NEUTRINO COUNTING AND A COMPOSITE Z-BOSON

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Received 19 June 1987

We calculate the contribution of an electric dipole $ZZ\gamma$ transition to the $e^+e^-\to\nu\bar{\nu}\gamma$ cross section. With suitable cuts in the photon spectrum, it should be possible to improve, by two orders of magnitude, the present bound on the coupling constant.

Despite the discovery at CERN of the Z and W particles with the masses predicted by the standard $SU(2)\times U(1)$ model, the question of whether these particles are gauge bosons or simply composite particles of a phenomenological theory remains open. At low energies it is difficult to distinguish between these two possibilities but, at LEP energies one expects that the composite nature of the W and Z will imply deviations from the standard model predictions.

Several authors (see ref. [1] for a review), have pointed out the importance of a careful study of the general γW^+W^- vertex which in the static limit is described by the charge, magnetic moment and electric quadrupole moment of the W. Any departure of the above parameters from their standard model values could indicate a scale of compositeness. The effect of these anomalous couplings in W^+W^- production at LEP-II was analysed in detail in a recent work by Hagiwara et al. [2], which gives a systematic summary of all previous contributions to this problem.

The study of the $ZZ\gamma$ vertex attracted some attention four years ago, when several authors [3,4], motivated by the desire to explain an apparently anomalous radiative Z decay, considered it. As the Z is neutral and the gauge sector of the standard model is *CP* conserving the only static electromagnetic moment of the Z is the anapole moment [5]. However, examining the $ZZ\gamma$ three-point function [5,6] one can see that there is also an electric dipole transition (EDT) which vanishes if both Z-bosons are on-shell. The existence of the EDT coupling can be tested in e^+e^- reactions with a photon in the final state. Since the reaction $e^+e^-\to\nu\bar{\nu}\gamma$ will receive, no doubt, a lot of attention in the near future, we shall use it as a testing ground for the $ZZ\gamma$ vertex. This is the purpose of the present letter.

As a quideline, we shall use the standard model results [5], but considering the couplings as free parameters. The off-shell $ZZ\gamma$ three-point function depends on several form factors. However, for our purpose the dominant contribution arises when $\sqrt{s}\approx M_Z$, which means that it is a good approximation to consider the initial Z on-shell. In this situation there are two form factors, but, for massless neutrinos only one, the EDT, contributes. This we write as

$$ef_1\,\epsilon^{\alpha\beta\mu\nu}e_\alpha e'_\beta\epsilon_\mu k_\nu\,, \tag{1}$$

where e is the electric charge, f_1 is a dimensionless form factor, $e_\alpha e_\beta$ and ϵ_μ are the polarization vectors of the initial Z, final Z and photon, respectively, and k_ν is the photon momentum. Recalling that the initial Z is on-shell and denoting by s' the q^2 of the final Z, the one-loop expression of the form factor is

$$f_1=(g/\pi\cos\theta_W)^2\sum_f g_V^f g_A^f Q_f$$
$$\times[s'I(s',M_Z^2)-M_Z^2I(M_Z^2,s')]\,, \tag{2}$$

where g_V^f, g_A^f and Q_f are the vector, axial-vector and charge (in units of e) of each fermion in the loop and

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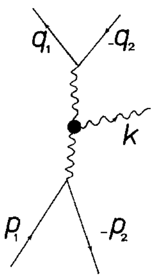

Fig. 1. New diagram for $e^+e^- \to \nu\bar{\nu}\gamma$.

the function I is given in ref. [5]. As one can see from eq. (2), f_1 vanishes when $s'=M_Z^2$. So, to copy this behaviour that has to be true in any composite model with CP conservation, we write

$$f_1=\beta(s'/M_Z^2-1) . \tag{3}$$

In the standard model a typical value of β is 4×10^{-5}, but, as Boudjema and Dombey [7] pointed out, if the Z is a bound state of two haplons β is enhanced by a large factor. We will come back to this point after we give our results.

Let us consider the neutrino counting amplitude. Now, there is an extra contribution stemming from the diagram with a Z-boson exchanged in the s channel. Evaluating this diagram it is fairly easy to obtain the helicity amplitudes, $M(\sigma_-,\sigma_+,\lambda)$, where σ_-, σ_+ and λ denote the electron, positron and photon helicity respectively. Using the spinor product formalism [8] we obtain

$$M(+,-,+)$$
$$=C_Z(g_V-g_A)s(q_2,p_2)s^*(k,p_1)s^*(q_1,k) ,$$
$$M(-,+,+)$$
$$=C_Z(g_V+g_A)s^*(k,p_2)s(q_2,p_1)s^*(q_1,k) , \tag{4}$$

with

$$C_Z=4eG_FM_Z^2\beta(s'/M_Z^2-1)[D(s)D(s')]^{-1} ,$$

$$D(x)=x-M_Z^2+iM_Z\Gamma_Z , \tag{5}$$

where M_Z and Γ_Z denote the mass and width of the Z-boson and G_F is the Fermi coupling constant. The kinematics for the reaction is defined in fig. 1 and the non-zero spinor products are

$$s(p_1,p_2)=\bar{u}_+(p_1)u_-(p_2) ,$$
$$s^*(p_2,p_1)=\bar{u}_-(p_1)u_+(p_2) , \tag{6}$$

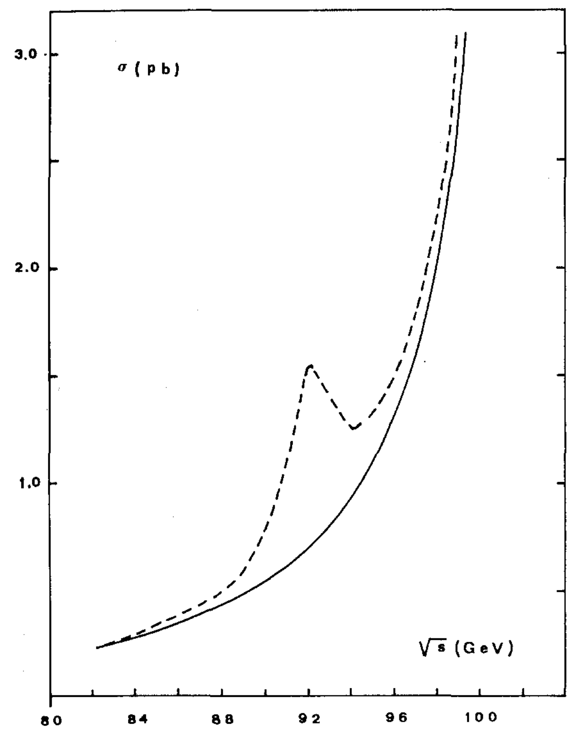

Fig. 2. Cross section as a function of $\sqrt{s}$, for $\beta=1$ and standard model.

where $u_\pm(p)$ are the chiral spinors. As we have shown before [9], the other two helicity amplitudes, corresponding to $\lambda=-$, can be obtained from eqs. (5) with the replacements $C_Z\to-C_Z$, $1\leftrightarrow2$ and $s\leftrightarrow s^*$.

Adding the new contribution to the exact standard model amplitudes evaluated in a previous work [9], and integrating over the neutrino and antineutrino phase space we obtain the differential cross section $d\sigma/dxdy$ where $x=2\omega/\sqrt{s}$ is the photon energy in units of the beam energy and $y=\cos\theta$ with θ the angle between k and p_1. The details of the calculation were given before [9] and so, there is no need to repeat them here.

The extra s-channel diagram implies that the total cross section, $\sigma(\beta)$, has a resonance peak at $\sqrt{s}=M_Z$. Outside of the resonance the effect is hardly seen. This is shown in fig. 2, where the full curve represents the standard model results for three families while the dashed curve gives the total cross section including the EDT contribution with $\beta=1$. In both cases the cut $0.2\leqslant x\leqslant1$ and $|y|\leqslant0.94$ was used. However, this is not the best cut to display the effect.

For this purpose, i.e., to enhance the signal-to-background ratio, $R=\sigma(\beta)/\sigma_{SM}$, one should take full advantage of the fact that the new Z diagram gives a photon spectrum different from the normal one. The $ZZ\gamma$ coupling favours a hard photon emission while the standard amplitudes give a bremsstrahlung-like spectrum. We illustrate this point in fig. 3 where we plot $d\sigma/dx$ as a function of x. The dashed curve and the dash-dotted curve correspond to $\beta=1$ and $\beta=0.5$, respectively, while the full curve gives the standard model results. It is quite clear that cutting the photons with $x<0.5$ one is essentially left with the signal.

The character of the EDT photon spectrum is also seen in the angular dependence of the cross section. Again, the ratio R increases when we cut the photons emitted at small angles in the forward and backward directions, i.e., with $\theta>\theta_{min}$. To give an idea of this effect we show in table 1 the value of R corresponding to $x>0.5$ and several cuts in θ. In the same table the values of $\sigma(\beta)$ are also displayed. Notice that R increases by a factor of two when θ_{min} goes from 5° to 25° with only a modest ($\approx 12\%$) reduction in σ.

So far we have considered EDT couplings of the order e ($\beta\approx 1$). However, the relevant question is: what is the smallest β measurable in the forthcoming experiments? To answer this question we adopt the following strategy. We assume an integrated luminosity of 100 pb^{-1} and require a signal larger than the standard model result by 5 standard deviations i.e.,

$$\sigma(\beta)\,100\ \mathrm{pb}^{-1} > \sigma_{SM}\ 100\ \mathrm{pb}^{-1} + 5\sqrt{(\sigma_{SM}\ 100\ \mathrm{pb}^{-1})}\,. \quad (7)$$

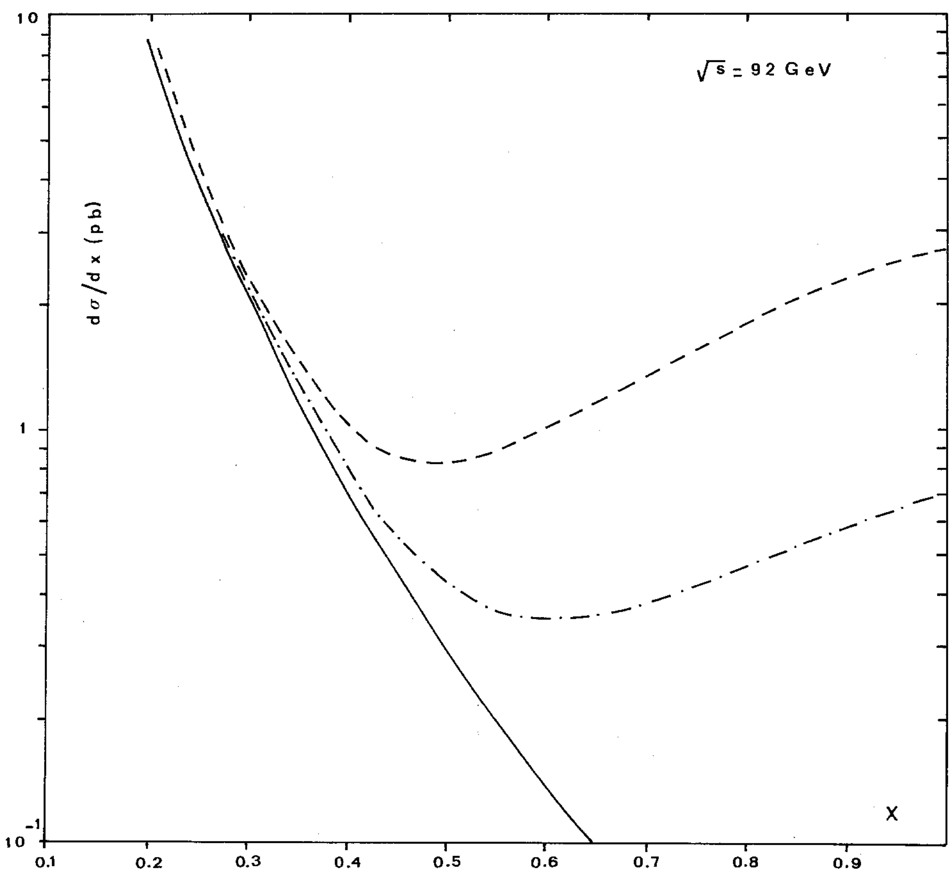

Fig. 3. $d\sigma/dx$ as a function of x, for $\beta=1$ (dashed curve), $\beta=0.5$ (dash-dotted curve) and standard model (solid line).

Table 1
Values of the cross section in pb, ratio R and $\beta_{\min}$ for several angular cuts

Cuts ($x>0.5$) $\theta_{\min}$ (deg)	σ ($\beta=1$)	R	$\beta_{\min}$
5	0.91	12.5	0.40
10	0.88	15.8	0.38
15	0.85	18.8	0.36
20	0.82	21.4	0.35
25	0.78	23.8	0.35

With this constraint we have $\beta_{\min}\approx 0.3$–0.4 with $\sigma\approx 0.1$–0.2 pb and relaxing the criterion to two standard deviations we obtain $\beta\approx 0.2$. It is quite clear that such values of β are extremely large in comparison with the standard model result. Perhaps, they are even larger than some values obtained in composite models of the Z-boson where recent estimates [7] give $\beta_c\approx 0.05$. In spite of that, it is important to point out that present limits on β are larger than the ones that could be derived from a neutrino counting experiment. From eq. (1) it is easy to obtain [4]

$$\Gamma(\mathrm{Z}\to\mathrm{e}^+\mathrm{e}^-\gamma)/\Gamma(\mathrm{Z}\to\mathrm{e}^+\mathrm{e}^-)=\beta^2\alpha/80\,\pi\,. \tag{8}$$

Then, using the data [10] from the pp collider, we derive $\beta<45$. Presently, the UA1 and UA2 events seem to be compatible with QED. In particular, it has been clearly demonstrated by Barger et al. [3] that the collider events have a photon spectrum different from the one predicted by the EDT coupling. Hence, the value above can be regarded as a pessimistic bound. However, given the total number of Z-bosons collected at CERN, eq. (8) shows that $\beta<10$ could not have been seen. On the contrary, a future neutrino counting experiment will be able to push down this limit by almost two orders of magnitude.

As we have seen before, the particular expression of the f_1 form factor given in eq. (3) was used to impose *CP* conservation. However, at a phenomenological level one can envisage composite models where *CP* is not conserved. In such a case, the existence of a Z-boson electric dipole moment (EDM) would imply a one-loop contribution to the EDM of the electron. Evaluating the loop diagram we obtain

$$d_e=f_1(k^2=0)$$
$$\propto(g_V^2+g_A^2)/4\pi\ (m_e\times 197\ \mathrm{MeV}/M_Z^2)\times 10^{-13}\ e\,\mathrm{cm},$$

i.e.,
$$d_e=4.2\times 10^{-26} f_1(0)\ e\,\mathrm{cm}\,. \tag{9}$$

Comparing with the experimental bound, $d_e<3\times 10^{-24} e$ cm [11], one can see that $f_1(k^2=0)<75$ and even the more stringent bound stemming from the neutron EDM, $d_n<4.6\times 10^{-25}$ e cm [12], implies $f_1(0)<10$. Like in the *CP*-conserving case, a future neutrino counting experiment will see an effect if $f_1(0)$ is larger than 10^{-1}.

We summarize our conclusions as follows:

(i) In a composite model of the Z-boson with *CP* violation, existing limits on the electron and neutron EDM imply the constraint $f_1(0)<10$.

(ii) If *CP* is conserved, there is a ZZγ dipole transition, β. Using the data from the CERN collider the upper bound on β is ≈ 10.

(iii) Future neutrino counting experiments will be able to constrain $f_1(0)$ or β at the level of 0.1.

One of us (A.B.) thanks F. Boudjema and N. Dombey for many stimulating discussions.

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