EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

LEPEWWG/TGC/2001-02
ALEPH 2001-035 PHYSIC 2001-010
DELPHI 2001-034 PHYS 889
L3 Note 2657
OPAL TN-685
March 30th, 2001

Combined Results for Electroweak Gauge Boson Couplings Measured on the LEP Experiments

The LEP Collaborations ALEPH, DELPHI, L3, OPAL, and the LEP GC Working Group*

Prepared from results of the LEP experiments published by March 2001

Abstract

A combination of published results from the LEP experiments is presented for electroweak gauge boson couplings. This note includes combinations of neutral triple gauge boson couplings h_i^V and f_i^V, as well as quartic gauge couplings a_0^w/Λ^2, a_c^w/Λ^2 and a_n^w/Λ^2.

*Contact: Helge Voss , e-mail: Helge.Voss@cern.ch
WWW access at http://www.cern.ch/LEPEWWG/tgc/

1 Introduction

During its second phase of operation, from 1996 until November 2000, the e^+e^- collider LEP at CERN steadily increased its centre-of-mass energy from 161 GeV up to 209 GeV, reached in the final year. Until the end of LEP2 operation, a total integrated luminosity of approximately 700 pb^{-1} per experiment was recorded. The combination of electroweak gauge boson couplings presented in this note includes published measurements on neutral and quartic gauge couplings, which are available for data taken at energies up to 189 GeV, from L3 and OPAL. The data sets correspond to an integrated luminosity of about 250 pb^{-1} per experiment. There are published results by all four LEP-collaborations on charged TGCs [1–4] including data up to 189 GeV. These measurements are not combined as explained at the end of section 2.1. In addition to these measurements, there are preliminary results for all gauge couplings using data up to 209 GeV, which are used for the preliminary combinations [5, 6]

The W-pair production process, $e^+e^- \to W^+W^-$, involves the triple gauge boson vertices between the W^+W^- and the Z or the photon. During LEP2 operation, about 10,000 W-pair events were collected by each experiment. Single W ($e\nu W$) and single photon ($\nu\bar{\nu}\gamma$) production at LEP are sensitive to the $WW\gamma$ vertex. The measurement of these charged triple gauge boson couplings and the search for possible anomalous contributions due to the effects of new physics beyond the Standard Model are among the principal physics goals at LEP2 [7].

At centre-of-mass energies exceeding twice the Z boson mass, pair production of Z bosons is kinematically allowed. Here, one searches for the possible existence of triple vertices involving only neutral electroweak gauge bosons. Such vertices could also contribute to $Z\gamma$ production. In contrast to triple gauge boson vertices with two charged gauge bosons, purely neutral gauge boson vertices do not occur in the Standard Model of electroweak interactions.

Within the Standard Model, quartic electroweak gauge boson vertices with at least two charged gauge bosons exist. In e^+e^- collisions at LEP2 centre-of-mass energies, the $WWZ\gamma$ and $WW\gamma\gamma$ vertices contribute to $WW\gamma$ and $\nu\bar{\nu}\gamma\gamma$ production in s-channel and t-channel, respectively. The effect of the Standard Model quartic electroweak vertices is below the sensitivity of LEP2. Thus anomalous quartic vertices are searched for in the production of $WW\gamma$, $\nu\bar{\nu}\gamma\gamma$ and also $Z\gamma\gamma$ final states.

2 Electroweak Gauge Boson Couplings

2.1 Charged Triple Gauge Boson Couplings

The parameterisation of the charged triple gauge boson vertices is described in References [7–13]. The most general Lorentz invariant Lagrangian which describes the charged triple gauge boson interaction contains fourteen independent complex couplings, seven of which describe the $WW\gamma$ vertex and the remainder describe the WWZ vertex. Assuming electromagnetic gauge invariance as well as CP conservation, the number of independent TGCs reduces to six. One common set is $\{g_1^Z,\ \kappa_\gamma,\ \kappa_Z,\ \lambda_\gamma,\ \lambda_Z,\ g_5^Z\}$ where $g_1^Z = \kappa_\gamma = \kappa_Z = 1$ and $\lambda_\gamma = \lambda_Z = g_5^Z = 0$ in the Standard Model. Except g_5^Z, all these couplings also conserve C and P separately.

The parameters used here are proposed in Ref. [7]:

$$\Delta g_1^{\mathrm{Z}} \equiv g_1^{\mathrm{Z}} - 1\,, \quad (1)$$
$$\Delta\kappa_\gamma \equiv \kappa_\gamma - 1\,, \quad (2)$$
$$\lambda_\gamma \quad , \quad (3)$$
$$g_5^{\mathrm{Z}} \quad , \quad (4)$$

with the gauge constraints:

$$\Delta\kappa_{\mathrm{Z}} \equiv \kappa_{\mathrm{Z}} - 1 = \Delta g_1^{\mathrm{Z}} - \Delta\kappa_\gamma \tan^2\theta_W\,, \quad (5)$$
$$\lambda_{\mathrm{Z}} = \lambda_\gamma\,, \quad (6)$$

where Δ indicates the deviation of the respective coupling from its Standard Model value of unity, and θ_W is the weak mixing angle. The couplings are considered as real, with the imaginary parts fixed to zero.

For the charged TGCs, new Monte Carlo calculations (RacoonWW [14] and YFSWW [15]) including $O(\alpha_{em})$ corrections to the WW production process have recently become available. They have the potential to largely affect the measurements of the charged TGCs in WW-pair production. The implications are still under investigation and no updated results are available yet from all the collaborations. Therefore no combinations are made for these measurements.

2.2 Neutral Triple Gauge Boson Couplings

There are two classes of Lorentz invariant structures associated with neutral TGC vertices which preserve $U(1)_{em}$ and Bose symmetry, as desribed in [9, 16].

The first class refers to anomalous $\mathrm{Z}\gamma\gamma^*$ and $\mathrm{Z}\gamma\mathrm{Z}^*$ couplings which are accessible at LEP in the process $\mathrm{e^+e^-} \to \mathrm{Z}\gamma$. The parametrisation contains eight couplings: h_i^V with $i = 1, ..., 4$ and $V = \gamma$,Z. The superscript γ refers to $\mathrm{Z}\gamma\gamma^*$ couplings and superscript Z refers to $\mathrm{Z}\gamma\mathrm{Z}^*$ couplings. The photon and the Z boson in the final state are considered as on-shell particles, while the third boson at the triple vertex is off shell. The couplings h_1^V and h_2^V are CP-odd while h_3^V and h_4^V are CP-even.

The second class refers to anomalous $\mathrm{ZZ}\gamma^*$ and ZZZ^* couplings which are accessible at LEP2 in the process $\mathrm{e^+e^-} \to \mathrm{ZZ}$. This anomalous vertex is parametrised in terms of four couplings: f_i^V with $i = 4, 5$ and $V = \gamma$,Z. The superscript γ refers to $\mathrm{ZZ}\gamma^*$ couplings and the superscript Z refers to ZZZ^* couplings, respectively. Both Z bosons in the final state are assumed to be on-shell, while the third boson at the triple vertex is off-shell. The couplings f_4^V are CP-odd whereas f_5^V are CP-even.

Note that the h_i^V and f_i^V couplings are independent of each other. They are assumed to be real and they vanish at tree level in the Standard Model.

2.3 Quartic Gauge Boson Couplings

Anomalous contributions to electroweak quartic vertices are treated in the framework of References [17–19]. Considered are the three lowest-dimensional operators leading to quartic vertices not causing anomalous TGCs. The corresponding couplings are a_0/Λ^2, a_c/Λ^2 and a_n/Λ^2, where Λ represents the energy scale of new physics. The couplings a_0/Λ^2 and a_c/Λ^2 parametrise variations in the WW$\gamma\gamma$ and ZZ$\gamma\gamma$ vertices, while a_n/Λ^2 solely affects the WWZγ vertex. The couplings a_0/Λ^2 and a_c/Λ^2 conserve C and P, while the coupling a_n/Λ^2 is CP violating. The production of WWγ depends on all three couplings. The production of $\nu\bar{\nu}\gamma\gamma$ and Z$\gamma\gamma$ depends only on a_0/Λ^2 and a_c/Λ^2, the former through the WW$\gamma\gamma$ vertex and the latter through the ZZ$\gamma\gamma$ vertex. The couplings are assumed to be real and they vanish at tree level in the Standard Model.

A detailed description of QGCs has recently been published in [20], where it is suggested that the coupling a_0/Λ^2 and a_c/Λ^2 describing the anomalous WW$\gamma\gamma$ vertex should not be assumed to be the same as those describing the anomalous ZZ$\gamma\gamma$ vertex. The measurements presented here probe the WW$\gamma\gamma$ vertex only and hence the measured couplings are marked a_0^w/Λ^2, a_c^w/Λ^2 and a_n^w/Λ^2 accordingly.

3 Measurements

The combined results presented here were obtained from updated neutral electroweak gauge boson coupling and quartic gauge coupling measurements as discussed above. These results are based on the data collected at LEP2 until the end of 1998 at centre-of-mass energies up to 189 GeV. The experiments already pre-combine different processes and final states for each of the couplings. The individual references should be consulted for details about the data samples used.

For neutral TGCs, the analyses use mainly measurements of the total cross sections of Zγ and ZZ production, although the use of differential distributions increases the sensitivity. The individual references should be consulted for details of the analyses of the h_i^V couplings [21, 22] and the f_i^V couplings [23, 24].

For QGCs, the experiments published measurements based on WWγ and $\nu\bar{\nu}\gamma\gamma$ production. In addition to the total cross section, the photon energy is used as a sensitive variable in the WWγ channel. Again, the individual references should be consulted for details of the determination of the QGCs a_0/Λ^2, a_c/Λ^2 and a_n/Λ^2 [25, 26].

4 Combination Procedure

The combination procedure is identical to the previous preliminary LEP combination of electroweak gauge boson couplings [5, 6].

Each experiment provides the negative log likelihood, $\log \mathcal{L}$, as a function of the coupling parameters to be combined. The single parameter analyses are performed fixing all other parameters to their Standard Model values.

The $\log \mathcal{L}$ functions from each experiment include statistical as well as those systematic uncertainties which are considered as uncorrelated between experiments. For both single- and multi-parameter combinations, the individual $\log \mathcal{L}$ functions are added. It is necessary to use the $\log \mathcal{L}$ functions directly in the combination, since in some cases they are not parabolic, and hence it is not possible to combine the results correctly by simply taking weighted averages of the measurements.

The main contributions to the systematic uncertainties that are uncorrelated between experiments arise from detector effects, background in the selected signal samples, limited Monte Carlo statistics and the fitting method. Their importance varies for each experiment and the individual references should be consulted for details.

The systematic uncertainties arising from the theoretical cross section prediction in $Z\gamma$-production ($\simeq 1\%$ in the $q\overline{q}\gamma$- and $\simeq 2\%$ in the $\nu\bar{\nu}\gamma$ channel) are treated as correlated. For ZZ production, the uncertainty on the theoretical cross section prediction is small compared to the statistical accuracy and therefore neglected. Smaller sources of correlated systematic uncertainties, such as those arising from the LEP beam energy, are for simplicity treated as uncorrelated.

The correlated systematic uncertainties are taken into account by scaling the combined log-likelihood functions by the squared ratio of the sum of statistical and uncorrelated systematic uncertainty over the total uncertainty including all correlated uncertainties. For the general case of non-Gaussian probability density functions, this treatment of the correlated errors is only an approximation.

The one standard deviation uncertainties (68% confidence level) are obtained by taking the coupling values for which $\Delta \log \mathcal{L} = +0.5$ above the minimum. The 95% confidence level (C.L.) limits are given by the coupling values for which $\Delta \log \mathcal{L} = +1.92$ above the minimum. Note that double minima structures appear in the negative log-likelihood curves.

5 Results

We present results from the four LEP experiments on the various electroweak gauge boson couplings, and their combination. The results quoted for each individual experiment are calculated using the method described in Section 4. Thus they may differ slightly from those reported in the individual references[1].

[1]E.g. for the QGC, L3 integrates the likelihood in order to determine the 95%CL, whereas here it is read off the $\log \mathcal{L}$-curve at $\Delta \log \mathcal{L} = 1.92$ as for Gaussian shaped likelihood functions.

5.1 Neutral Triple Gauge Boson Couplings in Zγ Production

The results from each experiment are shown in Table 1, where the errors include both statistical and systematic uncertainties. The individual $\log \mathcal{L}$ curves and their sum are shown in Figures 1 and 2. The results of the combination are given in Table 2.

5.2 Neutral Triple Gauge Boson Couplings in ZZ Production

The results from each experiment are shown in Table 3, where the errors include both statistical and systematic uncertainties. The individual $\log \mathcal{L}$ curves and their sum are shown in Figure 3. The results of the combination are given in Table 4.

5.3 Quartic Gauge Boson Couplings

The results from each experiment are shown in Table 5, where the uncertainties include both statistical and systematic effects. The individual $\log \mathcal{L}$ curves and their sum are shown in Figures 4. The results of the combination are given in Table 6.

Conclusions

No significant deviation from the Standard Model prediction is seen for any of the electroweak gauge boson couplings studied.

Acknowledgements

We would like to thank the CERN accelerator divisions for the efficient operation of the LEP accelerator.

Parameter	L3 [21]	OPAL [22]
h_1^γ	$[-0.20, \ +0.08]$	$[-0.11, \ +0.11]$
h_2^γ	$[-0.11, \ +0.11]$	$[-0.08, \ +0.08]$
h_3^γ	$[-0.11, \ +0.04]$	$[-0.17, \ -0.01]$
h_4^γ	$[-0.02, \ +0.10]$	$[+0.01, \ +0.14]$
h_1^Z	$[-0.26, \ +0.09]$	$[-0.19, \ +0.19]$
h_2^Z	$[-0.10, \ +0.16]$	$[-0.13, \ +0.13]$
h_3^Z	$[-0.26, \ +0.21]$	$[-0.27, \ +0.12]$
h_4^Z	$[-0.11, \ +0.20]$	$[-0.08, \ +0.18]$

Table 1: The 95% C.L. intervals ($\Delta \log \mathcal{L} = 1.92$) measured by L3 and OPAL. In each case the parameter listed is varied while the remaining ones are fixed to their Standard Model value. Both statistical and systematic uncertainties are included.

Parameter	95% C.L.
h_1^γ	$[-0.12, \ +0.07]$
h_2^γ	$[-0.07, \ +0.07]$
h_3^γ	$[-0.11, \ -0.01]$
h_4^γ	$[+0.01, \ +0.10]$
h_1^Z	$[-0.18, \ +0.09]$
h_2^Z	$[-0.08, \ +0.11]$
h_3^Z	$[-0.21, \ +0.10]$
h_4^Z	$[-0.06, \ +0.15]$

Table 2: The 95% C.L. intervals ($\Delta \log \mathcal{L} = 1.92$) obtained combining the results from L3 and OPAL. In each case the parameter listed is varied while the remaining ones are fixed to their Standard Model value. Both statistical and systematic uncertainties are included.

Parameter	L3 [23]	OPAL [24]
f_4^γ	$[-1.1, \ +1.2]$	$[-1.2, \ +1.2]$
f_4^Z	$[-1.9, \ +1.9]$	$[-2.1, \ +2.1]$
f_5^γ	$[-3.0, \ +2.9]$	$[-3.9, \ +3.6]$
f_5^Z	$[-5.0, \ +4.5]$	$[-6.2, \ +4.4]$

Table 3: The 95% C.L. intervals ($\Delta \log \mathcal{L} = 1.92$) measured by L3 and OPAL. In each case the parameter listed is varied while the remaining ones are fixed to their Standard Model value. Both statistical and systematic uncertainties are included.

Parameter	95% C.L.
f_4^γ	$[-1.1, \ +1.1]$
f_4^Z	$[-1.8, \ +1.8]$
f_5^γ	$[-3.0, \ +2.8]$
f_5^Z	$[-4.7, \ +2.9]$

Table 4: The 95% C.L. intervals ($\Delta \log \mathcal{L} = 1.92$) obtained combining the results from L3 and OPAL. In each case the parameter listed is varied while the remaining ones are fixed to their Standard Model value. Both statistical and systematic uncertainties are included.

Parameter [GeV^{-2}]	L3 [25]	OPAL [26]
a_0/Λ^2	$[-0.044, \ +0.044]$	$[-0.070, \ +0.070]$
a_c/Λ^2	$[-0.09, \ +0.13]$	$[-0.13, \ +0.19]$
a_n/Λ^2	$[-0.45, \ +0.42]$	$[-0.61, \ +0.57]$

Table 5: The 95% C.L. intervals ($\Delta \log \mathcal{L} = 1.92$) measured by L3 and OPAL. In each case the parameter listed is varied while the remaining ones are fixed to their Standard Model value. Both statistical and systematic uncertainties are included.

Parameter [GeV^{-2}]	95% C.L.
a_0/Λ^2	$[-0.050, \ +0.050]$
a_c/Λ^2	$[-0.09, \ +0.14]$
a_n/Λ^2	$[-0.45, \ +0.41]$

Table 6: The 95% C.L. intervals ($\Delta \log \mathcal{L} = 1.92$) obtained combining the results from L3 and OPAL. In each case the parameter listed is varied while the remaining ones are fixed to their Standard Model value. Both statistical and systematic uncertainties are included.

References

[1] The ALEPH Collaboration, R. Barate *et al.*, Phys. Lett. **B 462** (1999) 389;
The ALEPH Collaboration, R. Barate *et al.*, Phys. Lett. **B 445** (1998) 239;
The ALEPH Collaboration, R. Barate *et al.*, Phys. Lett. **B 422** (1998) 369.

[2] The DELPHI Collaboration, P. Abreu *et al.*, Phys. Lett. **B 397** (1997) 158;
The DELPHI Collaboration, P. Abreu *et al.*, Phys. Lett. **B 423** (1998) 194;
The DELPHI Collaboration, P. Abreu *et al.*, Phys. Lett. **B 459** (1999) 382;
The DELPHI Collaboration, P. Abreu *et al.*, Phys. Lett. **B 502** (2001) 9.

[3] The L3 Collaboration, M. Acciari *et al.*, Phys. Lett. **B 398** (1997) 223;
The L3 Collaboration, M. Acciari *et al.*, Phys. Lett. **B 413** (1998) 176;
The L3 Collaboration, M. Acciari *et al.*, Phys. Lett. **B 467** (1999) 171;
The L3 Collaboration, M. Acciarri *et al.*, Phys. Lett. **B 436** (1998) 417;
The L3 Collaboration, M. Acciarri *et al.*, Phys. Lett. **B 487** (2000) 229.

[4] The OPAL Collaboration, K. Ackerstaff *et al.*, Phys. Lett. **B 397** (1997) 147;
The OPAL Collaboration, K. Ackerstaff *et al.*, Eur. Phys. J. **C 2** (1998) 597;
The OPAL Collaboration, G. Abbiendi *et al.*, Eur. Phys. J. **C 8** (1999) 191;
The OPAL Collaboration, G. Abbiendi *et al.*, Eur. Phys. J. **C19** (2001) 1.

[5] The LEP-TGC combination group, LEPEWWG/TGC/2001-01, March 2001.

[6] The LEP-TGC combination group, LEPEWWG/TGC/2000-02, September 2000.

[7] G. Gounaris *et al.*, in *Physics at LEP 2*, Report CERN 96-01 (1996), eds G. Altarelli, T. Sjöstrand, F. Zwirner, Vol. 1, p. 525.

[8] K. Gaemers and G. Gounaris, Z. Phys. **C 1** (1979) 259.

[9] K. Hagiwara, K. Hikasa, R.D. Peccei and D. Zeppenfeld, Nucl. Phys. **B 282** (1987) 253.

[10] K. Hagiwara, S. Ishihara, R. Szalapski, and D. Zeppenfeld, Phys. Lett. **B 283** (1992) 353;
K. Hagiwara, S. Ishihara, R. Szalapski, and D. Zeppenfeld, Phys. Rev. **D 48** (1993) 2182;
K. Hagiwara, T. Hatsukano, S. Ishihara and R. Szalapski, Nucl. Phys. **B 496** (1997) 66.

[11] M. Bilenky, J.L. Kneur, F.M. Renard and D. Schildknecht, Nucl. Phys. **B 409** (1993) 22;
M. Bilenky, J.L. Kneur, F.M. Renard and D. Schildknecht, Nucl. Phys. **B 419** (1994) 240.

[12] I. Kuss and D. Schildknecht, Phys. Lett. **B 383** (1996) 470.

[13] G. Gounaris and C.G. Papadopoulos, Eur. Phys. J. **C 2** (1998) 365.

[14] A. Denner, S. Dittmaier, M. Roth and D. Wackeroth, Nucl. Phys. B **587** (2000) 67

[15] S. Jadach, W. Placzek, M. Skrzypek, B.F.L. Ward and Z.Wąs, Phys. Lett. **B 417** (1998) 326, hep-ph/0103163..

[16] G. J. Gounaris, J. Layssac and F. M. Renard, Phys. Rev. **D 61** (2000) 073013.

[17] G. Bélanger and F. Boudjema, Phys. Lett. **B 288** (1992) 201.

[18] W. J. Stirling and A. Werthenbach, Eur. Phys. J. **C 14** (2000) 103.

[19] W. J. Stirling and A. Werthenbach, Phys. Lett. **B 466** (1999) 369.

[20] G. Bélanger *et al.*, Eur. Phys. J. **C 13** (2000) 283.

[21] The L3 Collaboration, M. Acciari *et al.*, Phys. Lett. **B 436** (1999) 187;
The L3 Collaboration, M. Acciari *et al.*, Phys. Lett. **B 489** (2000) 55.

[22] The OPAL Collaboration, G. Abbiendi *et al.*, Eur. Phys. J. **C 17** (2000) 13.

[23] The L3 Collaboration, M. Acciari *et al.*, Phys. Lett. **B 450** (1999) 281;
The L3 Collaboration, M. Acciari *et al.*, Phys. Lett. **B 465** (1999) 363.

[24] The OPAL Collaboration, G. Abbiendi *et al.*, Phys. Lett. **B 476** (2000) 256.

[25] The L3 Collaboration, M.Acciarri *et al.*, Phys. Lett. **B 490** (2000) 187.

[26] The OPAL Collaboration, G. Abbiendi *et al.*, Phys. Lett. **B 471** (1999) 293.

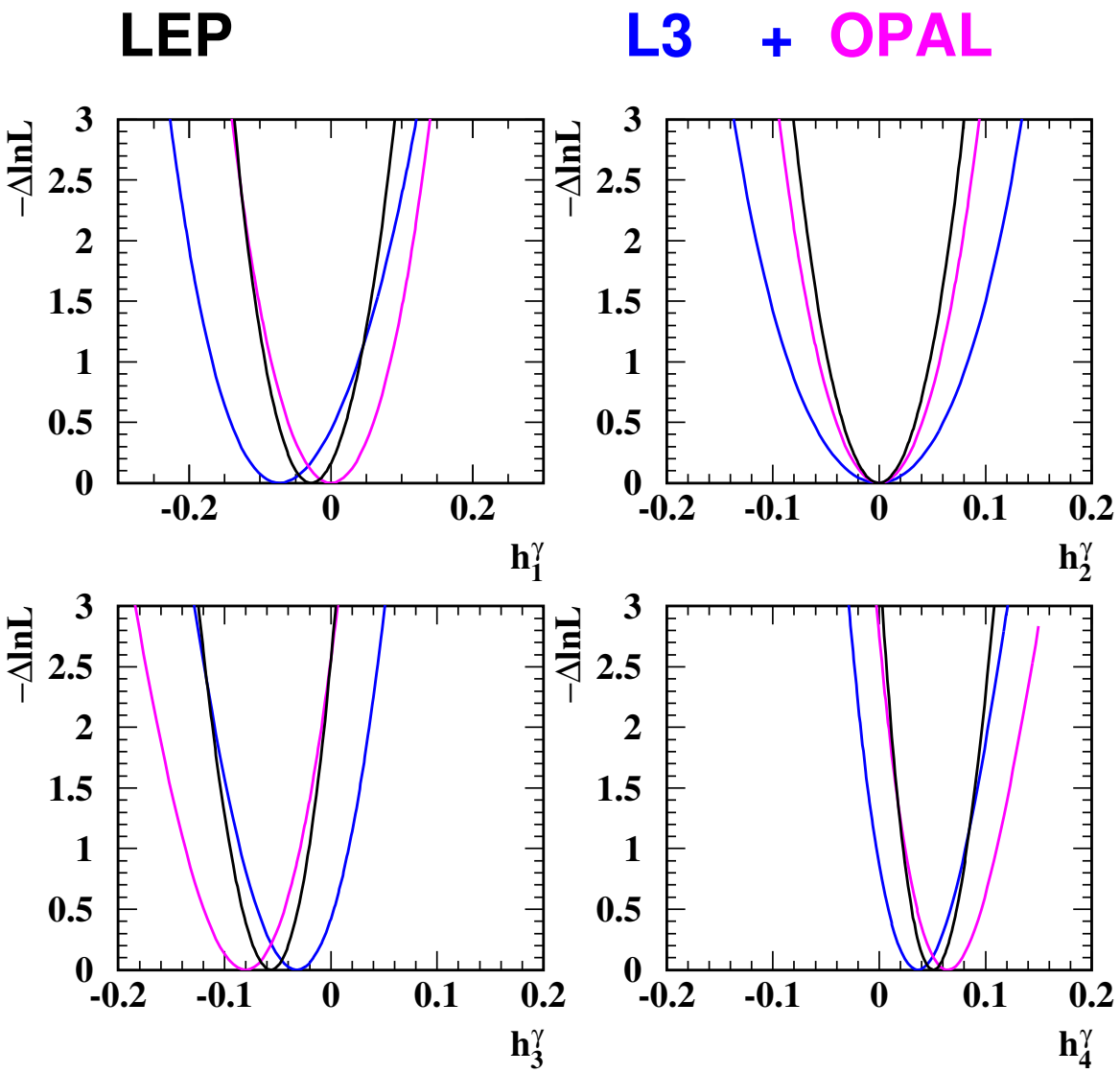

Figure 1: The $\log \mathcal{L}$ curves of L3 and OPAL, and the LEP combined curve for the four neutral TGCs h_i^γ, $i = 1, 2, 3, 4$. In each case, the minimal value is subtracted.

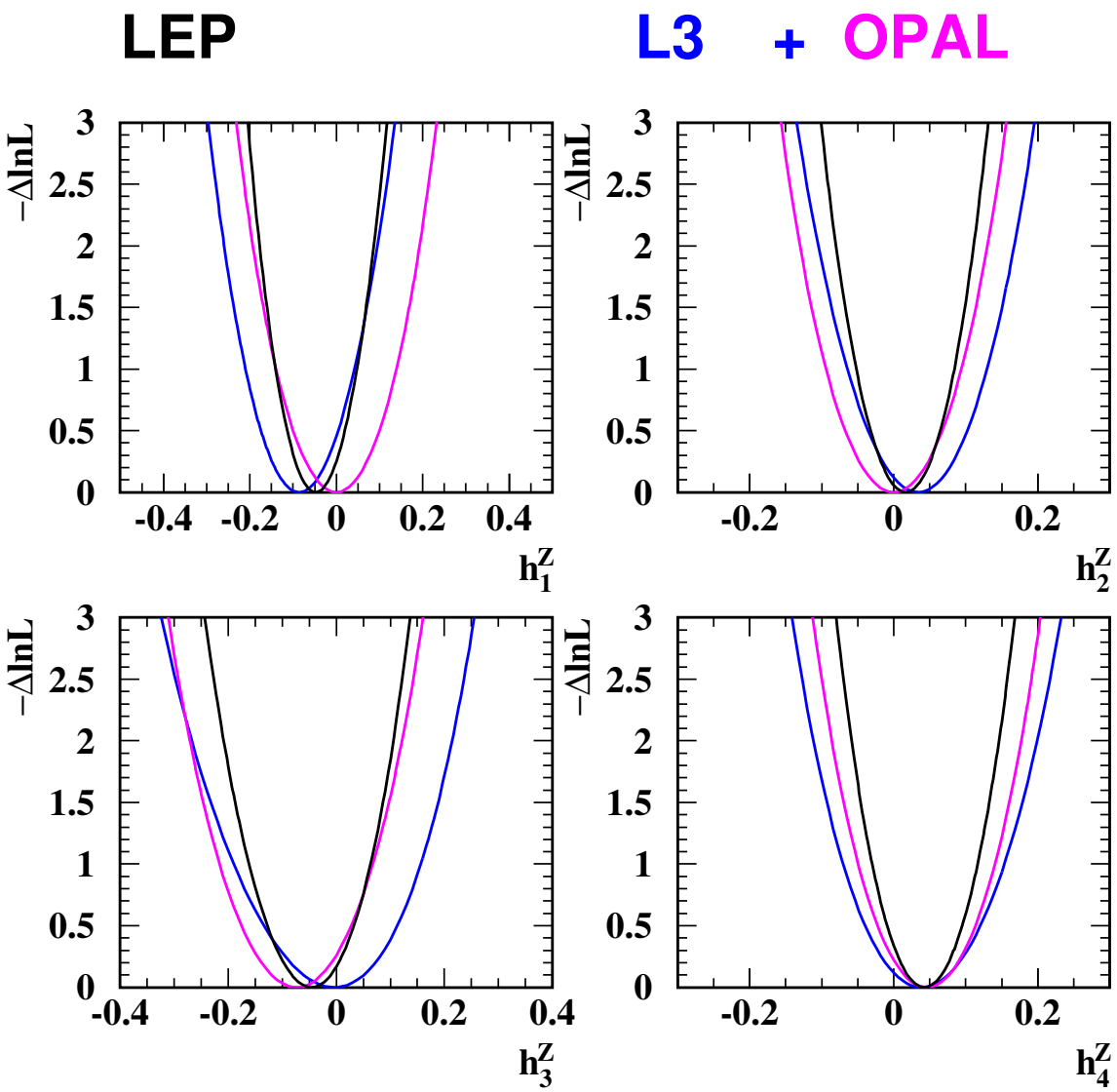

Figure 2: The $\log \mathcal{L}$ curves of L3 and OPAL, and the LEP combined curve for the four neutral TGCs h_i^Z, $i = 1, 2, 3, 4$. In each case, the minimal value is subtracted.

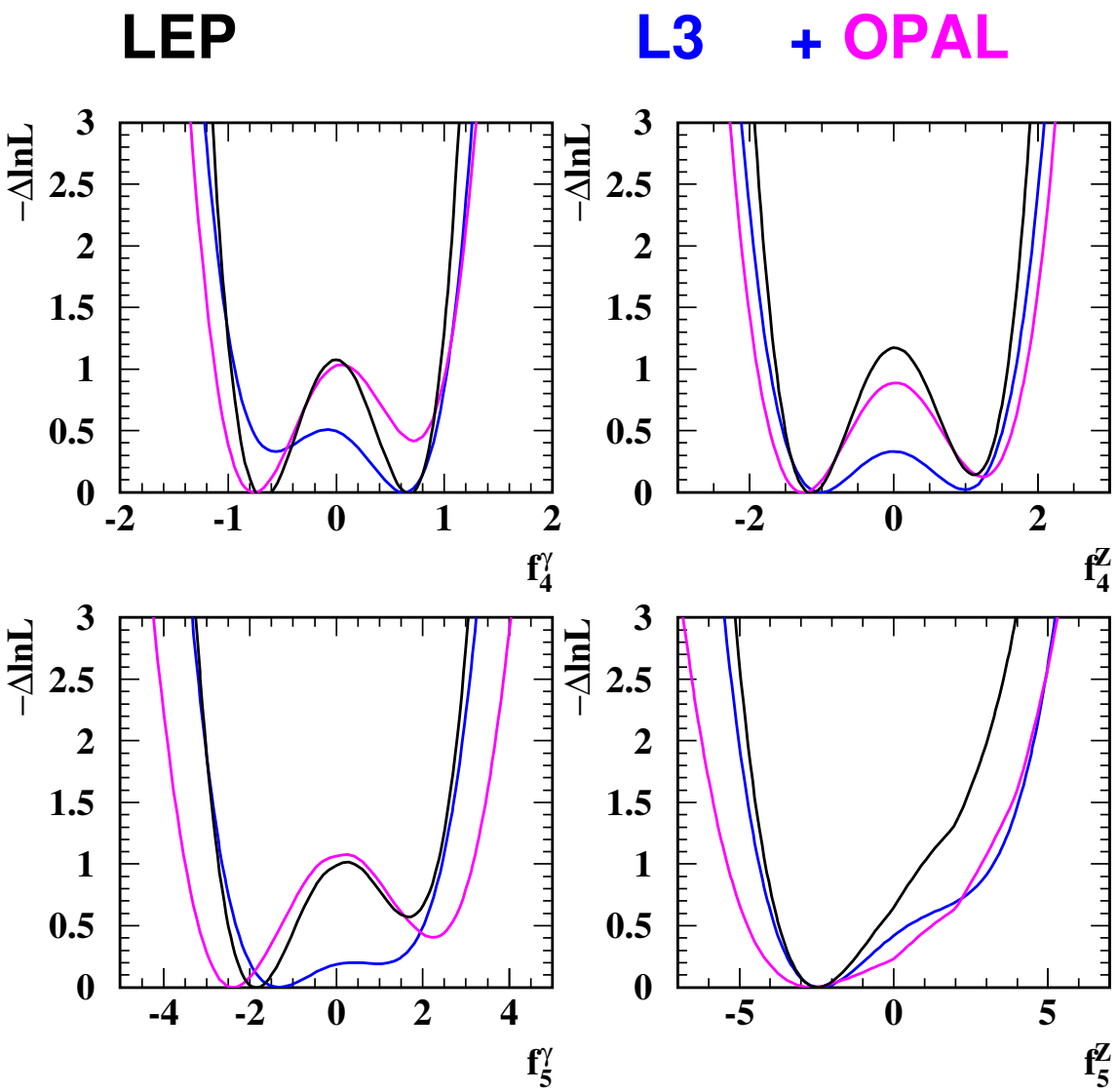

Figure 3: The $\log \mathcal{L}$ curves of L3 and OPAL, and the LEP combined curve for the four neutral TGCs $f_i^V,\ V = \gamma, Z,\ i = 4, 5$. In each case, the minimal value is subtracted.

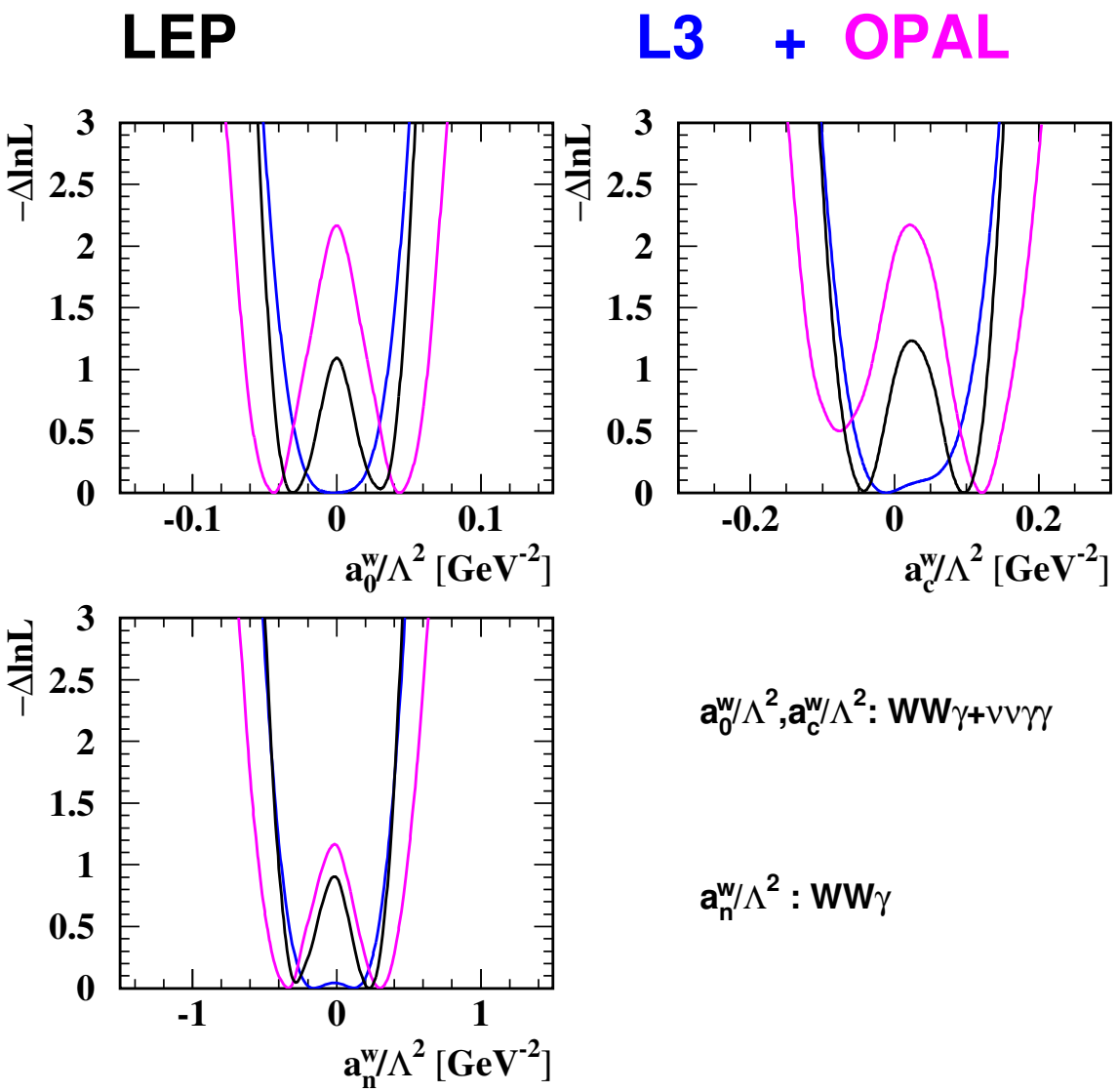

Figure 4: The log $\mathcal{L}$ curves of L3 and OPAL, and the LEP combined curve for the QGCs a_0/Λ^2, a_c/Λ^2 and a_n/Λ^2. In each case, the minimal value is subtracted.