m) \approx 0$  where one factor in the squares is due to production of the  $Z$  and the other factor is due to the decay. The interference terms either go with  $(v_i v_l - a_i a_l)(v_m^2 + a_m^2) \approx a_i a_l^3$  or  $(v_i a_l - a_i v_l)v_m a_m \approx 0$ , so that  $d\sigma_{NEW}/d\sigma_{SM} \sim a_i/a_l$  as claimed.

In order to be as sensitive as possible to new physics contributions, a sample of events with photons in the central region of the detector say  $0 < \cos \theta < 0.4$  should be chosen. We have taken an asymmetric bin (i.e. no event with  $\cos \theta < 0$ ) because some form factors yield contributions asymmetric in  $\cos \theta$ , as seen in Fig. 2. Next we assume that the  $Z$  decay to  $f\bar{f}$  with momentum  $p_f = \frac{\sqrt{s}}{2}x_1(1, \sin \phi_1 \sin \theta_1, \cos \phi_1 \sin \theta_1, \cos \theta_1)$  in the lab system. One can then study the energy ( $x_1$ ) and angle ( $c_1 := \cos \theta_1$ ) dependence. Ratios  $d\sigma_{NEW}/d\sigma_{SM}$  have been plotted as a function of these variables in

Figs. 3 and 4. The same values of couplings  $a_1 = 0.1$ ,  $a_2 = 0.2$ ,  $a_3 = 0.2$  and  $a_4 = 0.2$  and the same energy  $x_\gamma = 0.77$  as in Fig. 2 has been chosen. Furthermore, we have averaged over the bin  $0 < \cos\theta < 0.4$  and in Fig. 3 in addition over  $0.3 < x_1 < 0.7$  and in Fig. 4 over  $-0.4 < c_1 < 0$ .

#### 4. Summary and Discussion

In this letter possible new physics contributions to the LEP2 process  $e^+e^- \rightarrow Z\gamma$  have been analyzed by an effective vertex ansatz. Several non-trivial features of the new interactions have been derived. One may ask the question why we did not use the fashionable effective Lagrangian approach, in which new interactions are expanded in powers of higher dimensional operators, in particular dimension 6, and added to the Standard Model Lagrangian. Such operators are preferably chosen to respect the Standard Model  $SU(2)_L \times U(1)_Y$  gauge symmetries. The complete set of these operators inducing the process  $e^+e^- \rightarrow Z\gamma$  is given by

$$\begin{aligned}
& \bullet \bar{l}D_\mu e D^\mu \phi && D_\mu \bar{l}e D^\mu \phi \\
& \bullet \bar{l}\sigma_{\mu\nu}\tau^a e \phi W_{\mu\nu}^a \\
& \bullet i\bar{l}\tau^a \gamma_\mu D_\nu l W_{\mu\nu}^a && i\bar{l}\gamma_\mu D_\nu l B_{\mu\nu} \\
& \bullet i\bar{e}\gamma_\mu D_\nu B_{\mu\nu} e
\end{aligned}$$

where  $e$  and  $l$  denote the righthanded electron and left handed lepton doublet respectively.  $\phi$  is the Higgs doublet with vacuum expectation value  $\langle \phi \rangle = (0, v)$  and  $W_{\mu\nu}^a$  and  $B_{\mu\nu}$  are the  $SU(2)$  and  $U(1)$  field strengths. Note that in all the cases the  $e^+e^-Z\gamma$  interaction is induced indirectly as a higher order effect either by the gauge field in a covariant derivative  $D_\mu$  or by the nonlinear term in the nonabelian field strength. This implies that all these dimension 6 interactions induce  $e^+e^- \gamma$  or  $e^+e^-Z$  couplings much stronger than the  $e^+e^- \gamma Z$  coupling. For all of them therefore exist much stronger constraints from LEP1 than from LEP2.<sup>1</sup> This is the reason why we had to do without the effective Lagrangian approach to study new physics effects in  $e^+e^- \rightarrow Z\gamma$ . In our approach we avoided the restriction to dimension 6,

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<sup>1</sup>Actually, the first 3 operators above flip the helicity and therefore contribute only  $O(m_e)$  to all cross sections.

because the effective vertex in principle collects contributions from operators of arbitrary high dimension. For example, the first form factor  $f_1$  gets a contribution from a dimension 8 operator of the form  $\bar{l}\gamma^\mu l \epsilon_{\mu\nu\sigma\tau} D^\nu B^{\sigma\lambda} B_\lambda^\dagger$  first studied in ref. [5].

Now we come to the question of constraints from lower energies. As has already been discussed, bounds from really low energies can be avoided by assuming a suitable energy dependence of the form factors of the form  $f_i \sim s$ . In that case the only potentially important experiment to consider is LEP1 with an energy only a factor 2 below LEP2. At LEP1, events of the form  $Z \rightarrow f\bar{f}\gamma$  can be described by our vertex. With an energy dependence  $f_i \sim s$  the expected ratios  $\delta\sigma_{NEW}/\sigma_{SM}$  are roughly a factor of 4 smaller than those considered in section 3. This means for a comparable study LEP1 would need about  $4 \times 10000$  events of the type  $Z \rightarrow f\bar{f}\gamma$ . LEP1 has obtained a lot of photon events and analyzed them in various studies. However, the photons of interest here are hard and noncollinear, and there are only of the order of thousand such events in each detector at LEP1. They have been used by the L3 group [6] to derive constraints on  $ZZ\gamma$  and  $Z\gamma\gamma$  couplings and could in principle be used to obtain limits on our form factors as well.

If one considers our vertex (4) as part of a  $SU(2)_L$  symmetric system, one has in principle constraints from lepton–neutrino scattering processes  $l\nu \rightarrow W\gamma$ . However, apart from being done at rather low energies, lepton–neutrino scattering has much too small cross sections to compete with  $Z\gamma$  production at LEP2.

Another constraint could come from Tevatron data  $\bar{p}p \rightarrow Z\gamma X$  if one assumes in the spirit of quark–lepton universality that light quarks have similar anomalous couplings to  $Z\gamma$  as electrons. This process is well studied in conjunction with a parallel analysis of  $\bar{p}p \rightarrow W\gamma X$  which constrains the triple  $WW\gamma$  gauge coupling via  $\bar{u}d \rightarrow W^* \rightarrow Z\gamma$ . The authors of ref [7] have given an exhaustive review about the results from D0 and CDF. It turns out that there are less than 100 candidate events of the type  $\bar{q}q \rightarrow Z\gamma$  if one assumes that the  $Z$  decays leptonically. This latter restriction is important because the background in the hadronic channel is too large. The number of events is too low to compete with the statistics of the ‘radiative return’ events at LEP2. The ability to test nonstandard physics is further reduced, because the photon transverse momenta are not really large, typically  $E_T^\gamma > 10$  GeV. Furthermore, the form of the  $E_T^\gamma$  distribution is not as sensitive to the structure of new physics as the  $\cos\theta$  distribution which was considered

for LEP2.

Finally we want to stress that the main aim of this letter is to show that one can construct new physics possibilities for the LEP2 process  $e^+e^- \rightarrow Z\gamma$  in spite of various obstacles like gauge invariance, dominance of low dimensional operators, LEP1 constraints etc. Our main conclusion is therefore that it is worthwhile to analyze these events as precise as possible and that one should not look at them just as boring background from the Standard Model.

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