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Study of Trilinear Gauge Boson Couplings ZZZ, $ZZ\gamma$ and $Z\gamma\gamma$

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Preliminary

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Abstract

Trilinear neutral gauge boson couplings ZZZ, $ZZ\gamma$ and $Z\gamma\gamma$ have been studied with the DELPHI detector using data at energies between 189 and 208 GeV. Limits are derived on these couplings from an analysis of the reactions $e^+e^- \rightarrow \gamma f\bar{f}$, with $f = q$ or ν, and of the reactions $e^+e^- \rightarrow f\bar{f}f'\bar{f}'$ using all the visible channels except $\tau^+\tau^-q\bar{q}$, $\tau^+\tau^-\nu\bar{\nu}$ and $l^+l^-l^+l^-$. Limits are also derived from channels in which the final state boson is off-mass shell, using data from the reaction $e^+e^- \rightarrow \mu^+\mu^-q\bar{q}$.

1 Introduction

This note describes a measurement of the neutral triple gauge boson couplings ZZZ, $ZZ\gamma$ and $Z\gamma\gamma$ by DELPHI using LEP2 data taken between 1997 and 2000 at energies between 189 and 208 GeV.

The neutral coupling sector is probed by means of the reactions $e^+e^- \to Z\gamma$, $e^+e^- \to Z\gamma^*$ and $e^+e^- \to ZZ$. As shown in figure 1, within the Standard Model (SM) these processes receive contributions from the t-channel exchange of an electron. The same figure shows new physics contributions that come from the s-channel exchange of a virtual γ or Z, leading to $Z\gamma$, $Z\gamma^*$ or ZZ production via a triple vector boson coupling with subsequent decay of the Z in the final state.

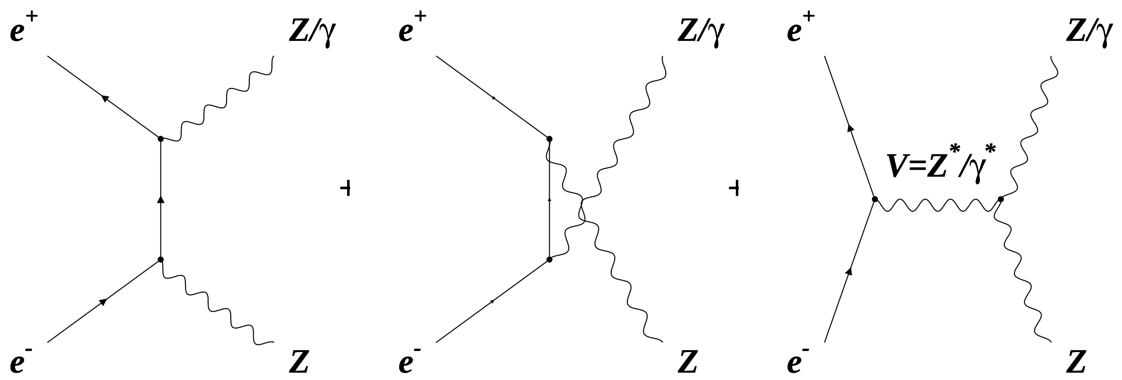

Figure 1: Feynman diagrams for the production of two gauge bosons ZZ and $Z\gamma$, where both on- and off-shell γ production is implied. The first two on the left represent the Standard Model contribution, while the third one involves an anomalous interaction among three neutral gauge bosons.

The parametrizations of the ZZZ, $ZZ\gamma$ and $Z\gamma\gamma$ vertex functions used here follow those suggested in [1] for case of on-shell vector boson production and in [2] for the generalized case, where one or both final state bosons may be off-shell.

In the on-shell case, there are twelve independent anomalous couplings. Calling V the exchanged boson ($V = Z, \gamma$), the couplings f_i^V (i =4,5) produce a ZZ final state and h_i^V ($i = 1, \cdots, 4$) the $Z\gamma$ final state. The couplings f_4^V, h_1^V and h_2^V are CP-violating and f_5^V, h_3^V and h_4^V are CP-conserving.

When the final photon is on-shell, the $Z\gamma$ production contributes to the $f\bar{f}\gamma$ final state. The differential cross-section for this process in presence of anomalous couplings has been calculated using code [3] with vertex factors modified by a factor i according to the correction suggested in [4]. The kinematic region with high photon energy and large photon polar angle is sensitive to the anomalous couplings. In this region, the anomalous interactions give rise to a change in the total rate and to an enhancement of the production of longitudinally polarized Z bosons [5].

The total ZZ cross-section is very sensitive to the anomalous couplings and the sensitivity strongly increases with $\sqrt{s}$. Large interference between SM and anomalous amplitudes arises for CP-conserving couplings (expecially for f_5^Z) when one considers the differential cross-section $d\sigma/d\cos\theta_Z$, where θ_Z is the Z production angle with respect to the beam axis [4].

A complete phenomenological description of the anomalous neutral gauge couplings in the off-shell case has been developed in [2]. This description corresponds to the general case with an arbitrary mass assignment to the gauge bosons. The $V_1^* V_2^* V_3^*$ vertex functions are expressed as sums of transverse and scalar terms (the latter contributing in the case where one off-shell Z decays to a heavy fermion pair through its axial coupling) multiplied by coupling functions f, which depend on the bosons' squared momenta $s_i = q_i^2$:

$$\Gamma_{\alpha\beta\mu}^{V_1^* V_2^* V_3^*}(q_1, q_2, q_3) = i \sum_j I_{\alpha\beta\mu}^{V_1^* V_2^* V_3^*, j}(q_1, q_2, q_3) f_j^{V_1^* V_2^* V_3^*}(s_1, s_2, s_3).$$

Any vertex ($Z^* Z^* Z^*$, $Z^* Z^* \gamma^*$ and $Z^* \gamma^* \gamma^*$) accepts contributions from the coefficients of an effective Lagrangian decomposition in terms of both CP-conserving and CP-violating operators [2]. The effective Lagrangian, written assuming $U(1)_{em}$ and Lorentz invariance, as well as Bose statistics, holds in the case that the New Physics scale Λ is very high, *i.e.* $\Lambda \gg m_Z$:

$$\mathcal{L} = e(\sum_{i,CP+}^{9} \ell_i \mathcal{O}_i + \sum_{i,CP-}^{12} \tilde{\ell}_i \tilde{\mathcal{O}}_i + \sum_{i,CP+}^{6} \ell_i^s \mathcal{O}_i^s + \sum_{i,CP-}^{17} \tilde{\ell}_i^{\,s} \tilde{\mathcal{O}}_i^{\,s}) \, ,$$

where tilde denotes CP-violating operators and coefficients, the superscript s stands for scalar terms and ℓ_i simply denotes, here and in the following, $\ell_i^{V_1^* V_2^* V_3^*}$. In the analysis of LEP data only transverse terms need be considered, due to the negligible contribution of $Z \to t\bar{t}$ decays. The neutral triple gauge boson vertex occurring in the four-fermion final state produced in e^+e^- collisions has been parametrized in terms of the ℓ coefficients in the generator DELTGC [6], and this code has been used in the analysis reported here.

The dimension of the operators in the effective Lagrangian $\mathcal{L}$ above ranges from dim=6 to dim=12, and, restricting to transverse terms, eight of these have the lowest dimension (dim=6). The present analysis has been restricted to determination of the coefficients of these 8 operators; they are listed in table 4.

The functions $f^{V_1^* V_2^* V_3^*}$ defined above are linear functions of the coupling constants ℓ_i and $\tilde{\ell}_i$. Such coupling constants appear in the function multiplied by powers of m_Z, in the case of the lowest dimension operators, by m_Z^2. The complete set of relations between the functions $f^{V_1^* V_2^* V_3^*}$ and the ℓ_i and $\tilde{\ell}_i$ parameters is given in [2]; the relations between the on-shell coefficients f_i^V and h_i^V and the on-shell limits of the lowest dimension ℓ_i and $\tilde{\ell}_i$ parameters are also shown in table 4.

Compared to [5] and [7, 8], the analyses of $Z\gamma$ and ZZ production presented in this note include the data collected in the year 2000 at energies ranging up to $\sqrt{s} \sim 208$ GeV corresponding to a total integrated luminosity of 638 pb^{-1}. Moreover, the analysis of the ZZ final state is improved in sensitivity because the measurement of the anomalous f_i^V couplings is based on a maximum likelihood fit to $d\sigma/d\cos\theta_Z$.

An analysis using the data distributions in the plane $[m_{(q\bar{q})}, m_{(\mu^-\mu^+)}]$ for $Z\gamma^*$ and ZZ production leading to the final state $\mu^+\mu^- q\bar{q}$ is presented from data corresponding to the same integrated luminosity. Results are given for the first time for the ℓ_i and $\tilde{\ell}_i$ coeffcients using data from processes described by both on- and off-shell neutral vector boson production.

2 Selection of events

Events were recorded in the DELPHI detector. Detailed descriptions of the DELPHI components can be found in [9] and the description of its performance, as well as of the trigger system and of the luminosity monitor, can be found in [10].

2.1 $Z\gamma$ final state

Events with only a very energetic photon in the final state were searched for in the region covered by the HPC, the barrel electromagnetic calorimeter of DELPHI, in the range $45° < \theta_\gamma < 135°$ where θ_γ is the polar angle of the photon. The selection criteria and the data samples obtained at $\sqrt{s}$ from 189 to 202 GeV are described in [5]. Table 1 shows the results of the selection of events from the data collected in the year 2000.

The experimental signature of $Z\gamma$ events where the Z decays into jets of particles is an energetic and well isolated photon recoiling against a hadronic system. Events with this topology, and where the photon has an energy greater than 50 GeV and is produced in the region $45° < \theta_\gamma < 135°$, have been selected at energies ranging from 189 GeV to 208 GeV. For $\nu\bar{\nu}\gamma$ channel, the selection criteria and the results obtained at $\sqrt{s}$ ranging from 189 to 202 GeV are described in [5] while the results at higher energies are shown in table 1. The expected number of $q\bar{q}\gamma$ events has been calculated with PYTHIA relying on JETSET 7.4 [11] for quark fragmentation while the expected number of $\nu\bar{\nu}\gamma$ events has been computed with KORALZ [12].

The total numbers of observed (expected) events used in this note are 296 (298.8) and 1581 (1601.5) in the $\nu\bar{\nu}\gamma$ and $q\bar{q}\gamma$ channels, respectively.

Channel	$L(pb^{-1})$	$<\sqrt{s}>$	N_{DATA}	N_{MC}	efficiency(%)	purity(%)
$\nu\bar{\nu}\gamma$	214.6	206.1	98	102.3	51.0 ± 1.7	~ 100
$q\bar{q}\gamma$	218.8	205.9	507	515.1	77.0 ± 0.1	97.3 ± 0.2

Table 1: Results of the selection of $\nu\bar{\nu}\gamma$ and $q\bar{q}\gamma$ events collected in the year 2000.

2.2 ZZ final state

The same ZZ events selected by DELPHI to measure the ZZ cross-section are used here. A detailed description is reported in [8]. The measurement of the anomalous couplings has been done using all the visible channels except $\tau^+\tau^-q\bar{q}$, $\tau^+\tau^-\nu\bar{\nu}$ and $l^+l^-l^+l^-$.

The $ZZ \rightarrow \mathrm{q\bar{q}q\bar{q}}$ process represents 49% of the ZZ final states and produces four or more jets in the final state. After a four-jet preselection, in order to discriminate the ZZ signal from the large background from WW and $\mathrm{q\bar{q}}(\gamma)$ processes, a probability corresponding to ZZ production has been calculated. This probability is based on invariant mass information, on the b-tag probability per jet and on topological information.

The process $e^+e^- \rightarrow l^+l^-q\bar{q}$ has a branching ratio of $4.7\times 2\%$. High efficiency and high purity are attainable with a cut-based analysis thanks to the clear experimental signature given by the two leptons typically well isolated from all other particles.

The decay mode $\nu\bar{\nu}q\bar{q}$ represents 28% of the ZZ final states. The signature of this decay mode is a pair of rather acoplanar jets with visible and recoil masses compatible with the Z mass. The most difficult backgrounds arise from single resonant $We\nu_e$ processes, from WW processes where one of the W bosons decays into $\tau\nu_\tau$, and from $q\bar{q}$ events accompanied by energetic isolated photons escaping detection. The selection of events is done using a combined discriminant variable obtained with an Iterative Discriminant Analysis program (IDA) [13].

Finally the final state $l^+l^-\nu\bar{\nu}$ has a branching ratio of $2 \times 2.7\%$, and has been selected with a sequential cut-based analysis.

2.3 Jets and a pair of isolated leptons

In this section the signal is defined as $\mu^+\mu^-q\bar{q}$ events fulfilling the requirements described in [14]. The two final state leptons in the process $e^+e^- \rightarrow \mu^+\mu^-q\bar{q}$ are typically well isolated from all other particles. This property can be used to select such events with high efficiency. Events were selected without explicit cuts on the masses of the final state fermion pairs in order to select ZZ, $Z\gamma^*$ events.

The selection procedure used for the data collected at 188.6 GeV was applied without major changes up to centre-of-mass energies of 208 GeV. Its detailed description can be found in [15].

The numbers of events observed before and after the mass selection are shown in table 2.

Energy(GeV)	$\mu^+\mu^-q\bar{q}$		
	Data	Signal	Background
182.7	10	3.9 ± 0.1	0.21 ± 0.04
188.6	14	13.3 ± 0.2	0.9 ± 0.1
191.6-201.6	16	21.1 ± 0.2	1.1 ± 0.1
204-208	24	21.3 ± 0.2	1.2 ± 0.1

Table 2: The predicted numbers of signal and background events and the observed numbers of events in the $\mu^+\mu^-q\bar{q}$ channel at centre-of-mass energies from 182.7-208 GeV. The errors quoted are from simulation statistics.

3 Results on anomalous on-shell couplings

Values of the neutral triple gauge boson coupling parameters h_i^V ($V = Z/\gamma, i = 1, 2, 3, 4$), were derived from the data in the channel $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ by comparing the observed number of events with the number predicted from the total cross-section for this process, and in the channel $e^+e^- \rightarrow q\bar{q}\gamma$ by comparing the observed distribution of the decay angle $\alpha^\star$ of the Z in its rest frame with predictions derived from the differential distribution $d\sigma/d\cos\alpha^\star$. The definition and reconstruction of $\alpha^\star$ are described in [5] and its distribution for the full data sample collected between 1998 and 2000 is compared to Standard Model expectations, in figure 2. The same figure shows the expected distributions for $h_3^\gamma = \pm 0.2$ obtained by reweighting [16] events generated under the Standard Model hypothesis with the inclusion of the full detector simulation.

The results of the fit of each h_i^V coupling are shown in table 3. These results have been obtained by combining the likelihoods for both $q\bar{q}\gamma$ and $\nu\bar{\nu}\gamma$ channels and for the different centre-of-mass energies. In the fit to each coupling parameter, the value of the others were put to zero, their Standard Model value. Figure 3 shows the combined likelihoods.

In performing 2-parameter fits to the couplings, a total of 28 combinations $(h_i^V, h_{i'}^{V'})$ are possible for the 8 couplings considered. Despite this large number of pairs, there are essentially only three situations that are conceptually different and they are described in [5]; they correspond to different regimes of interference between the two anomalous terms and the Standard Model term in the production amplitude. The unexcluded regions at the 95% and 68% of confidence level are shown in figure 4 for the pairs (h_1^Z, h_2^Z), (h_3^Z, h_4^Z), (h_1^γ, h_2^γ) and (h_3^γ, h_4^γ), in the upper part of figure 5 for the pairs (h_3^Z, h_3^γ) (h_4^Z, h_4^γ), and in the lower part of figure 5 for the pairs (h_1^Z, h_1^γ) (h_2^Z, h_2^γ), corresponding to examples of the three different situations.

Several sources of systematic effects have been studied for data at $\sqrt{s}$ ranging from 189 to 202 GeV [5]. They have not yet been evaluated for data collected in 2000, but their effect is expected to be similar to that estimated at lower energies: $\Delta h^{syst}/\Delta h^{stat} \sim 40\%$ for couplings $h_1^Z, h_2^Z, h_3^Z, h_4^Z, h_1^\gamma$ and h_2^γ, and $\Delta h^{syst}/\Delta h^{stat} \sim 100\%$ for h_3^γ and h_4^γ.

The neutral triple gauge boson coupling parameters f_i^V $(V = Z/\gamma, i = 4, 5)$, have been measured by means of an extended maximum likelihood fit of the Z production angle $(\cos\theta_Z)$ distribution for the channels selected with cut-based analyses ($q\bar{q}l^+l^-$ and $l^+l^-\nu\bar{\nu}$). For $q\bar{q}q\bar{q}$ ($q\bar{q}\nu\bar{\nu}$) channels, in order to benefit from the performance of the analysis to distinguish the signal from the large background, the $\cos\theta_Z$ distribution has been fitted simultaneously to the ZZ probability (IDA output variable) distribution. The reconstruction of θ_Z is free from ambiguity for all channels, except for $q\bar{q}q\bar{q}$ where the indistinguibility of the jets leads to wrong pairing. The combination with the minimum value of the χ^2 obtained on application to the event of a 4C kinematic fit has been retained.

Figure 2 shows the $\cos\theta_Z$ distributions for the full data sample and the Standard Model expectations. For illustrative purposes, only $q\bar{q}q\bar{q}$ and $q\bar{q}\nu\bar{\nu}$ candidates in a high purity region are shown.

Using the information of the Z production angle differential cross-section improves the sensitivity with respect to the analysis described in [7]. Also the correct dependence of the efficiency and purity on the anomalous couplings has been taken into account in this updated analysis. It was obtained by reweighting [16] events generated within the Standard Model hypothesis, including all the detector effects. Figure 2 shows the distributions obtained with this technique for $f_5^Z = \pm 1.5$.

The preliminary results of the single parameter fit of f_i^V couplings, obtained combining all channels and energies, are shown in table 3. The corresponding likelihoods are reported in figure 6, together with the unexcluded regions for 2-parameter fits for pairs (f_4^Z, f_4^γ) and (f_5^Z, f_5^γ). Systematic effects are expected from both experimental and theoretical sources but they have not yet been evaluated.

4 Experimental results on off-shell anomalous couplings

The complete set of off-shell neutral couplings is implemented in the framework of the DELTGC package [6], which provides general 4-fermion and $\gamma f\bar{f}$ final state calculations

Vertex	Coup.	68% C.L.	95% C.L.
ZZZ	f_4^Z	$-0.13^{+0.33}_{-0.21}$	$[-0.49, +0.42]$
	f_5^Z	$+0.11^{+0.29}_{-0.28}$	$[-0.42, +0.69]$
$ZZ\gamma$	f_4^γ	$+0.05^{+0.14}_{-0.20}$	$[-0.26, +0.28]$
	f_5^γ	$+0.15^{+0.27}_{-0.38}$	$[-0.49, +0.61]$
	h_1^Z	$+0.10^{+0.09}_{-0.26}$	$[-0.24, 0.24]$
	h_2^Z	$-0.07^{+0.17}_{-0.05}$	$[-0.14, 0.14]$
	h_3^Z	$-0.18^{+0.28}_{-0.08}$	$[-0.32, 0.17]$
	h_4^Z	$+0.10^{+0.04}_{-0.17}$	$[-0.11, 0.18]$
$Z\gamma\gamma$	h_1^γ	$+0.05^{+0.05}_{-0.16}$	$[-0.14, 0.14]$
	h_2^γ	$+0.037^{+0.031}_{-0.103}$	$[-0.086, 0.087]$
	h_3^γ	$+0.003^{+0.015}_{-0.017}$	$[-0.030, 0.034]$
	h_4^γ	$-0.003^{+0.011}_{-0.010}$	$[-0.023, 0.018]$

Table 3: Preliminary results of fits of the neutral trilinear gauge coupling parameters f_i^V and h_i^V at the 68% and 95% confidence intervals. In the fit to each coupling parameter, the other couplings were set to their Standard Model value. The errors shown are statistical only.

with a special emphasis on the anomalous charged and neutral couplings in the gauge boson sector. DELTGC deals with a complete set of Feynman diagrams including those with neutral triple gauge boson vertices.

If only one coupling parameter ℓ is taken to be different from zero at a time, any corresponding effect on a given quantity $\mathcal{A}$ (squared matrix element, cross-section) will depend on ℓ as a parabola,

$$\mathcal{A}_\ell = \mathcal{A}(\text{SM}) + \ell \cdot \mathcal{A}(\text{interference}) + \ell^2 \cdot \mathcal{A}(\text{TGC}).$$

The four-fermion final state $\mu^+\mu^- q\bar{q}$ has been used to derive limits on the off-shell neutral triple gauge coupling parameters ℓ_i and $\tilde{\ell}_i$ related to the lowest dimension operators described in section 1. No mass cut has been applied to $\mu^+\mu^- q\bar{q}$ data samples used in the present work. The "on-shell" ZZ region defined in the on-shell analysis is included as well, since the whole spectra of both Z and photon have been considered.

Events in the $\mu^+\mu^- q\bar{q}$ channel were generated with EXCALIBUR [17], passed through the detector simulation [18], and reweighted for the presence of each anomalous coupling using DELTGC. The maximum likelihood values were computed by comparison with the observed distribution in the $[m_{(q\bar{q})}, m_{(\mu^-\mu^+)}]$ plane. The likelihood curves are shown as functions of the coupling parameters in figures 7 and 8.

The method was checked by applying the same procedure to 100 independent $\mu^+\mu^- q\bar{q}$ EXCALIBUR samples of the same size as that expected from the integrated luminosity of real data, generated with Standard Model values of the couplings. For each sample the difference between the value of each coupling parameter at the minimum of the likelihood distribution and its Standard Model value was computed. The corresponding distribu-

coefficient GeV^{-2}	operator	95% C.L.	Related on-shell coefficient
$\ell_1^{Z^*Z^*Z^*}$	$\tilde{Z}_{\mu\nu}(\partial_\sigma Z^{\sigma\mu})Z^\nu$	$[-3.0 \cdot 10^{-4}, 2.8 \cdot 10^{-4}]$	f_5^Z
$\tilde{\ell}_1^{Z^*Z^*Z^*}$	$-Z_\sigma(\partial^\sigma Z_\nu)(\partial_\mu Z^{\mu\nu})$	$[-1.5 \cdot 10^{-4}, 1.5 \cdot 10^{-4}]$	f_4^Z
$\ell_1^{Z^*Z^*\gamma^*}$	$-\tilde{F}_{\mu\nu}Z^\nu(\partial_\sigma Z^{\sigma\mu})$	$[-1.5 \cdot 10^{-4}, 1.4 \cdot 10^{-4}]$	h_3^Z
$\ell_2^{Z^*Z^*\gamma^*}$	$\tilde{Z}^{\mu\nu}Z_\nu(\partial^\sigma F_{\sigma\mu})$	$[-1.9 \cdot 10^{-4}, 1.9 \cdot 10^{-4}]$	f_5^γ
$\tilde{\ell}_1^{Z^*Z^*\gamma^*}$	$-F^{\mu\beta}Z_\beta(\partial^\sigma Z_{\sigma\mu})$	$[-1.3 \cdot 10^{-4}, 1.25 \cdot 10^{-4}]$	h_1^Z
$\tilde{\ell}_3^{Z^*Z^*\gamma^*}$	$-(\partial_\mu F^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta)$	$[-0.95 \cdot 10^{-4}, 0.93 \cdot 10^{-4}]$	f_4^γ
$\ell_1^{\gamma^*\gamma^*Z^*}$	$-\tilde{F}_{\rho\alpha}(\partial_\sigma F^{\sigma\rho})Z^\alpha$	$[-1.1 \cdot 10^{-4}, 0.9 \cdot 10^{-4}]$	h_3^γ
$\tilde{\ell}_1^{\gamma^*\gamma^*Z^*}$	$-(\partial^\sigma F_{\sigma\mu})Z_\beta F^{\mu\beta}$	$[-1.1 \cdot 10^{-4}, 1.1 \cdot 10^{-4}]$	h_1^γ

Table 4: 95% CL upper limits on off-shell NTGC coefficients. The coefficient and the related operators are described in the main text. In the last column the related on-shell coefficient is indicated. As described in the text, if only one ℓ taken to be different from zero at a time, the relation between the on-shell and off-shell coefficients is of the form $h, f = m_Z^2 \ell$.

tions were found to be as expected for samples without any contribution from anomalous couplings.

In table 4 the 95% CL limits obtained from the data are listed. The first column lists the coefficients, the second column shows the operators corresponding to the coefficients, and in the third column the preliminary limits are presented. In the last column the related on-shell coefficient is indicated. As indicated in section 1, with the approximation of only one ℓ taken to be different from zero at a time, the relation between the on-shell parameters h, f and the lowest dimension off-shell coefficients is of the form $h, f = m_Z^2 \ell$. The results show no deviations from the predictions of the Standard Model.

5 Conclusions

The neutral triple gauge boson coupling parameters h_i^V (i =1,4, $V = \gamma/Z$) and f_i^V (i =4,5, $V = \gamma/Z$), have been measured studying the production of two on-shell neutral gauge bosons ($Z\gamma$, ZZ).

In addition, fits to neutral gauge coupling parameters from off-shell four-fermion final states have been presented for the first time, and provide a new test of the predictions of the Standard Model in the gauge boson sector. In future work, other four-fermion channels will be included in the analysis and results from on- and off-shell data combined according to the formalism used in this paper.

No deviation from the expectations of the Standard Model is found in any of the results reported.

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$DELPHI \quad (PRELIMINARY)$

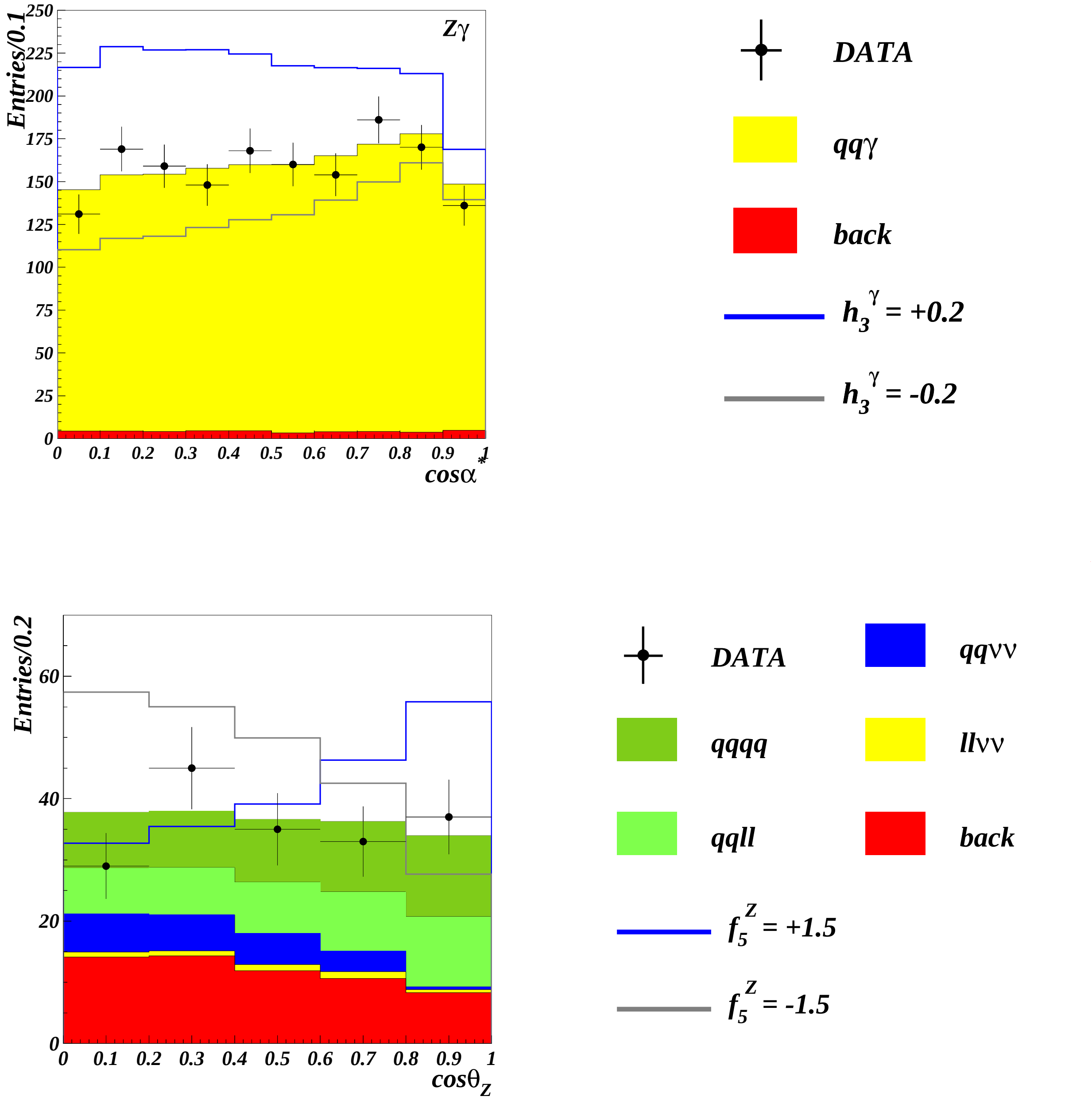

Figure 2: Upper plot: distribution of the decay angle of the Z in its rest frame in hadronic $Z\gamma$ events. Lower plot: distribution of the Z polar angle in ZZ events. In both cases, all the data selected at different centre-of-mass energies are included, except for $q\bar{q}q\bar{q}$ and $q\bar{q}\nu\bar{\nu}$ channels where only candidates in high purity region have been considered.

$$DELPHI \quad q\bar{q}\gamma + \nu\bar{\nu}\gamma \qquad (PRELIMINARY)$$

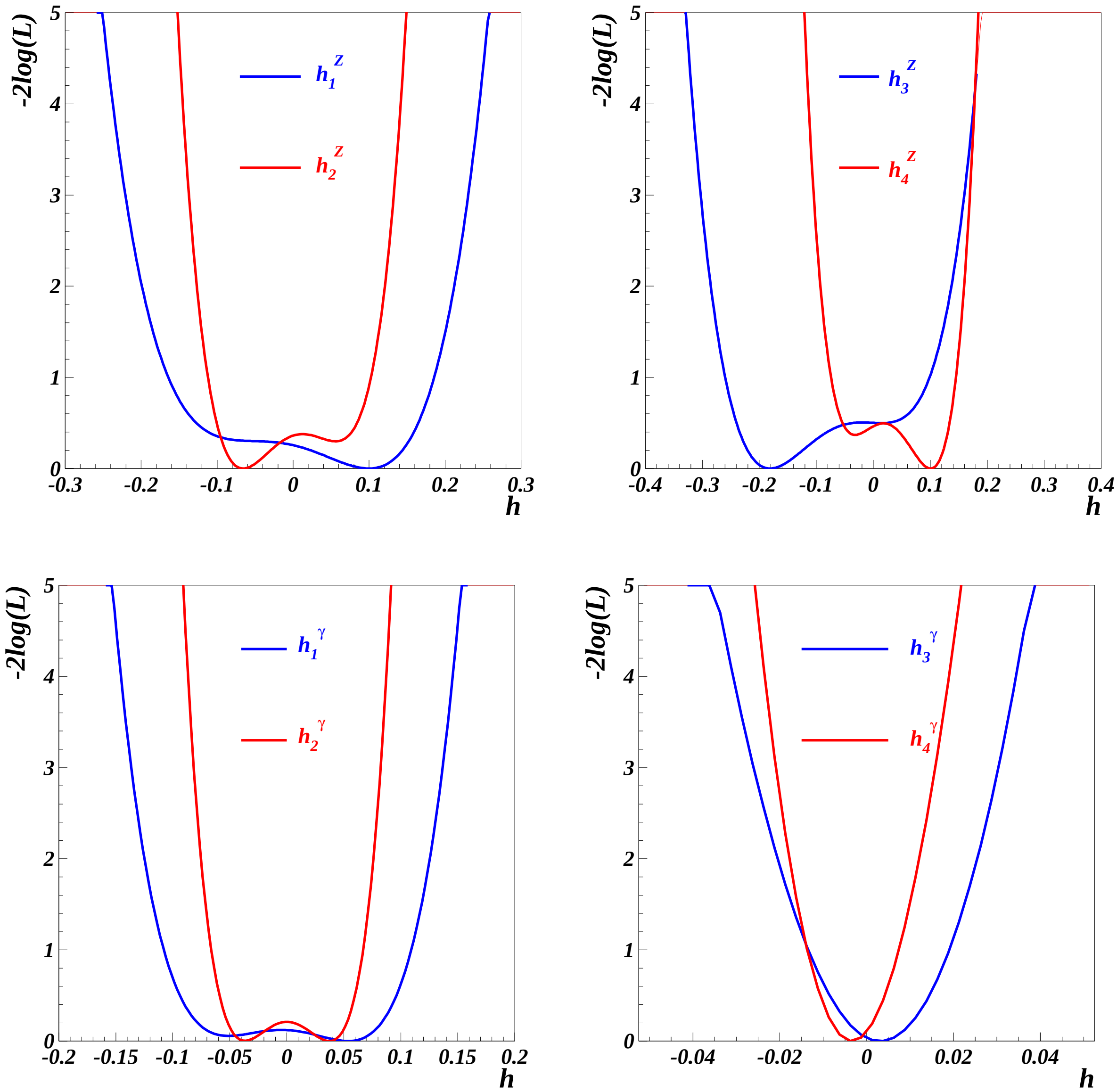

Figure 3: Likelihoods ($-2\log L$) obtained for the single parameter fits in the $e^+e^- \to \nu\bar{\nu}\gamma$ and $e^+e^- \to q\bar{q}\gamma$ channels. In the fits, the values of the other couplings were fixed to zero, their Standard Model values.

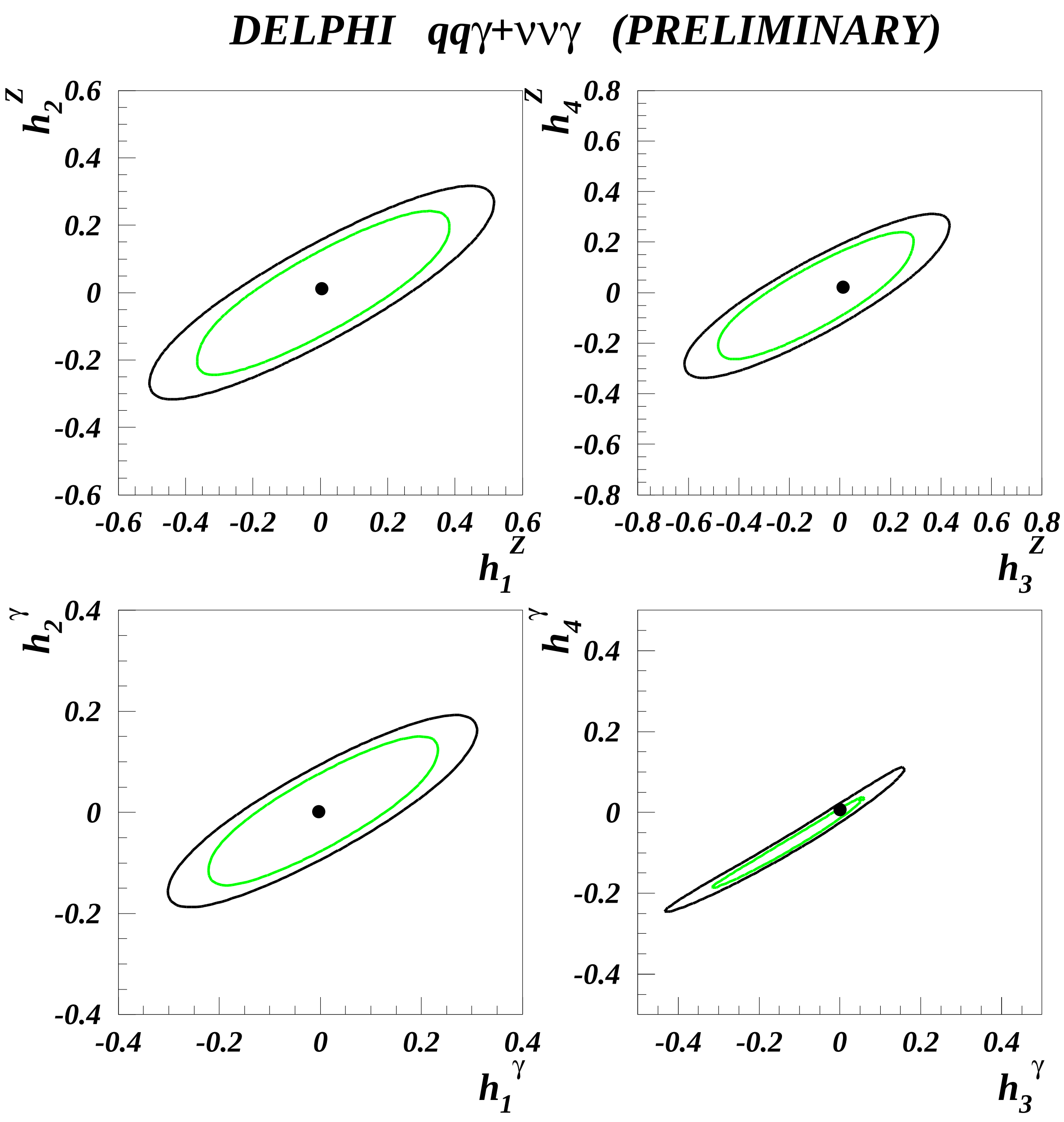

Figure 4: The regions accepted at the 95% (external contour) and at 68% confidence level (internal contour) for pairs of couplings whose amplitudes interfere strongly. The fits were made combining the measurements for $q\bar{q}\gamma$ and $\nu\bar{\nu}\gamma$ channels and for the different centre-of-mass energies. The points represent the Standard Model expectations for these couplings.

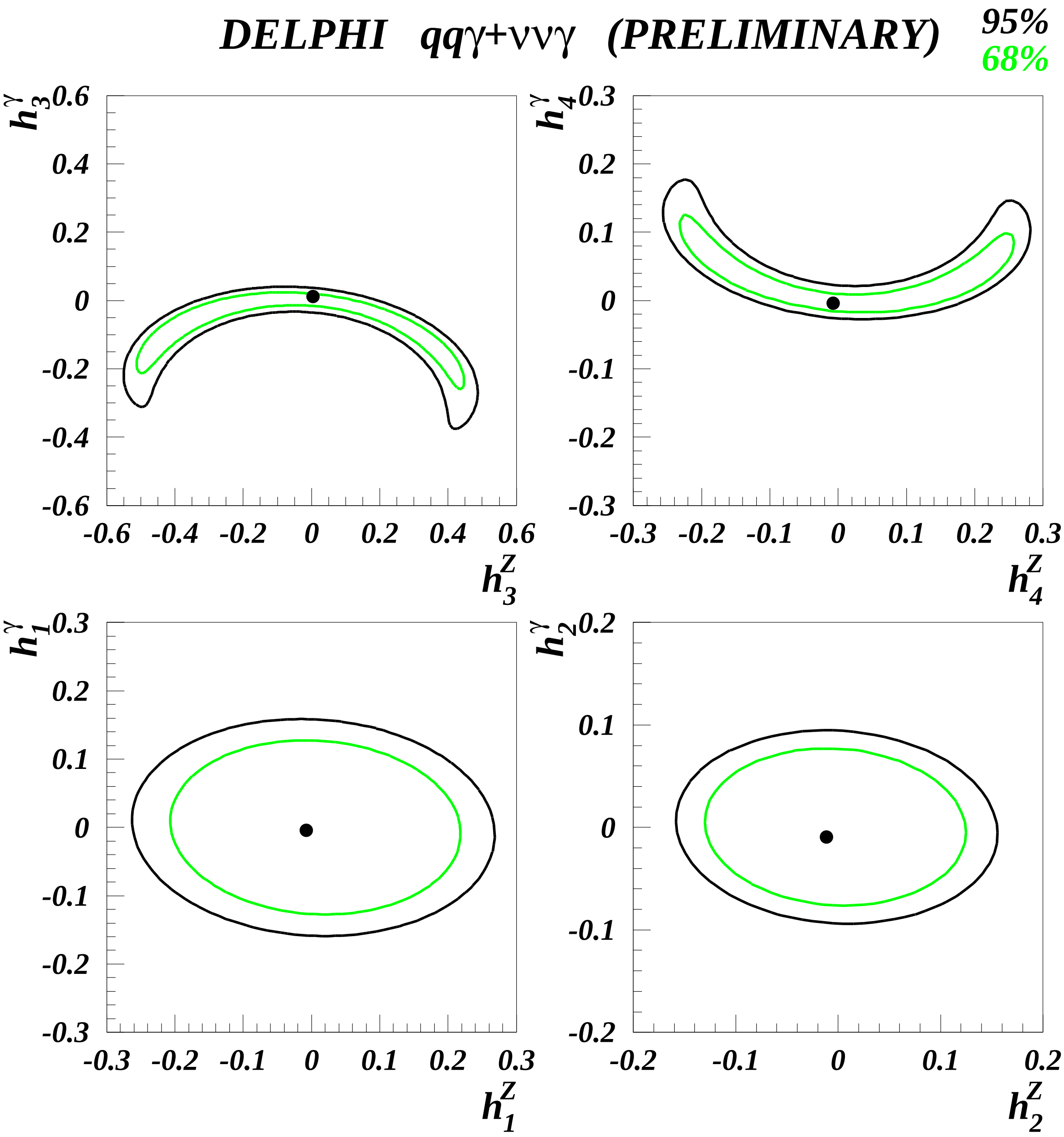

Figure 5: The regions accepted at the 95% (external contour) and at 68% confidence level (internal contour) for pairs of couplings (h_i^γ, h_i^Z). The fits were made combining the measurements for $q\bar{q}\gamma$ and $\nu\bar{\nu}\gamma$ channels and for the different centre-of-mass energies. The points represent the Standard Model expectations for these couplings.

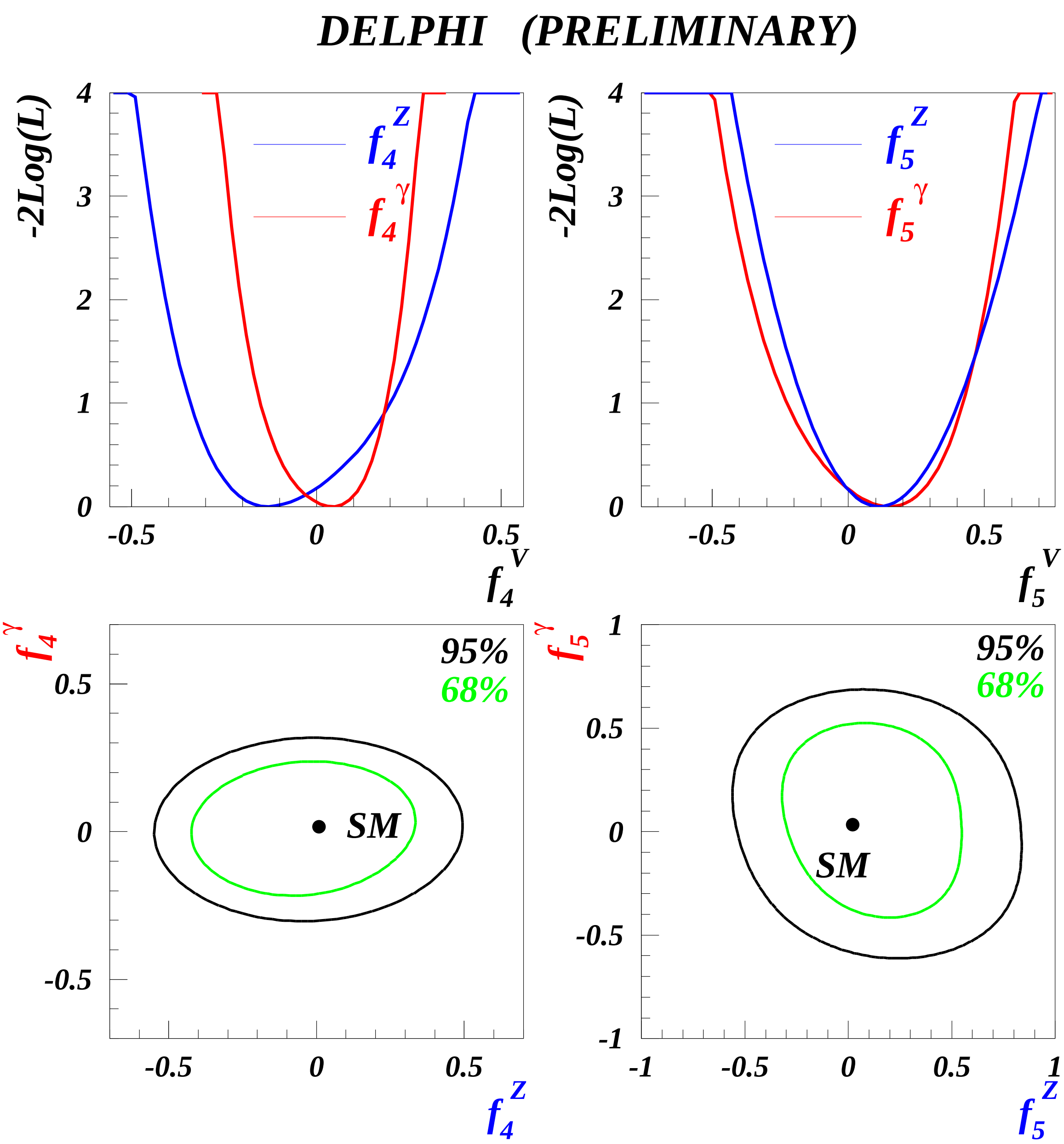

Figure 6: Upper figures show the likelihoods ($-2\log L$) obtained for the single parameter fits to the f_i^V couplings. Lower figures show the regions accepted at the 95% (external contour) and at 68% confidence level (internal contour) for pairs of couplings with the same CP behaviour. The likelihoods have been obtained combining the measurements performed in all channels at the different centre-of-mass energies.

DELPHI (PRELIMINARY)

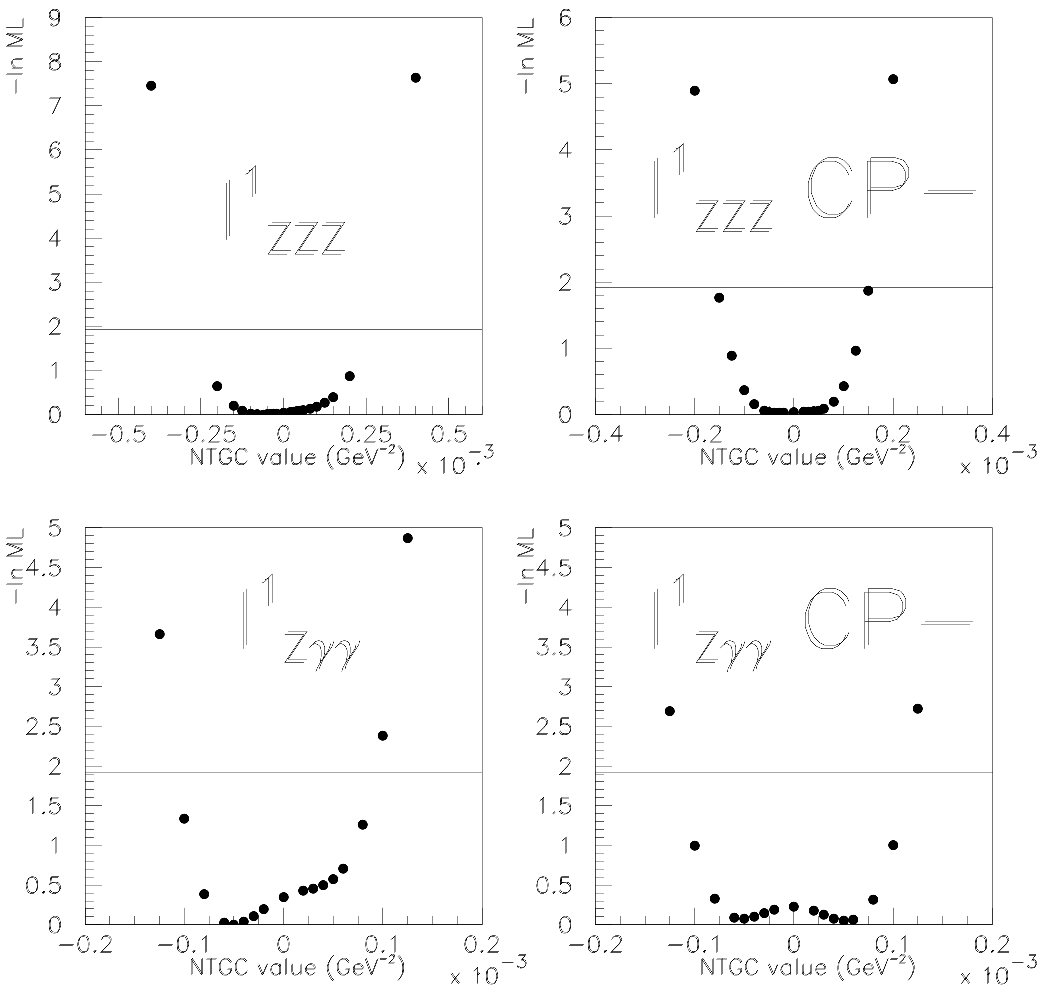

Figure 7: Preliminary results of Maximum Likelihood fits of off-shell neutral TGC coefficients $\ell_1^{Z^*Z^*Z^*}$, $\tilde{\ell}_1^{Z^*Z^*Z^*}$, $\ell_1^{Z^*\gamma^*\gamma^*}$, $\tilde{\ell}_1^{Z^*\gamma^*\gamma^*}$ to DELPHI data from the channels $e^+e^- \to \mu^+\mu^- q\bar{q}$ at energies between 184 and 208 GeV.

DELPHI (PRELIMINARY)

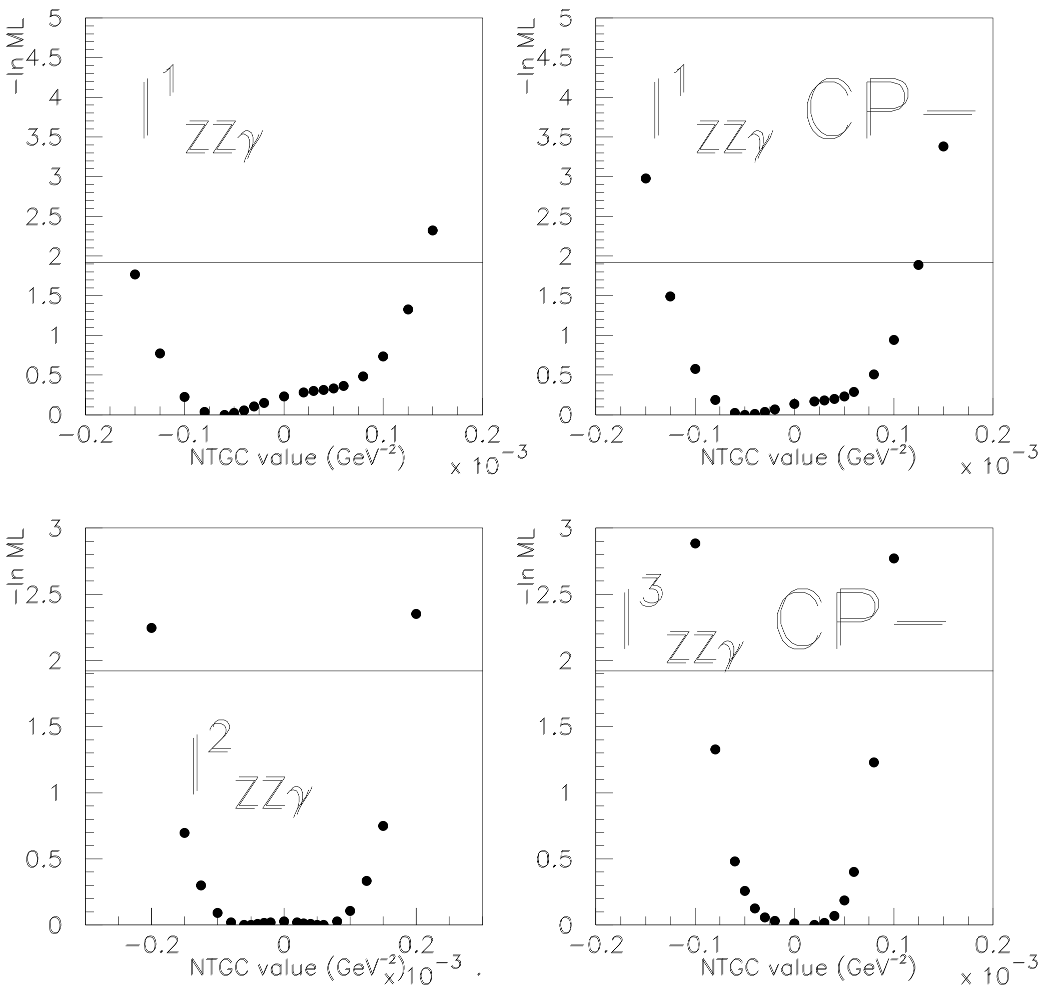

Figure 8: Preliminary results of Maximum Likelihood fits of off-shell neutral TGC coefficients $\ell_1^{Z^*Z^*\gamma^*}$, $\tilde{\ell}_1^{Z^*Z^*\gamma^*}$, $\ell_2^{Z^*Z^*\gamma^*}$, $\tilde{\ell}_3^{Z^*\gamma^*\gamma^*}$ to DELPHI data from the channels $e^+e^- \rightarrow \mu^+\mu^- q\bar{q}$ at energies between 184 and 208 GeV.