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ANOMALOUS QUARTIC GAUGE COUPLINGS AT OPAL

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Quartic couplings between the electroweak gauge bosons may contribute to various final states arising from e^+e^- collisions. Event topologies include acoplanar photon pairs together with two neutrinos or the production of three gauge bosons, such as $W^+W^-\gamma$ or $Z\gamma\gamma$. Constraints are presented on anomalous quartic couplings using the LEP-2 OPAL data sample at centre-of-mass energies up to 209 GeV.

1 Introduction

The $SU(2) \times U(1)$ gauge invariant form of the Standard Model (SM) specifies the form and strength of the self-interactions of the vector boson fields, including the quartic gauge couplings (QGCs) WWWW, WWZZ, WW$\gamma\gamma$ and WWZγ. Studying processes to which these QGCs can contribute may yield further confirmation of the non-Abelian structure of the SM or signal the presence of new physics at as yet unprobed energy scales. At LEP energies it was possible to probe only the QGCs which produce at most two massive vector bosons in the final state, through the processes shown in Fig. 1.

The formalism for the extra genuine quartic terms relevant at LEP has been discussed widely in the literature [1,2,3,4,5]. Genuine quartic terms refer to those that are not associated with any tri-linear couplings, which are already constrained by analyses using the $e^+e^- \to W^+W^-$ process. The two lowest dimension terms that give rise to quartic couplings involving at least two photons are [4] :

$$\mathcal{L}_6^0 = -\frac{e^2}{8}\frac{a_0^{\mathrm{W}}}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-_{\alpha} - \frac{e^2}{16\cos^2\theta_W}\frac{a_0^{\mathrm{Z}}}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}Z^{\alpha}Z_{\alpha},$$
$$\mathcal{L}_6^{\mathrm{c}} = -\frac{e^2}{16}\frac{a_{\mathrm{c}}^{\mathrm{W}}}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W^-_{\beta} + W^{-\alpha}W^+_{\beta}) - \frac{e^2}{16\cos^2\theta_W}\frac{a_{\mathrm{c}}^{\mathrm{Z}}}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}Z^{\alpha}Z_{\beta},$$

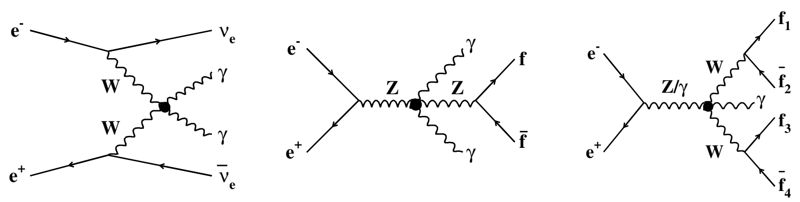

Figure 1. Diagrams with anomalous quartic gauge couplings (AQGCs) contributing to the (a) $e^+e^- \to \nu\bar{\nu}\gamma\gamma$, (b) $e^+e^- \to f\bar{f}\gamma\gamma$ and (c) $e^+e^- \to W^+W^-\gamma$ final states. No $ZZ\gamma\gamma$ vertex is present in the SM.

where $F^{\mu\nu}$ is the photon field strength tensor. Both $\mathcal{L}_6^0$ and $\mathcal{L}_6^c$ generate $W^+W^-\gamma\gamma$ and $ZZ\gamma\gamma$ couplings, governed by the parameters a_0^W, a_0^Z and a_c^W, a_c^Z, respectively. The strengths of the couplings are also proportional to $1/\Lambda^2$, where Λ is interpreted as the energy scale of the new physics and is conventionally set equal to M_W.

Limits on AQGCs are presented here using the $\nu\bar{\nu}\gamma\gamma$, $q\bar{q}\gamma\gamma$ and $W^+W^-\gamma$ final states recorded by the OPAL detector [6] at LEP.

2 Acoplanar Photon Pair Analysis

The $e^+e^- \rightarrow \nu\bar{\nu}\gamma\gamma$ process is dominated by the SM doubly radiative return to the Z and is characterised by an acoplanar photon pair in the final state. Following an initial selection of these events, the two highest energy photons were required to possess energies and polar angles satisfying $E_\gamma > 10$ GeV and $|\cos\theta_\gamma| < 0.9$ [7] in order to suppress the SM background. In the energy range $180 < \sqrt{s} < 209$ GeV 20 data events are accepted.

The $\nu\bar{\nu}\gamma\gamma$ process is sensitive to the anomalous $W^+W^-\gamma\gamma$ and $ZZ\gamma\gamma$ vertices (Fig. 1(a) and Fig. 1(b)) and thus all of the four coupling parameters introduced above. Reweighted and fully simulated Monte Carlo (MC) samples generated with NUNUGPV [8] were used to model both the SM and the AQGC contributions. Good sensitivity to the AQGCs was obtained from the distribution of the invariant mass of the system recoiling against the photons, $M_{\rm rec}$, and the energy of the second highest energy photon, $E_{\gamma 2}$. These are plotted in Fig. 2, illustrating the good SM compatibility of the data, and possible anomalous effects.

Constraints on the AQGCs were derived from a maximum likelihood fit employing bins in $M_{\rm rec}$ versus $E_{\gamma 2}$, in seven centre-of-mass energy ranges [7]. Systematic effects were included, the main source arising from the accuracy of the modelling of the energy scale and resolution of the electromagnetic calorimeter.

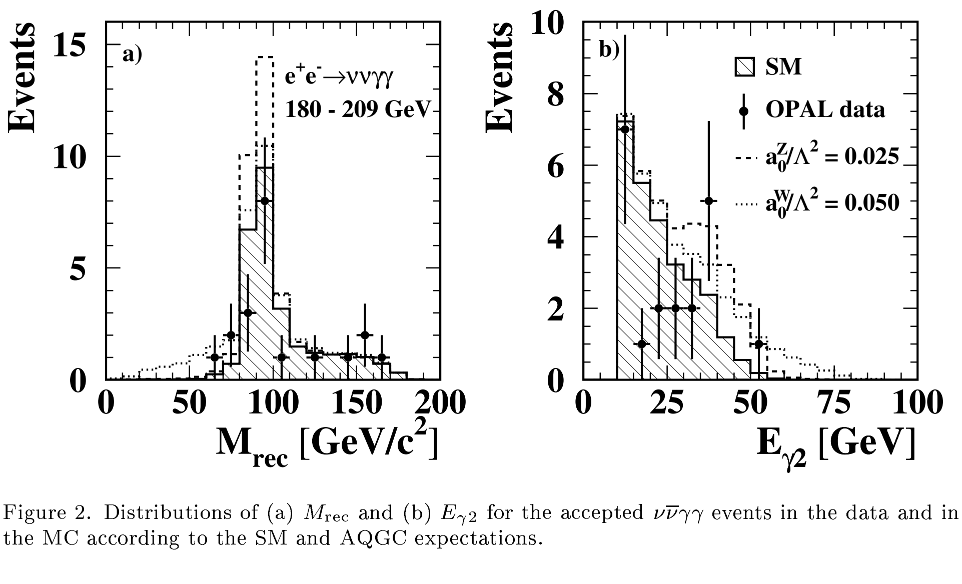

Figure 2. Distributions of (a) $M_{\rm rec}$ and (b) $E_{\gamma 2}$ for the accepted $\nu\bar{\nu}\gamma\gamma$ events in the data and in the MC according to the SM and AQGC expectations.

3 Triple Vector Boson Production

The processes $e^+e^- \to q\bar{q}\gamma\gamma$ and $e^+e^- \to W^+W^-\gamma$ are sensitive to the anomalous couplings $ZZ\gamma\gamma$ and $W^+W^-\gamma\gamma$, respectively (Fig. 1(b) and Fig. 1(c)). The $q\bar{q}\gamma\gamma$ events were selected from candidates passing the $e^+e^- \to q\bar{q}$ selection by demanding two photons with $E_\gamma > 5$ GeV and $|\cos\theta_\gamma| < 0.95$, isolated from the jet activity [7]. Similarly, the $W^+W^-\gamma$ event selection required an isolated photon with $E_\gamma >$ 2.5 GeV and $|\cos\theta_\gamma| < 0.975$ in those events passing the usual W^+W^- criteria [9]. In the energy range $130 < \sqrt{s} < 209$ GeV, 176 $q\bar{q}\gamma\gamma$ data events were accepted. For $W^+W^-\gamma$ the number was 187 in the range $180 < \sqrt{s} < 209$ GeV. Both numbers are consistent with the SM expectations in those channels.

Using the $q\bar{q}\gamma\gamma$ events, limits on the AQGC parameters a_0^Z and a_c^Z were assigned through a binned maximum likelihood fit to the observed distribution of $E_{\gamma 2}$. The effects of the anomalous couplings were introduced by reweighting events generated with KK2F [10] using the WRAP program [5]. From the $W^+W^-\gamma$ events, limits on a_0^W and a_c^W were extracted from the measured differential cross-section as a function of the photon energy and polar angle. In both analyses, photon identification and isolation, the photon energy scale and resolution, the photon angular acceptance and uncertainty in the modelling of the SM background were considered as systematic uncertainties.

4 Limits on AQGCs

The one-dimensional likelihood curves for the parameters a_0^Z and a_c^Z from the $q\bar{q}\gamma\gamma$ and $\nu\bar{\nu}\gamma\gamma$ final states were summed, neglecting the small effect of correlated systematic uncertainties. The corresponding 95% confidence level (CL) limits on possible anomalous contributions to the $ZZ\gamma\gamma$ vertex are

$$-0.007 \text{ GeV}^{-2} < a_0^Z/\Lambda^2 < 0.023 \text{ GeV}^{-2},$$
$$-0.029 \text{ GeV}^{-2} < a_c^Z/\Lambda^2 < 0.029 \text{ GeV}^{-2}.$$

Similarly, the 95% CL limits on the anomalous couplings at the $W^+W^-\gamma\gamma$ vertex have been obtained by combining the results from the $W^+W^-\gamma$ and $\nu\bar{\nu}\gamma\gamma$ analyses:

$$-0.020 \text{ GeV}^{-2} < a_0^W/\Lambda^2 < 0.020 \text{ GeV}^{-2},$$
$$-0.052 \text{ GeV}^{-2} < a_c^W/\Lambda^2 < 0.037 \text{ GeV}^{-2}.$$

When both parameters associated with the same AQGC vertex are allowed to vary simultaneously the combined likelihood contours of Fig. 3(a) and Fig. 3(b) are obtained. Compatibility with the SM is illustrated.

Under an additional assumption that $a_i^Z = a_i^W = a_i$ [3] an overall combination of the likelihood curves from the $\nu\bar{\nu}\gamma\gamma$, $q\bar{q}\gamma\gamma$ and $W^+W^-\gamma$ final states can be made, yielding 95% CL intervals of

$$+0.002 \text{ GeV}^{-2} < a_0/\Lambda^2 < 0.019 \text{ GeV}^{-2},$$
$$-0.022 \text{ GeV}^{-2} < a_c/\Lambda^2 < 0.029 \text{ GeV}^{-2}.$$

The corresponding two-dimensional fit is shown in Fig. 3(c).

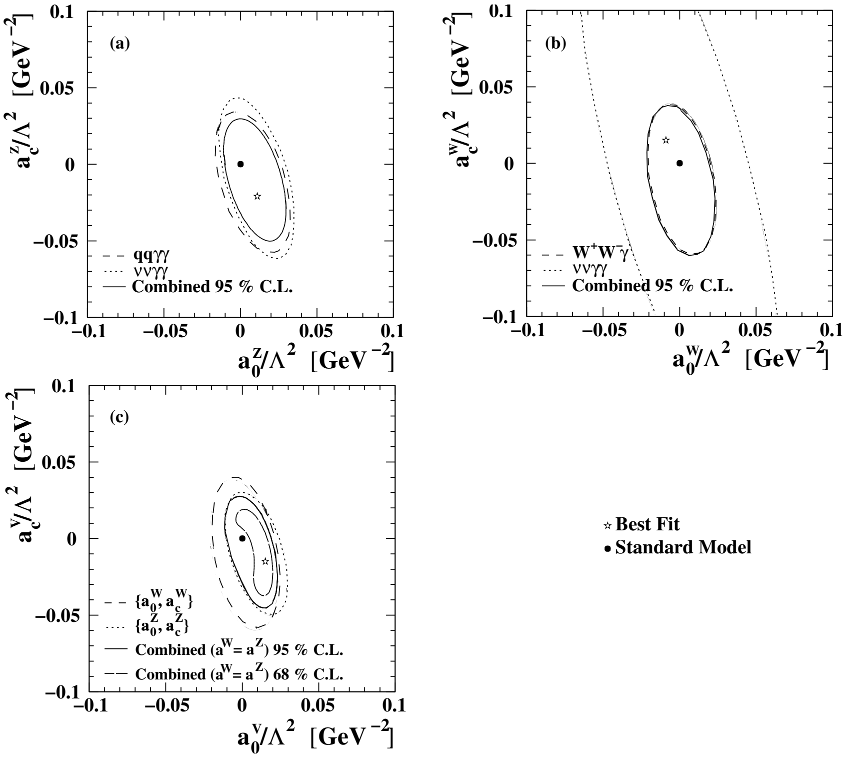

Figure 3. The 95% CL region in (a) (a_0^Z, a_c^Z), (b) (a_0^W, a_c^W) and (c) (a_0, a_c).

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