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# Combined Preliminary Results on Electroweak Gauge Boson Couplings Measured by the LEP Experiments

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

**Prepared from contributions of the LEP experiments to the summer conferences 2000 and winter conferences 2001.**

Abstract

A new combination of published and preliminary results on electroweak gauge boson couplings, $h_i^V$ and $f_i^V$, measured by the four LEP experiments is presented. This extends the combined results given in the previous note LEPEWWG/TGC/2000-02.

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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 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 preliminary combination of electroweak gauge boson couplings presented in this note includes, in addition to previously presented results, new data from the year 2000 operation analysed by ALEPH and DELPHI. New or updated results for the neutral gauge boson couplings only are available for the combination and reported in this note. All other results have not been updated here and we refer to our previous note LEPEWWG/TGC/2000-02 [1] instead.

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 also sensitive to just 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 [2].

For the charged TGCs, new Monte Carlo calculations (RacoonWW [3] and YFSWW [4]) 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 new combinations are made for these measurements, however there is a preliminary result from ALEPH taking into accout this effect as a systematic uncertainty [5].

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 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 [6, 7].

The first class refers to anomalous $Z\gamma\gamma^*$ and $Z\gamma Z^*$ couplings which are accessible at LEP in the process $e^+e^- \rightarrow Z\gamma$. The parametrisation contains eight couplings: $h_i^V$ with $i = 1, ..., 4$ and $V = \gamma$,Z. The superscript $\gamma$ refers to $Z\gamma\gamma^*$ couplings and superscript Z refers to $Z\gamma Z^*$ 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 $ZZ\gamma^*$ and $ZZZ^*$ couplings which are accessible at LEP2 in the process $e^+e^- \rightarrow ZZ$. This anomalous vertex is parametrised in terms of four couplings: $f_i^V$ with $i = 4, 5$ and $V = \gamma$,Z. The superscript $\gamma$ refers to $ZZ\gamma^*$ 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.

# 3 Measurements

The combined results presented here were obtained from updated neutral electroweak gauge boson coupling measurements, as discussed above. The $h$-coupling analyses use data collected at LEP2 until the end of 1999 at centre-of-mass energies up to 202 GeV. The results of the $f$-couplings also contain data from the year 2000 recorded by ALEPH and DELPHI at centre-of-mass energies up to 209 GeV. Preliminary results from L3 including the year 2000 data [13] are now available, but unfortunatly were not ready in time for the combination and hence included here. The same is true for recently updated results on the Quartic Gauge Couplings from L3 [15].

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 measurements of the total cross sections of $Z\gamma$ and ZZ production and the differential distributions. The individual references should be consulted for details of the analyses of the $h_i^V$ couplings [8–10] and the $f_i^V$ couplings [11–14].[1]

[1]Contrary to previous results, the latest preliminary results on the $f_i^V$ couplings from DELPHI use the same convention for the sign of $f_i^V$ as used by ALEPH [11], L3 [13] and OPAL [14].

# 4 Combination Procedure

The combination procedure is identical to the previous LEP combination of electroweak gauge boson couplings [1].

Each experiment provides the negative log likelihood, $\log\mathcal{L}$, as a function of the coupling parameters (one or two) to be combined. The single parameter analyses are performed fixing all other parameters to their Standard Model values. The two-parameter analyses are performed setting the remaining 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 $\mathrm{q\overline{q}}\gamma$- 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. These cut-off values are used for obtaining the results of both single- and multi-parameter analyses reported here. Note that in the case of the neutral TGCs, double minima structures appear in the negative log-likelihood curves. For multi-parameter analyses, the 68% C.L. contour curves for any pair of couplings are obtained by requiring $\Delta\log\mathcal{L} = +1.15$, while for the 95% C.L. contour curves $\Delta\log\mathcal{L} = +3.0$ is required.

# 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.

## 5.1 Neutral Triple Gauge Boson Couplings in Z$\gamma$ Production

### Single-Parameter Analyses

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.

### Two-Parameter Analyses

The results from each experiment are shown in Table 3, where the errors include both statistical and systematic uncertainties. The 68% C.L. and 95% C.L. contours curves resulting from the combinations of the two-dimensional likelihood curves are shown in Figures 3, 4, 5, and 6. The LEP average values are given in Table 4.

## 5.2 Neutral Triple Gauge Boson Couplings in ZZ Production

### Single-Parameter Analyses

The results from each experiment are shown in Table 5, where the errors include both statistical and systematic uncertainties. The individual $\log\mathcal{L}$ curves and their sum are shown in Figure 7. The results of the combination are given in Table 6.

### Two-Parameter Analyses

The results from each experiment are shown in Table 7, where the errors include both statistical and systematic uncertainties. The 68% C.L. and 95% C.L. contours curves resulting from the combinations of the two-dimensional likelihood curves are shown in Figures 8 and 9. The LEP average values are given in Table 8.

## 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 | DELPHI [8] | L3 [9] | OPAL [10] |
|---|---|---|---|
| $h_1^\gamma$ | $[-0.17, \quad +0.17]$ | $[-0.11, \quad +0.06]$ | $[-0.11, \quad +0.11]$ |
| $h_2^\gamma$ | $[-0.11, \quad +0.11]$ | $[-0.056, \quad +0.058]$ | $[-0.077, \quad +0.077]$ |
| $h_3^\gamma$ | $[-0.058, \quad +0.051]$ | $[-0.087, \quad -0.004]$ | $[-0.17, \quad -0.01]$ |
| $h_4^\gamma$ | $[-0.036, \quad +0.040]$ | $[-0.001, \quad +0.061]$ | $[+0.01, \quad +0.14]$ |
| $h_1^Z$ | $[-0.28, \quad +0.29]$ | $[-0.23, \quad +0.20]$ | $[-0.19, \quad +0.19]$ |
| $h_2^Z$ | $[-0.18, \quad +0.18]$ | $[-0.15, \quad +0.15]$ | $[-0.13, \quad +0.13]$ |
| $h_3^Z$ | $[-0.37, \quad +0.21]$ | $[-0.27, \quad +0.12]$ | $[-0.27, \quad +0.12]$ |
| $h_4^Z$ | $[-0.14, \quad +0.22]$ | $[-0.08, \quad +0.19]$ | $[-0.08, \quad +0.18]$ |

Table 1: The 95% C.L. intervals ($\Delta \log \mathcal{L} = 1.92$) measured by DELPHI, 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. |
|---|---|
| $h_1^\gamma$ | $[-0.09, \quad +0.05]$ |
| $h_2^\gamma$ | $[-0.05, \quad +0.05]$ |
| $h_3^\gamma$ | $[-0.07, \quad -0.002]$ |
| $h_4^\gamma$ | $[+0.002, \quad +0.05]$ |
| $h_1^Z$ | $[-0.15, \quad +0.14]$ |
| $h_2^Z$ | $[-0.10, \quad +0.10]$ |
| $h_3^Z$ | $[-0.22, \quad +0.07]$ |
| $h_4^Z$ | $[-0.05, \quad +0.15]$ |

Table 2: The 95% C.L. intervals ($\Delta \log \mathcal{L} = 1.92$) obtained combining the results from DELPHI, 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 | DELPHI [8] | L3 [9] |
|---|---|---|
| $h_1^\gamma$ | $[-0.35, \quad +0.35]$ | $[-0.24, \quad +0.07]$ |
| $h_2^\gamma$ | $[-0.23, \quad +0.23]$ | $[-0.16, \quad +0.05]$ |
| $h_3^\gamma$ | $[-0.27, \quad +0.38]$ | $[-0.14, \quad +0.15]$ |
| $h_4^\gamma$ | $[-0.32, \quad +0.43]$ | $[-0.07, \quad +0.12]$ |
| $h_1^Z$ | $[-0.58, \quad +0.58]$ | $[-0.65, \quad +0.48]$ |
| $h_2^Z$ | $[-0.38, \quad +0.38]$ | $[-0.42, \quad +0.33]$ |
| $h_3^Z$ | $[-0.70, \quad +0.50]$ | $[-0.51, \quad +0.48]$ |
| $h_4^Z$ | $[-0.41, \quad +0.37]$ | $[-0.29, \quad +0.35]$ |

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

| Parameter | 95% C.L. | Correlations | |
|---|---|---|---|
| $h_1^\gamma$ | $[-0.22, \quad +0.07]$ | 1.00 | +0.77 |
| $h_2^\gamma$ | $[-0.15, \quad +0.05]$ | +0.77 | 1.00 |
| $h_3^\gamma$ | $[-0.14, \quad +0.14]$ | 1.00 | +0.97 |
| $h_4^\gamma$ | $[-0.08, \quad +0.11]$ | +0.97 | 1.00 |
| $h_1^Z$ | $[-0.51, \quad +0.42]$ | 1.00 | +0.60 |
| $h_2^Z$ | $[-0.34, \quad +0.28]$ | +0.60 | 1.00 |
| $h_3^Z$ | $[-0.49, \quad +0.40]$ | 1.00 | +0.69 |
| $h_4^Z$ | $[-0.28, \quad +0.30]$ | +0.69 | 1.00 |

Table 4: The 95% C.L. intervals ($\Delta \log \mathcal{L} = 1.92$) obtained combining the results from DELPHI and L3. In each case the two parameters listed are varied while the remaining ones are fixed to their Standard Model value. Both statistical and systematic uncertainties are included. Since the shape of the log-likelihood is not parabolic, there is some ambiguity in the definition of the correlation coefficients and the values quoted here are approximate.

| Parameter | ALEPH [11] | DELPHI [12] | L3 [13] | OPAL [14] |
|---|---|---|---|---|
| $f_4^\gamma$ | $[-0.25, +0.27]$ | $[-0.26, +0.28]$ | $[-0.59, +0.58]$ | $[-0.45, +0.43]$ |
| $f_4^Z$ | $[-0.46, +0.41]$ | $[-0.49, +0.42]$ | $[-0.97, +0.99]$ | $[-0.74, +0.75]$ |
| $f_5^\gamma$ | $[-0.45, +0.56]$ | $[-0.49, +0.61]$ | $[-1.4, +1.4]$ | $[-0.90, +0.84]$ |
| $f_5^Z$ | $[-0.33, +0.39]$ | $[-0.42, +0.69]$ | $[-2.2, +2.6]$ | $[-0.99, +0.54]$ |

Table 5: The 95% C.L. intervals ($\Delta \log \mathcal{L} = 1.92$) measured by ALEPH, DELPHI, 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. |
|---|---|
| $f_4^\gamma$ | $[-0.21, +0.23]$ |
| $f_4^Z$ | $[-0.40, +0.33]$ |
| $f_5^\gamma$ | $[-0.37, +0.49]$ |
| $f_5^Z$ | $[-0.27, +0.29]$ |

Table 6: The 95% C.L. intervals ($\Delta \log \mathcal{L} = 1.92$) obtained combining the results from ALEPH, DELPHI, 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 | DELPHI [12] | L3 [13] | OPAL [14] |
|---|---|---|---|
| $f_4^\gamma$ | $[-0.49, +0.49]$ | $[-0.58, +0.58]$ | $[-0.45, +0.43]$ |
| $f_4^Z$ | $[-0.82, +0.83]$ | $[-0.97, +0.99]$ | $[-0.73, +0.75]$ |
| $f_5^\gamma$ | $[-1.2, +1.2]$ | $[-1.4, +1.4]$ | $[-0.9, +0.9]$ |
| $f_5^Z$ | $[-1.9, +2.1]$ | $[-2.2, +2.5]$ | $[-1.0, +0.7]$ |

Table 7: The 95% C.L. intervals ($\Delta \log \mathcal{L} = 1.92$) measured by DELPHI, L3 and OPAL. In each case the two parameters listed are varied while the remaining ones are fixed to their Standard Model value. Both statistical and systematic uncertainties are included.

| Parameter | 95% C.L. | Correlations | |
|---|---|---|---|
| $f_4^\gamma$ | $[-0.28, \quad +0.28]$ | 1.00 | +0.27 |
| $f_4^Z$ | $[-0.49, \quad +0.44]$ | +0.27 | 1.00 |
| $f_5^\gamma$ | $[-0.55, \quad +0.60]$ | 1.00 | −0.14 |
| $f_5^Z$ | $[-0.49, \quad +0.47]$ | −0.14 | 1.00 |

Table 8: The 95% C.L. intervals ($\Delta \log \mathcal{L} = 1.92$) obtained combining the results from DELPHI, L3 and OPAL. In each case the two parameters listed are varied while the remaining ones are fixed to their Standard Model value. Both statistical and systematic uncertainties are included. Since the shape of the log-likelihood is not parabolic, there is some ambiguity in the definition of the correlation coefficients and the values quoted here are approximate.

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The physics notes describing the preliminary results of the LEP experiments submitted to the summer conferences 2000 and winter conference 2001 are available on the world-wide web at:

| | |
|---|---|
| ALEPH: | `http://alephwww.cern.ch/ALPUB/oldconf/osaka00/osaka.html` |
| | `http://alephwww.cern.ch/ALPUB/oldconf/oldconf_01.html` |
| DELPHI: | `http://delphiwww.cern.ch/~pubxx/delwww/www/delsec/conferences/osaka/` |
| | `http://delphiwww.cern.ch/ pubxx/www/delsec/conferences/moriond01/` |
| L3: | `http://l3www.cern.ch/conferences/Osaka2000/index.html` |
| | `http://l3www.cern.ch/conferences/Moriond2001/index.html` |
| OPAL: | `http://opal.web.cern.ch/Opal/pubs/ichep2000/abstract/abstr.html` |

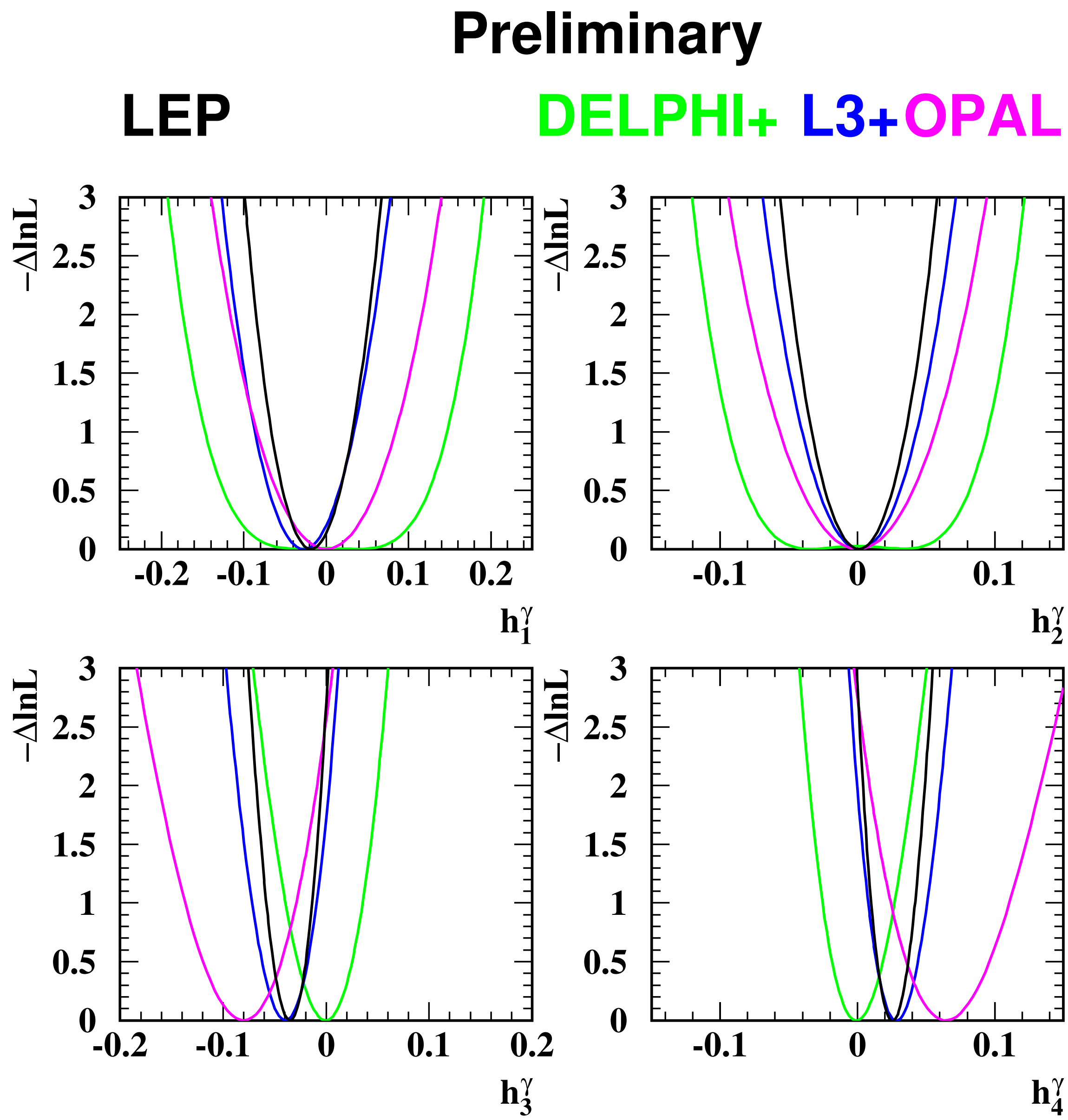


Figure 1: The $\log \mathcal{L}$ curves of DELPHI, L3 and OPAL, and the LEP combined curve for the four neutral TGCs $h_i^\gamma,\ i = 1, 2, 3, 4$. In each case, the minimal value is subtracted.

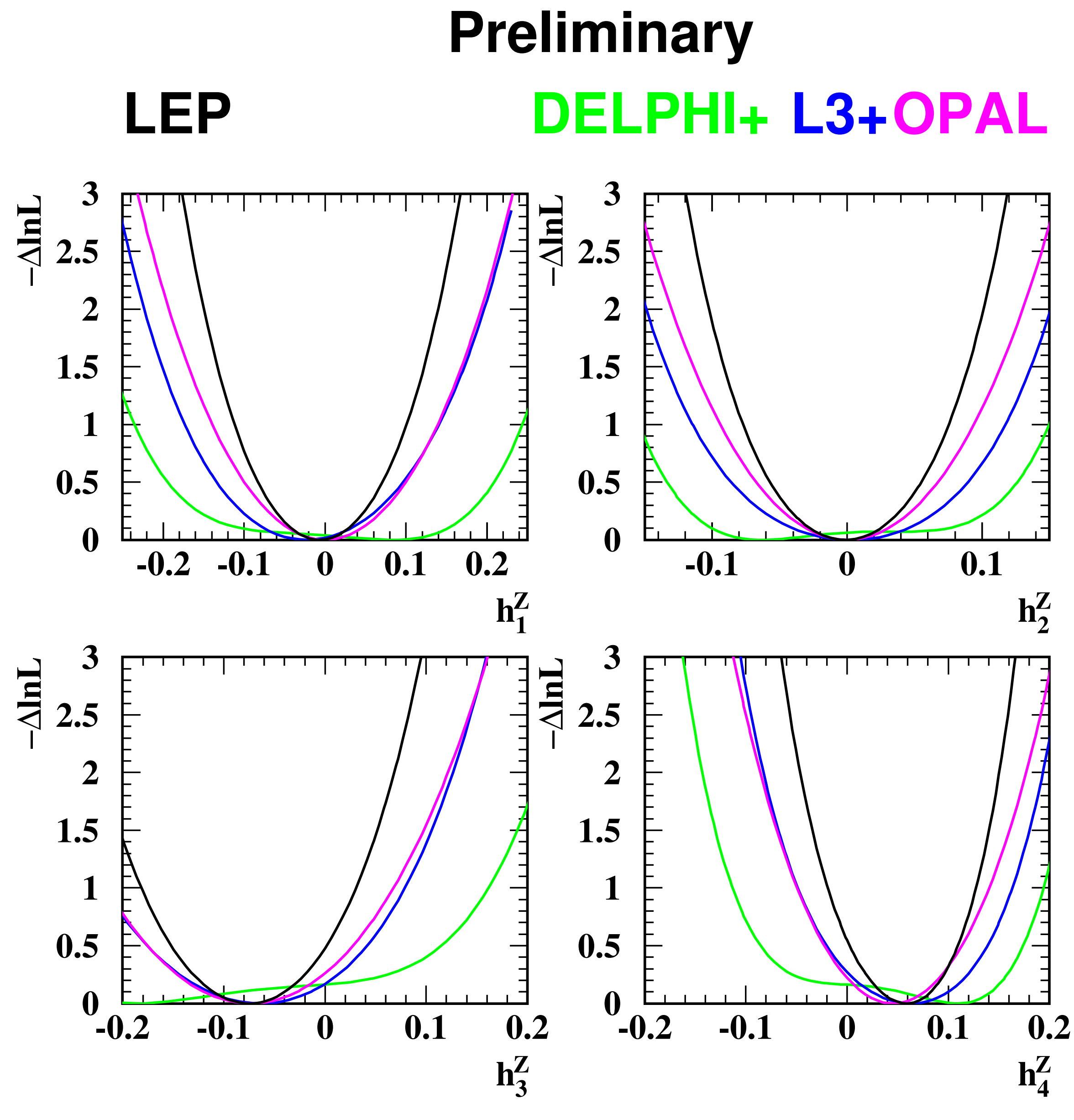


Figure 2: The $\log\mathcal{L}$ curves of DELPHI, L3 and OPAL, and the LEP combined curve for the four neutral TGCs $h_i^Z,\ i = 1, 2, 3, 4$. In each case, the minimal value is subtracted.

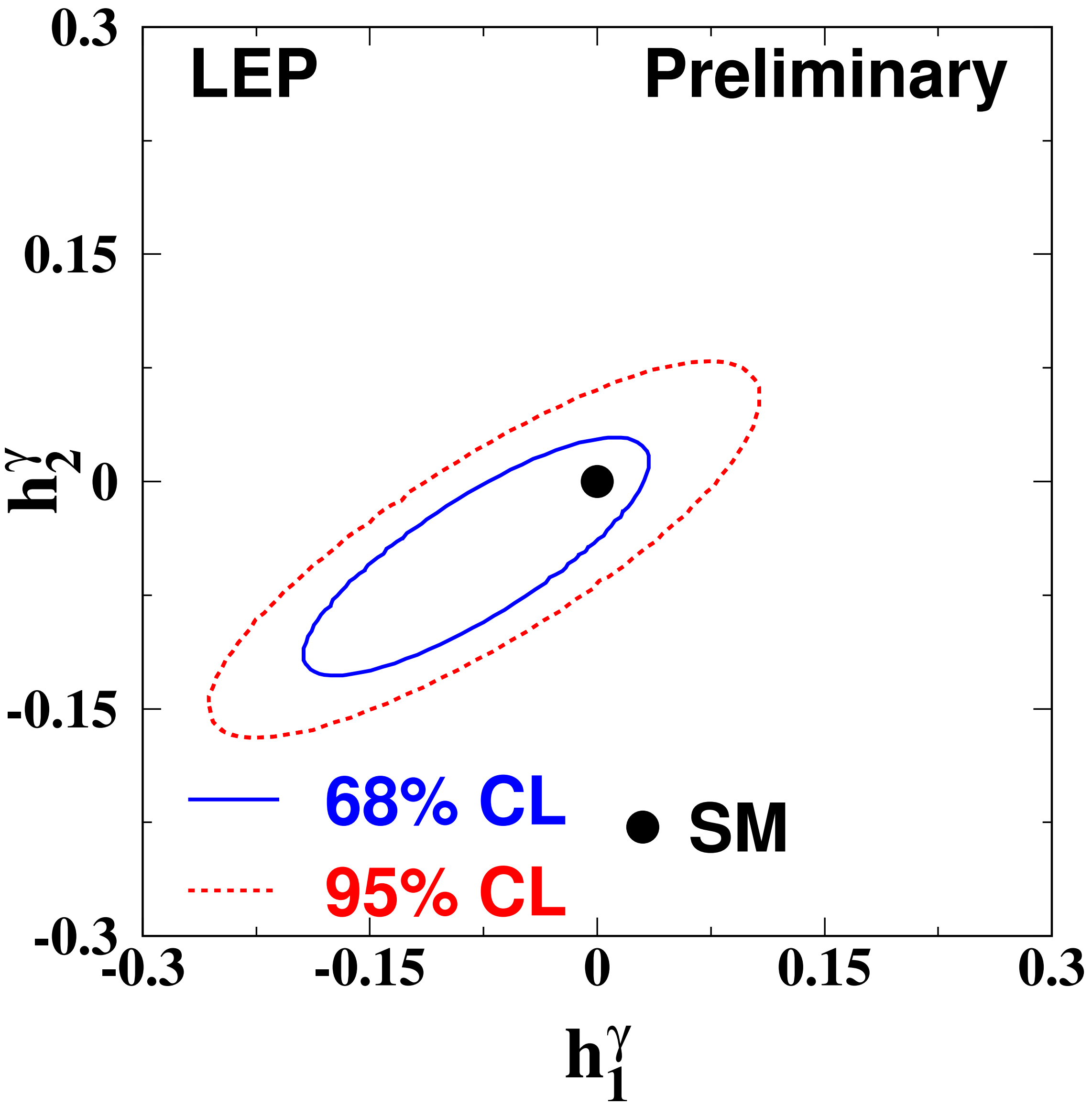


Figure 3: Contour curves of 68% C.L. and 95% C.L. in the plane $(h_1^\gamma, h_2^\gamma)$ showing the LEP combined result.

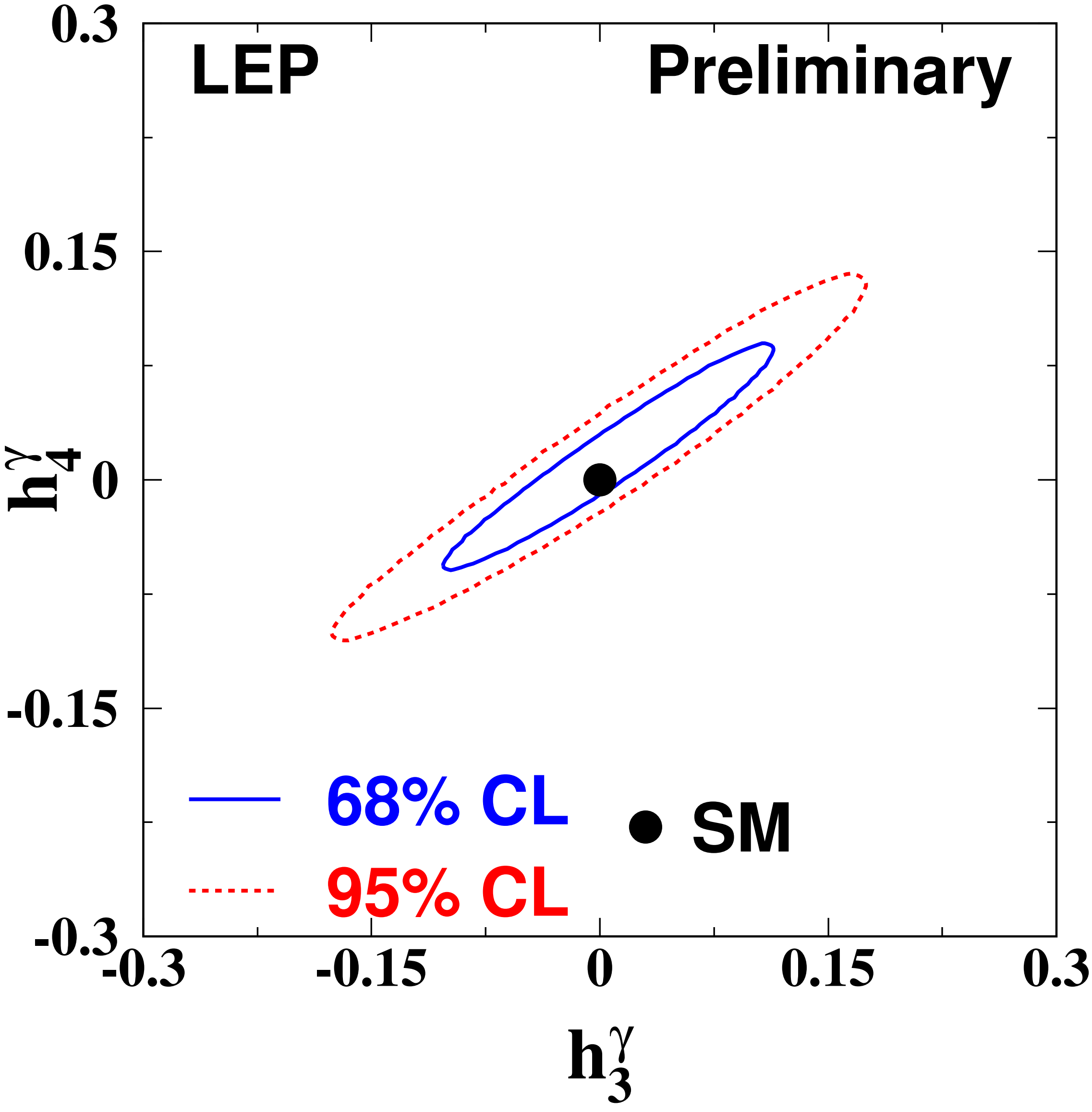


Figure 4: Contour curves of 68% C.L. and 95% C.L. in the plane $(h_3^\gamma, h_4^\gamma)$ showing the LEP combined result.

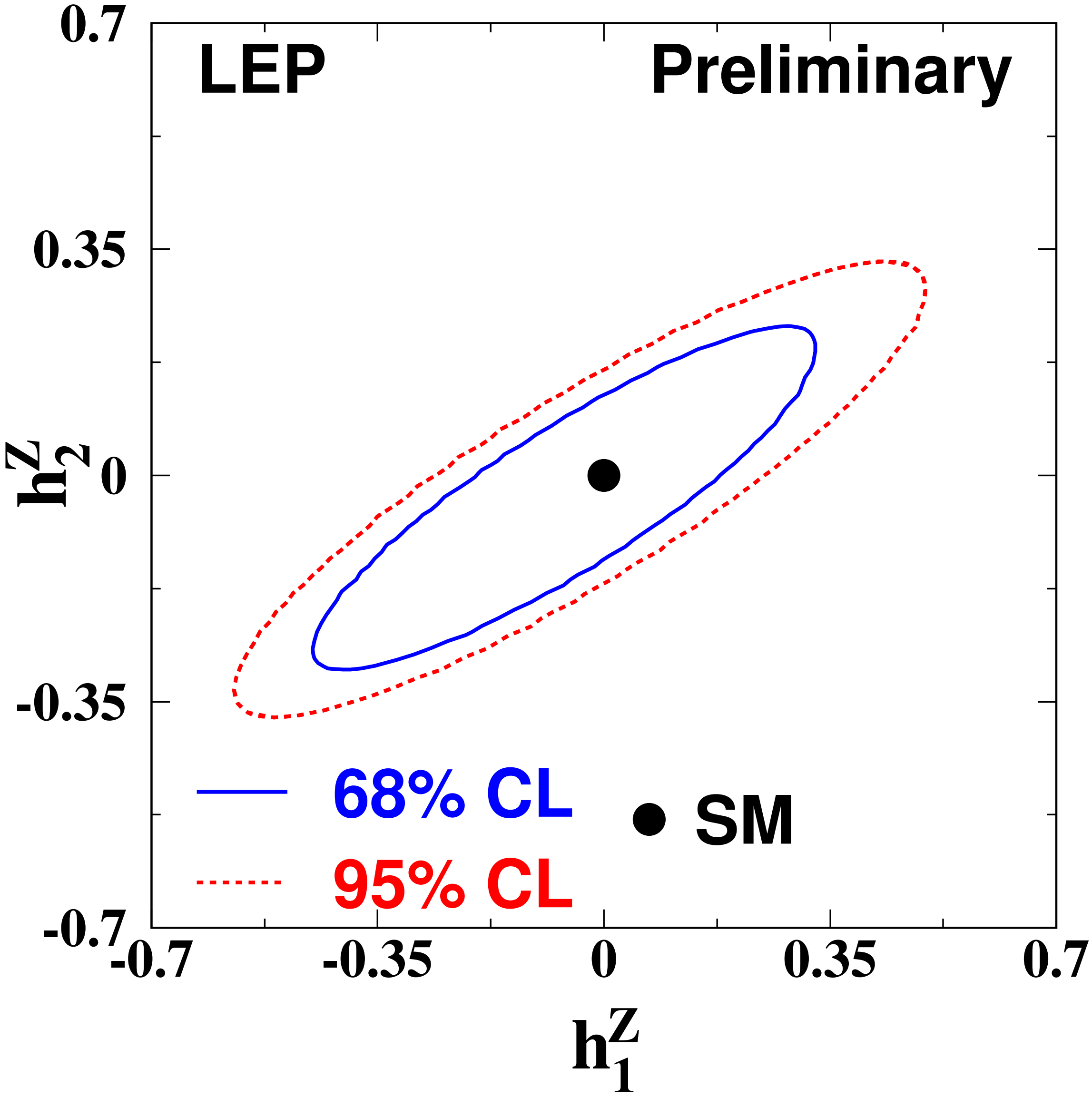


Figure 5: Contour curves of 68% C.L. and 95% C.L. in the plane $(h_1^Z, h_2^Z)$ showing the LEP combined result.

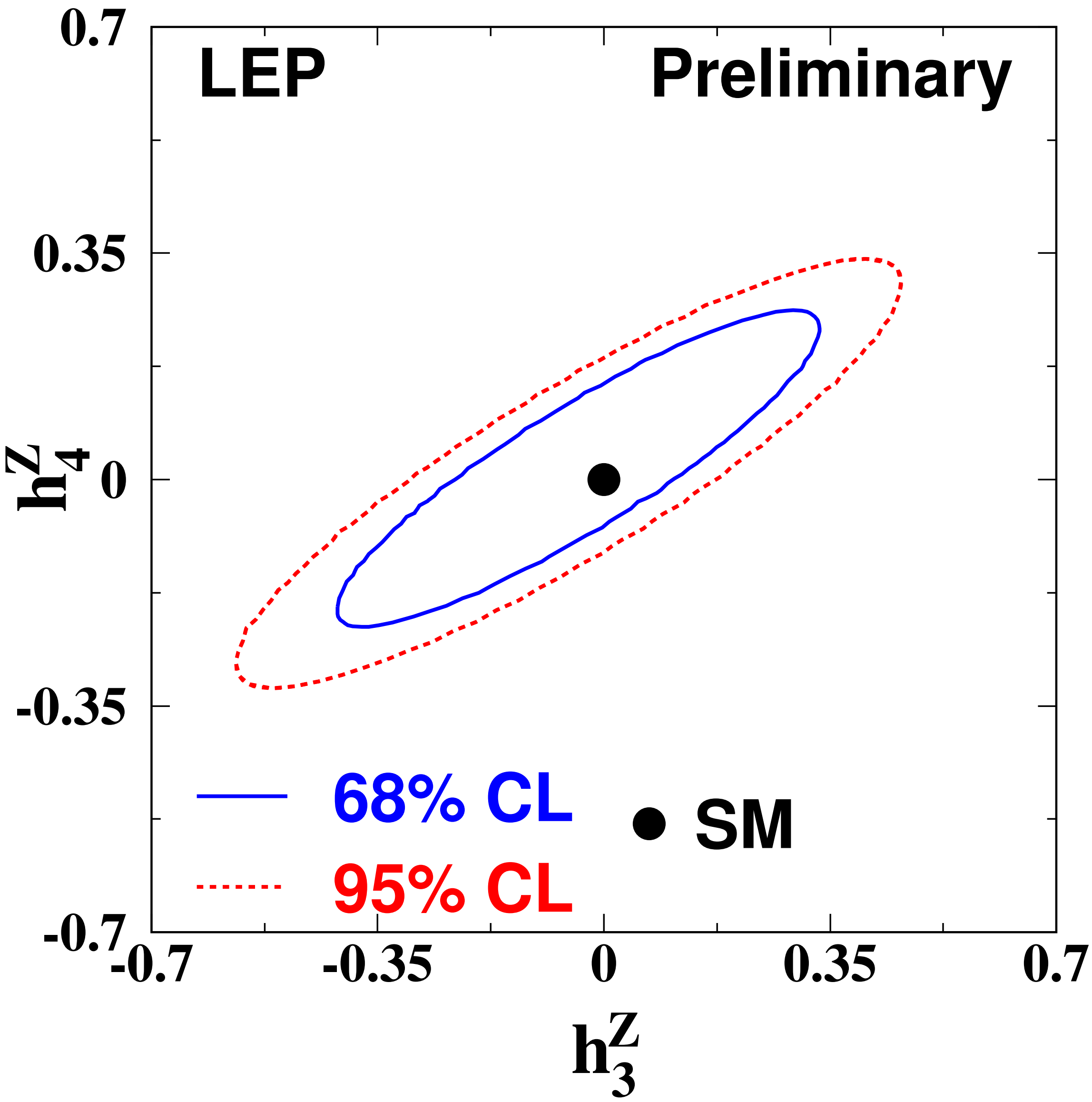


Figure 6: Contour curves of 68% C.L. and 95% C.L. in the plane $(h_3^Z, h_4^Z)$ showing the LEP combined result.

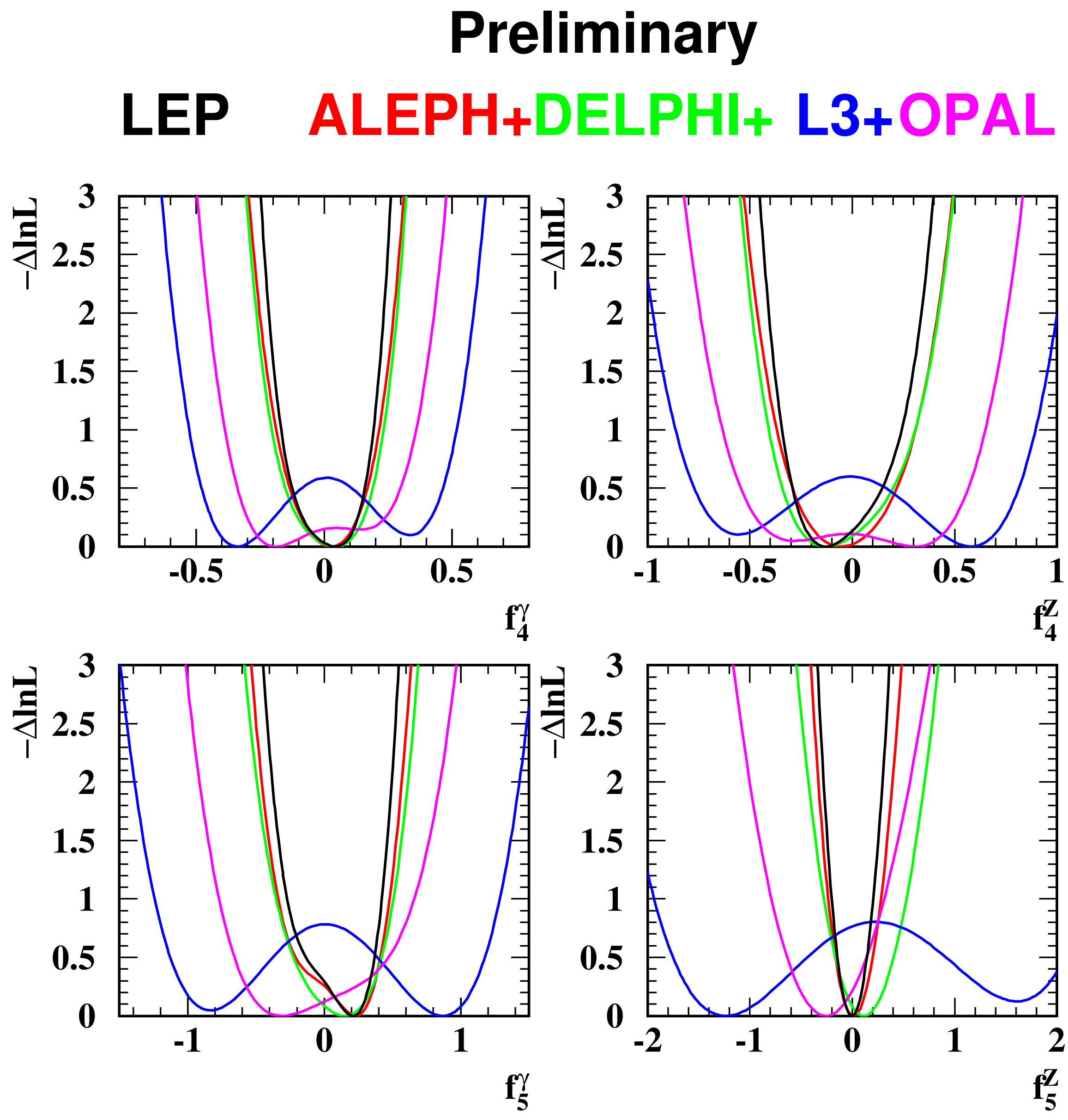


Figure 7: The $\log \mathcal{L}$ curves of ALEPH, DELPHI, L3 and OPAL, and the LEP combined curve for the four neutral TGCs $f_i^V$, $V = \gamma, Z$, $i = 4, 5$. In each case, the minimal value is subtracted.

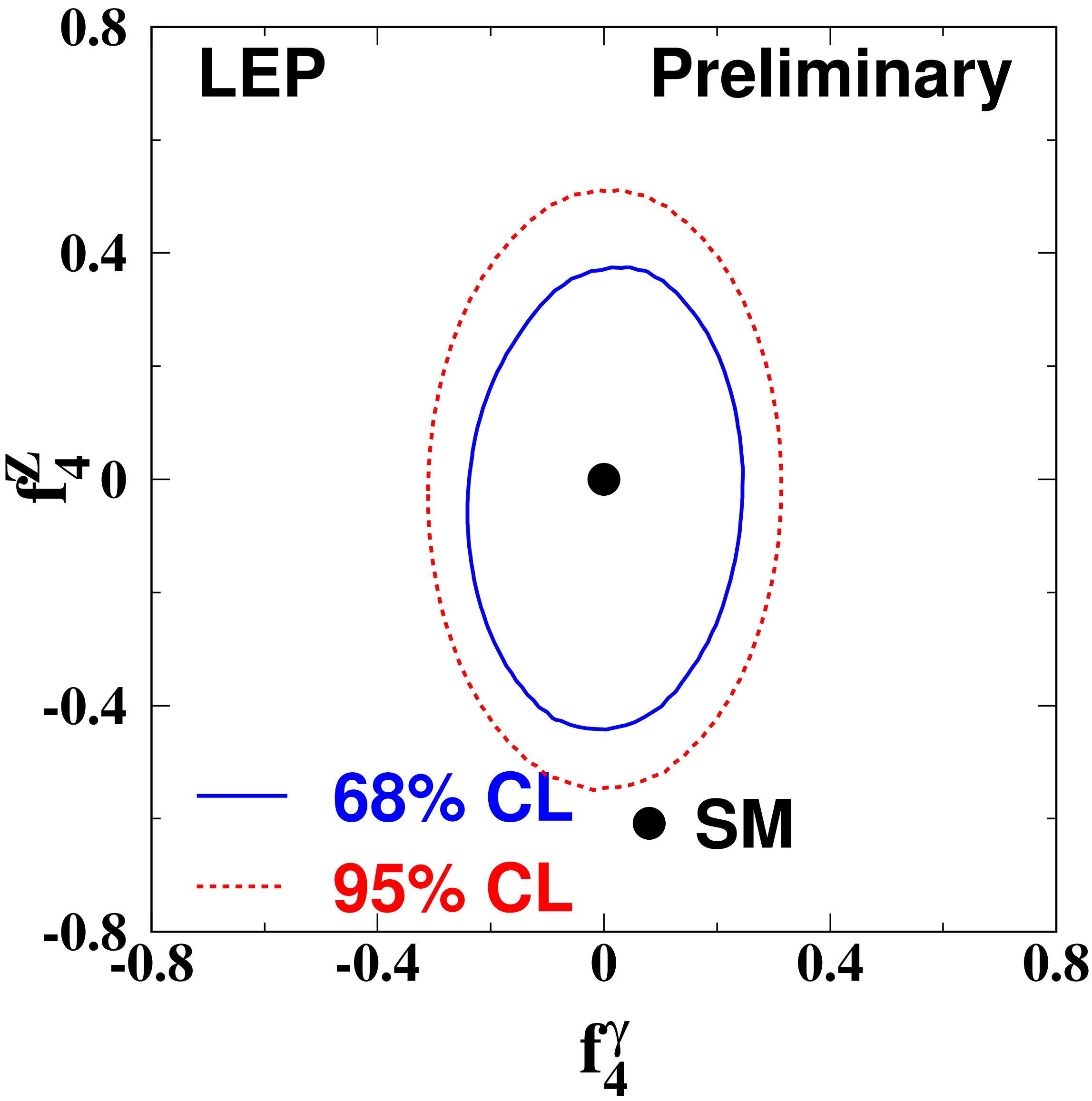


Figure 8: Contour curves of 68% C.L. and 95% C.L. in the plane $(f_4^\gamma, f_4^Z)$ showing the LEP combined result.

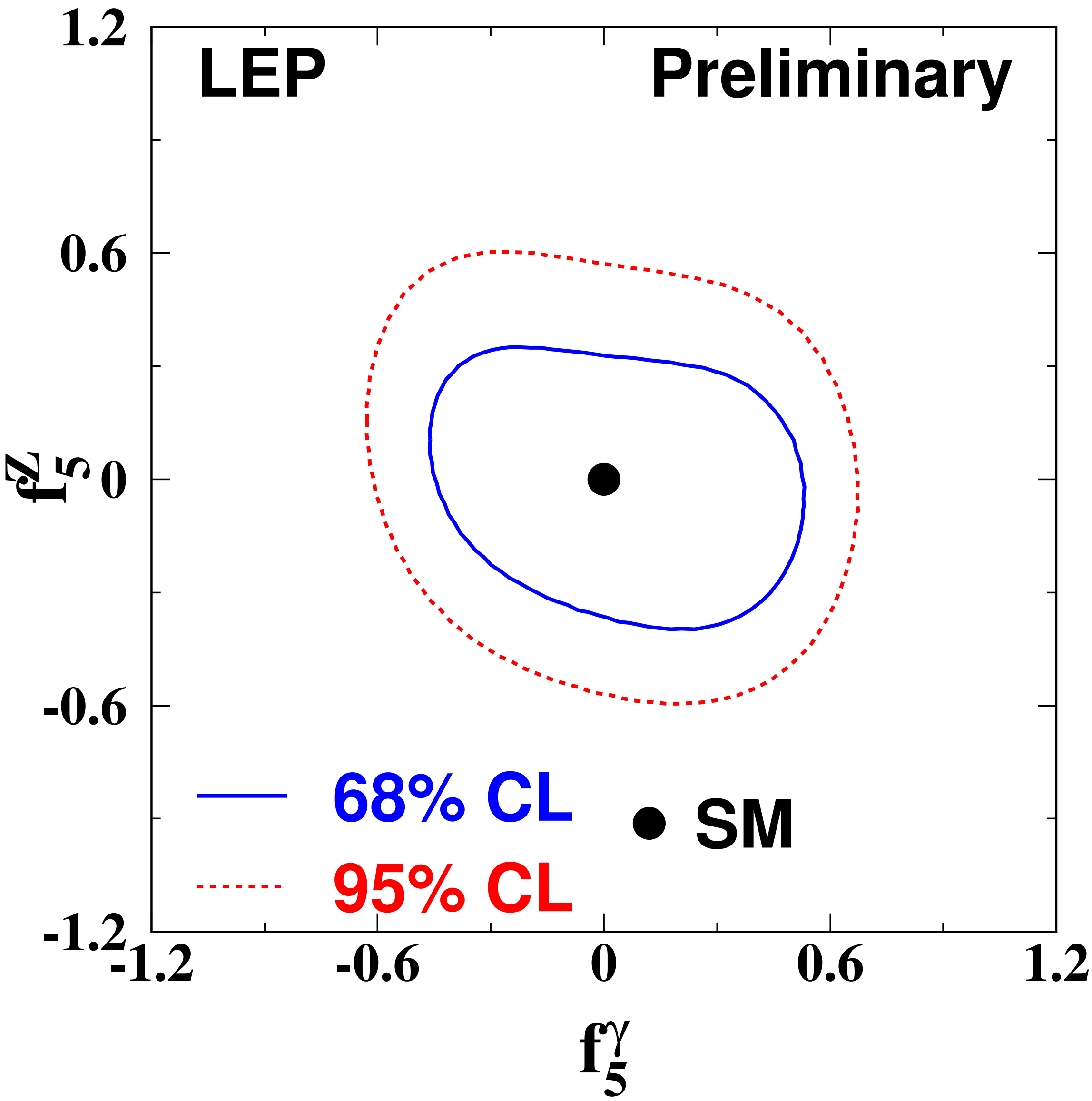


Figure 9: Contour curves of 68% C.L. and 95% C.L. in the plane $(f_5^\gamma, f_5^Z)$ showing the LEP combined result.