EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

LEPEWWG/TGC/2001-03
ALEPH 2001-072 PHYSIC 2001-022
DELPHI 2001-127 PHYS-903
L3 Note 2710
OPAL TN-703
September 13th, 2001

Combined Preliminary Results of Electroweak Gauge Boson Coupling Measurements 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 2001

Abstract

A new combination of published and preliminary results on trilinear neutral electroweak gauge boson couplings, h_i^V and f_i^V, as well as quartic gauge boson couplings $a_0^{\rm W}/\Lambda^2$, $a_c^{\rm W}/\Lambda^2$ and a_n/Λ^2, measured by the four LEP experiments, is presented. This replaces the combined results given in the previous note LEPEWWG/TGC/2001-01 [1].

*Contact: Helge Voss , e-mail: `Helge.Voss@cern.ch`
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 reaching up to 209 GeV in the final year. Until the end of LEP2 operation, a total integrated luminosity of approximately 700 pb^{-1} per experiment have been recorded. The measurement of 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 aims at LEP2 [2].

Combined preliminary measurements of the neutral triple gauge boson couplings and quartic gauge couplings are presented here. The results for the neutral couplings already include the full data set for all but the OPAL results from $Z\gamma$-production. For the quartic gauge couplings the whole data set has been analysed so far only by L3 and ALEPH ($\nu\bar{\nu}\gamma\gamma$ -channel).

The W-pair production process, $e^+e^- \rightarrow W^+W^-$, involves the charged 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 the $WW\gamma$ vertex. Results from these channels have been combined for previous summer conferences.

For the charged TGCs, new Monte Carlo calculations (RacoonWW [3] and YFSWW [4, 5]) 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 W-pair production. Their implications are still under investigation. Preliminary results including these $O(\alpha_{em})$ corrections are so far available only from ALEPH [6]. Therefore, as for the winter conferences this year, no new combinations are made for these measurements.

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 do 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 only anomalous quartic vertices are searched for in the production of $WW\gamma$, $\nu\bar{\nu}\gamma\gamma$ and also $Z\gamma\gamma$ final states. No results from the $Z\gamma\gamma$ final state analysis are included in the combinations due to current investigations of differences in the description of the anomalous contributions to this vertex [7].

1.1 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 described in [8, 9].

The first class refers to anomalous $Z\gamma\gamma^*$ and $Z\gamma Z^*$ couplings which are accessible at LEP in the process $e^+e^- \to Z\gamma$. 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 $Z\gamma Z^*$ couplings. The photon and the Z boson in the final state are considered as on-shell particles, while the third boson at the 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 $e^+e^- \to ZZ$. 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 $ZZ\gamma^*$ 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.

1.2 Quartic Gauge Boson Couplings

Anomalous contributions to electroweak quartic vertices are treated in the framework of References [10–12]. Considered are the three lowest-dimensional operators leading to quartic vertices not causing anomalous TGCs. According to a more recent description of the QGCs [13], anomalous contributions to the $WW\gamma\gamma$ and $ZZ\gamma\gamma$ vertex are treated separately, although their structure is the same. The corresponding couplings are parametrised by a_0^V/Λ^2 and a_c^V/Λ^2, where Λ represents the energy scale of new physics and V=W,Z for the respective $WW\gamma\gamma$ and $ZZ\gamma\gamma$ vertices. An anomalous contribution to the $WWZ\gamma$ vertex is parametrised by a_n/Λ^2. The couplings a_0^V/Λ^2 and a_c^V/Λ^2 conserve C and P, while the coupling a_n/Λ^2 is CP violating. The production of $WW\gamma$ depends on all three a_0^W/Λ^2, a_c^W/Λ^2, and a_n/Λ^2 couplings. The production of $\nu\bar{\nu}\gamma\gamma$ and $Z\gamma\gamma$ depend only on a_0^V/Λ^2 and a_c^V/Λ^2 (for V=W,Z or Z respectively), as they do not involve the $WWZ\gamma$ vertex. The coupling parameters are assumed to be real and they vanish at tree level in the Standard Model. At present there are differences between the Monte Carlo descriptions [11] and [7] of the quartic gauge coupling vertex, especially in the $Z\gamma\gamma$-final state. This issue is still under investigation as stated in [7] and currently effort is going on the repeat the measurement using the latter description. No new results are available using this framework so far and therefore no new combinations are presented for the $ZZ\gamma\gamma$ couplings. The analyses of the $\nu\bar{\nu}\gamma\gamma$ final state do not include possible contributions from the $ZZ\gamma\gamma$ vertex and hence the presented measurements here assume a vanishing $ZZ\gamma\gamma$ vertex measuring only a_0^W/Λ^2, a_c^W/Λ^2 and a_n/Λ^2 accordingly.

2 Measurements

The combined results presented here were obtained from updated neutral electroweak gauge boson coupling measurements and quartic gauge coupling measurements as discussed above. The

h-coupling analyses of ALEPH, DELPHI and L3 use the data collected at LEP2 up to centre-of-mass energies of 209 GeV. The OPAL measurements so far use the data at 189 GeV. The results of the f-couplings are now obtained from the whole data set above the ZZ-production threshold by all of the experiments. 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 the 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 [14–17] and the f_i^V couplings [14, 15, 18, 19].

For QGCs, the combined results are based on measurements from $WW\gamma$ 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 $WW\gamma$ channel. The analyses in the $\nu\bar{\nu}\gamma\gamma$ channel generally restrict to low recoil masses where contributions from the Standard Model and a possible $ZZ\gamma\gamma$ vertex are small. Again, the individual references should be consulted for details of the determination of the QGCs $a_0^{\mathrm{V}}/\Lambda^2$, $a_c^{\mathrm{V}}/\Lambda^2$ and a_n/Λ^2 [20–22].

3 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 $q\bar{q}\gamma$- 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 is 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 in the h-coupling analyses 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 two dimensional 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.

4 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 3. Thus they may differ slightly from those reported in the individual references. In particular for the h-coupling result from OPAL and DELPHI, a slightly modified estimate of the systematic uncertainty due to the theoretical cross section prediction is responsible for slightly different limits compared to the published results. Furthermore, 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.

4.1 Neutral Triple Gauge Boson Couplings in Zγ Production

The individual analyses and results of the experiments for the h-couplings are described in [14–17].

Single-Parameter Analyses

The results for 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. From Figures 1 and 2 it is clear that the sensitivity of the L3 analysis [16] is the highest amongst the LEP experiments. This is partially due to the use of a larger phase space region, which increases the statistics by about a factor two, and partially due to added information from using an Optimal Observable technique.

Two-Parameter Analyses

The results for each experiment are shown in Table 3, where the errors include both statistical and systematic uncertainties. The 68% C.L. and 95% C.L. contour 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.

4.2 Neutral Triple Gauge Boson Couplings in ZZ Production

The individual analyses and results of the experiments for the f-couplings are described in [14, 15, 18, 19].

Single-Parameter Analyses

The results for 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. contour 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.

4.3 Quartic Gauge Boson Couplings

The individual analyses and results of the experiments for the qarutic gauge couplings are described in [20–22].

The results for each experiment are shown in Table 9, where the uncertainties include both statistical and systematic effects. The individual $\log \mathcal{L}$ curves and their sum are shown in Figures 10. The results of the combination are given in Table 10.

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	ALEPH	DELPHI	L3	OPAL
h_1^γ	$[-0.14, \ +0.14]$	$[-0.15, \ +0.15]$	$[-0.06, \ +0.06]$	$[-0.13, \ +0.13]$
h_2^γ	$[-0.07, \ +0.07]$	$[-0.09, \ +0.09]$	$[-0.053, \ +0.024]$	$[-0.089, \ +0.089]$
h_3^γ	$[-0.069, \ +0.037]$	$[-0.047, \ +0.047]$	$[-0.062, \ -0.014]$	$[-0.16, \ +0.00]$
h_4^γ	$[-0.020, \ +0.045]$	$[-0.032, \ +0.030]$	$[-0.004, \ +0.045]$	$[+0.01, \ +0.13]$
h_1^Z	$[-0.23, \ +0.23]$	$[-0.24, \ +0.25]$	$[-0.17, \ +0.16]$	$[-0.22, \ +0.22]$
h_2^Z	$[-0.12, \ +0.12]$	$[-0.14, \ +0.14]$	$[-0.10, \ +0.09]$	$[-0.15, \ +0.15]$
h_3^Z	$[-0.28, \ +0.19]$	$[-0.32, \ +0.18]$	$[-0.23, \ +0.11]$	$[-0.29, \ +0.14]$
h_4^Z	$[-0.10, \ +0.15]$	$[-0.12, \ +0.18]$	$[-0.08, \ +0.16]$	$[-0.09, \ +0.19]$

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

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	$[-0.05, \ +0.12]$

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

Parameter	ALEPH	DELPHI	L3
h_1^γ	$[-0.32, +0.32]$	$[-0.28, +0.28]$	$[-0.17, +0.04]$
h_2^γ	$[-0.18, +0.18]$	$[-0.17, +0.18]$	$[-0.12, +0.02]$
h_3^γ	$[-0.17, +0.38]$	$[-0.48, +0.20]$	$[-0.09, +0.13]$
h_4^γ	$[-0.08, +0.29]$	$[-0.08, +0.15]$	$[-0.04, +0.11]$
h_1^Z	$[-0.54, +0.54]$	$[-0.45, +0.46]$	$[-0.48, +0.33]$
h_2^Z	$[-0.29, +0.30]$	$[-0.29, +0.29]$	$[-0.30, +0.22]$
h_3^Z	$[-0.58, +0.52]$	$[-0.57, +0.38]$	$[-0.43, +0.39]$
h_4^Z	$[-0.29, +0.31]$	$[-0.31, +0.28]$	$[-0.23, +0.28]$

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

Parameter	95% C.L.	Correlations	
h_1^γ	$[-0.16, +0.05]$	1.00	+0.79
h_2^γ	$[-0.11, +0.02]$	+0.79	1.00
h_3^γ	$[-0.08, +0.14]$	1.00	+0.97
h_4^γ	$[-0.04, +0.11]$	+0.97	1.00
h_1^Z	$[-0.35, +0.28]$	1.00	+0.77
h_2^Z	$[-0.21, +0.17]$	+0.77	1.00
h_3^Z	$[-0.37, +0.29]$	1.00	+0.76
h_4^Z	$[-0.19, +0.21]$	+0.76	1.00

Table 4: The 95% C.L. intervals ($\Delta \log \mathcal{L} = 1.92$) obtained combining the results from ALEPH, DELPHI and L3. In each case the two parameters listed are varied while the remaining ones are fixed to their Standard Model values. 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	DELPHI	L3	OPAL
f_4^γ	$[-0.26, +0.26]$	$[-0.26, +0.28]$	$[-0.24, +0.26]$	$[-0.36, +0.36]$
f_4^Z	$[-0.44, +0.43]$	$[-0.49, +0.42]$	$[-0.43, +0.41]$	$[-0.55, +0.64]$
f_5^γ	$[-0.54, +0.56]$	$[-0.48, +0.61]$	$[-0.48, +0.56]$	$[-0.82, +0.72]$
f_5^Z	$[-0.73, +0.83]$	$[-0.42, +0.69]$	$[-0.46, +1.2]$	$[-0.96, +0.31]$

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 values. Both statistical and systematic uncertainties are included.

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	$[-0.36, \ +0.39]$

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

Parameter	ALEPH	DELPHI	L3	OPAL
f_4^γ	$[-0.26, \ +0.26]$	$[-0.26, \ +0.28]$	$[-0.24, \ +0.26]$	$[-0.36, \ +0.36]$
f_4^Z	$[-0.44, \ +0.43]$	$[-0.49, \ +0.42]$	$[-0.43, \ +0.41]$	$[-0.54, \ +0.63]$
f_5^γ	$[-0.52, \ +0.53]$	$[-0.52, \ +0.61]$	$[-0.48, \ +0.56]$	$[-0.77, \ +0.73]$
f_5^Z	$[-0.77, \ +0.86]$	$[-0.44, \ +0.69]$	$[-0.46, \ +1.2]$	$[-0.96, \ +0.44]$

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

Parameter	95% C.L.	Correlations	
f_4^γ	$[-0.17, \ +0.19]$	1.00	$+0.10$
f_4^Z	$[-0.30, \ +0.28]$	$+0.10$	1.00
f_5^γ	$[-0.34, \ +0.38]$	1.00	-0.18
f_5^Z	$[-0.36, \ +0.38]$	-0.18	1.00

Table 8: The 95% C.L. intervals ($\Delta \log \mathcal{L} = 1.92$) obtained combining the results from all four experiments. In each case the two parameters listed are varied while the remaining ones are fixed to their Standard Model values. 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 [GeV^{-2}]	ALEPH	L3	OPAL
$a_0^{\mathrm{W}}/\Lambda^2$	$[-0.029, \ +0.029]$	$[-0.017, \ +0.017]$	$[-0.065, \ +0.065]$
$a_c^{\mathrm{W}}/\Lambda^2$	$[-0.079, \ +0.080]$	$[-0.03, \ +0.05]$	$[-0.13, \ +0.17]$
a_n/Λ^2	—	$[-0.15, \ +0.14]$	$[-0.61, \ +0.57]$

Table 9: The 95% C.L. intervals ($\Delta \log \mathcal{L} = 1.92$) measured by ALEPH, L3 and OPAL. In each case the parameter listed is varied while the remaining ones are fixed to their Standard Model values. Both statistical and systematic uncertainties are included.

Parameter [GeV^{-2}]	95% C.L.
$a_0^{\mathrm{W}}/\Lambda^2$	$[-0.018, \quad +0.018]$
$a_c^{\mathrm{W}}/\Lambda^2$	$[-0.033, \quad +0.047]$
a_n/Λ^2	$[-0.17, \quad +0.15]$

Table 10: The 95% C.L. intervals ($\Delta \log \mathcal{L} = 1.92$) obtained combining the results from ALEPH, L3 and OPAL. In each case the parameter listed is varied while the remaining ones are fixed to their Standard Model values. Both statistical and systematic uncertainties are included.

References

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

[2] 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..

[3] A. Denner *et al.*, Nucl. Phys. **B587** (2000) 67–117.

[4] S. Jadach *et al.*, Phys. Lett. **B417** (1998) 326.

[5] Jadach, S. and Placzek, W. and Skrzypek, M. and Ward, B. F. L. and Was, Z., *The Monte Carlo event generator YFSWW3 version 1.16 for W production and decay at LEP2/LC energies*, hep-ph/0103163..

[6] The ALEPH Collaboration, *Measurement of Triple Gauge-Boson Couplings in e^+e^- collisions up to 208GeV*, ALEPH 2001-027 CONF (CONFerence) 2001-021..

[7] G. Montagna *et al.*, Phys. Lett. **B515** (2001) 197–205.

[8] K. Hagiwara *et al.*, Nucl. Phys. **B282** (1987) 253.

[9] G. J. Gounaris, J. Layssac, and F. M. Renard, Phys. Rev. **D62** (2000) 073013.

[10] G. Belanger and F. Boudjema, Phys. Lett. **B288** (1992) 210–220.

[11] W. J. Stirling and A. Werthenbach, Eur. Phys. J. **C14** (2000) 103–110.

[12] W. J. Stirling and A. Werthenbach, Phys. Lett. **B466** (1999) 369.

[13] G. Belanger *et al.*, Eur. Phys. J. **C13** (2000) 283–293.

[14] The ALEPH Collaboration, *Limits on anomalous neutral gauge couplings using data from ZZ and $Z\gamma$ production between 183-208 GeV*, ALEPH 2001-061 (July 2001) CONF 2001-041..

[15] The DELPHI Collaboration, *Study of Trilinear Gauge Boson Couplings ZZZ, $ZZ\gamma$ and $Z\gamma\gamma$*, DELPHI 2001-097 (July 2001) CONF 525..

[16] 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.
The L3 Collaboration, *Search for anomalous ZZg and Zgg couplings in the process ee$\rightarrow$Zg at LEP*, L3 Note 2672 (July 2001)..

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

[18] 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;
The L3 Collaboration, *Z Boson Pair-Production at LEP*, L3 Note 2696 (July 2001)..

[19] The OPAL Collaboration, G. Abbiendi *et al.*, Phys. Lett. **B476** (2000) 256;
The OPAL Collaboration, *Study of Z Pair Production and Anomalous Couplings in e^+e^- Collisions at $\sqrt{s}$ between 190 and 209 GeV* , OPAL PN482 (July 2001)..

[20] The ALEPH Collaboration, *Constraints on Anomalous Quartic Gauge Boson Couplings*, ALEPH 2001-069 CONF 2001-049..

[21] 39. The L3 Collaboration, M.Acciarri *et al.*, Phys. Lett. **B 490** (2000) 187;
The L3 Collaboration, *Measurement of the W^+W^-g Cross Section and Direct Limits on Anomalous Quartic Gauge Boson Couplings at LEP*, L3 Note 2675 (June 2001)..

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

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

ALEPH:	`http://alephwww.cern.ch/ALPUB/oldconf/summer01/summer.html`
DELPHI:	`http://delphiwww.cern.ch/~pubxx/delsec/conferences/summer01/`
L3:	`http://l3www.cern.ch/conferences/Budapest2001/`
OPAL:	`http://opalinfo.cern.ch/opal/public/pubs/eps2001/abstr.html`

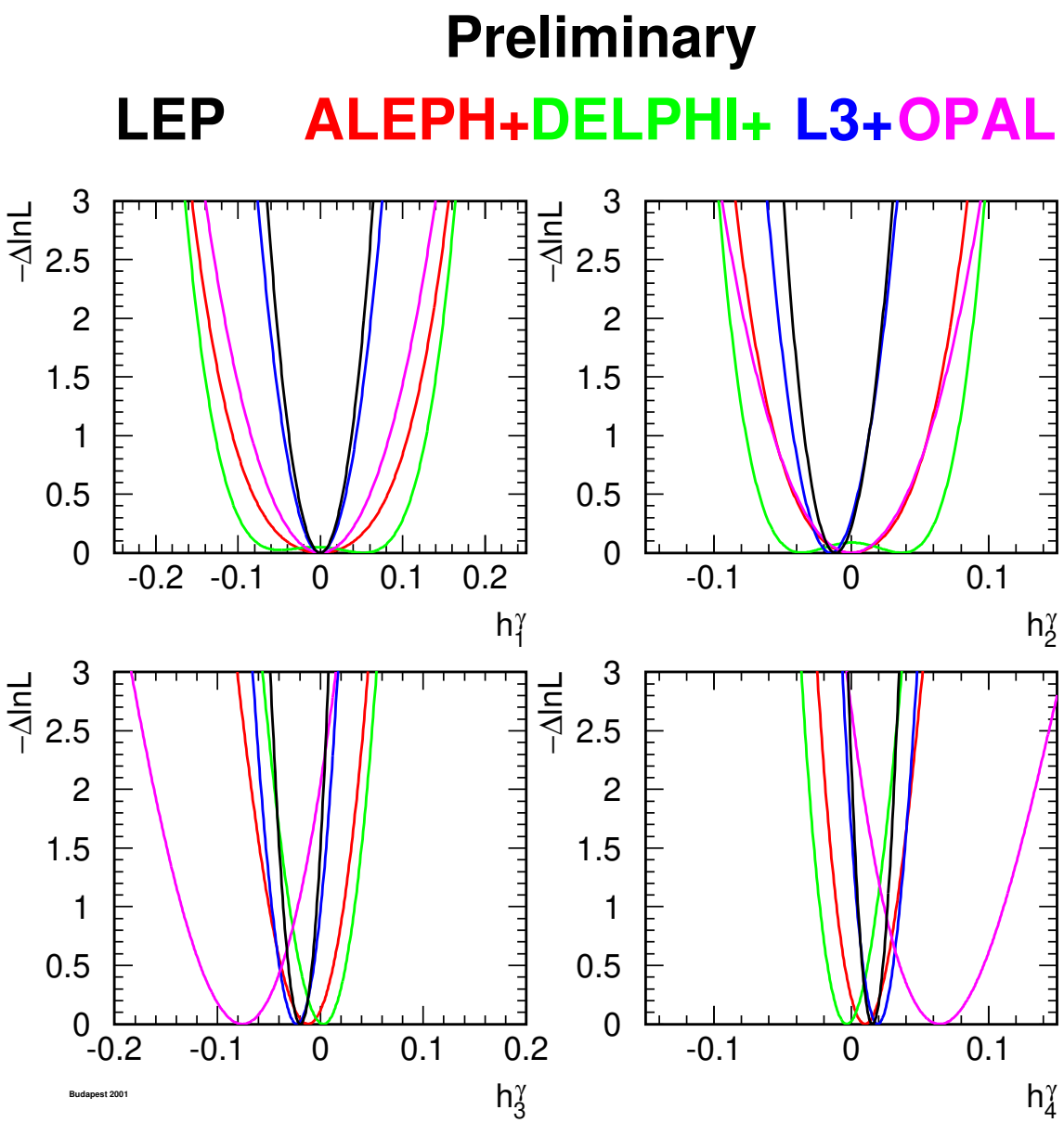

Figure 1: The $\log \mathcal{L}$ curves of the four experiments, and the LEP combined curve for the four neutral TGCs h_i^γ, $i = 1, 2, 3, 4$. In each case, the minimal value is subtracted.

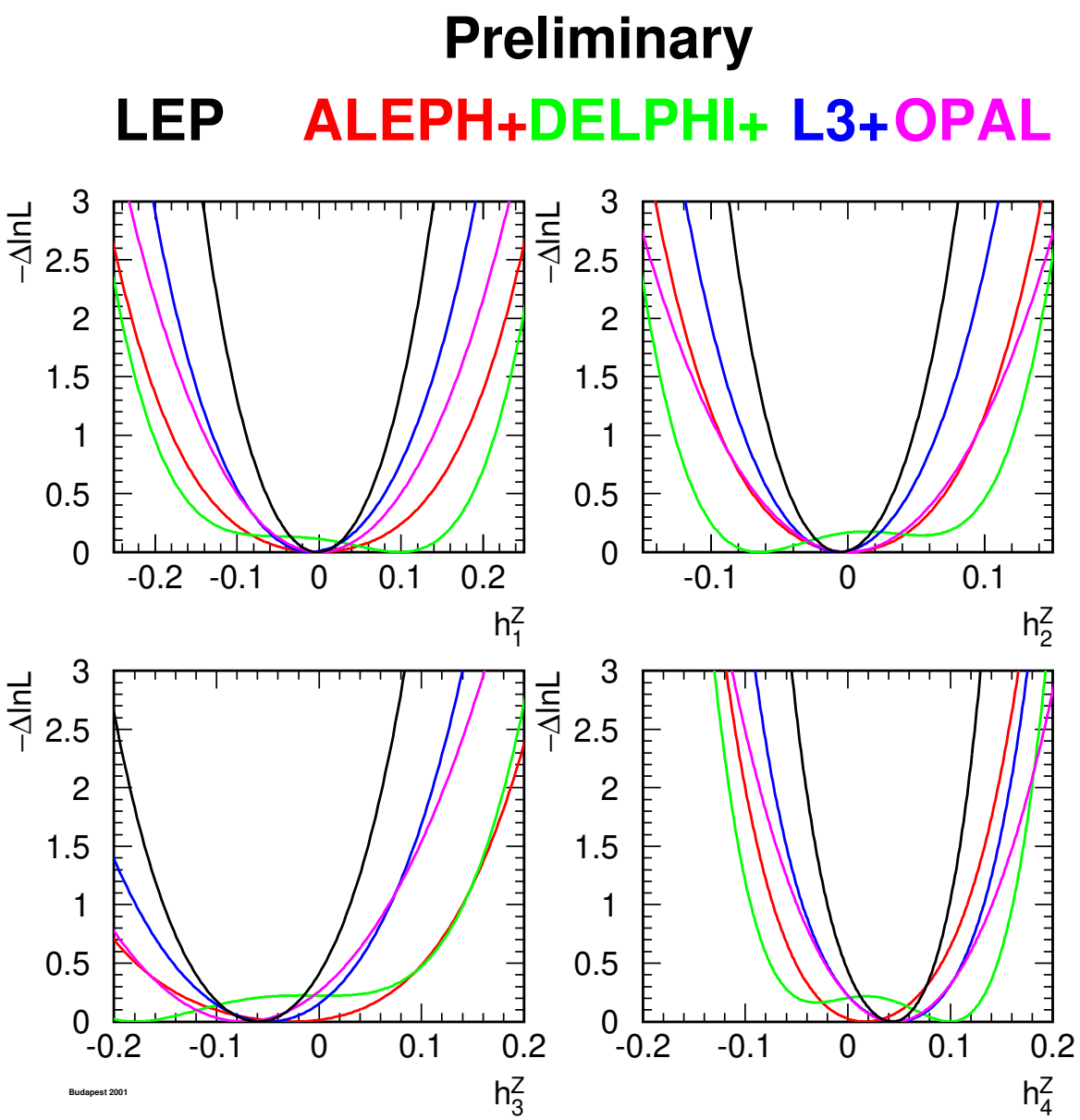

Figure 2: The $\log \mathcal{L}$ curves of the four experiments, and the LEP combined curve for the four neutral TGCs h_i^Z, $i = 1, 2, 3, 4$. In each case, the minimal value is subtracted.

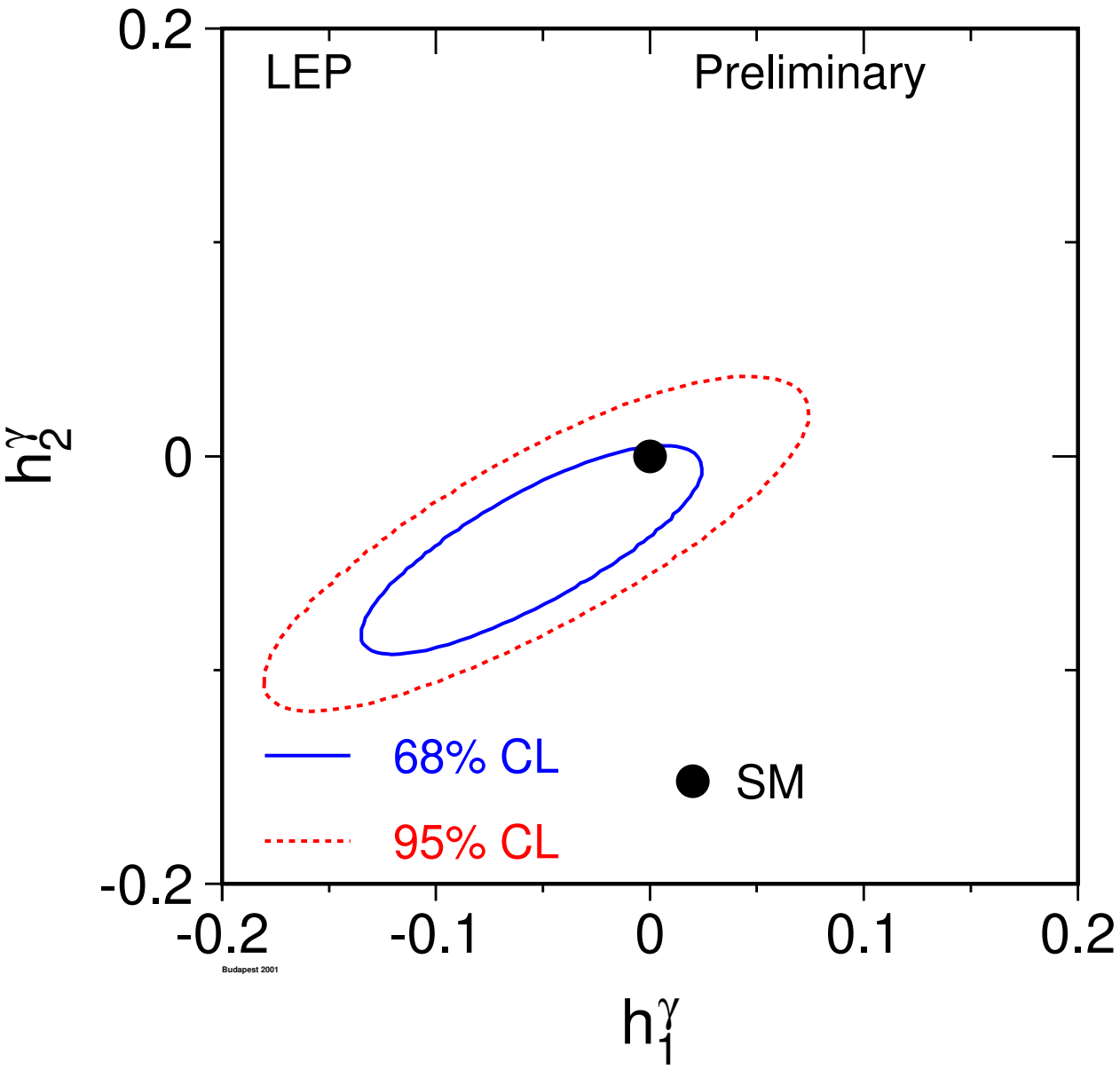

Figure 3: Contour curves of 68% C.L. and 95% C.L. in the plane (h_1^γ, h_2^γ) showing the LEP combined result.

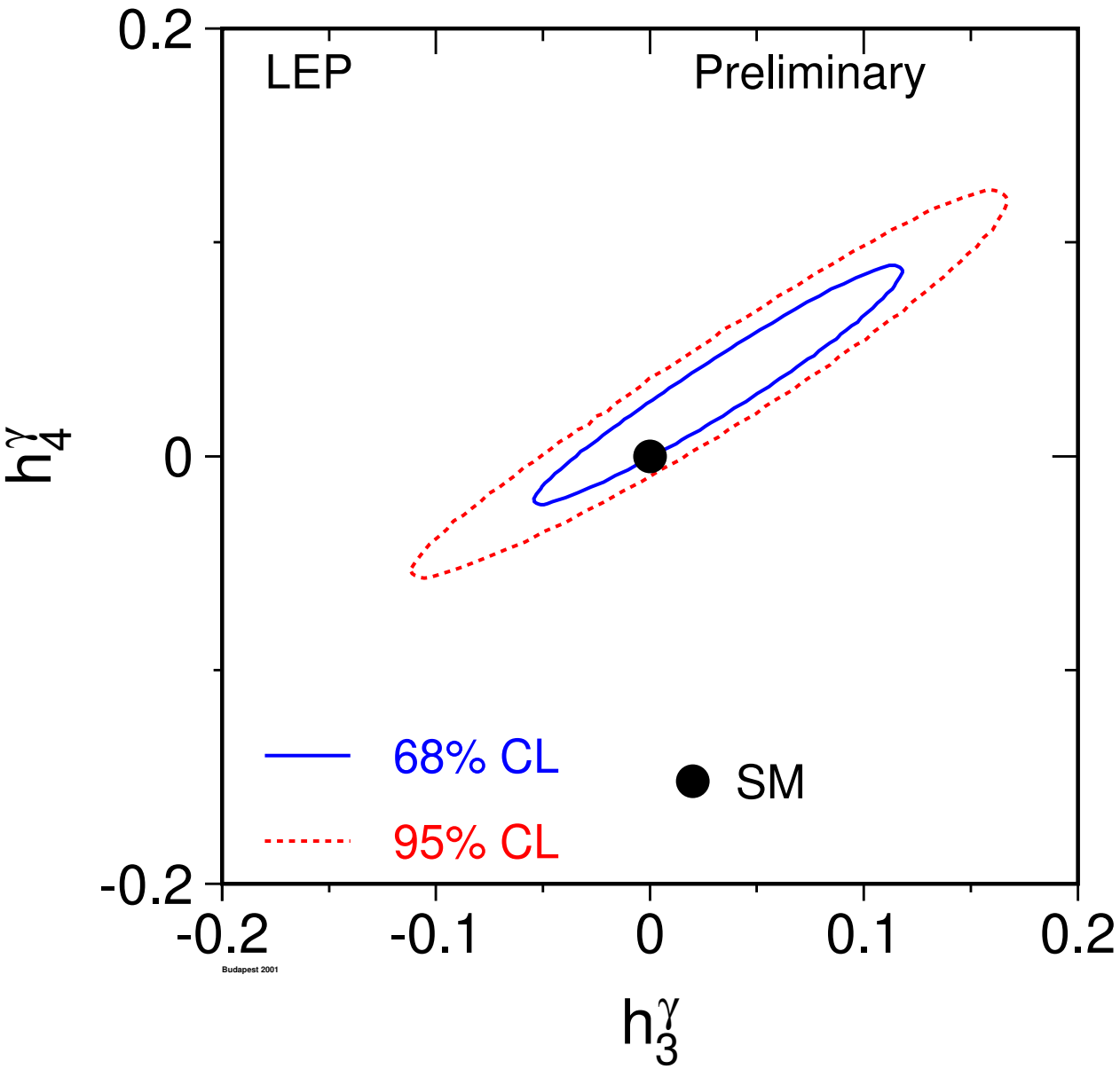

Figure 4: Contour curves of 68% C.L. and 95% C.L. in the plane (h_3^γ, h_4^γ) showing the LEP combined result.

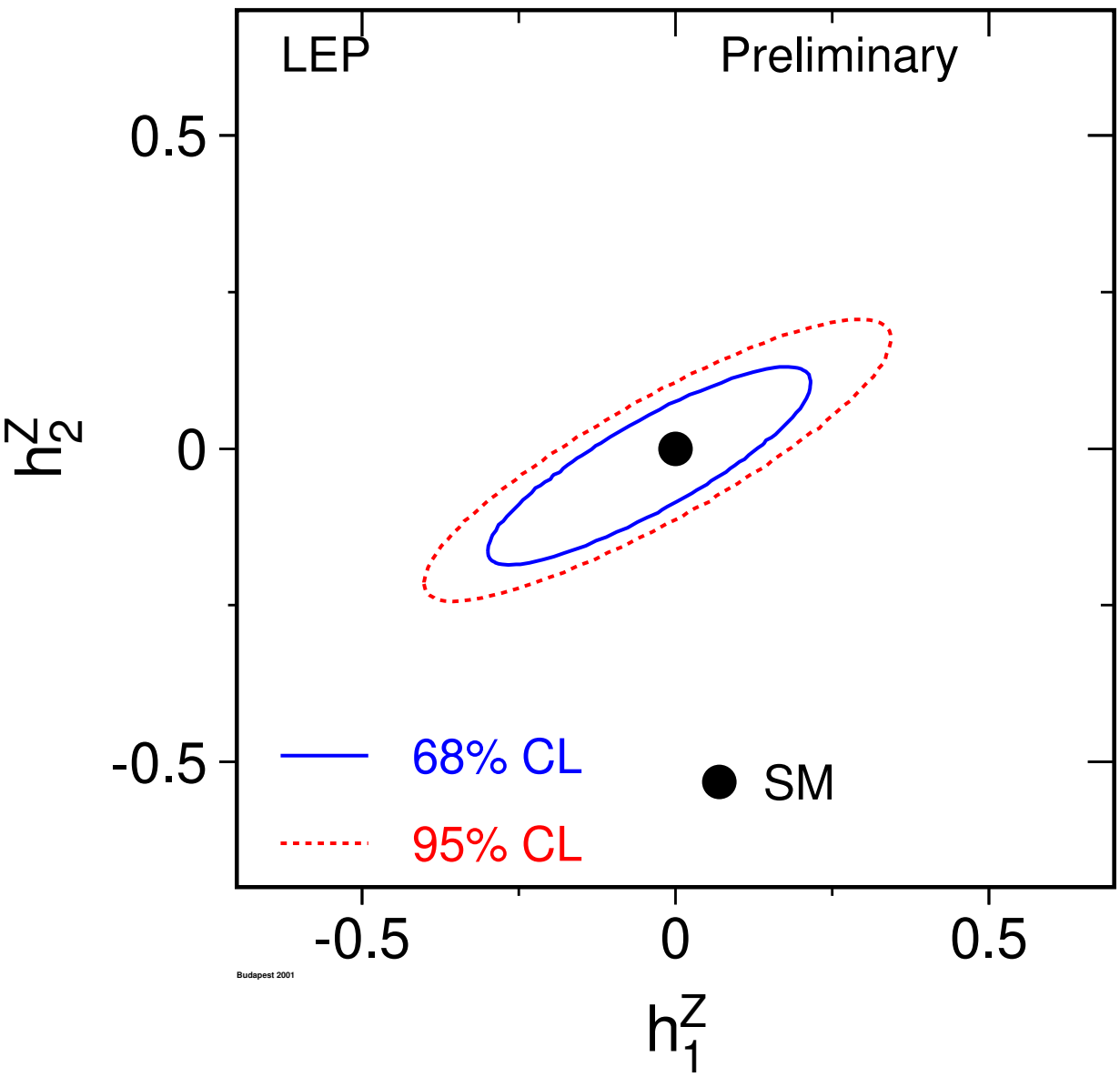

Figure 5: Contour curves of 68% C.L. and 95% C.L. in the plane (h_1^Z, h_2^Z) showing the LEP combined result.

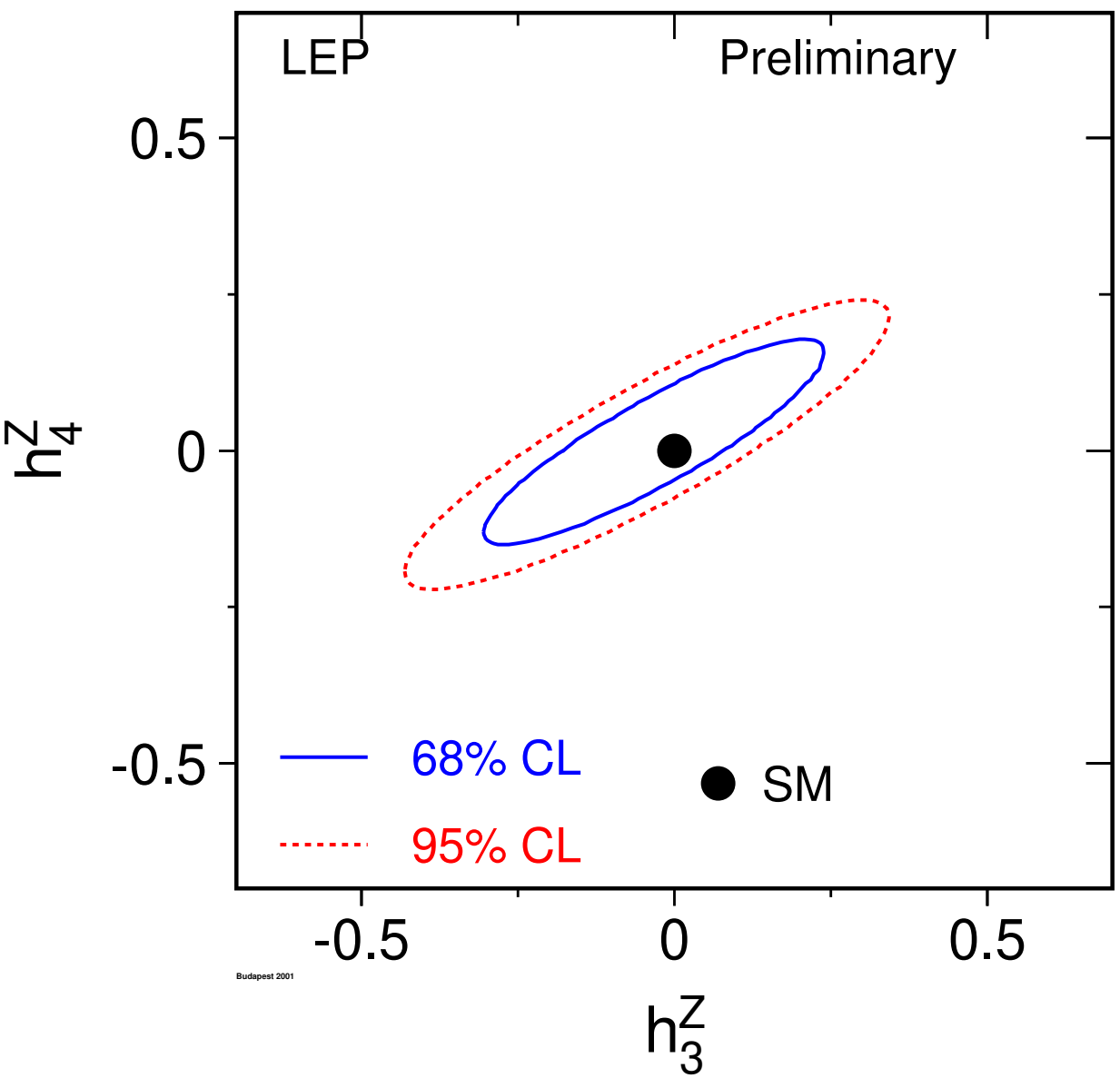

Figure 6: Contour curves of 68% C.L. and 95% C.L. in the plane (h_3^Z, h_4^Z) showing the LEP combined result.

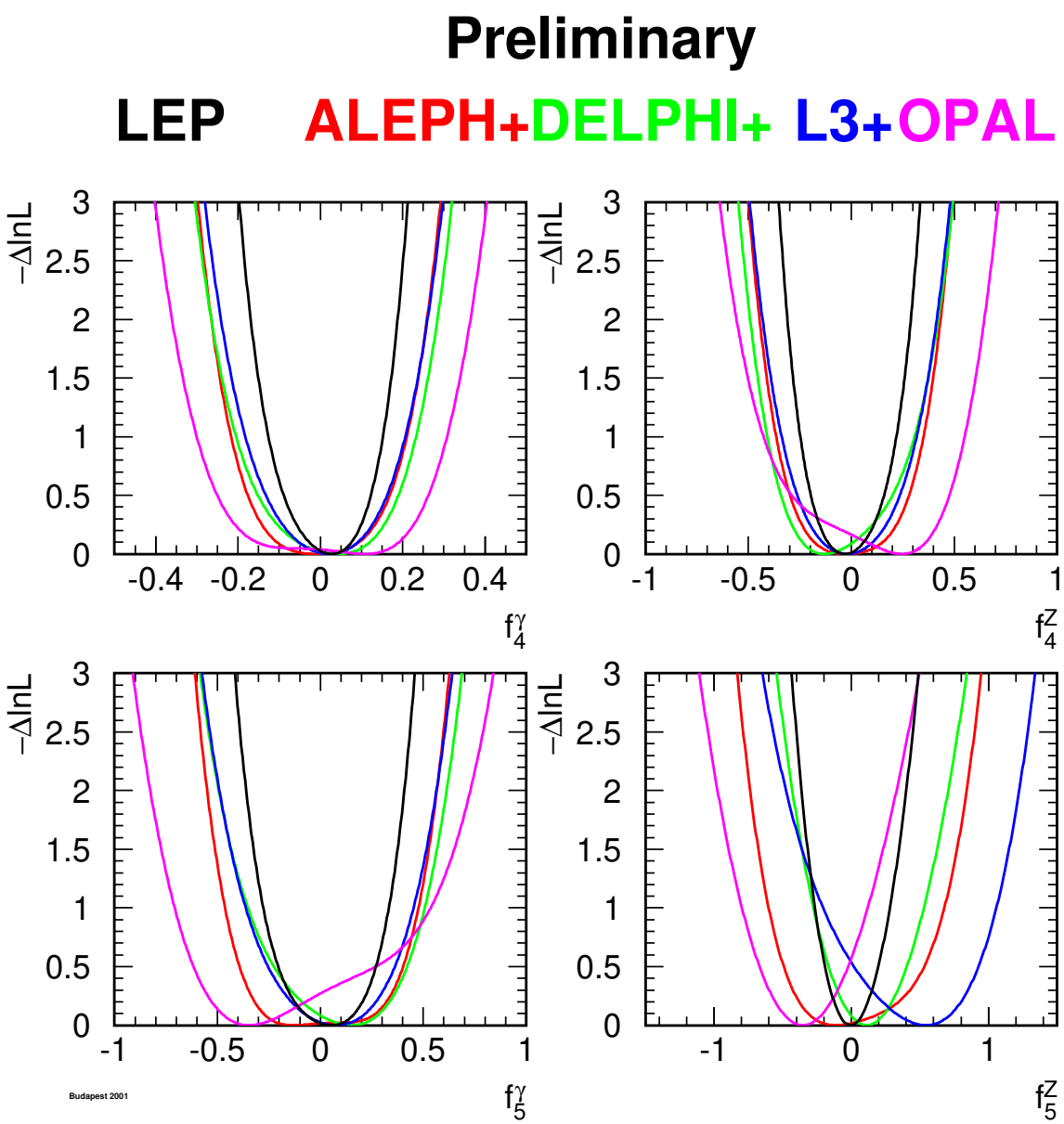

Figure 7: The $\log \mathcal{L}$ curves of the four experiments, and the LEP combined curve for the four neutral TGCs $f_i^V,\ V = \gamma, Z,\ i = 4, 5$. In each case, the minimal value is subtracted.

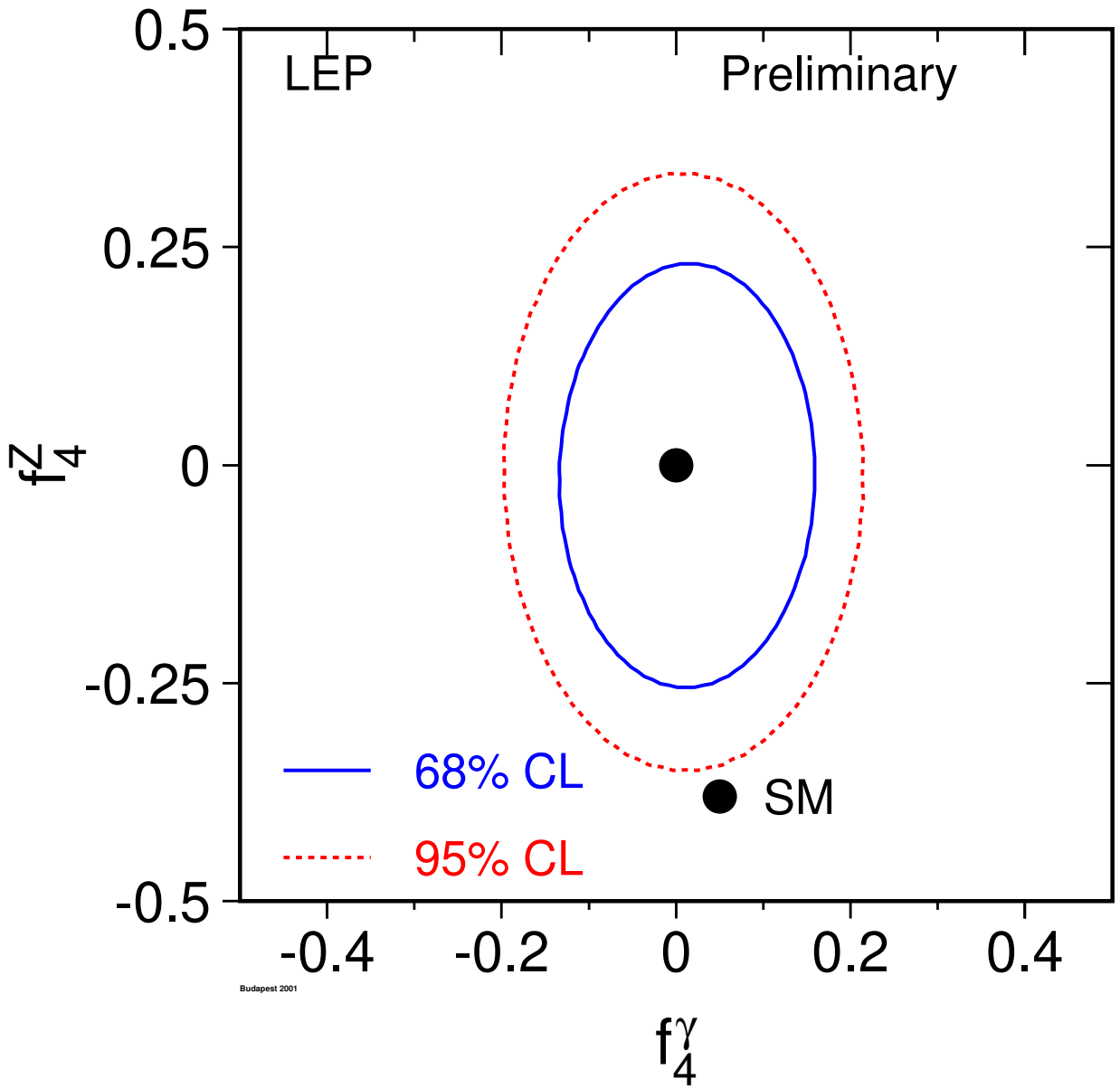

Figure 8: Contour curves of 68% C.L. and 95% C.L. in the plane (f_4^γ, f_4^Z) showing the LEP combined result.

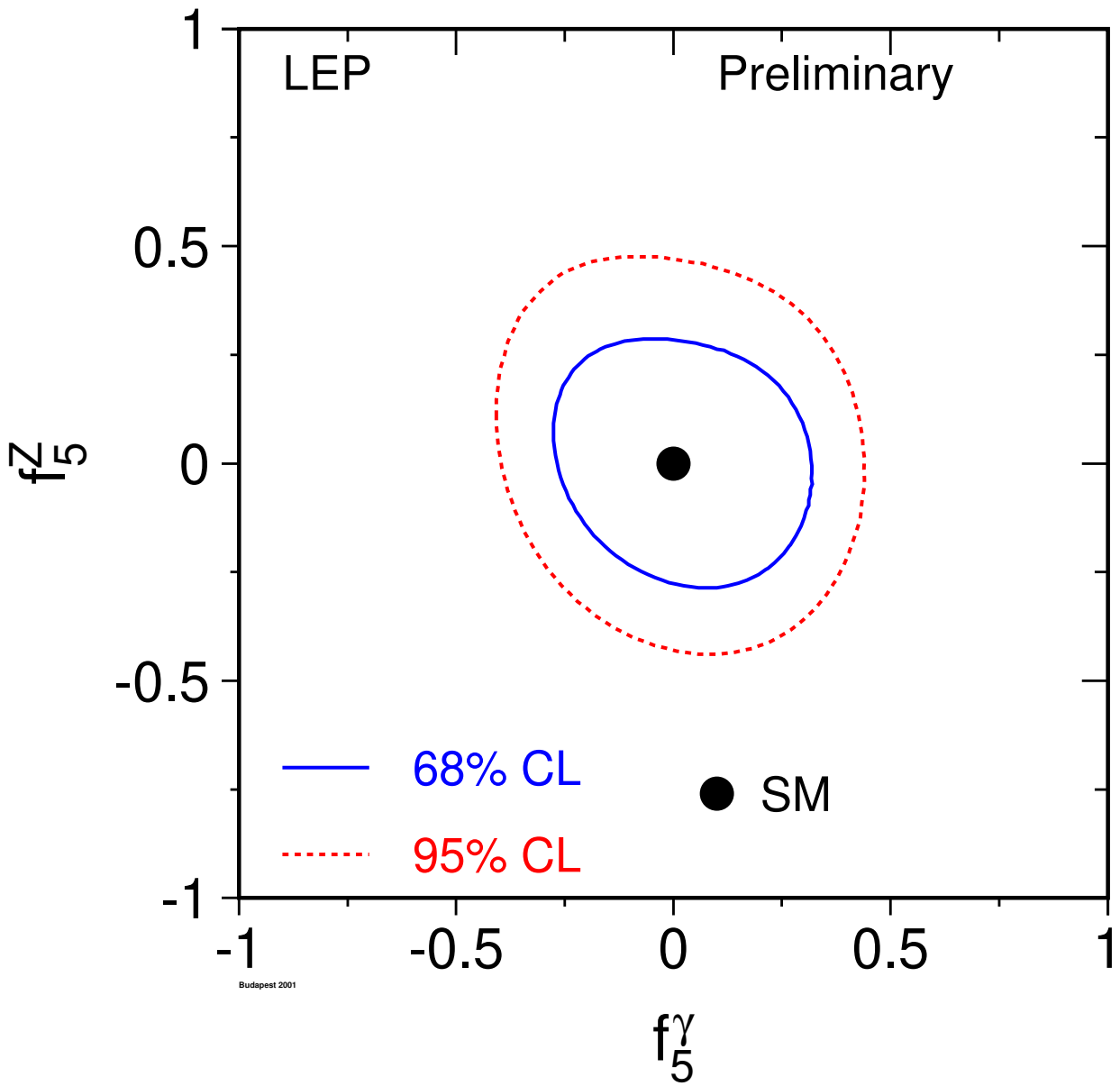

Figure 9: Contour curves of 68% C.L. and 95% C.L. in the plane (f_5^γ, f_5^Z) showing the LEP combined result.

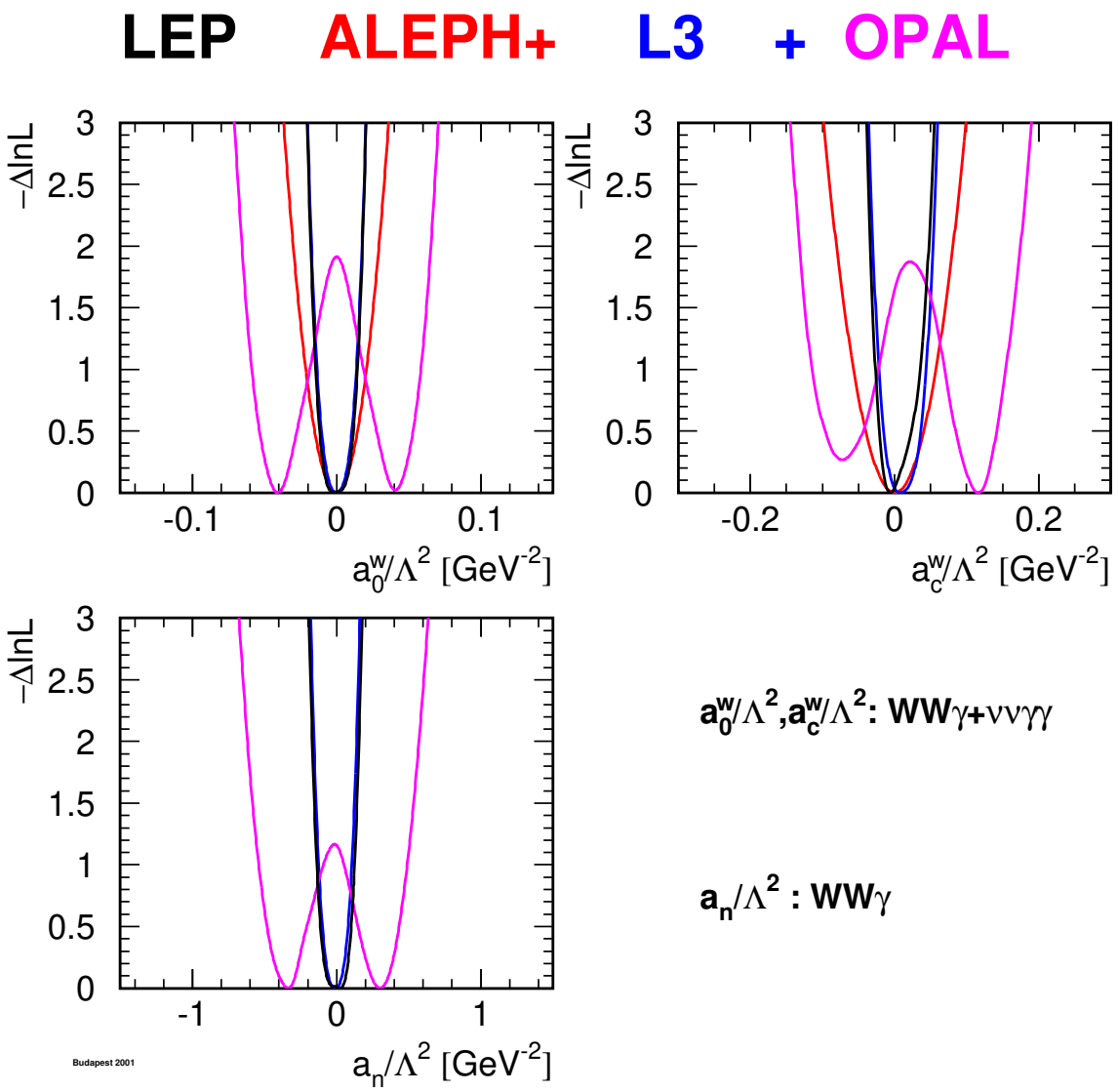

Figure 10: The $\log \mathcal{L}$ curves of ALEPH, L3 and OPAL, and the LEP combined curve for the QGCs $a_0^{\mathrm{W}}/\Lambda^2$, $a_c^{\mathrm{W}}/\Lambda^2$ and a_n/Λ^2. In each case, the minimal value is subtracted.