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A Combination of Preliminary Results on Triple Gauge Boson Couplings Measured by the LEP Experiments

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Prepared from contributions of the LEP experiments to the winter conferences 2000.

Abstract

This note presents a combination of published and preliminary measurements of triple gauge boson couplings (TGCs) from the four LEP experiments. Besides the charged TGCs g_1^Z, κ_γ, and λ_γ, the neutral TGCs h_i^V and f_i^V are also combined for the first time.

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The collaborations each take responsibility for the preliminary data of their own experiment.
WWW access at `http://www.cern.ch/LEPEWWG/tgc/`

1 Introduction

During the second phase of its operation, which started in 1996, the e^+e^- collider LEP at CERN steadily increased its centre-of-mass energy from 161 GeV to 202 GeV. Until the end of 1999, a total luminosity of approximately 475 pb^{-1} per experiment has been recorded at LEP2, corresponding to more than 7000 W-pair events collected by each experiment.

The W-pair production process, $e^+e^- \rightarrow W^+W^-$, involves the triple gauge boson vertices between the W^+W^- and the Z or the photon. Single W ($e\nu W$) and single gamma ($\nu\bar{\nu}\gamma$) 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 is one of the principal physics goals at LEP2 [1].

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 neutral triple gauge boson vertices involving only neutral gauge bosons. Such vertices could also occur in $Z\gamma$ production. In contrast to triple gauge boson vertices with two charged gauge bosons, purely neutral gauge boson vertices do not exist in the Standard Model of electroweak interactions.

In this note we present the results of a combination of TGC results based on the data collected by the four LEP experiments up to the end of 1999. Both charged TGCs [2–5] as well as neutral TGCs [6–10] are combined.

2 Charged Triple Gauge Boson Couplings

The parametrisation of the charged triple gauge boson vertices is described in References [1, 11–16]. The most general Lorentz invariant Lagrangian which describes the triple gauge boson interaction has fourteen independent complex couplings, seven describing the $WW\gamma$ vertex and seven describing the WWZ vertex. Assuming electromagnetic gauge invariance as well as C and P conservation, the number of independent TGCs reduces to five. One common set is $\{g_1^Z, \kappa_Z, \kappa_\gamma, \lambda_Z,\ \lambda_\gamma\}$ where $g_1^Z = \kappa_Z = \kappa_\gamma = 1$ and $\lambda_Z = \lambda_\gamma = 0$ in the Standard Model. The parameters proposed in [1] and used here are:

$$\Delta g_1^Z \equiv g_1^Z - 1\,, \tag{1}$$
$$\Delta\kappa_\gamma \equiv \kappa_\gamma - 1\,, \tag{2}$$
$$\lambda_\gamma \quad , \tag{3}$$

with the gauge constraints:

$$\Delta\kappa_Z \equiv \kappa_Z - 1 = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W \tag{4}$$
$$\lambda_Z = \lambda_\gamma\,, \tag{5}$$

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

3 Neutral Triple Gauge Boson Couplings

There are two possible anomalous vertices in the neutral sector. Each is parametrised by the most general Lorentz and $U(1)_{em}$ invariant Lagrangian plus Bose symmetry, as described in references [12, 17].

The first vertex refers to anomalous Z$\gamma\gamma$ and ZZγ couplings, accessible at LEP in the process $e^+e^- \to$ Zγ. The parametrisation contains eight couplings: h_i^V with $i = 1, ..., 4$ and $V = \gamma$,Z. The superscript γ refers to Z$\gamma\gamma$ couplings and superscript Z refers to ZZγ couplings. The photon and the Z boson in the final state are considered as on-shell particles. 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 vertex refers to anomalous ZZγ and ZZZ couplings, accessible at LEP in the process $e^+e^- \to$ 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 ZZγ couplings and the superscript Z refers to ZZZ couplings. Both Z bosons in the final state are assumed to be on-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 considered as real, with the imaginary parts fixed to zero. They vanish in the Standard Model at tree level, as a triple gauge boson vertex involving only neutral electroweak gauge bosons does not exist in the SM.

4 Input Measurements

The results presented comprise measurements of all couplings discussed above. The experiments combine different processes and final states for each coupling. In each case, the individual references should be consulted for details on data samples used.

For charged TGCs, updated analyses are reported using different channels, typically the semileptonic, fully hadronic and fully leptonic W-pair decays [2–5]. Anomalous TGCs affect both the total production cross-section and the shape of the differential cross-section as a function of the polar W$^-$ production angle. The relative contributions of each helicity state of the W bosons are also changed, which in turn affects the distributions of their decay products. The analyses presented by each experiment make use of different combinations of each of these quantities. In general, however, all analyses use at least the expected variations of the total production cross-section and the W$^-$ production angle.

Results from eνW and $\nu\bar{\nu}\gamma$ production have been included by some experiments. Single W production is particularly sensitivity to κ_γ, thus providing information complementary to that from W-pair production.

For neutral TGCs, the analyses use mainly measurements of the total cross section, though the use of differential distributions increases the sensitivity. Again, the individual references should be consulted concerning the details of the analyses for the h_i^V couplings [6, 7] and the f_i^V couplings [8–10].

5 Combination of Measurements

The combination method is the same as already used in the previous combinations, e.g. [18]. Each experiment provides the negative log likelihood, $\log\mathcal{L}$, as a function of the TGC parameters (one, two, or three) to be combined. The $\log\mathcal{L}$ functions from each experiment include both statistical and systematic effects. It is necessary to use the $\log\mathcal{L}$ functions directly for the combination as in general they are not parabolic, so that it is not possible to combine the results correctly by simply taking weighted averages of one standard deviation measurements.

For both single- and multi-parameter combinations, the individual $\log\mathcal{L}$ functions are added. The one standard deviation errors (68% confidence level) are obtained by taking the TGC values where $\Delta\log\mathcal{L} = +0.5$ above the minimum. The 95% confidence level (C.L.) limits are given by the TGC values where $\Delta\log\mathcal{L} = +1.92$ above the minimum. Note that in the case of the neutral TGCs, double minima structures appear in the $\log\mathcal{L}$ curves.

The single parameter analyses are performed fixing the values of all other parameters to their Standard Model value. The two-parameter analyses are performed setting the third parameter to its SM value. The 68% C.L. contour curves are obtained by requiring $\Delta\log\mathcal{L} = +1.15$, while for the 95% C.L. contour curves a value of $\Delta\log\mathcal{L} = +3.0$ is required.

In principle there are common systematic effects which should be treated in a correlated way. These include the uncertainties in the theoretical calculation of the total cross section, uncertainties on the LEP beam energy and the W mass, and some effects estimated by varying Monte Carlo generators. However, in the current combination such correlations are neglected as they are small.

The main contributions to the uncorrelated systematic errors arise due to the background in the selected W^+W^- sample, detector resolutions, fitting methods and limited Monte Carlo statistics. Their importance varies for each experiment and the individual references should be consulted for details.

6 Results

We present below results from the four experiments on charged and neutral triple gauge boson couplings. In most but not all cases, the results are based on data collected at LEP2 until the end of 1999 at centre-of-mass energies up to 202 GeV.

6.1 Charged Triple Gauge Boson Couplings

Single-Parameter Analyses

The results from each experiment are shown in Table 1, where the errors include both statistical and systematic effects.

Parameter	ALEPH [2]	DELPHI [3]	L3 [4]	OPAL [5]
Δg_1^{Z}	$-0.009^{+0.041}_{-0.041}$	$-0.026^{+0.042}_{-0.041}$	$-0.071^{+0.064}_{-0.060}$	$-0.013^{+0.059}_{-0.057}$
$\Delta\kappa_\gamma$	$-0.01^{+0.10}_{-0.09}$	$+0.12^{+0.13}_{-0.13}$	$-0.20^{+0.18}_{-0.15}$	$+0.04^{+0.14}_{-0.13}$
λ_γ	$+0.001^{+0.040}_{-0.039}$	$+0.046^{+0.051}_{-0.049}$	$-0.079^{+0.083}_{-0.073}$	$-0.112^{+0.056}_{-0.054}$

Table 1: The measured central values and one standard deviation errors obtained by the four LEP experiments. In each case the parameter listed is varied while the remaining two are fixed to the SM. Both statistical and systematic errors are included.

The individual $\log \mathcal{L}$ curves and their sum are shown in Figure 1. The results of the combination are given in Table 2.

Parameter	68% C.L.	95% C.L.
Δg_1^{Z}	$-0.024^{+0.024}_{-0.024}$	$[-0.071, \quad 0.024]$
$\Delta\kappa_\gamma$	$+0.021^{+0.063}_{-0.059}$	$[-0.09, \quad 0.15]$
λ_γ	$-0.016^{+0.026}_{-0.026}$	$[-0.066, \quad 0.035]$

Table 2: The combined 68% C.L. errors and 95% C.L. intervals obtained combining the results from the four LEP experiments. In each case the parameter listed is varied while the other two are fixed to their SM value. Both statistical and systematic errors are included.

Two-Parameter Analyses

The results from each experiment are shown in Table 3, where the errors include both statistical and systematic effects.

Parameter	ALEPH [2]	DELPHI [3]	L3 [4]	OPAL [5]
Δg_1^{Z}	$+0.024^{+0.059}_{-0.058}$	$-0.070^{+0.047}_{-0.042}$	$-0.030^{+0.084}_{-0.075}$	$-0.032^{+0.059}_{-0.058}$
$\Delta\kappa_\gamma$	$+0.03^{+0.11}_{-0.11}$	$+0.26^{+0.14}_{-0.14}$	$-0.16^{+0.19}_{-0.16}$	$+0.07^{+0.16}_{-0.14}$
Δg_1^{Z}	$+0.012^{+0.075}_{-0.074}$	$-0.109^{+0.061}_{-0.056}$	$-0.03^{+0.14}_{-0.16}$	$+0.052^{+0.064}_{-0.063}$
λ_γ	$+0.016^{+0.081}_{-0.079}$	$+0.118^{+0.068}_{-0.070}$	$-0.04^{+0.19}_{-0.15}$	$-0.148^{+0.072}_{-0.070}$
$\Delta\kappa_\gamma$	$+0.02^{+0.11}_{-0.11}$	$+0.11^{+0.12}_{-0.11}$	$+0.03^{+0.16}_{-0.14}$	$+0.11^{+0.14}_{-0.14}$
λ_γ	$+0.021^{+0.065}_{-0.063}$	$+0.023^{+0.055}_{-0.054}$	$-0.14^{+0.12}_{-0.09}$	$-0.127^{+0.061}_{-0.060}$

Table 3: The measured central values and one standard deviation errors obtained by the four LEP experiments. In each case the two parameters listed are varied while the remaining one is fixed to its SM value. Both statistical and systematic errors are included.

The 68% C.L. and 95% C.L. contours curves resulting from the combinations of the two-dimensional likelihood curves are shown in Figures 2, 3 and 4. The LEP average values are given in Table 4.

Parameter	68% C.L.	95% C.L.	Correlations	
Δg_1^Z	$-0.026^{+0.027}_{-0.031}$	[−0.088, 0.025]	1.00	−0.52
$\Delta\kappa_\gamma$	$+0.083^{+0.079}_{-0.074}$	[−0.05, 0.24]	−0.52	1.00
Δg_1^Z	$-0.019^{+0.034}_{-0.032}$	[−0.090, 0.055]	1.00	−0.63
λ_γ	$-0.006^{+0.038}_{-0.041}$	[−0.088, 0.075]	−0.63	1.00
λ_γ	$-0.023^{+0.032}_{-0.033}$	[−0.088, 0.038]	1.00	−0.38
$\Delta\kappa_\gamma$	$-0.068^{+0.066}_{-0.063}$	[−0.05, 0.20]	−0.38	1.00

Table 4: The combined 68% C.L. errors and 95% C.L. intervals obtained combining the results from the four LEP experiments. In each case the two parameters listed are varied while the third one is fixed to its SM value. Since the shape of the likelihood is not parabolic, there is some ambiguity in the definition of the correlation coefficients and the values quoted here are approximate.

Three-Parameter Analyses

The results from each experiment are shown in Table 5, where the errors include both statistical and systematic effects.

Parameter	ALEPH [2]	L3 [4]	OPAL [5]
Δg_1^Z	$-0.028^{+0.049}_{-0.048}$	$-0.02^{+0.12}_{-0.12}$	$+0.044^{+0.067}_{-0.068}$
$\Delta\kappa_\gamma$	$+0.003^{+0.085}_{-0.083}$	$-0.13^{+0.31}_{-0.20}$	$+0.09^{+0.15}_{-0.13}$
λ_γ	$-0.017^{+0.056}_{-0.054}$	$-0.03^{+0.16}_{-0.15}$	$-0.154^{+0.074}_{-0.071}$

Table 5: The measured central values and one standard deviation errors obtained by ALEPH, L3 and OPAL. Both statistical and systematic errors are included.

The LEP average values are given in Table 6.

6.2 Neutral Triple Gauge Boson Couplings

$Z\gamma$ Couplings

The results from each experiment are shown in Table 7, where the errors include both statistical and systematic effects.

Parameter	68% C.L.	95% C.L.	Correlations		
Δg_1^Z	$-0.003^{+0.039}_{-0.036}$	$[-0.073, \; 0.075]$	1.00	−0.14	−0.63
$\Delta\kappa_\gamma$	$+0.017^{+0.074}_{-0.071}$	$[-0.12, \; 0.16]$	−0.14	1.00	−0.14
λ_γ	$-0.066^{+0.042}_{-0.045}$	$[-0.15, \; 0.01]$	−0.63	−0.14	1.00

Table 6: The combined 68% C.L. errors and 95% C.L. intervals obtained combining the results from ALEPH, L3 and OPAL. Since the shape of the likelihood is not parabolic, there is some ambiguity in the definition of the correlation coefficients and the values quoted here are approximate.

Parameter	DELPHI [6]	L3 [7]
h_1^γ	$+0.118^{+0.045}_{-0.077}$	$-0.073^{+0.078}_{-0.069}$
h_1^Z	$-0.20^{+0.13}_{-0.08}$	$-0.086^{+0.090}_{-0.088}$
h_2^γ	$-0.071^{+0.054}_{-0.028}$	$-0.001^{+0.061}_{-0.061}$
h_2^Z	$+0.120^{+0.047}_{-0.081}$	$-0.034^{+0.068}_{-0.070}$
h_3^γ	$+0.021^{+0.019}_{-0.020}$	$-0.032^{+0.035}_{-0.037}$
h_3^Z	$+0.14^{+0.07}_{-0.12}$	$0.00^{+0.12}_{-0.13}$
h_4^γ	$-0.014^{+0.014}_{-0.013}$	$+0.036^{+0.031}_{-0.028}$
h_4^Z	$-0.091^{+0.075}_{-0.046}$	$+0.039^{+0.082}_{-0.078}$

Table 7: The measured central values and one standard deviation errors obtained by DELPHI and L3. In each case the parameter listed is varied while the remaining ones are fixed to the SM. Both statistical and systematic errors are included.

The individual $\log\mathcal{L}$ curves and their sum are shown in Figures 5 and 6. The results of the combination are given in Table 8.

Parameter	68% C.L.	95% C.L.
h_1^γ	$-0.098^{+0.062}_{-0.043}$	$[-0.17, \; 0.08]$
h_1^Z	$-0.13^{+0.10}_{-0.07}$	$[-0.26, \; 0.09]$
h_2^γ	$-0.05^{+0.12}_{-0.04}$	$[-0.11, \; 0.10]$
h_2^Z	$+0.071^{+0.053}_{-0.088}$	$[-0.11, \; 0.16]$
h_3^γ	$0.008^{+0.017}_{-0.018}$	$[-0.027, \; 0.041]$
h_3^Z	$+0.07^{+0.08}_{-0.16}$	$[-0.29, \; 0.21]$
h_4^γ	$-0.003^{+0.013}_{-0.012}$	$[-0.026, \; 0.022]$
h_4^Z	$0.08^{+0.08}_{-0.16}$	$[-0.12, \; 0.20]$

Table 8: The combined 68% C.L. errors and 95% C.L. intervals obtained combining the results from DELPHI and L3. In each case the parameter listed is varied while the others are fixed to their SM value. Both statistical and systematic errors are included.

ZZ Couplings

The results from each experiment are shown in Table 9, where the errors include both statistical and systematic effects.

Parameter	DELPHI [8]	L3 [9]	OPAL [10]
f_4^γ	$-0.16^{+0.53}_{-0.20}$	$+0.63^{+0.30}_{-0.63}$	$-0.38^{+0.21}_{-0.14}$
f_4^Z	$+0.26^{+0.34}_{-0.88}$	$-1.0^{+2.5}_{-0.5}$	$+0.63^{+0.23}_{-0.36}$
f_5^γ	$+0.4^{+0.5}_{-1.3}$	$-1.3^{+3.3}_{-1.0}$	$-0.7^{+1.9}_{-0.4}$
f_5^Z	$-0.7^{+2.1}_{-0.8}$	$-2.4^{+2.9}_{-1.5}$	$+0.01^{+0.59}_{-0.51}$

Table 9: The measured central values and one standard deviation errors obtained by DELPHI, L3 and OPAL. In each case the parameter listed is varied while the remaining ones are fixed to the SM. Both statistical and systematic errors are included.

The individual $\log\mathcal{L}$ curves and their sum are shown in Figure 7. The results of the combination are given in Table 10.

Parameter	68% C.L.	95% C.L.
f_4^γ	$+0.29^{+0.11}_{-0.21}$	$[-0.49,\ \ 0.49]$
f_4^Z	$+0.49^{+0.19}_{-0.31}$	$[-0.82,\ \ 0.82]$
f_5^γ	$-0.6^{+1.4}_{-0.3}$	$[-1.1,\ \ 1.1]$
f_5^Z	$-0.01^{+0.56}_{-0.57}$	$[-1.1,\ \ 1.1]$

Table 10: The combined 68% C.L. errors and 95% confidence intervals obtained after combination of the results from DELPHI, L3 and OPAL. Only the parameter listed is varied while the other two are fixed to their SM value. Both statistical and systematic errors are included.

Conclusions

No deviation from the Standard Model predictions is seen for any of the combined TGCs. As an example, these data allow the Kaluza-Klein theory [19], in which $\kappa_\gamma = -2$, to be excluded completely [20].

Acknowledgements

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

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The physics notes describing the preliminary results of the LEP experiments submitted to the winter conferences 2000 are available at:

ALEPH:	`http://alephwww.cern.ch/ALPUB/oldconf/oldconf_00.html`
DELPHI:	`http://delphiwww.cern.ch/~pubxx/www/delsec/conferences/`
L3:	`http://l3www.cern.ch/conferences/contributions.html`
OPAL:	`http://www.cern.ch/Opal/pubs/latest_docs.html`

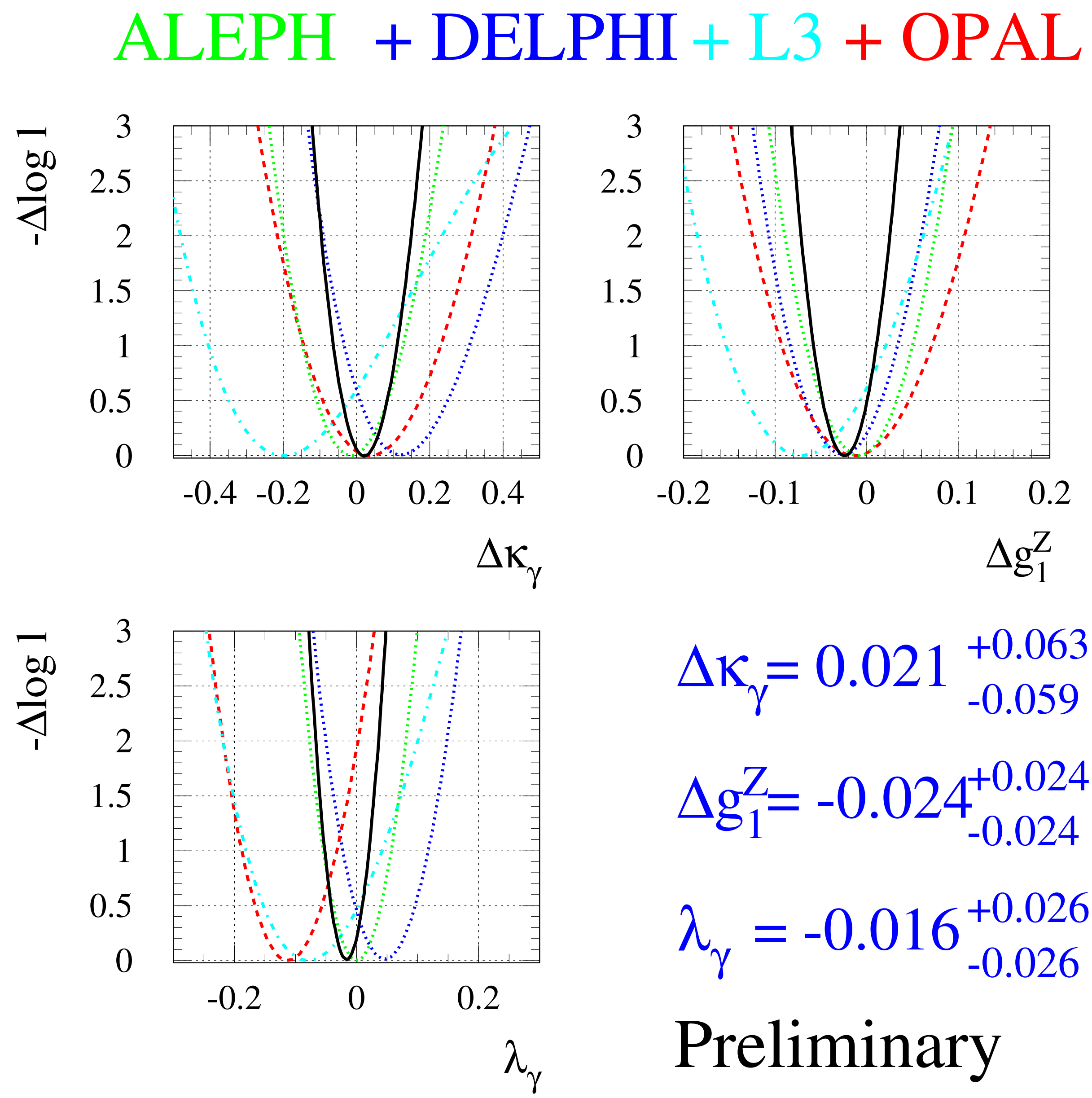

Figure 1: The $\log \mathcal{L}$ curves of the four experiments (dashed lines) and the LEP combined curve (solid line) for the three charged TGCs Δg_1^Z, $\Delta\kappa_\gamma$ and λ_γ. In each case, the minimal value is subtracted.

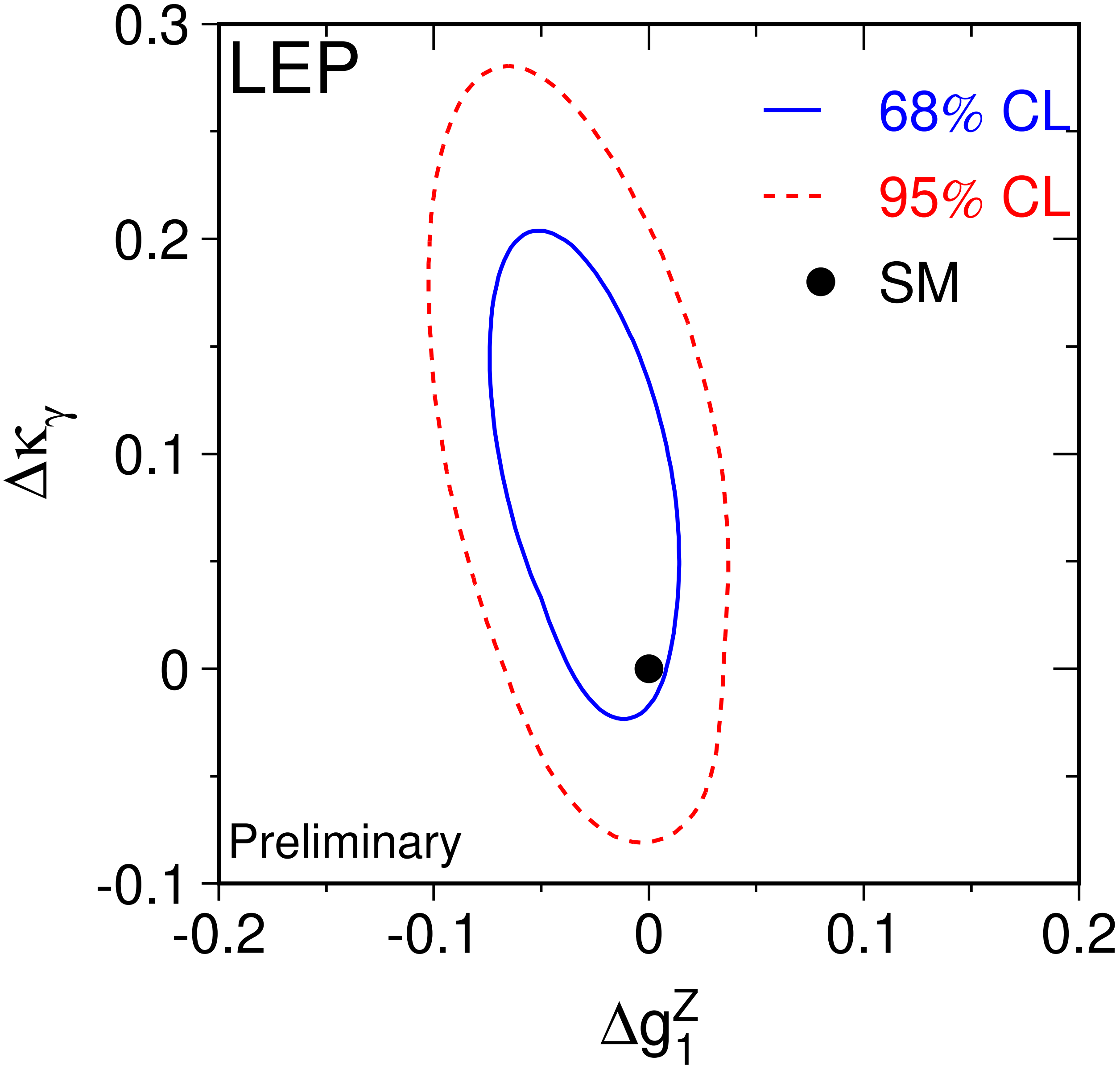

Figure 2: Contour curves of 68% C.L. and 95% C.L. in the plane $(\Delta g_1^Z, \Delta\kappa_\gamma)$ showing the LEP combined result.

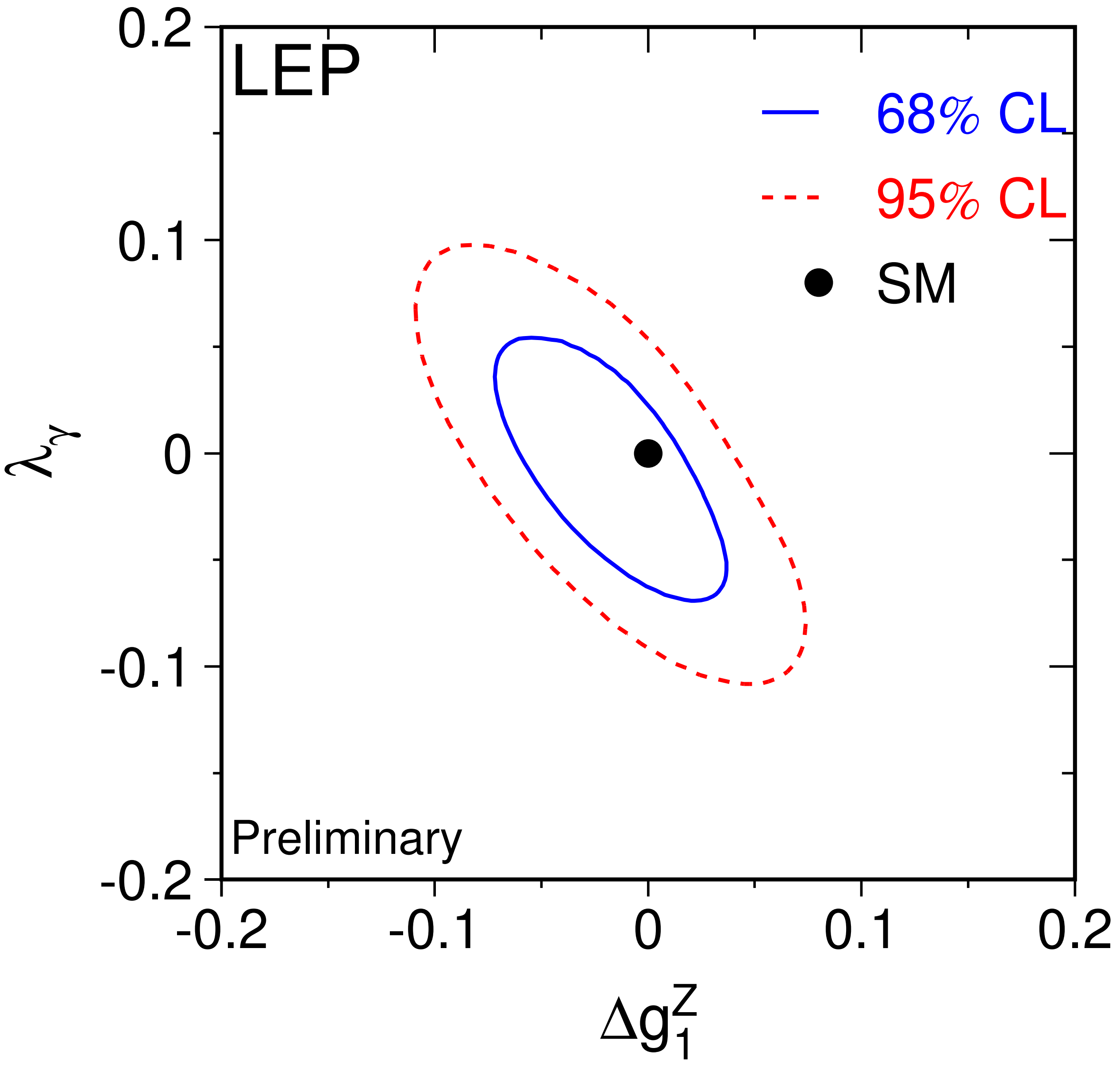

Figure 3: Contour curves of 68% C.L. and 95% C.L. in the plane $(\Delta g_1^Z, \lambda_\gamma)$ showing the LEP combined result.

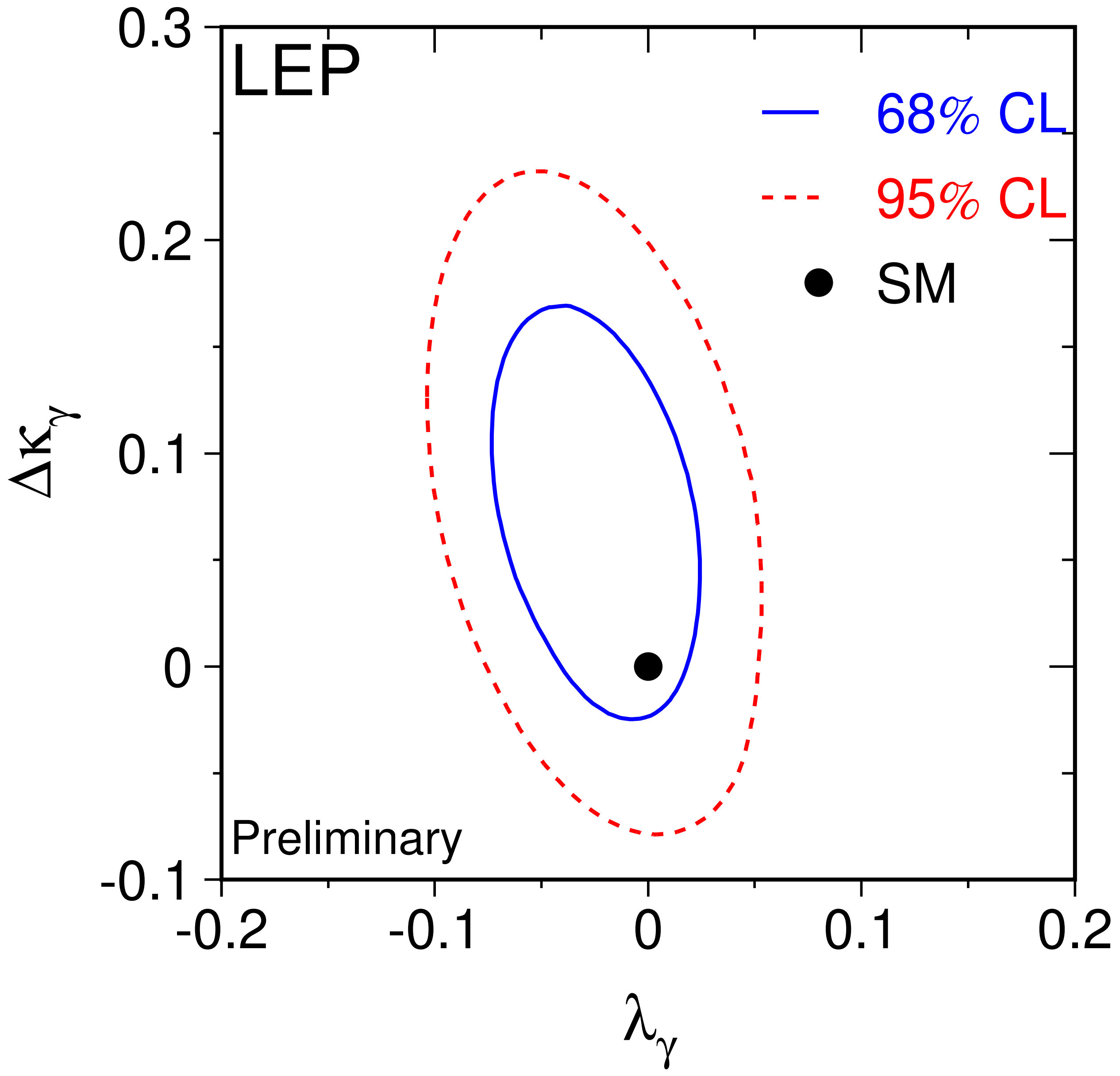

Figure 4: Contour curves of 68% C.L. and 95% C.L. in the plane $(\lambda_\gamma, \Delta\kappa_\gamma)$ showing the LEP combined result.

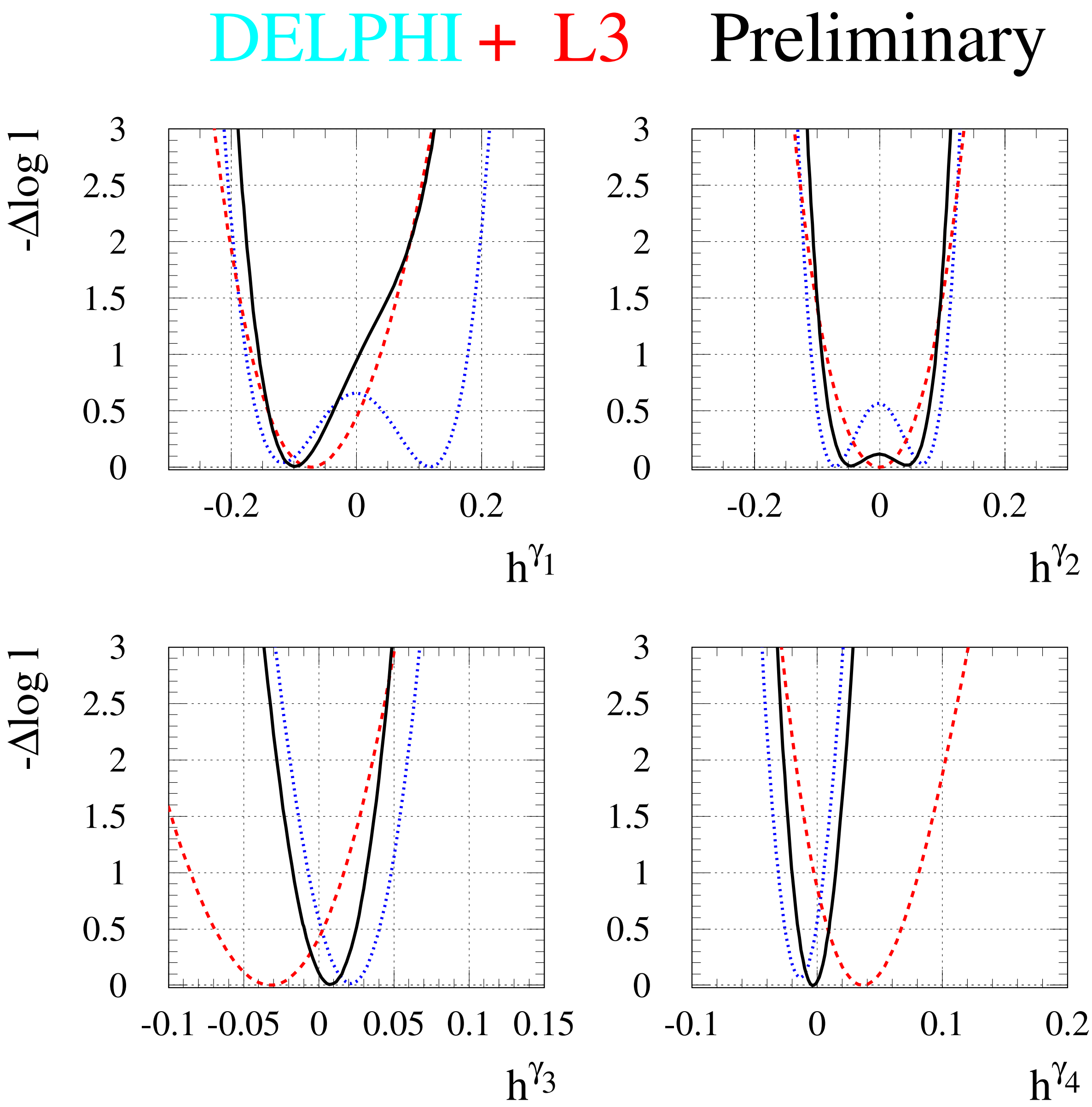

Figure 5: The log $\mathcal{L}$ curves of DELPHI (dotted line) and L3 (dashed line)and the LEP combined curve (solid line) for the four neutral TGCs h_i^γ, $i = 1, 2, 3, 4$. In each case, the minimal value is subtracted.

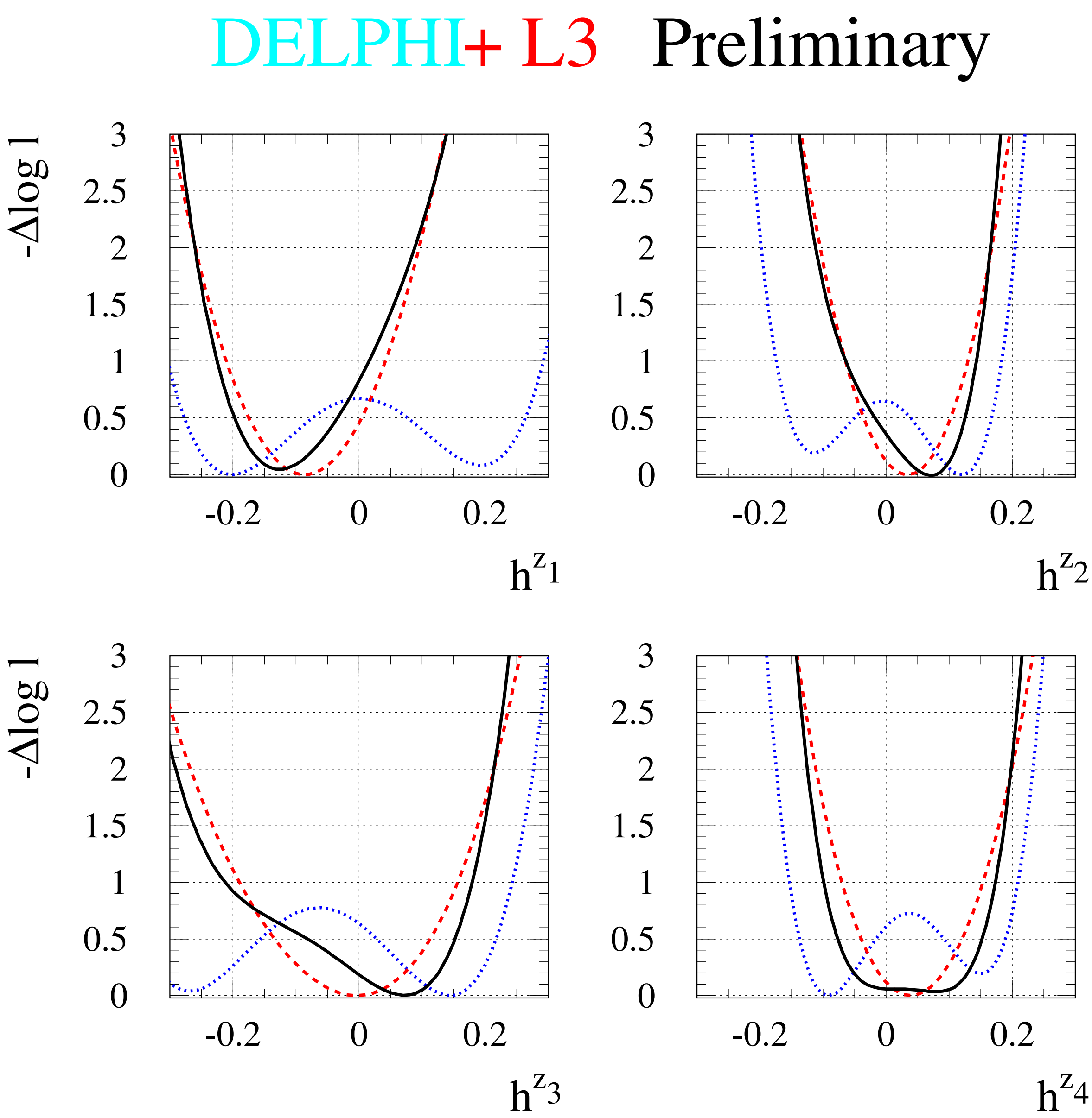

Figure 6: The log $\mathcal{L}$ curves of DELPHI (dotted line) and L3 (dashed line) and the LEP combined curve (solid line) for the four neutral TGCs h_i^Z, $i = 1, 2, 3, 4$. In each case, the minimal value is subtracted.

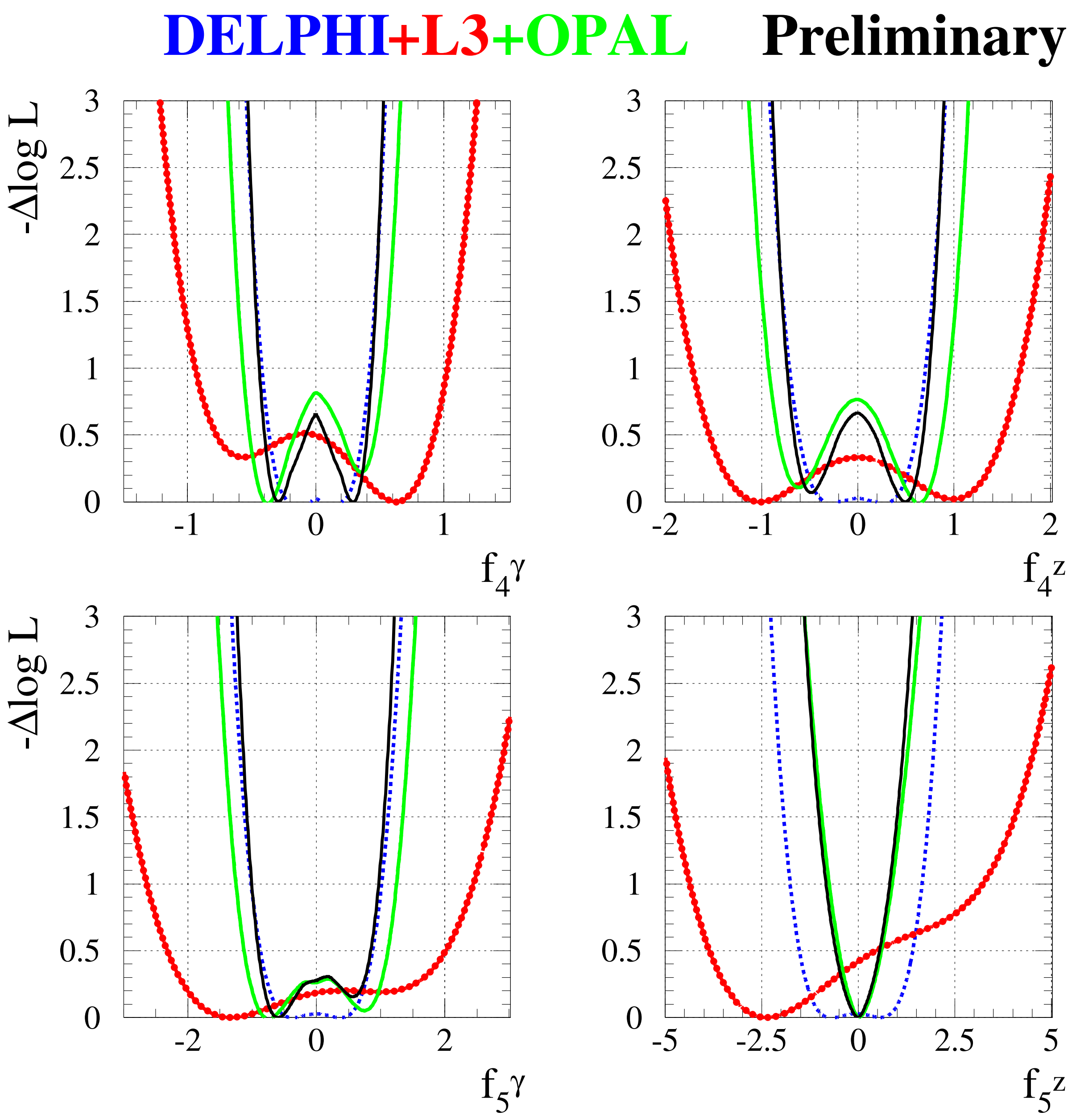

Figure 7: The $\log\mathcal{L}$ curves of DELPHI, L3 and OPAL and the LEP combined curve (solid line) for the four neutral TGCs f_i^V, $V=\gamma, Z$, $i=4,5$. In each case, the minimal value is subtracted.