Neutral Triple and Quartic Gauge Couplings at LEP

R. Ofierzynski[a] *

[a]ETH Zürich, CH-8093 Zürich, Switzerland

The possible existence of neutral triple ZZZ, ZZγ and Z$\gamma\gamma$ and quartic ZZ$\gamma\gamma$ gauge boson couplings is investigated. Based on data collected at LEP2 at centre-of-mass energies up to 208 GeV no evidence has been found for such couplings. Preliminary limits for neutral triple gauge couplings as obtained from the combination of the LEP experiments are presented.

1. INTRODUCTION

The test for neutral triple and quartic gauge couplings is one of the principal physics aims at LEP2. Unlike couplings involving charged gauge bosons, purely neutral gauge boson couplings do not occur in the Standard Model (SM) of electroweak interactions.

The presence of neutral triple gauge couplings (TGC) can indicate new physics beyond the Standard Model, such as *e.g.* heavy fermions with non-standard couplings to neutral bosons. Quartic gauge couplings (QGC) could be generated without modifying the triple couplings. New physics effects could emerge due to heavy new particle exchange. For reviews of the theory of neutral TGC's and QGC's see [1–3].

At LEP, neutral triple gauge couplings can be probed in the $e^+e^- \to$ ZZ, Zγ processes, and neutral quartic gauge couplings in the $e^+e^- \to$ Z$\gamma\gamma$ process. Most of the analyses use now the complete data set, including the data taken during the year 2000 at c.m. energies up to 208 GeV.

2. NEUTRAL TRIPLE GAUGE COUPLINGS

Couplings of the type ZZZ, ZZγ and Z$\gamma\gamma$ are considered. In the Standard Model, neutral TGC's vanish at tree level. At the one-loop level, only CP-conserving couplings are allowed receiving a small contribution of the order of 10^{-4}, which is well below the current experimental sensitivity.

2.1. Theoretical Framework

Constraints due to Bose statistics require one of the particles to be off-shell for nonvanishing contribution to the vertex. The vertices ZγV and ZZV (V denoting the off-shell particle, being either Z or γ) of three neutral gauge bosons are then described [1,2] by the Feynman rule

$$ie\Gamma^{\alpha,\beta,\mu}_{V_1V_2V_3}(q_1,q_2,P) \tag{1}$$

with the vertex functions

$$\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1,q_2,P) = \frac{i(P^2-m_V^2)}{m_Z^2}\cdot \left\{ h_1^V(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}) + \frac{h_2^V}{m_Z^2}P^\alpha[(Pq_2)g^{\mu\beta} - q_2^\mu P^\beta] - h_3^V\epsilon^{\mu\alpha\beta\rho}q_{2\,\rho} - \frac{h_4^V}{m_Z^2}P^\alpha\epsilon^{\mu\beta\rho\sigma}P_\rho q_{2\,\sigma}\right\}, \tag{2}$$

$$\Gamma^{\alpha\beta\mu}_{ZZV}(q_1,q_2,P) = \frac{i(P^2-m_V^2)}{m_Z^2}\cdot \left[f_4^V(P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) - f_5^V\epsilon^{\mu\alpha\beta\rho}(q_1-q_2)_\rho\right]. \tag{3}$$

for the ZγV and ZZV vertex, respectively. P denotes the momentum of the boson V, the momenta of Z,γ or of the Z-pair are denoted by q_1 and q_2. Four independent couplings ($h^V_{1,2,3,4}$) are allowed in the ZγV vertex, and two independent couplings ($f^V_{4,5}$) in the ZZV vertex.

*Current address: CERN, CH-1211 Genève 23, Switzerland

No additional symmetry constraints can be used to reduce the number of free parameters in the vertex, since operators of higher dimensionality would be required. h_1^V, h_3^V, f_4^V and f_5^V are dimension 6 operators, whereas h_2^V and h_4^V are of dimension 8. h_i^V and f_i^V coupling parameters are independent of each other. Below the $2m_t$ threshold the imaginary part of the parameters is negligible, and only the real part is relevant.

The couplings h_1^V, h_2^V and f_4^V are CP-violating, hence they lead to amplitudes which do not interfere with the Standard Model ones, thus the differential cross-section of the considered processes gets additive contributions from possible anomalous processes. On the contrary, h_3^V, h_4^V and f_5^V are CP-conserving, and lead to amplitudes which interfere with the Standard Model ones, hence the differential and total cross-sections of the considered processes are enhanced or suppressed.

2.2. Processes at LEP

Neutral triple gauge boson couplings are tested at LEP in the $e^+e^- \to Z\gamma$ and $e^+e^- \to ZZ$ processes. Unlike the Standard Model processes which proceed through the t-channel exchange of an electron, the neutral TGC processes are described by s-channel graphs with a Z or γ coupling to either ZZ or Zγ (figure 1 top) with the Z decaying into two fermions.

In $e^+e^- \to Z\gamma$, the couplings h_i^V are tested. The production of Zγ final states via anomalous neutral TGC's has a large Standard Model background consisting of 2 fermion final states with initial state radiation. Main effects of anomalous couplings would consist in an increase of the total cross-section – this contribution increasing with the centre-of-mass energy –, a modification of the differential spectrum of the photon – mainly at large polar angles –, and an enhancement of the production of longitudinally polarised Z bosons, which could be seen in the angular distribution of the jets.

In $e^+e^- \to ZZ$ the couplings f_i^V are tested. Important Standard Model background consists of 4 fermion processes. Anomalous triple gauge couplings result in a change of the observed total cross-section, as presented in figure 2, where the impact of non-zero coupling parameters on the total cross-section is shown at various energies together with a comparison with OPAL data [4]. Again, as a consequence of the increasing contributions with the centre-of-mass energy, the sensitivity increases with energy. Furthermore, a modification of the angular distribution of the Z bosons and a change in the average polarisation of the Z bosons could be expected [5].

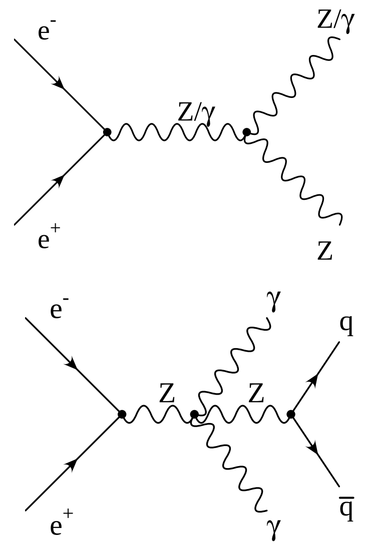

Figure 1. Feynman graphs of the investigated neutral TGC (top) and neutral QGC (bottom) processes.

2.3. Results

Results from a combination [6] of the four LEP experiments ALEPH, DELPHI, L3 and OPAL are presented. For details of the analyses the individual references should be consulted [4,7–9].

The collected integrated luminosities used for the analyses at the LEP experiments are given in table 1. For both processes, one- and two-parameter analyses are being performed, *i.e.* only one (or two) parameter is (are) varied, the remaining ones are fixed to their Standard Model values. Data from all four experiments agree in all respects well with the Standard Model Monte Carlo predictions, therefore only limits can be derived on the TGC parameters.

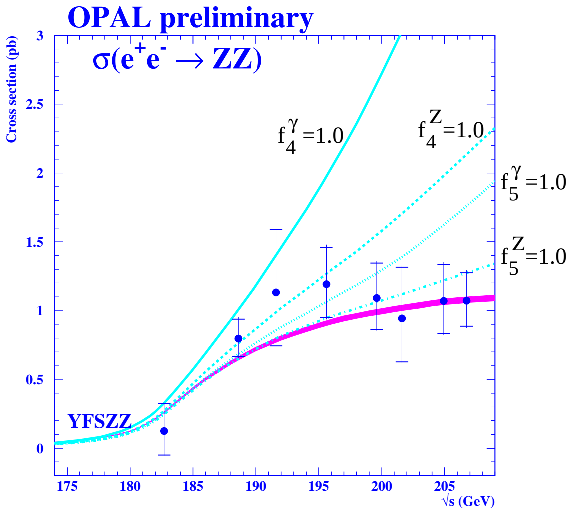

Figure 2. Total cross-section of $e^+e^- \to ZZ$ as predicted by YFSZZ Monte Carlo for the Standard Model (band) and for nonzero values of the coupling parameters f_i^V and comparison with OPAL data for $\sqrt{s}$ = 183-208 GeV [4].

For the LEP combination, the experiments pre-combine different final states for each coupling. Each experiment then provides the negative log-likelihood, $-\log\mathcal{L}$, as a function of the coupling parameter (one or two) for the combination. These log-likelihoods contain statistical and uncorrelated systematic uncertainties. Uncertainties which are considered to be correlated between the experiments are taken into account after combination of the $-\log\mathcal{L}$ functions. The 95% confidence level (C.L.) limits are obtained for $\Delta\log\mathcal{L} = +1.92$ (for 2-parameter analyses $\Delta\log\mathcal{L} = +3.0$) above minimum.

For tests of h_i^V in $e^+e^- \to Z\gamma$, ALEPH, DELPHI and L3 use data up to 208 GeV (preliminary results), so far OPAL uses only 189 GeV data (published results). The final states $q\bar{q}\gamma$ and $\nu\bar{\nu}\gamma$ are investigated, which comprise 70% and 20% of all final states, respectively (all except ALEPH, which uses only $q\bar{q}\gamma$).

For an evaluation of the coupling parameters, the experiments perform a fit to the cross-section, using additional information from the angular distributions to improve the sensitivity. Due to the usage of a larger phase space region – this increases the statistics by about a factor two –, and due to additional information from an Optimal Observables technique, the sensitivity of the L3 analysis is the highest among all four experiments.

The results show no evidence for neutral triple gauge boson couplings; the LEP combination yields the 95% C.L. limits on the parameters shown in table 2.

When performing 2-parameter fits to the couplings, three different situations can occur: a) the amplitudes relative to the couplings strongly interfere between themselves, b) the amplitudes only marginally interfere between themselves, but strongly interfere with the Stan-

Table 1
Integrated luminosity used in the analyses of neutral TGC's collected in the LEP experiments for the processes $e^+e^- \to Z\gamma$ and $e^+e^- \to ZZ$. [7–9,4]

	$e^+e^- \to Z\gamma$	$e^+e^- \to ZZ$
ALEPH	605 pb^{-1}	660 pb^{-1}
DELPHI	638 pb^{-1}	638 pb^{-1}
L3	620 pb^{-1}	680 pb^{-1}
OPAL	176 pb^{-1}	609 pb^{-1}

Table 2
LEP combined 95% C.L. ranges for h^γ and h^Z ($Z\gamma V$ couplings). The parameter listed is varied while the remaining ones are fixed to their SM values. Both statistical and systematic errors are included. [6]

Parameter	95% C.L.
h_1^γ	$[-0.056, +0.055]$
h_2^γ	$[-0.045, +0.025]$
h_3^γ	$[-0.049, -0.008]$
h_4^γ	$[-0.002, +0.034]$
h_1^Z	$[-0.13, +0.13]$
h_2^Z	$[-0.078, +0.071]$
h_3^Z	$[-0.20, +0.07]$
h_4^Z	$[-0.05, +0.12]$

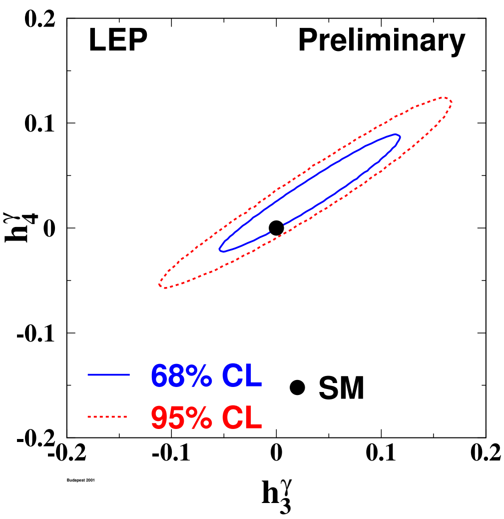

Figure 3. Contour curves of 68% C.L. and 95% C.L. in the plane (h_3^γ, h_4^γ) showing the LEP combined result. [6]

dard Model amplitudes, and c) the amplitudes only marginally interfere with any other amplitudes. In case a) the possible combinations are $(h_1^\gamma, h_2^\gamma), (h_3^\gamma, h_4^\gamma), (h_1^Z, h_2^Z), (h_3^Z, h_4^Z)$, and the allowed region has an elliptical shape with the axis at about 45° in the parameter plane. This case is investigated by all LEP experiments and hence combinations of these results are performed.

An example is shown in figure 3 where the high correlation for the combination (h_3^γ, h_4^γ) can be seen. For all 2-parameter analyses the 95% C.L. contours enclose the Standard Model value, and the corresponding limits are presented in table 3.

For tests of f_i^V in $\mathrm{e^+e^-} \to \mathrm{ZZ}$, all experiments use data up to 208 GeV (preliminary results), and in general all visible channels are used. The relevant quantity is the cross-section, the experiments perform a fit to the event rates, some using additional information from the angular distributions; in addition, OPAL uses an Optimal Observables technique for channels with jets.

Again the results show no evidence for nonzero parameters, the obtained 95% C.L. limits are shown in table 4.

The 2-parameter analyses show no correlation between parameters belonging to Z and to γ, corresponding to the above discussed case c). The 95% C.L. contours enclose the Standard Model value, and the corresponding limits are shown in table 5.

Table 3
LEP combined 95% C.L. ranges for h^γ and h^Z (ZγV couplings). In each case the two parameters listed are varied while the remaining ones are fixed to their SM values. Both statistical and systematic errors are included. [6]

Parameter	95% C.L.
h_1^γ	$[-0.16, +0.05]$
h_2^γ	$[-0.11, +0.02]$
h_3^γ	$[-0.08, +0.14]$
h_4^γ	$[-0.04, +0.11]$
h_1^Z	$[-0.35, +0.28]$
h_2^Z	$[-0.21, +0.17]$
h_3^Z	$[-0.37, +0.29]$
h_4^Z	$[-0.19, +0.21]$

Table 4
LEP combined 95% C.L. ranges for f^γ and f^Z (ZZV couplings). The parameter listed is varied while the remaining ones are fixed to their SM values. Both statistical and systematic errors are included. [6]

Parameter	95% C.L.
f_4^γ	$[-0.17, +0.19]$
f_4^Z	$[-0.31, +0.28]$
f_5^γ	$[-0.36, +0.40]$
f_5^Z	$[-0.36, +0.39]$

3. NEUTRAL QUARTIC GAUGE COUPLINGS

Out of all possible combinations among four neutral gauge bosons, $\gamma\gamma\gamma\gamma$ and Z$\gamma\gamma\gamma$ have already been exploited at energies below those presently available. Couplings of the type ZZZZ on the other hand would require a process involving three massive gauge bosons in the final state,

Table 5
LEP combined 95% C.L. ranges for f^γ and f^Z (ZZV couplings). In each case the two parameters listed are varied while the remaining ones are fixed to their SM values. Both statistical and systematic errors are included. [6]

Parameter	95% C.L.
f_4^γ	$[-0.17, +0.19]$
f_4^Z	$[-0.30, +0.28]$
f_5^γ	$[-0.34, +0.38]$
f_5^Z	$[-0.36, +0.38]$

which is inaccessible at LEP2. Thus the couplings of interest at LEP2 are ZZ$\gamma\gamma$ and ZZZγ, the latter one however can only be probed by means of the process $e^+e^-\to$ZZγ which – due to phase space – unfortunately has only marginal sensitivity. The experimental signature involving the ZZ$\gamma\gamma$ coupling is shown in figure 1 (bottom).

3.1. Theoretical Framework

The commonly used parametrisation is done through additional terms in the effective Lagrangian. Assuming C and P conservation separately, furthermore electromagnetic U(1) and custodial SU(2) symmetries, the terms relevant to ZZ$\gamma\gamma$ couplings are [3]:

$$\mathcal{L}^0 = -\frac{\pi\alpha}{4}\frac{a_0}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}Z^\rho \cdot Z_\rho \tag{4}$$

$$\mathcal{L}^c = -\frac{\pi\alpha}{4}\frac{a_c}{\Lambda^2}F_{\mu\rho}F^{\mu\sigma}Z^\rho \cdot Z_\sigma \tag{5}$$

with α being the fine structure constant, $F_{\mu\nu}$ the field strength tensor and Z^ρ the physical field of the Z boson. Here, only genuine quartic couplings are considered, *i.e.* terms which do not generate triple gauge couplings. The latter type of terms can be probed directly through the search for the corresponding TGC's, where experimental limits are more restrictive.

The strength of the QGC's is described by the parameters a_0/Λ^2 and a_c/Λ^2, where Λ represents the scale of new physics responsible for the couplings. This parameter is in principle unknown and model-dependent, however the ratios themselves can be extracted in a model-independent

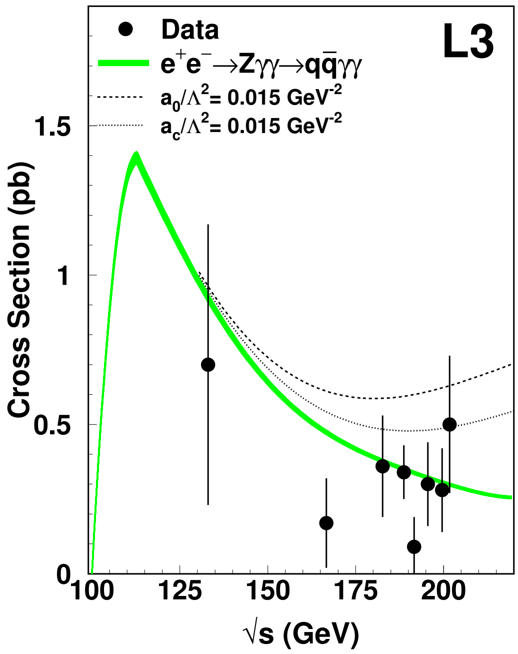

Figure 4. Total cross-section of the process $e^+e^- \to Z\gamma\gamma \to q\bar{q}\gamma\gamma$ for different c.m. energies for the Standard Model (band) and for nonzero contributions from anomalous QGC's, and comparison with L3 data at $\sqrt{s}$= 130–202 GeV [10].

way. The parameters are assumed to be real and vanish in the Standard Model.

3.2. Processes at LEP

Quartic gauge couplings of the type ZZ$\gamma\gamma$ are tested at LEP in the process $e^+e^- \to Z\gamma\gamma$, where the hadronic final state $q\bar{q}\gamma\gamma$ is analysed. Standard Model background emerges from hadronic Z decays with initial state (ISR) or final state radiation (FSR), where the FSR can be also mimicked by misidentified electrons or unresolved π^0s.

The main effects of anomalous quartic couplings are deviations in the total cross-section and changes in the event rates w.r.t. angular distributions and energies. The produced photons would tend to have similar energies and to be produced more centrally; this could be seen as an excess of photons with high transverse momentum. Again the sensitivity increases with centre-of-mass energy. Figure 4 shows the effect of non-zero coupling parameters on the total cross-section together with the L3 data [10].

3.3. Current Status

The currently available results date from January 2001 (L3, published) [10] and July 2001 (OPAL, preliminary) [11]. Only these two experiments presently perform searches for neutral quartic gauge couplings, L3 using centre-of-mass energies of 130–202 GeV resulting in an integrated luminosity of 498 pb^{-1} and OPAL using centre-of-mass energies of 130–208 GeV with an integrated luminosity of 578 pb^{-1}. Results are obtained by a fit to the distributions of the variables which are considered to be the most sensitive ones in each experiment. L3 uses the transverse momentum of the less energetic photon and OPAL the double differential cross-section as function of the energy of the less energetic jet and the larger one of the photon polar angles. The sensitivity of both approaches is comparable.

Data from both experiments agree with the Standard Model Monte Carlo. Therefore limits are derived on the QGC parameters. This interpretation of the results is performed so far using the EEZGG Monte Carlo generator [12] that contains the analytical calculation of the anomalous matrix element. L3 has set the 95% C.L. limits in units of GeV^{-2} for the parameter a_0/Λ^2 of $[-0.008, +0.005]$, for a_c/Λ^2 of $[-0.007, +0.011]$, OPAL has set the 95% C.L. limits for a_0/Λ^2 of $[-0.006, +0.008]$, for a_c/Λ^2 of $[-0.008, +0.0012]$.

Recently, the WRAP Monte Carlo generator [13] was modified to include QGC's, yielding results different from those of EEZGG. Consensus is reached on the use of WRAP, with which the significance is expected to drop. Experiments are currently implementing this generator in their analyses.

4. SUMMARY

The $e^+e^- \to Z\gamma$ and the $e^+e^- \to ZZ$ processes are used to search for anomalous triple gauge boson couplings. The data agree in all respects with the Standard Model and no evidence for neutral TGC's has been found at LEP. Thus, limits on the coupling parameters can be calculated. 95% confidence level limits of the order of 10^{-1} on the parameters from a combination of the results of the four LEP experiments were obtained (tables 2,3,4,5).

The process $e^+e^- \to Z\gamma\gamma$ is used at LEP to study $ZZ\gamma\gamma$ quartic couplings. No evidence for neutral QGC's has been found. This general result is not expected to change, even if the current 95% C.L. limits will change with the new Monte Carlo generator used for the analyses. At present, the experiments repeat their analyses using the WRAP generator.

Final LEP combined numbers for both the neutral triple and quartic gauge boson couplings will be published in the LEP electroweak report.

REFERENCES

1. K.Hagiwara *et al.*, Nucl. Phys. B282 (1987), 253.
2. G.J.Gounaris, J.Layssac, F.M.Renard, Phys. Rev. D 61 (2000), 073013.
3. G. Bélanger *et al.*, Eur. Phys. J. C 13 (2000), 283.
4. OPAL Collaboration, Eur. Phys. J. C 17 (2000) 553, PN482
5. J.Alcaraz, M.A.Falagán, E.Sánchez, Phys. Rev. D 61 (2000), 075006.
6. The LEP Collaborations ALEPH, DELPHI, L3, OPAL and the LEP GC Working Group, Combined Preliminary Results of Electroweak Gauge Boson Coupling Measurements by the LEP Experiments, LEPEWWG/TGC/2001-03.
7. ALEPH Collaboration, ALEPH 2001/061, CONF 2000/041.
8. DELPHI Collaboration, DELPHI 2001-097, CONF 525.
9. L3 Collaboration, L3 Note 2672, L3 Note 2696.
10. L3 Collaboration, Phys. Lett. B 505 (2001), 47.
11. OPAL Collaboration, PN452.
12. W.J.Stirling, A.Werthenbach, Eur. Phys. J. C 14 (2000), 103.
13. G.Montagna *et al.*, Phys. Lett. B 515 (2001), 197.