Measurement of Charged Current Triple Gauge Boson Couplings

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- ☞ Definition of TGC's
- ☞ The new $\mathcal{O}(\alpha)$ Monte Carlo generators
- ☞ Measurement of TGC's from WW production
- ☞ Spin density matrix and W polarisation
- ☞ TGC's from single W and single γ
- ☞ Results, conclusions and outlook

Definition of TGC's

The most general Lorentz invariant Lagrangian of the type WWV (V either Z or γ):

$$i\mathcal{L}_{eff}^{\mathrm{WWV}} = g_{WWV}\Bigg[\overset{C,P}{g_1^V} V^\mu\left(W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}\right) + \overset{C,P}{\kappa_V} W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\overset{C,P}{\lambda_V}}{m_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu}$$

$$+ i\,\overset{\cancel{C},P}{g_4^V} W^+_\mu W^-_\nu\left(\partial^\mu V^\nu + \partial^\nu V^\mu\right) + i\,\overset{CP,\cancel{C},\cancel{P}}{g_5^V}\,\varepsilon_{\mu\nu\rho\sigma}\left((\partial^\rho W^{-\mu})W^{+\nu} - W^{-\mu}(\partial^\rho W^{+\nu})\right)V^\sigma$$

$$-\frac{\overset{C,\cancel{P}}{\tilde{\kappa}_V}}{2} W^-_\mu W^+_\nu \varepsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \frac{\overset{C,\cancel{P}}{\tilde{\lambda}_V}}{2m_W^2} W^-_{\rho\mu} W^{+\mu}_\nu \varepsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}\Bigg]$$

A total of 14 couplings

In the Standard Model:

$g_{WW\gamma} = e$
$g_{WWZ} = e\cot\theta_W$
$g_1^Z = g_1^\gamma = 1$
$\kappa_Z = \kappa_\gamma = 1$
all others $= 0$

Define deviations from SM:

$$\Delta g_1^Z \equiv g_1^Z - 1$$
$$\Delta\kappa_\gamma \equiv \kappa_\gamma - 1$$
$$\Delta\kappa_Z \equiv \kappa_Z - 1$$

Definition of TGC's

C and P conserving couplings:

$\Delta g_1^Z, \Delta\kappa_\gamma, \Delta\kappa_Z, \lambda_\gamma, \lambda_Z$

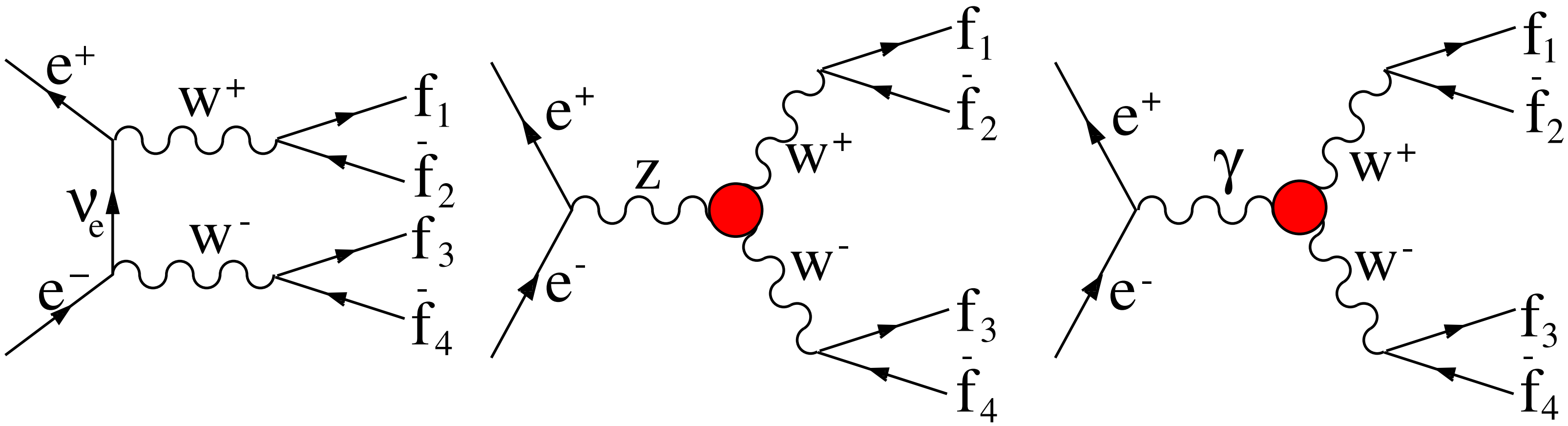
low energy constraints and gauge invariance:

$$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W$$
$$\lambda_Z = \lambda_\gamma$$

Gauge constraints on CP violating couplings:

$$\tilde{\kappa}_Z = -\tan^2\theta_W \tilde{\kappa}_\gamma$$
$$\tilde{\lambda}_Z = \tilde{\lambda}_\gamma$$
$$g_4^Z = g_4^\gamma$$

W-pair production:

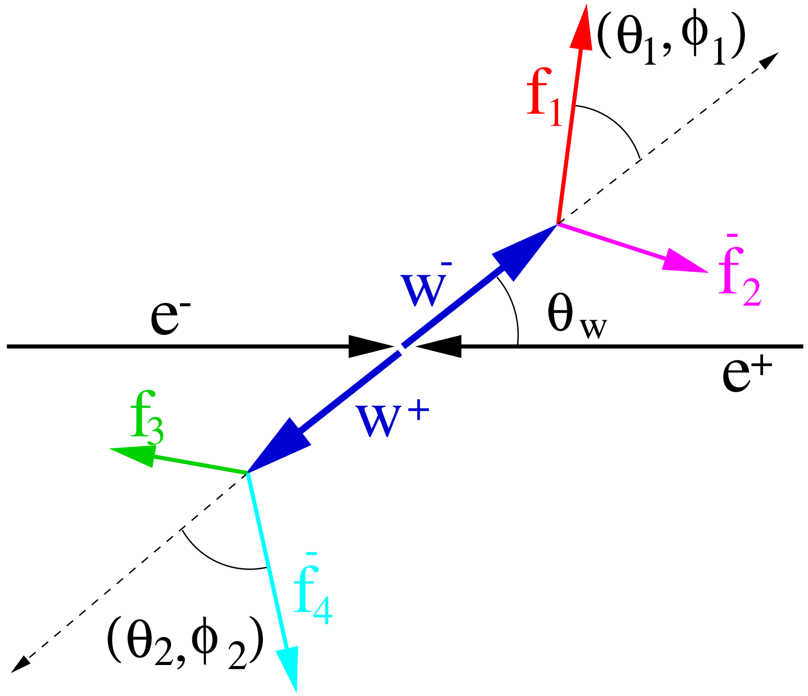


Effects of Anomalous Couplings

Anomalous Couplings affect polarization, production angles and σ_{WW}.

WW event described with
5 variables:

- $\cos\theta_{W^-}$ polar angle of the W^-
- $\cos\theta_1$, ϕ_1 angles of the fermion in W^- rest frame
- $\cos\theta_2$, ϕ_2 angles of antifermion in the W^+ rest frame



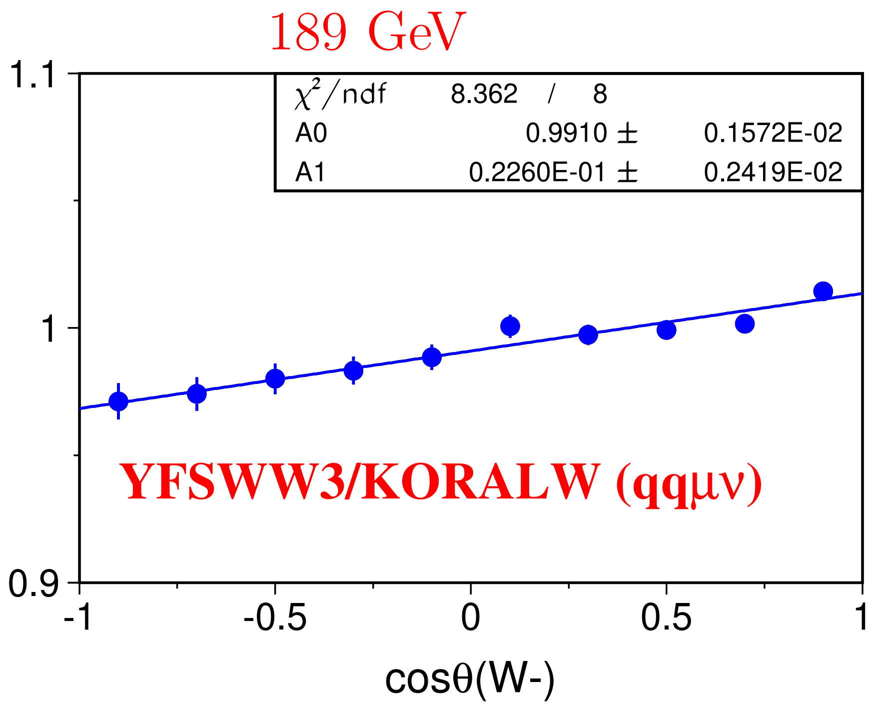
MC description of WW production

- high accuracy of W physics at LEP $\rightarrow$ theoretical effort to improve description of WW production
- new MC generators available (YFSWW3, RacoonWW): $\mathcal{O}(\alpha)$ description of WW production in Double Pole Approximation (DPA).

$\mathcal{O}(\alpha)$ generators for WW production

With respect to old generators (KoralW), $\mathcal{O}(\alpha)$ MCs predict:

- $\sim$2.5% lower σ_{WW}
- sizeable ($\sim$ 2%) change in the slope of the $\cos\theta_{W^-}$ distribution



- implementation/testing of new generators not trivial $\Rightarrow$ LEP experiments are working on it
- use new generators as suggested by authors; KoralW$\oplus$YFSWW3 or latest version of RacoonWW
- not clear how to evaluate systematics due to higher order corrections on differential cross sections

TGC measurement at LEP

Status of TGC measurement from WW data at LEP:

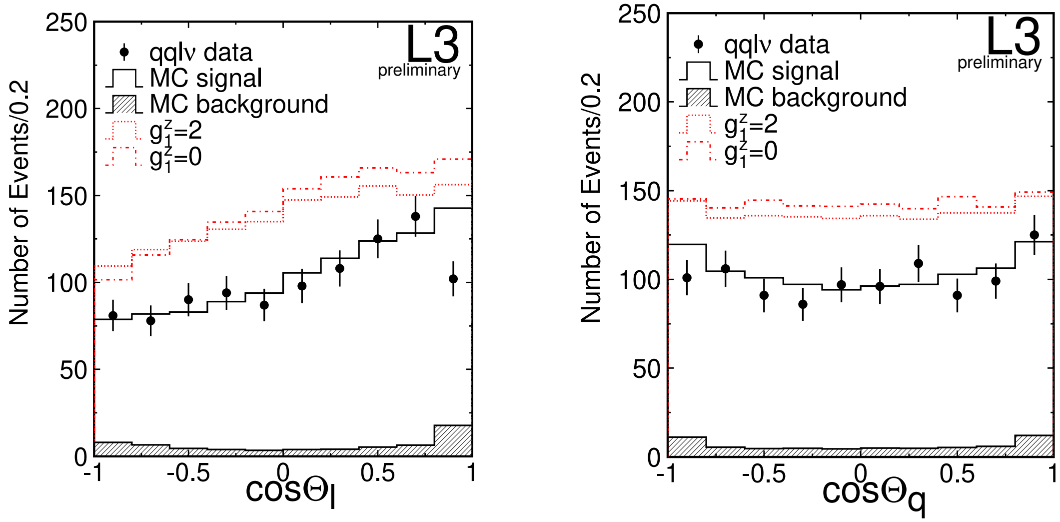
- only ALEPH has preliminary results based on implementation of $\mathcal{O}(\alpha)$ corrections via reweighting of KoralW events
- all other experiments don't have any new results but are testing/using KoralW$\oplus$YFSWW3
- no LEP combination of charged TGC's since last summer...

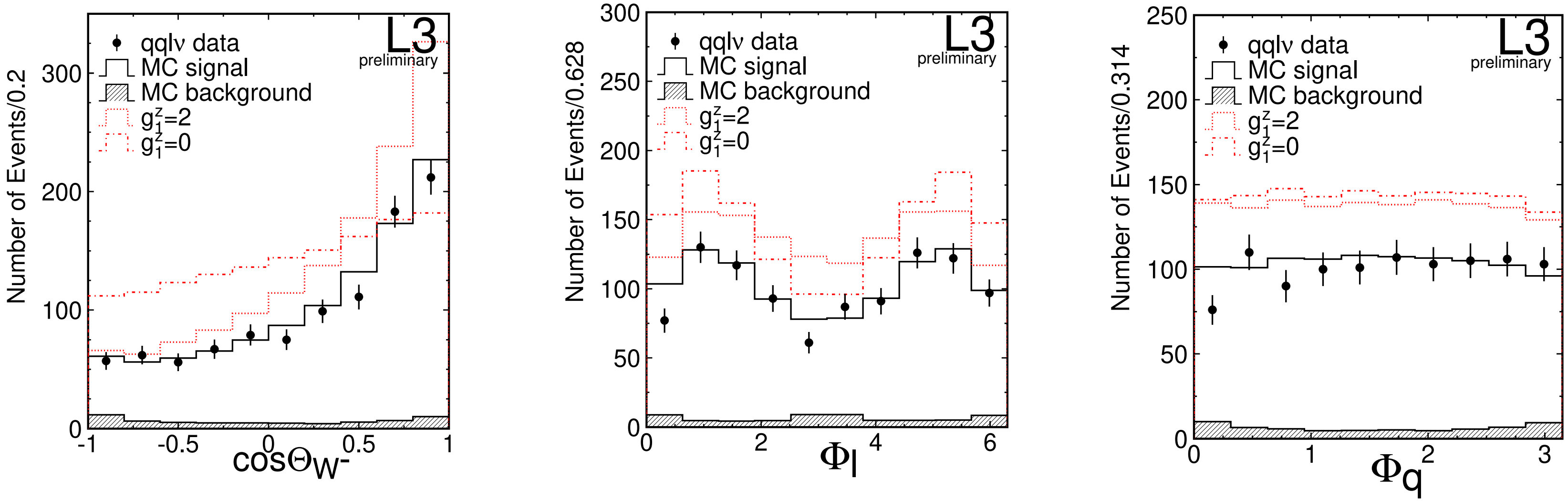
Different strategies used to extract the couplings:

1. Fit the multidimensional distribution of the phase-space angles (or some subspace) $\rightarrow$ALEPH, L3
2. Project all information in new variables (Optimal Observables) $\rightarrow$ALEPH, DELPHI, L3, OPAL
3. Reconstruct the Spin Density Matrix (SDM) and fit its elements $\rightarrow$(DELPHI), OPAL

Multidimensional phase-space fit (L3 analysis)

- perform a Binned Maximum Likelihood fit in the 5D phase space
- ambiguity due to unknown quark flavour ⇒ “fold” the corresponding distributions
- shown here: semileptonic WW at 189 GeV

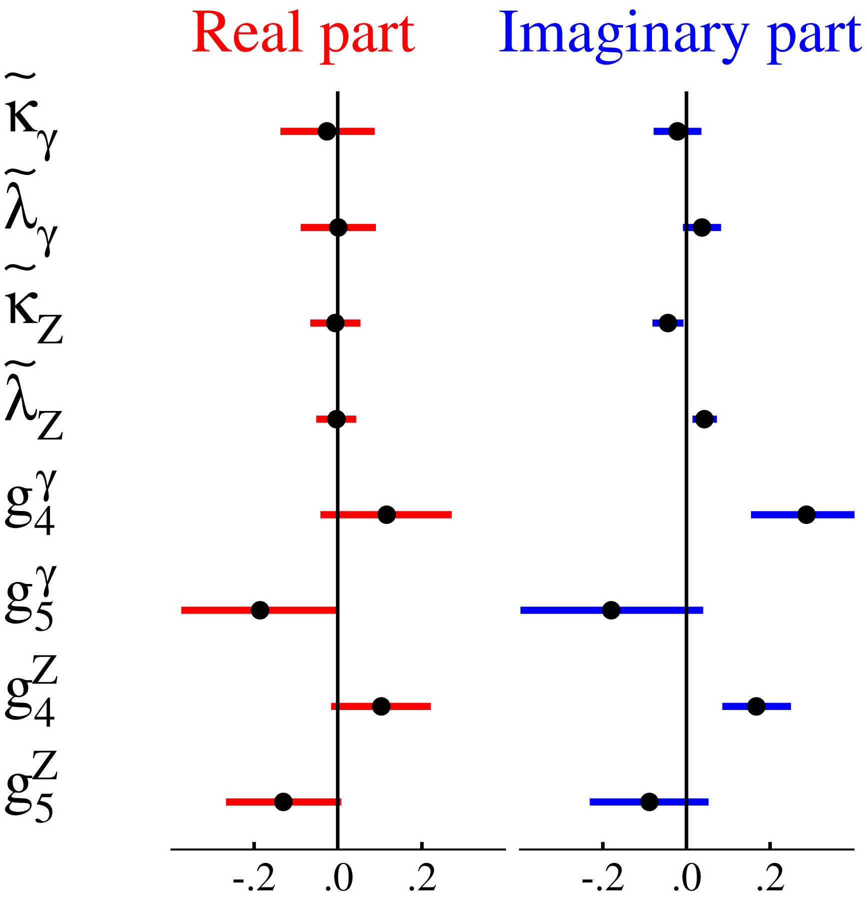




Multidimensional phase-space fit (ALEPH analysis)

Measure real and imaginary part of CP violating couplings

- Unbinned Maximum Likelihood fit
- probability density functions obtained convoluting analytic differential cross section with detector resolution and efficiency and ISR function
- results based on 183-208 GeV WW data



Good agreement with SM expectation

Optimal Observables

$\frac{d\sigma(\alpha)}{d\Omega} = c_0(\Omega) + \sum_i c_1^i(\Omega)\alpha_i + \sum_{i\leq j} c_2^{ij}(\Omega)\alpha_i\alpha_j$; Ω = phase-space variables

Define Optimal Observables (OO):

$$\mathcal{O}_i^1 = \frac{c_1^i(\Omega)}{c_0(\Omega)}$$
$$\mathcal{O}_{ij}^2 = \frac{c_2^{ij}(\Omega)}{c_0(\Omega)}$$

Optimal Observables contain same information as phase-space angles
but: more couplings $\rightarrow$ need more variables

Small α $\rightarrow$ approximations:

- neglect second order OO's
- assume that all information is contained in the Mean of OO

To treat the general case (couplings not zero):

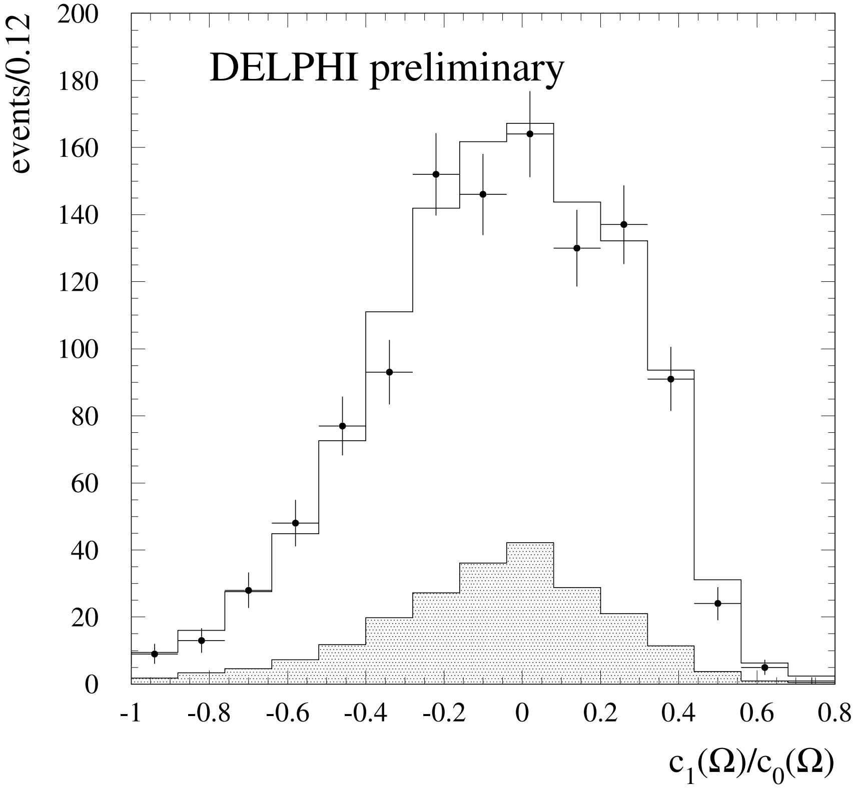
- iterative procedure
- relax the approximations:
  - fit OO distributions (not just mean values)
  - include second order terms

Optimal Observables: iterative method

DELPHI analysis of qqqq channel, 2-parameter fits

- Perform a 2D fit of the distribution of the two first order Optimal Observables of two couplings α_1 and α_2.
- Repeat the procedure each time expanding differential cross section about the values of (α_1, α_2) obtained in the previous iteration.

OO[1] for Δg_1^Z from qqqq at 189 GeV



Mean Optimal Observables, OO1+OO2

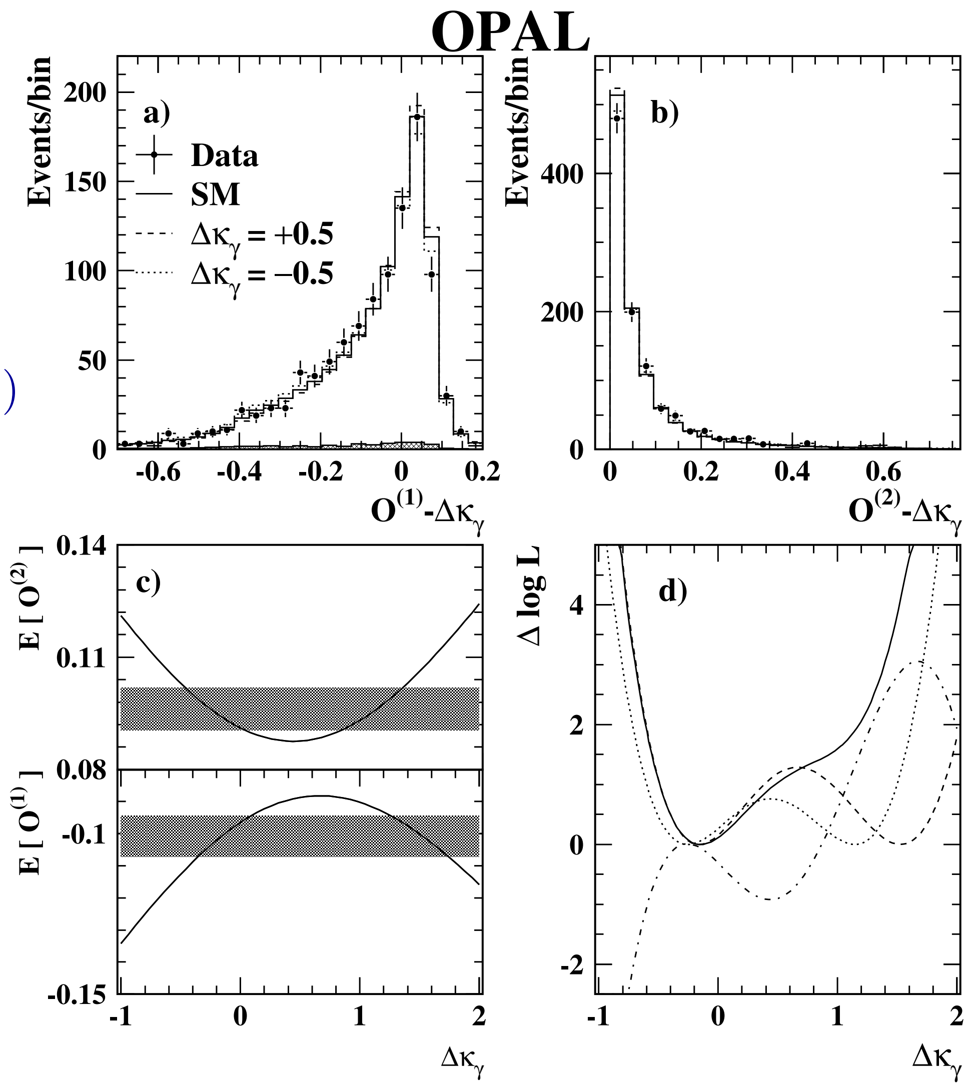
Minimise:

$$\chi^2(\alpha) = \sum_{ij} \left(\langle \mathcal{O}_i \rangle - E[\mathcal{O}_i]\right) V_{ij}^{-1} \left(\langle \mathcal{O}_j \rangle - E[\mathcal{O}_j]\right)$$

where:

$\langle \mathcal{O}_i \rangle \longrightarrow$ measured mean OO
$E[\mathcal{O}_i] \longrightarrow$ expected mean OO
$V_{ij} \longrightarrow$ covariance matrix

plot: $qq\ell\nu$, $\sqrt{s} = 189$ GeV



Spin Density Matrix (DELPHI, OPAL)

Spin Density Matrix: $$\rho_{\tau_-\tau'_-\tau_+\tau'_+}(s,\cos\theta_W) = \frac{\sum_\lambda F^\lambda_{\tau_-\tau_+}\left(F^\lambda_{\tau'_-\tau'_+}\right)^*}{\sum_{\lambda\tau_-\tau_+}\left|F^\lambda_{\tau_-\tau_+}\right|^2}$$

$F^\lambda_{\tau_-\tau_+} \rightarrow$ amplitude for producing a W^+ and W^- with helicity τ^+ and τ^- when e^- has helicity λ.

80 independent real coefficients to determine...

Useful (and easier) to consider the single particle density matrix:

$$\rho^{W^-}_{\tau_-\tau'_-}(s,\cos\theta_W) = \sum_{\tau_+}\rho_{\tau_-\tau'_-\tau_+\tau_+}(s,\cos\theta_W)$$

- CP + CPT $\Rightarrow$ all elements of $\rho^W_{\tau_1\tau_2}$ are real
- imaginary parts are sensitive to the CP-violating couplings
- SDM elements obtained from differential cross sections in $\cos\theta_W$, $\cos\theta^*$ and ϕ^* by application of projection operators

Spin Density Matrix and CP violating couplings

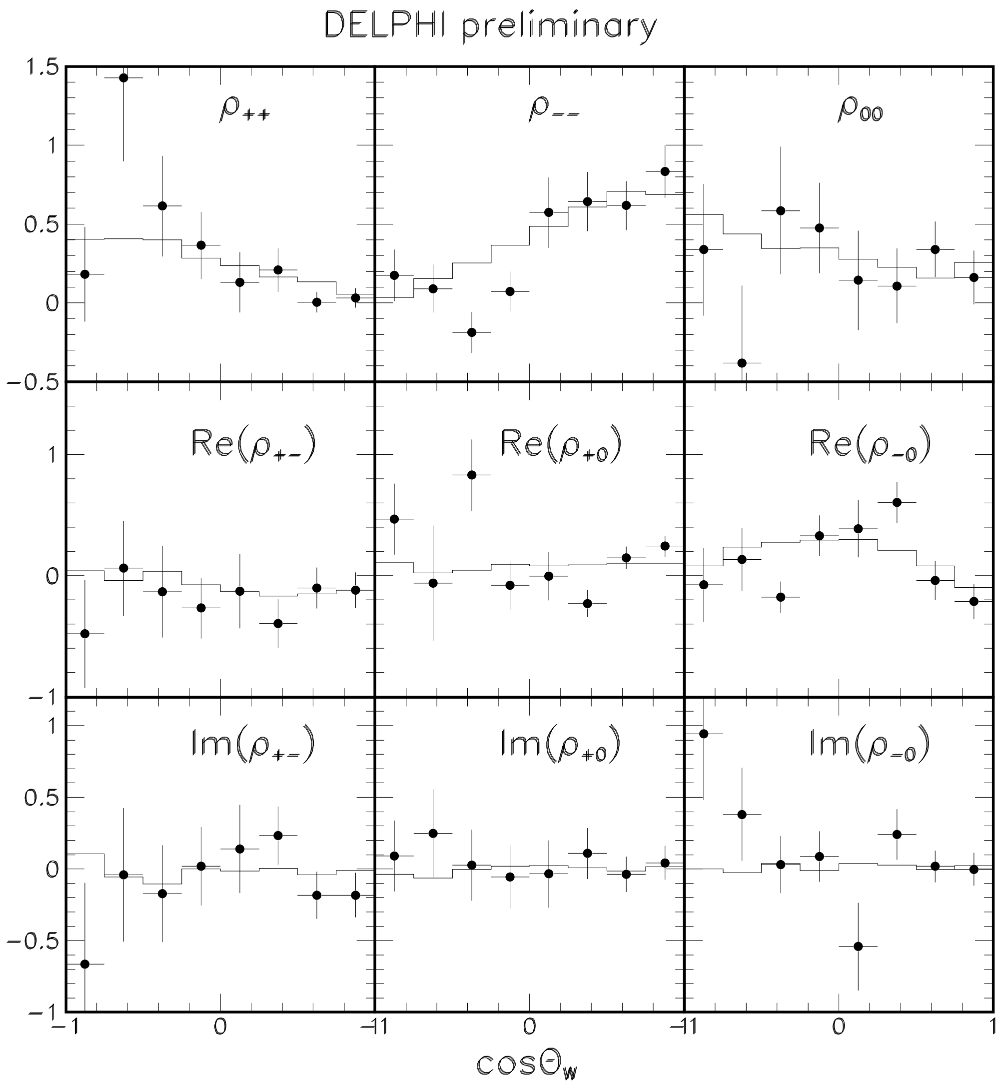
SDM elements are TGC dependent:
from 189 GeV data, imposing gauge constraints, OPAL gets:

$$\tilde{\kappa}_Z = -0.20^{+0.10}_{-0.07}$$

$$g_4^Z = -0.02^{+0.32}_{-0.33}$$

$$\tilde{\lambda}_Z = -0.18^{+0.24}_{-0.16}$$

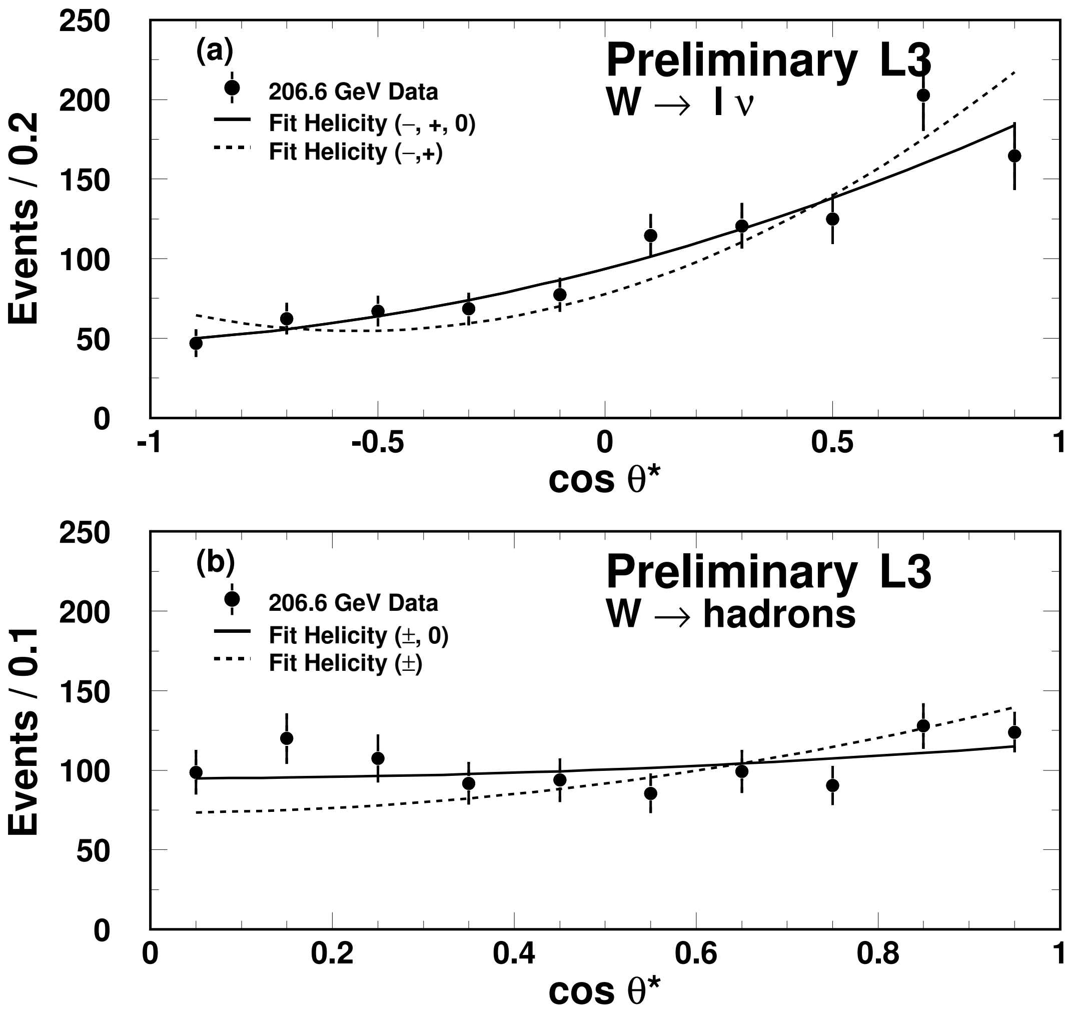
including statistical and systematic errors.



W polarisation: helicity fractions (L3)

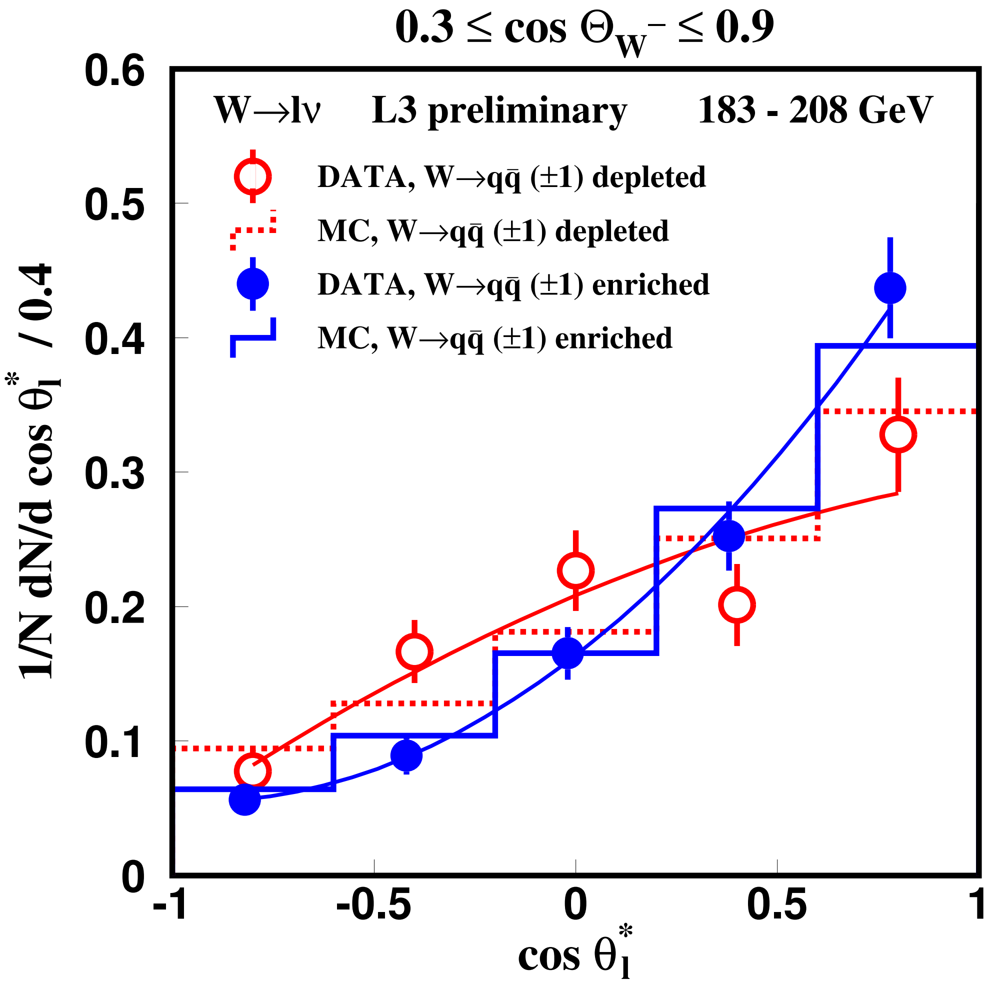
- Direct observation of longitudinally polarized W bosons
- $W^{\pm}$ helicity states $(+\ ,\ -\ ,\ 0) \rightarrow$ different angular distributions of decay products
- fit leptonic (e, μ) and hadronic decay angles to extract helicity fractions:

$\langle\sqrt{s}\rangle = 206.6$ GeV		
	Data	MC
-1	0.647 ± 0.066	0.623
$+1$	0.137 ± 0.034	0.157
0	0.216 ± 0.053	0.220



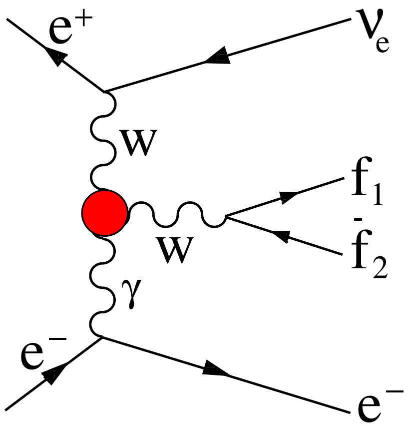
W polarisation: spin correlations (L3)

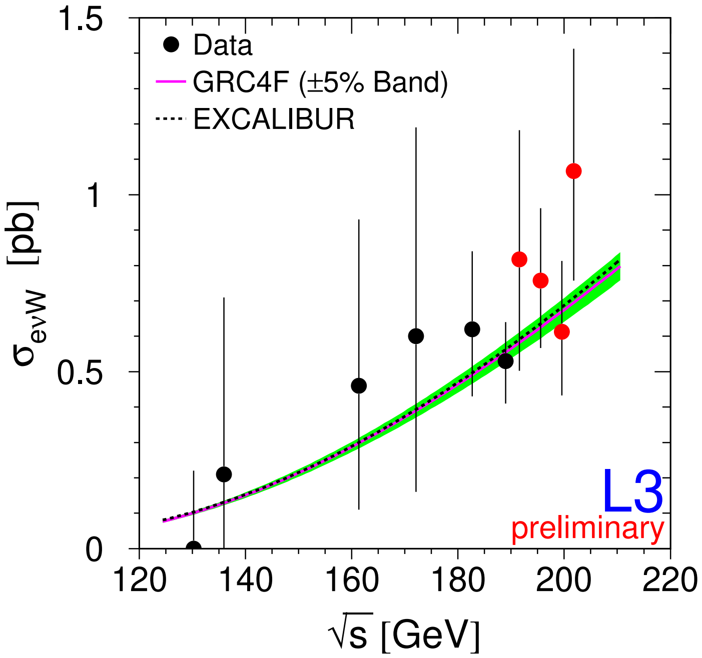
- measure helicity fraction of leptonically decaying W as a function of decay angle of hadronically decaying W
- good agreement between data and MC: WW spin correlations are observed with 3.6 σ significance



TGC from Single W

Single W sensitive to WWγ couplings:

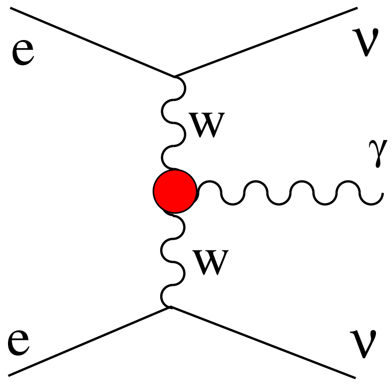




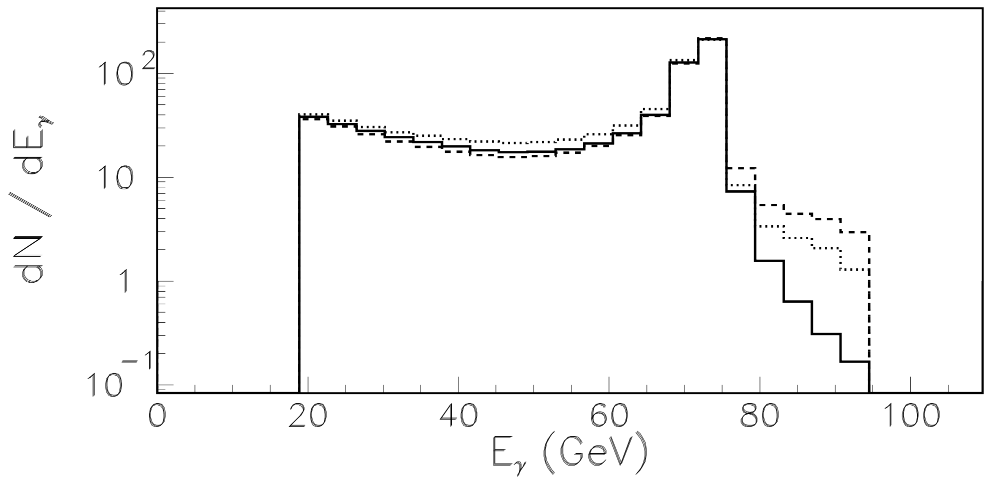
	λ_γ	$\Delta\kappa_\gamma$
ALEPH 161-202 GeV	[-0.57, 0.44] 95% CL	[-0.54, 0.15] 95% CL
DELPHI 189 GeV: lept.	$0.48^{+0.39}_{-1.29}$	$0.23^{+0.33}_{-0.39}$
hadr.	$0.42^{+0.39}_{-1.21}$	$0.19^{+0.36}_{-0.58}$
L3 161-202 GeV	$-0.20^{+0.60}_{-0.19}$	$0.10^{+0.13}_{-0.13}$
OPAL 189 GeV	$-0.44^{+0.43}_{-0.24}$	$0.06^{+0.17}_{-0.19}$

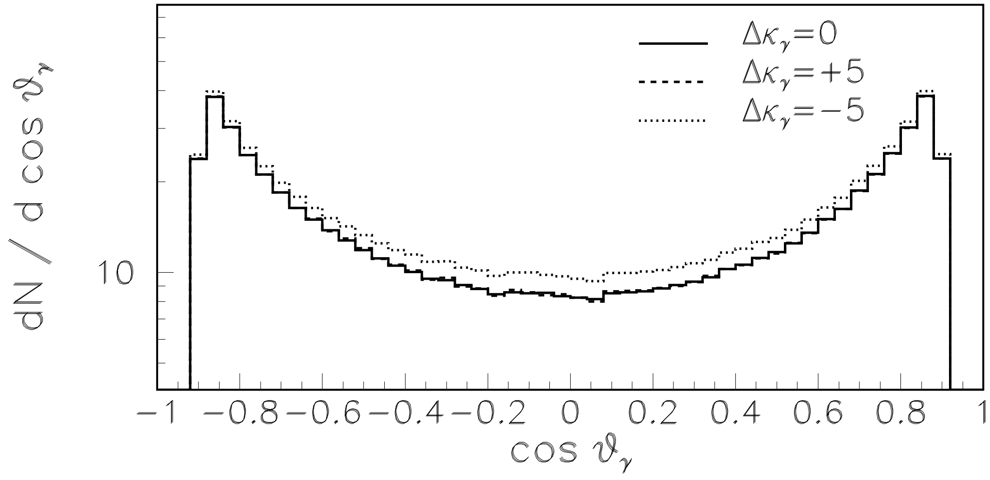
TGC from Single γ

Single photon production sensitive to $\Delta\kappa_\gamma, \lambda_\gamma$ through W-W fusion:



	λ_γ	$\Delta\kappa_\gamma$
ALEPH 183-208 GeV	$0.10^{+0.35}_{-0.35}$	$-0.05^{+0.30}_{-0.25}$
DELPHI 189 GeV	$0.65^{+1.03}_{-1.79}$	$0.70^{+0.77}_{-0.99}$
L3 189-202 GeV	0.1 ± 0.8	0.5 ± 0.7
OPAL 189-202 GeV	$-0.18^{+1.38}_{-1.34}$	$-0.15^{+1.07}_{-1.03}$





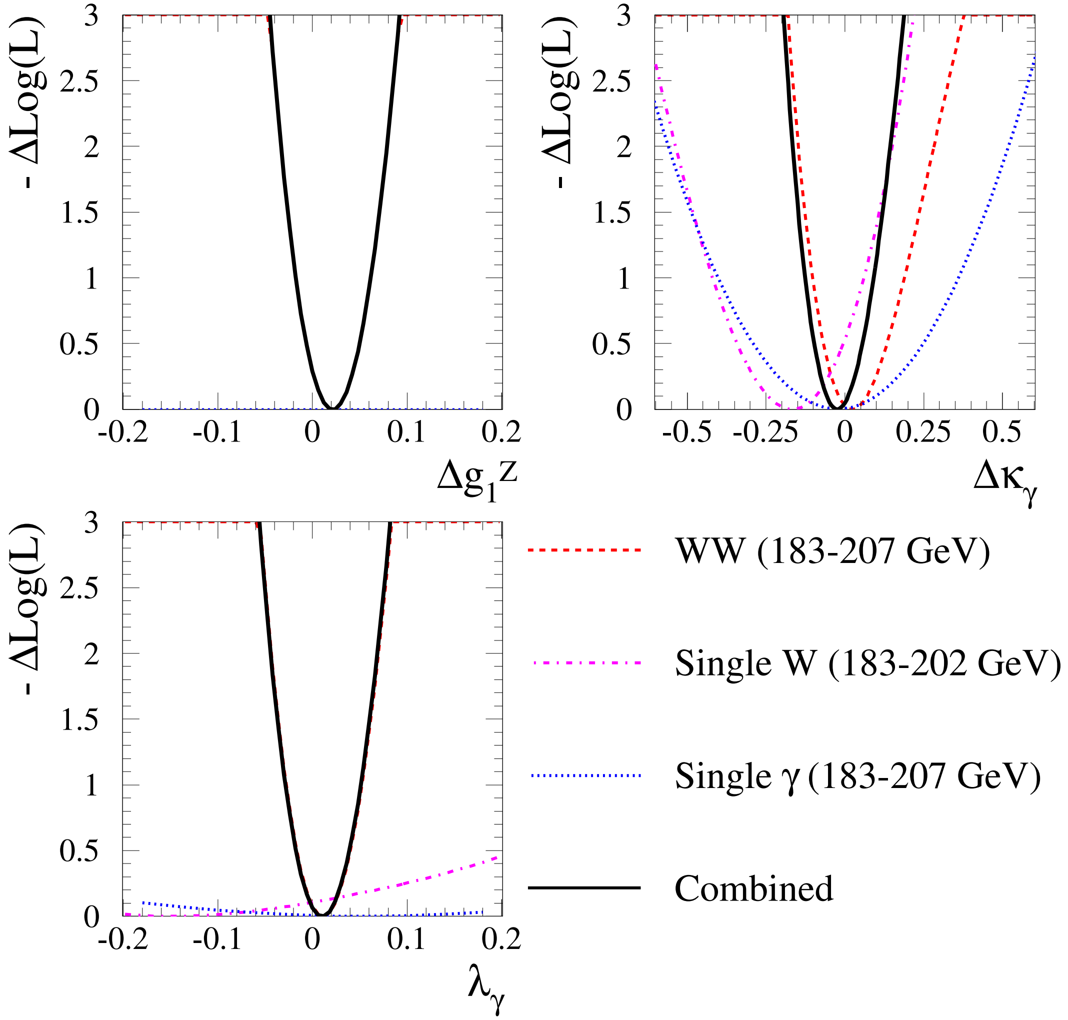
Results

ALEPH: 1-parameter fits with gauge constraints

Coup.	Fit result	95% CL
Δg_1^Z	$0.015^{+0.035}_{-0.032}$	[-0.048 , 0.080]
$\Delta\kappa_\gamma$	$-0.020^{+0.078}_{-0.072}$	[-0.164 , 0.132]
λ_γ	$-0.001^{+0.034}_{-0.031}$	[-0.059 , 0.065]

- result is dominated by WW data
- systematic error due to $\mathcal{O}(\alpha)$ corrections on shape included:
  ≈ 0.015 for Δg_1^Z, λ_γ
  ≈ 0.040 for $\Delta\kappa_\gamma$

ALEPH preliminary



Conclusions and Outlook

- We have presented TGC measurements based on WW, single W and single γ production at LEP
- The ongoing work of implementation and test of the $\mathcal{O}(\alpha)$ generators has to be finalised in order to have TGC results based on the whole WW data set
- We expect a combined LEP precision of
  - ≈ 0.025 for Δg_1^Z and λ_γ
  - ≈ 0.055-0.060 for $\Delta\kappa_\gamma$
- Very interesting results on W polarisation and CP violating couplings measurements have been presented
- All results show good agreement with the Standard Model expectations