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First Direct Limits on Anomalous Quartic Couplings

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Abstract
A study of hard photon radiation in W^+W^- events recorded at $\sqrt{s} = 189$ GeV with the OPAL detector at LEP is presented. The photon energy spectrum is used to set the limits on possible anomalous $W^+W^-\gamma\gamma$ and $W^+W^-Z^0\gamma$ couplings. Limits on anomalous $W^+W^-\gamma\gamma$ couplings are also derived from the WW fusion process $e^+e^- \rightarrow \nu_e\overline{\nu}_e\gamma\gamma$. These are the first direct limits on anomalous electro-weak quartic gauge boson couplings.

1. Introduction

The W^+W^- cross-section has been precisely measured at LEP over a range of centre-of-mass energies, and is well described by the Standard Model (SM) expectation. Here these measurements are extended to include also W^+W^- events with energetic photons. This report describes the first measurement of the $W^+W^-\gamma$ cross-section at LEP performed by the OPAL experiment[1]. In addition to probing the modelling of the electro-magnetic radiation in W^+W^- events, the $W^+W^-\gamma$ final state may be sensitive to anomalous contributions to the $W^+W^-\gamma\gamma$ and $W^+W^-Z^0\gamma$ quartic gauge vertices, shown in Figure 1. The measured differential $W^+W^-\gamma$ cross-section, $d^2\sigma/dE_\gamma d\cos\theta_\gamma$, is used to obtain the first direct limits on possible anomalous quartic gauge couplings (QGCs)[1]. Further limits on anomalous contributions to the $W^+W^-\gamma\gamma$ vertex are obtained from the W^+W^- fusion process $e^+e^- \rightarrow \nu_e\overline{\nu}_e\gamma\gamma$[2].

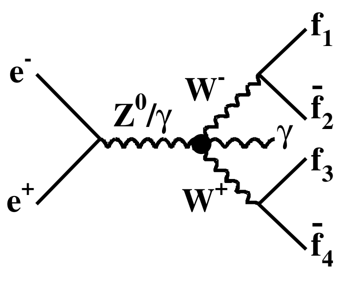

Figure 1. Standard Model $W^+W^-\gamma\gamma$ and $W^+W^-Z^0\gamma$ QGCs

2. Anomalous Quartic Gauge Couplings

The non-Abelian nature of the Standard Model results in vector boson self-interactions. In addition to the familiar $W^+W^-\gamma$ and W^+W^-Z couplings triple gauge couplings (TGCs), the Standard Model predicts the existence of four electro-weak QGCs, $W^+W^-W^+W^-$, $W^+W^-Z^0Z^0$, $W^+W^-Z^0\gamma$ and $W^+W^-\gamma\gamma$. These quartic couplings are not expected to play a significant role at LEP energies. However, new physics might appear as anomalous contributions to the SM quartic vertices. Previously there were no direct limits on anomalous QGCs, although indirect limits can be derived from the precise LEP/SLD Z^0 data[3].

As is the case for TGCs [4], in extensions to the Standard Model, anomalous quartic couplings can be parametrised by additional terms in the Lagrangian [5, 6, 7]. Only operators which do not introduce anomalous TGCs are considered. For example, the anomalous quadrupole moment operator generates both $W^+W^-\gamma$ and $W^+W^-\gamma\gamma$ couplings. Therefore, it is not considered as a source of genuine anomalous quartic couplings since its strength, λ_γ, is already tightly constrained from the study of TGCs at LEP [8] and at the Tevatron [9]. The lowest dimension operators which generate genuine anomalous quartic couplings involving photons are of dimension six. Three such possibilities are considered here, $\mathcal{L}_6^0$, $\mathcal{L}_6^c$ [5] and $\mathcal{L}_6^n$ [3, 7]:

$$\mathcal{L}_6^0 = -\frac{e^2}{16\Lambda^2} a_0 F^{\mu\nu} F_{\mu\nu} \vec{W}^\alpha . \vec{W}_\alpha ,$$

$$\mathcal{L}_6^c = -\frac{e^2}{16\Lambda^2} a_c F^{\mu\alpha} F_{\mu\beta} \vec{W}^\beta . \vec{W}_\alpha ,$$

$$\mathcal{L}_6^n = i\frac{e^2}{16\Lambda^2}a_n\epsilon_{ijk}W_{\mu\alpha}{}^{(i)}W_\nu{}^{(j)}W^{(k)\alpha}\mathrm{F}^{\mu\nu},$$

where $\mathrm{F}^{\mu\nu}$ and $W^{\mu\nu}$ are the field strength tensors of the photon and W fields respectively. Both $\mathcal{L}_6^0$ and $\mathcal{L}_6^c$, which conserve C and P (separately), generate anomalous $\mathrm{W^+W^-}\gamma\gamma$ and $\mathrm{Z^0Z^0}\gamma\gamma$ couplings. The CP violating term $\mathcal{L}_6^n$ results in an anomalous $\mathrm{W^+W^-Z^0}\gamma$ coupling. In each case, the strength of the coupling is proportional to a_i/Λ^2, where Λ represents a scale for new physics. A more general description of the operators leading to anomalous quartic couplings accessible at LEP can be found in the recent paper of Bélanger *et al.*[10].

3. $\mathrm{e^+e^-} \to \mathrm{W^+W^-}\gamma$ Cross section

A measurement of the $\mathrm{W^+W^-}\gamma \to f_1\overline{f}_2f_3\overline{f}_4\gamma$ cross-section only makes sense within a well-defined acceptance. For the measurement presented here, the acceptance is defined both to be sensitive to anomalous QGCs, which would result in an excess of high energy photons, and to be insensitive to the uncertainties associated with the modelling of FSR. The $\mathrm{W^+W^-}\gamma \to f_1\overline{f}_2f_3\overline{f}_4\gamma$ cross-section, denoted by $\hat{\sigma}_{\mathrm{WW}\gamma}$, is defined within the theoretical acceptance:

- $|\cos\theta_\gamma| < 0.9$, where θ_γ is the polar angle of the photon.
- $\cos\theta_{\gamma f} < 0.9$, where $\theta_{\gamma f}$ is the minimum angle between the photon and any of the charged fermions in the four-fermion final state.
- $\min(M_{f_1\overline{f}_2}, M_{f_3\overline{f}_4}) > 73$ GeV, where $M_{f_1\overline{f}_2}$ and $M_{f_3\overline{f}_4}$ are the invariant masses of the fermion pairs from the $\mathrm{W^-}$ and from the $\mathrm{W^+}$.
- $E_\gamma > 10$ GeV, where E_γ is the photon energy.

The first two cuts suppress initial and final state radiation respectively. The cuts on the invariant masses of the fermion pairs further suppress the contribution from FSR. The Standard Model expectation for the above signal definition is approximately 90 fb (see Table 1).

Program	$\hat{\sigma}_{\mathrm{WW}\gamma}$
EEWWG[7]	85.5 ± 0.4 fb
WWF[11]	89.3 ± 0.6 fb
KORALW[12]	102.4 ± 2.2 fb

Table 1. Standard Model cross-sections for the process $\mathrm{e^+e^-} \to \mathrm{W^+W^-}\gamma$ within the $f_1\overline{f}_2f_3\overline{f}_4\gamma$ signal definition.

3.1. Event Selection

For the determination of the $\mathrm{W^+W^-}\gamma$ cross-section and the anomalous coupling analysis $\mathrm{W^+W^-}\gamma$ events with photon energies $E_\gamma > 10$ GeV are identified. A detailed description of the selection criteria, summarised below, can be found in reference [1]. The selection proceeds in three stages. **$\mathrm{W^+W^-}$ Selection**: Identification of $\mathrm{e^+e^-} \to \mathrm{W^+W^-} \to \mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ and $\mathrm{e^+e^-} \to \mathrm{W^+W^-} \to \mathrm{q\overline{q}q\overline{q}}$ events. **Photon Identification**: Photons are identified as either isolated energy deposits in the electro-magnetic calorimeter or as isolated tracks consistent with being from a photon conversion. Photons are required lie within $|\cos\theta_\gamma| < 0.9$. **Kinematic Requirements**: After photon identification there is a significant background from FSR and from fake photons from the decays of π^0 and η mesons, particularly in the region of interest for anomalous QGCs, *i.e.* events with high energy photons, as indicated in Figure 2(before). These backgrounds are reduced using kinematic fits requiring events to be consistent with being from a three body final state of two on-shell W-bosons and a photon. The photon energy distribution after the kinematic requirements is indicated in Figure 2(after), showing a large reduction in background.

3.2. Results

In total, 17 $\mathrm{W^+W^-}\gamma$ events with $E_\gamma > 10$ GeV are selected in the 183 $\mathrm{pb^{-1}}$ of OPAL data recorded at $\sqrt{s} = 189$ GeV, corresponding to a measured cross-section of $\hat{\sigma}_{\mathrm{WW}\gamma} = 136 \pm 37 \pm 8$ fb, where the first error is statistical and the second systematic. This cross-section corresponds to the signal definition stated previously and is consistent with the Standard Model expectations determined using the available calculations, summarised in Table 1.

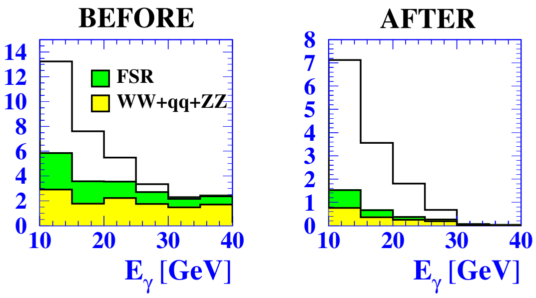

Figure 2. The expected photon energy spectrum before and after the kinematic requirements.

4. QGC Limits from $W^+W^-\gamma$

The observed energy spectrum of the photons in the selected $W^+W^-\gamma$ events is compared to the Monte Carlo expectation in Figure 3. The Monte Carlo distributions were constructed from three components: the contribution from $W^+W^-\gamma$ determined with the EEWWG[7] calculation, the contribution for FSR and photons from π^0 and η mesons estimated using KORALW[12], and two- and four-fermion backgrounds estimated using PYTHIA[13]. Also shown in Figure 3 are the expected energy spectra for two different values of the anomalous QGC parameter a_0.

A binned maximum likelihood fit to the the measured differential $W^+W^-\gamma$ cross-section, $d^2\sigma/dE_\gamma d\cos\theta_\gamma$, is used to extract limits on anomalous QGCs. The 95% confidence level upper limits are obtained from the resulting likelihood curves (shown in Figure 4):

$$
\begin{aligned}
-0.070\ \mathrm{GeV}^{-2} < \quad & a_0/\Lambda^2 & < 0.070\ \mathrm{GeV}^{-2}, \\
-0.13\ \mathrm{GeV}^{-2} < \quad & a_c/\Lambda^2 & < 0.19\ \mathrm{GeV}^{-2}, \\
-0.61\ \mathrm{GeV}^{-2} < \quad & a_n/\Lambda^2 & < 0.57\ \mathrm{GeV}^{-2}.
\end{aligned}
$$

These limits are higher than the expected limits due to the slight excess of high energy photons in the data. The probability of obtaining a limit greater than or equal to the observed limit is approximately 2%. These direct limits on the $W^+W^-\gamma\gamma$ vertex (a_0 and a_c) are significantly weaker than the indirect limits obtained from fits to precise electro-weak data[3]. However, the indirect limits are obtained under a restrictive set of assumptions and their validity has been questioned [10]. There are currently no indirect limits on a_n corresponding to an anomalous $W^+W^-Z^0\gamma$ coupling.

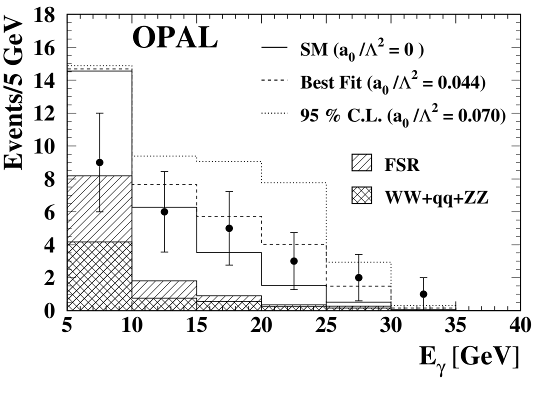

Figure 3. Photon energy spectrum for selected $W^+W^-\gamma$ events compared to the Monte Carlo expectation with and without anomalous QGCs

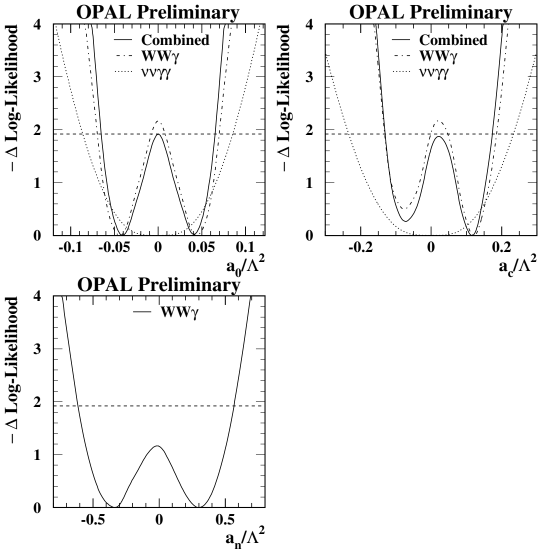

Figure 4. Likelihood curves from $W^+W^-\gamma$, $e^+e^- \rightarrow \nu_e\overline{\nu}_e\gamma\gamma$, and the combined likelihood curves.

5. QGC Limits from $e^+e^- \rightarrow \nu_e\overline{\nu}_e\gamma\gamma$

The process $e^+e^- \rightarrow \nu_e\overline{\nu}_e\gamma\gamma$ is sensitive to anomalous $W^+W^-\gamma\gamma$ QGCs through the WW-fusion process shown in Figure 5. The EENUNUGGANO calculation[14], which allows for anomalous QGCs, is used to assess the contribution from the WW-fusion process. This program does not include radiative return to the Z^0 which constitutes the main background and, as a consequence, the calculation is only valid for $\nu_e\overline{\nu}_e$ invariant masses below the Z^0 resonance. The SM background from double-radiative return to the Z^0 also shown in Figure 5 is estimated using the NUNUGPV[15] Monte Carlo generator.

In the OPAL study of the process $e^+e^- \rightarrow$

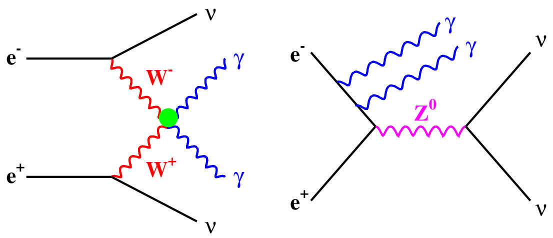

Figure 5. QGC in $e^+e^- \rightarrow \nu_e\overline{\nu}_e\gamma\gamma$ and the main background from double-radiative return to the Z^0.

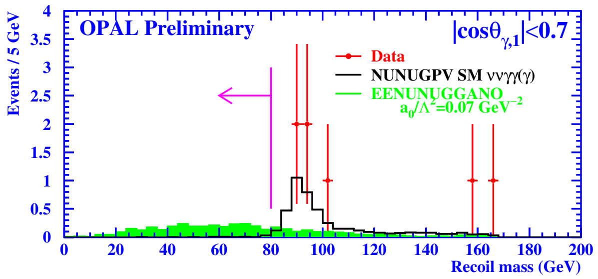

Figure 6. Recoil mass distribution for events with two photons and missing transverse energy.

$\nu_{\mathrm{e}}\overline{\nu}_{\mathrm{e}}\gamma\gamma$ events with two photons with $E_\gamma > 5$ GeV and $|\cos\theta_\gamma| < 0.9$ are identified[2]. Figure 6 shows the distribution of invariant mass of the recoil missing energy system ($M_{\nu_{\mathrm{e}}\overline{\nu}_{\mathrm{e}}}$) for the data (in the region where the higher energy photon has $|\cos\theta_\gamma| < 0.7$) compared to the SM expectation from NUNUGPV[15]. Also shown is the expected recoil mass distribution for a large anomalous QGC determined using EENUNUGGANO. To extract limits on anomalous QGCs a signal region is defined with recoil masses below the Z^0 peak where there is almost no SM background. No events are observed and limits can be placed on possible anomalous contributions to the $\mathrm{W}^+\mathrm{W}^-\gamma\gamma$ vertex:

$$\begin{aligned} -0.086\ \mathrm{GeV}^{-2} < & \quad a_0/\Lambda^2 & < 0.085\ \mathrm{GeV}^{-2}, \\ -0.23\ \mathrm{GeV}^{-2} < & \quad a_c/\Lambda^2 & < 0.23\ \mathrm{GeV}^{-2}. \end{aligned}$$

These limits are weaker than those obtained from the $\mathrm{W}^+\mathrm{W}^-\gamma$ final state.

6. Combined Limits

Combining the limits on the anomalous contributions to the $\mathrm{W}^+\mathrm{W}^-\gamma\gamma$ vertex from $\mathrm{e}^+\mathrm{e}^- \to \nu_{\mathrm{e}}\overline{\nu}_{\mathrm{e}}\gamma\gamma$ with those from $\mathrm{W}^+\mathrm{W}^-\gamma$ gives:

$$\begin{aligned} -0.065\ \mathrm{GeV}^{-2} < & \quad a_0/\Lambda^2 & < 0.065\ \mathrm{GeV}^{-2}, \\ -0.13\ \mathrm{GeV}^{-2} < & \quad a_c/\Lambda^2 & < 0.17\ \mathrm{GeV}^{-2}. \end{aligned}$$

The combined likelihood curves for a_0 and a_c and the likelihood curve for a_n from $\mathrm{W}^+\mathrm{W}^-\gamma$ are shown in figure 4

7. Conclusion

The first direct limits on electro-weak anomalous quartic gauge couplings have been obtained from a study of $\mathrm{e}^+\mathrm{e}^- \to \mathrm{W}^+\mathrm{W}^-\gamma$ and $\mathrm{e}^+\mathrm{e}^- \to \nu_{\mathrm{e}}\overline{\nu}_{\mathrm{e}}\gamma\gamma$ at LEP. Since the sensitivity to anomalous QGCs increases rapidly with centre-of-mass energy, these results will be significantly improved upon in the last years of LEP running.

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