ANOMALOUS $\mathrm{ZZ}\gamma$ AND $\mathrm{Z}\gamma\gamma$ COUPLINGS AT LEP2

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Abstract

We have studied the existence of anomalous $\mathrm{ZZ}\gamma$ and $\mathrm{Z}\gamma\gamma$ couplings using the L3 detector at LEP. The analysis is based on the study of the process $\mathrm{e^+e^-} \rightarrow \mathrm{Z}\gamma$ at center-of-mass energies between 161 GeV and 183 GeV. The observed rates of events with $E_\gamma \approx \frac{\sqrt{s}}{2}(1 - M_Z^2/s)$ and the characteristic distributions are in agreement with the Standard Model expectations. This is used to set limits on the eight possible anomalous couplings and to exclude new physics scales in the range 250-750 GeV , depending on the type of coupling.

The $e^+e^- \to Z\gamma$ Standard Model process at lowest order takes place through electron-exchange in the t-channel. Deviations arising from $ZZ\gamma$ and $Z\gamma\gamma$ couplings are extremely small in the Standard Model, but they can be enhanced in compositeness models [4] or if new particles enter in higher order corrections. The main experimental signature of this process at LEP2 is the production of an almost monoenergetic photon, $E_\gamma \approx \frac{\sqrt{s}}{2}(1 - M_Z^2/s)$, where $\sqrt{s}$ is the energy of the collision. Anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings would manifest as a global enhancement of the number of $Z\gamma$ events, especially when the photon is emitted at large angles with respect to the beam axis.

In the following analysis the most sensitive channels, $e^+e^- \to q\bar{q}\gamma(\gamma)$ and $e^+e^- \to \nu\bar{\nu}\gamma(\gamma)$, are used to set limits on anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings.

1 Limits on anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings

The most general expression for $ZZ\gamma$ and $Z\gamma\gamma$ vertexes is quantified in terms of eight anomalous couplings [1] h_i^V (i = 1,4; V = γ, Z). In the frame of the Standard Model, at tree level, all eight couplings h_i^V vanish. At one loop level, only the CP conserving couplings h_3^V and h_4^V are nonzero ($\leq 10^{-4}$) [2, 3].

We prefer another choice of the parameters to be fitted [5]:

$$\frac{\sqrt{\alpha}h_i^V}{m_Z^2} \equiv \frac{1}{\Lambda_{iV}^2}; i = 1,3 \quad ; \quad \frac{\sqrt{\alpha}h_i^V}{m_Z^4} \equiv \frac{1}{\Lambda_{iV}^4}; i = 2,4 \tag{1}$$

These scales of new physics Λ_{iV} have a more direct physical meaning,especially for future colliders, where h_i^V limits are expected to reach very small values.

1.1 Analysis procedure

We have computed the Standard Model amplitude (M_{SM}) and the anomalous coupling amplitudes ($M_{AC}(h_i^V)$) of the $e^+e^- \to f\bar{f}\gamma$ process following the same formalism used in [1] and taking into account the effects of the spin correlations, non-resonant contributions such as $e^+e^- \to \gamma^*\gamma \to f\bar{f}\gamma$ and the t-channel W-exchange corrections in $e^+e^- \to \nu_e\bar{\nu}_e\gamma$. We have used the following variables : the photon energy E_γ, its polar and azimuthal angles θ_γ, ϕ_γ, and the angles of the fermion f in the center-of-mass frame of the Z system: θ_f^{CM}, ϕ_f^{CM}.

Distributions in the presence of anomalous couplings can be obtained from the corresponding Standard Model distributions simply by reweighting every event by the scale factor:

$$w(E_\gamma, \theta_\gamma, \phi_\gamma, \theta_f^{CM}, \phi_f^{CM}; h_i^V) = \frac{|(M_{SM} + M_{AC})(E_\gamma, \theta_\gamma, \phi_\gamma, \theta_f^{CM}, \phi_f^{CM}; h_i^V)|^2}{|M_{SM}(E_\gamma, \theta_\gamma, \phi_\gamma, \theta_f^{CM}, \phi_f^{CM}; h_i^V)|^2} \tag{2}$$

For the $e^+e^- \to \nu\bar{\nu}\gamma(\gamma)$ case, the neutrino angular variables have been integrated out. On the other hand, we consider that additional photon radiation effects are small or cancel in the ratio of amplitudes. For the $e^+e^- \to q\bar{q}\gamma(\gamma)$ process, the angles θ_f^{CM} and ϕ_f^{CM} are substituted by the angles of the trust axis in the Z center-of-mass frame, and the square of the amplitudes is symmetrized under the interchange $q \leftrightarrow \bar{q}$.

To quantify the deviations from the Standard Model, we determine the value of a given anomalous coupling h_i^V which maximizes the likelihood funtion:

$$\mathcal{L}(h_i^V) = \frac{N_t(h_i^V)^{N_o} exp(-N_t(h_i^V))}{N_o!} \prod_{j=1}^{N_o} \frac{w_j(E_\gamma, \theta_\gamma, \phi_\gamma, \theta_f^{CM}, \phi_f^{CM}; h_i^V)}{N_t(h_i^V)} \tag{3}$$

where N_o is the number of observed events and $N_t(h_i^V)$ is the total number of expected events. The expression $w_j/N_t(h_i^V)$ is proportional to the probability density function of the event j.

2 Results

2.1 Analysis of $\mathrm{e}^+\mathrm{e}^- \to \mathrm{Z}\gamma$ events

The following data samples, collected with the L3 detector, are used: 9.95 pb^{-1} at $\sqrt{s}$ = 161 GeV, 0.97 pb^{-1} at $\sqrt{s}$ = 170 GeV, 8.48 pb^{-1} at $\sqrt{s}$ = 172 GeV and 55.46 pb^{-1} at $\sqrt{s}$ = 183 GeV. To obtain a sample of events with a Z boson and only one high energy photon in the final state, we require that the energy of the photon candidate must recoil against a system of invariant mass consistent with that of a Z : 80 GeV $< (s - 2E_\gamma\sqrt{s})^{1/2} <$ 110 GeV

The details of the selection of the $\mathrm{e}^+\mathrm{e}^- \to q\bar{q}\gamma(\gamma)$ and $\mathrm{e}^+\mathrm{e}^- \to \nu\bar{\nu}\gamma(\gamma)$ events can be found in [7].

For the channel $\mathrm{e}^+\mathrm{e}^- \to q\bar{q}\gamma(\gamma)$, 585.9 events are expected with at least one radiative photon in the fiducial volume $14° < \theta_\gamma < 166°$; applying the same cuts, 593 events are selected. The following backgrounds have been studied at the four center-of-mass energies: $\mathrm{e}^+\mathrm{e}^- \to q\bar{q}e\nu$, where the electron fakes a photon, mainly at low polar angles, giving 1.5% of background in the data sample; and $\mathrm{e}^+\mathrm{e}^- \to W^+W^- \to qql\nu,\ l = \mu, \tau$, which contributes with a negligible 0.019% to the data sample.

For the process $\mathrm{e}^+\mathrm{e}^- \to \nu\bar{\nu}\gamma(\gamma)$, 153 events are found with a high energy photon in the region: $16° < \theta_\gamma < 164°$. The number of expected events is 134.2. In this case, the studied sources of background are : radiative bhabha events $\mathrm{e}^+\mathrm{e}^- \to \mathrm{e}^+\mathrm{e}^-\gamma(\gamma)$; and $\mathrm{e}^+\mathrm{e}^- \to WW \to e\nu_e l\nu_l$, where the electron fakes a photon. No events passed the imposed cuts and therefore, we consider this channel as background free.

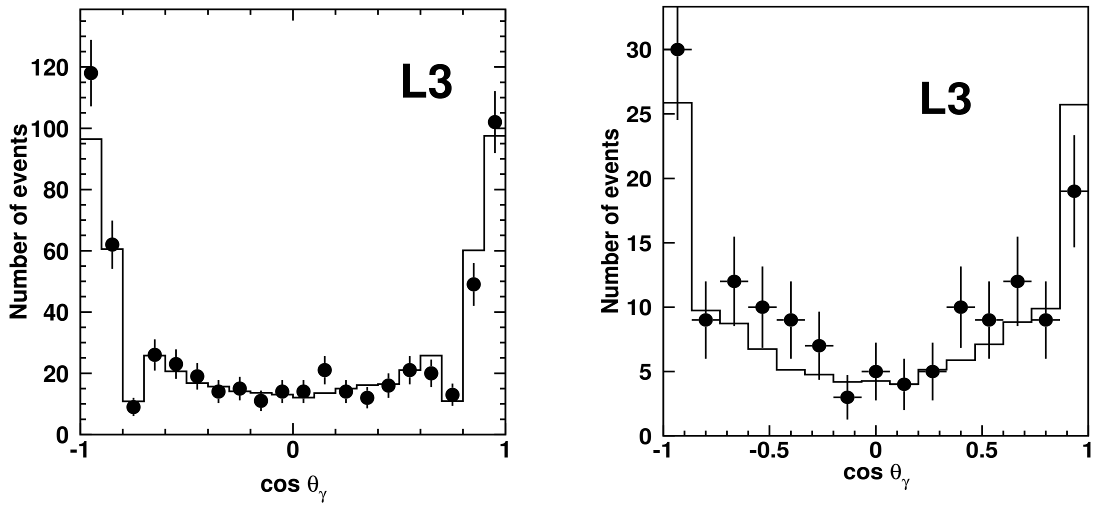

Figure 1: Polar angle distribution of the photon candidates in $\mathrm{e}^+\mathrm{e}^- \to q\bar{q}\gamma$ events (right) and in $\mathrm{e}^+\mathrm{e}^- \to \nu\bar{\nu}\gamma$ (left). Dots are data and the histogram is the Standard Model Monte Carlo prediction.

For both channels, the measured cross sections and the angular distributions are in good agreement with the expectations from the Standard Model generator.

Figure 1 shows the polar angle distribution of the photon candidates in $e^+e^- \to q\bar{q}\gamma$ events and in $e^+e^- \to \nu\nu\gamma$ events, respectively.

2.2 Results

Using the $q\bar{q}\gamma$ and $\nu\bar{\nu}\gamma$ altogether the limits summarized in Table 1 are obtained. We have estimated that the largest systematic error is smaller than 10% of the statistical error.

Parameter	95% CL Limits	Parameter	95% CL Sensitivity
h_1^Z	$-0.50 < h_{10}^Z < 0.20$	Λ_{1Z}	$\Lambda_{1Z} > 491$ GeV
h_2^Z	$-0.12 < h_{20}^Z < 0.34$	Λ_{2Z}	$\Lambda_{2Z} > 248$ GeV
h_3^Z	$-0.48 < h_{30}^Z < 0.31$	Λ_{3Z}	$\Lambda_{3Z} > 462$ GeV
h_4^Z	$-0.11 < h_{40}^Z < 0.38$	Λ_{4Z}	$\Lambda_{4Z} > 249$ GeV
h_1^γ	$-0.23 < h_{10}^\gamma < 0.21$	$\Lambda_{1\gamma}$	$\Lambda_{1\gamma} > 670$ GeV
h_2^γ	$-0.16 < h_{20}^\gamma < 0.17$	$\Lambda_{2\gamma}$	$\Lambda_{2\gamma} > 262$ GeV
h_3^γ	$-0.31 < h_{30}^\gamma < 0.03$	$\Lambda_{3\gamma}$	$\Lambda_{3\gamma} > 719$ GeV
h_4^γ	$-0.03 < h_{40}^\gamma < 0.22$	$\Lambda_{4\gamma}$	$\Lambda_{4\gamma} > 290$ GeV

Table 1: Limits on the anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings and on new physics scales, all limits are obtained by combining the process $e^+e^- \to q\bar{q}\gamma$ and $e^+e^- \to \nu\bar{\nu}\gamma$ at center of mass energies in the range 161-183 GeV. In all fits, only one parameter is varied while the others are kept at zero.

3 Conclusions

No evidence of anomalous couplings has been found. The obtained limits are comparable in sensitivity to the latest published limits [6] and they are the first limits which make use of hadronic decays of the Z boson. Since there is no need of energy-dependent form factors for e^+e^- colliders, our limits with no energy scale assumed can be considered as independent of the coupling behaviour at energies larger than $\sqrt{s}$ [8].

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