Measurement of Trilinear Couplings of the Electroweak Gauge Bosons at L3/LEP

Stefano Villa
Northeastern University; L3 Collaboration

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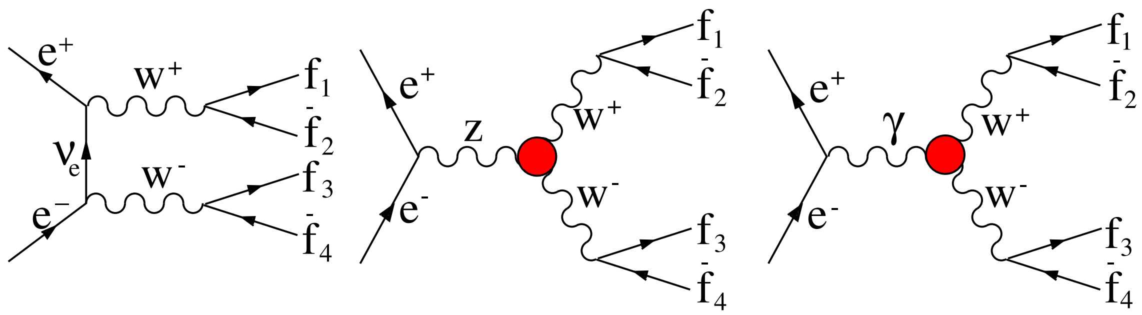
- WWV Couplings from W pairs
- Couplings from single W
- Neutral Couplings from ZZ and Zγ

Definition of the TGC's

Non-Abelian gauge structure of the electroweak theory $\Rightarrow$ existence of Triple Gauge Couplings (TGC)

For W-pair production :



Extend the Standard Model $\rightarrow$ write the most general Lorentz invariant Lagrangian of the type WWV (V either Z or γ):

$$
\begin{aligned}
i\mathcal{L}_{eff}^{WWV} = \\
& g_{WWV}\Big[g_1^V V^\mu \left(W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \\
& \frac{\lambda_V}{m_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu} + i g_4^V W^+_\mu W^-_\nu \left(\partial^\mu V^\nu + \partial^\nu V^\mu\right) + \\
& i g_5^V \varepsilon_{\mu\nu\rho\sigma}\left((\partial^\rho W^{-\mu})W^{+\nu} - W^{-\mu}(\partial^\rho W^{+\nu})\right)V^\sigma \\
& -\frac{\tilde{\kappa}_V}{2} W^-_\mu W^+_\nu \varepsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \frac{\tilde{\lambda}_V}{2m_W^2} W^-_{\rho\mu} W^{+\mu}_\nu \varepsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}\Big]
\end{aligned}
$$

In the Standard Model:

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

- EM gauge invariance $\Rightarrow g_1^\gamma = 1$ and $g_5^\gamma = 0$
- g_1^V, κ_V, λ_V conserve C and P separately
- g_5^V conserves CP but not C and P separately
- g_4^V, $\tilde{\kappa}_V$, $\tilde{\lambda}_V$ are CP violating

Physical constraints on TGC's

From a multipole expansion of the W-γ interaction:

$$\begin{aligned}
\mu_W &= \frac{e}{2m_W}(1+\kappa_\gamma+\lambda_\gamma) \stackrel{\mathrm{SM}}{=} \frac{e}{m_W} \\
q_W &= -\frac{e}{m_W^2}(\kappa_\gamma-\lambda_\gamma) \stackrel{\mathrm{SM}}{=} -\frac{e}{m_W^2}
\end{aligned}$$

Define deviations from SM:

$$\begin{aligned}
\Delta g_1^Z &\equiv g_1^Z - 1 \\
\Delta\kappa_\gamma &\equiv \kappa_\gamma - 1 \\
\Delta\kappa_Z &\equiv \kappa_Z - 1
\end{aligned}$$

Consider only the couplings which conserve both C and P: only 5 (of 14) are left

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

For a further reduction, require SU(2) symmetry:

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

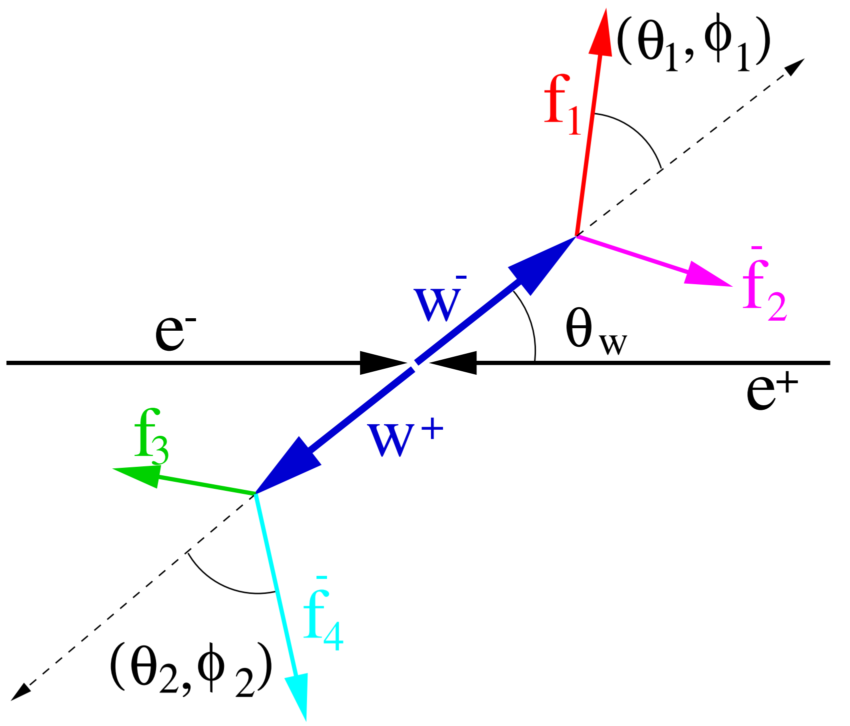
$$\boxed{\Delta g_1^Z, \Delta\kappa_\gamma, \lambda_\gamma}$$

Phase space variables definition

Anomalous Couplings would affect polarization, angular distributions and total cross section of WW.

A given W pair event can be described in terms of 5 variables (neglect γ radiation):

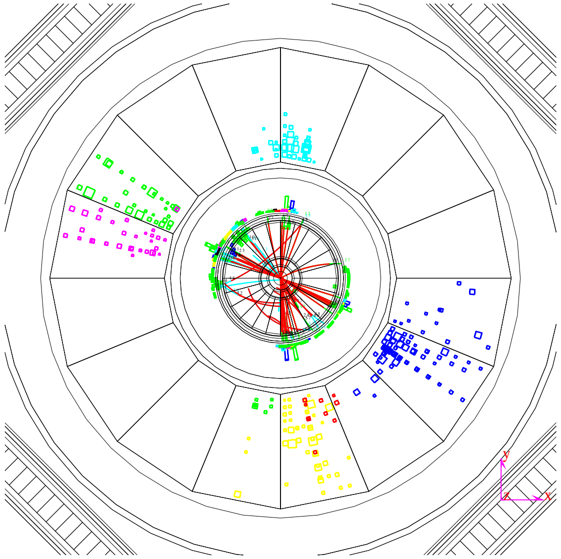
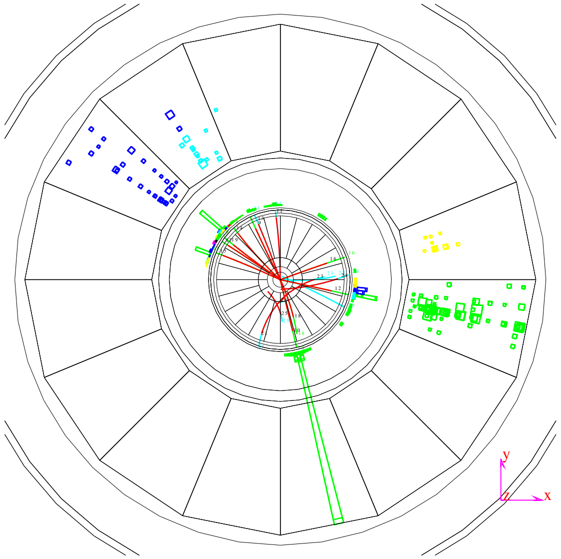
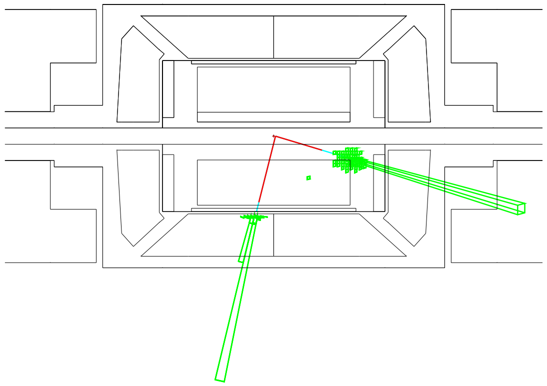
- $\cos\theta_{W^-}$ polar angle of the W^-
- $\cos\theta_1$, ϕ_1 polar and azimuthal angles of the fermion in the W^- rest frame
- $\cos\theta_2$, ϕ_2 polar and azimuthal angles of the antifermion in the W^+ rest frame



Information used in the different channels:

- qqqq $\longrightarrow$ $\cos\theta_{W^-}$
- qqeν, qq$\mu\nu$ and qq$\tau\nu$ $\longrightarrow$ $\cos\theta_{W^-}$, $\cos\theta_{lepton}$ and ϕ_{lepton}
- $\ell\nu\ell\nu$ $\longrightarrow$ only total cross section, will use $\cos\theta_{W^-}$

WW selection

qqqq	$qq\ell\nu$	$\ell\nu\ell\nu$
		
No missing energy, high multiplicity. Neural Net based selection	2 jets and an isolated lepton. Missing energy.	2 acoplanar leptons, large missing energy.

WW events collected by L3:

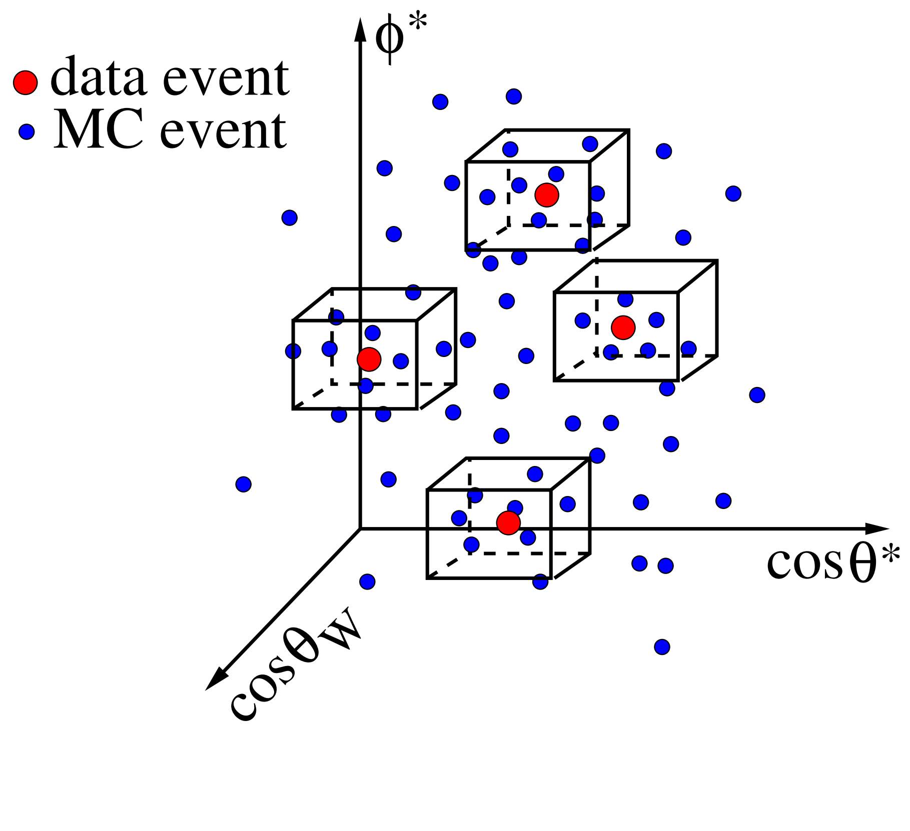
Year	Energy	Luminosity	WW events
1996	161 GeV	11 pb^{-1}	21
1996	172 GeV	10.2 pb^{-1}	113
1997	183 GeV	55.5 pb^{-1}	844
1998	189 GeV	176.4 pb^{-1}	2663

Fit Method

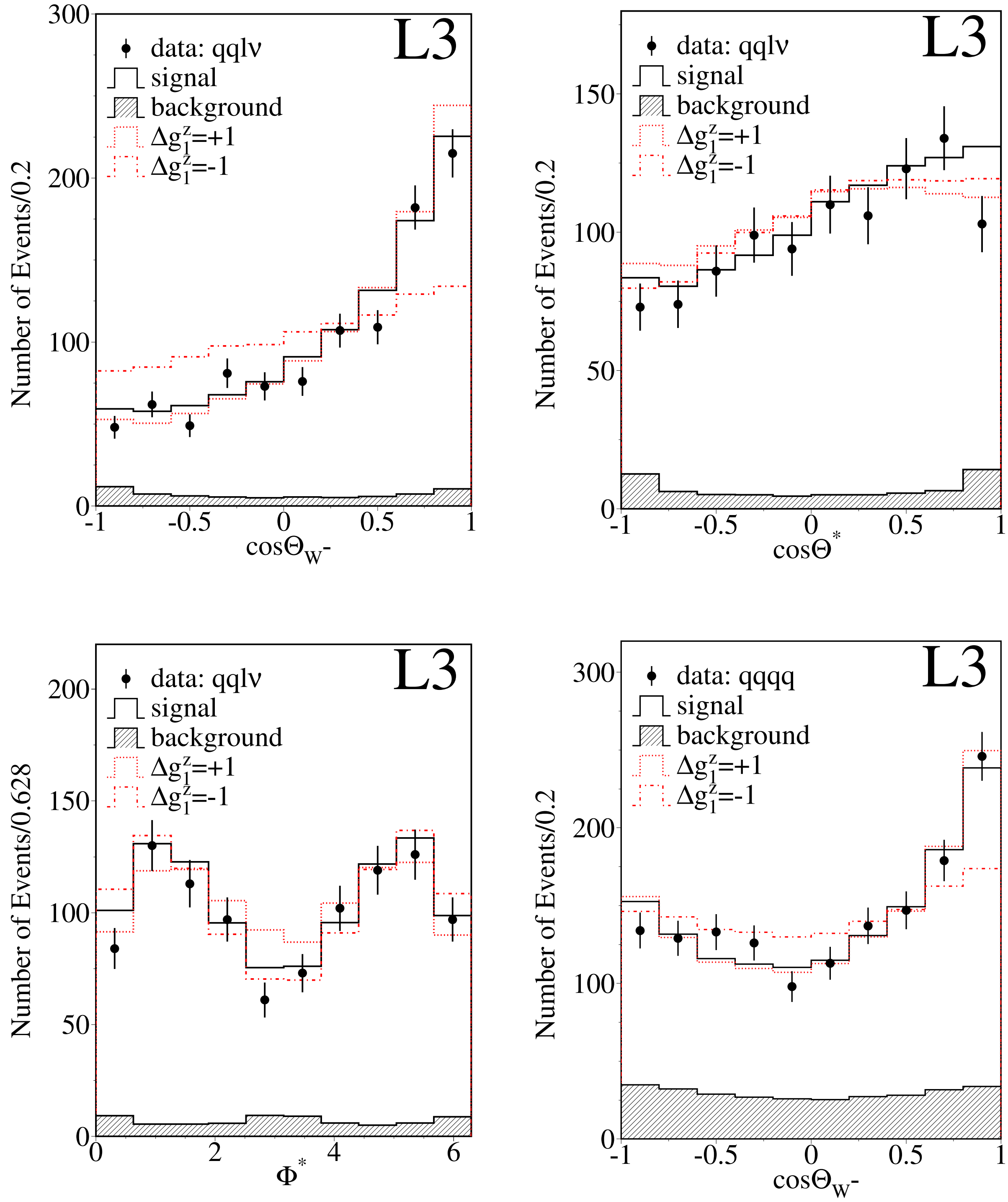
- Couplings are determined maximising an unbinned likelihood L
- L depends on shape and total normalisation of the distributions
- The shape is proportional to the differential cross section computed with box method and MC reweighting.

$$\frac{d\sigma(\Psi)}{d\Omega} = \frac{\sigma}{N_{MC}} \frac{1}{V_{box}} \sum_{i \in box} \frac{|\mathcal{M}(\Omega_i, \Psi)|^2}{|\mathcal{M}(\Omega_i, \Psi_{SM})|^2}$$

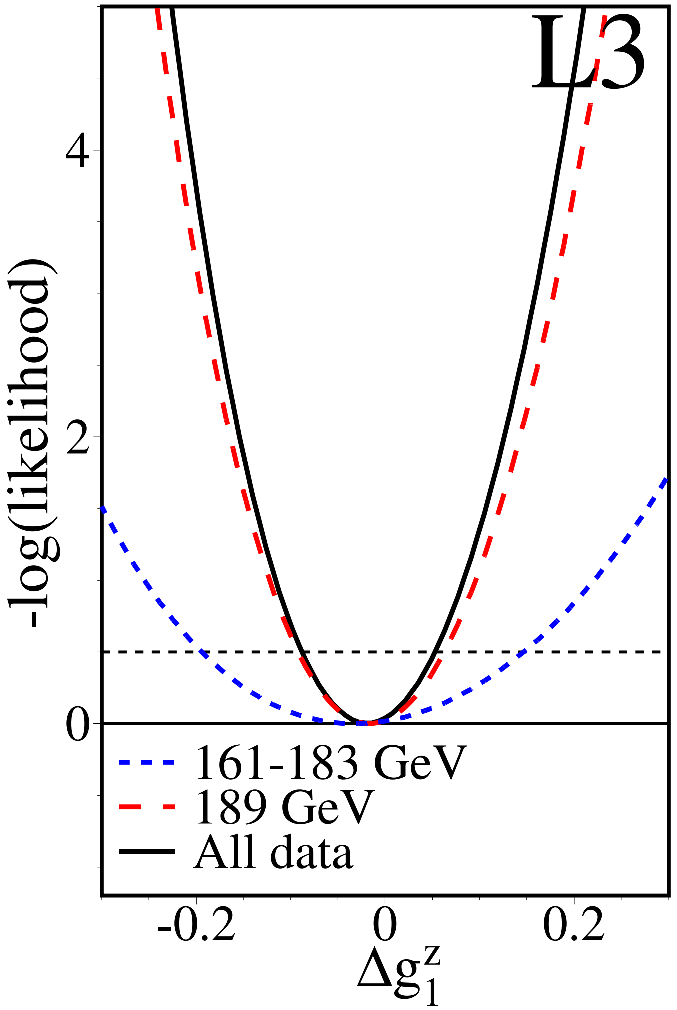
($\Psi \rightarrow$ couplings; $\Omega \rightarrow$ phase space variables)



Distributions with non-zero values of Δg_1^Z



Results of 1-D fits



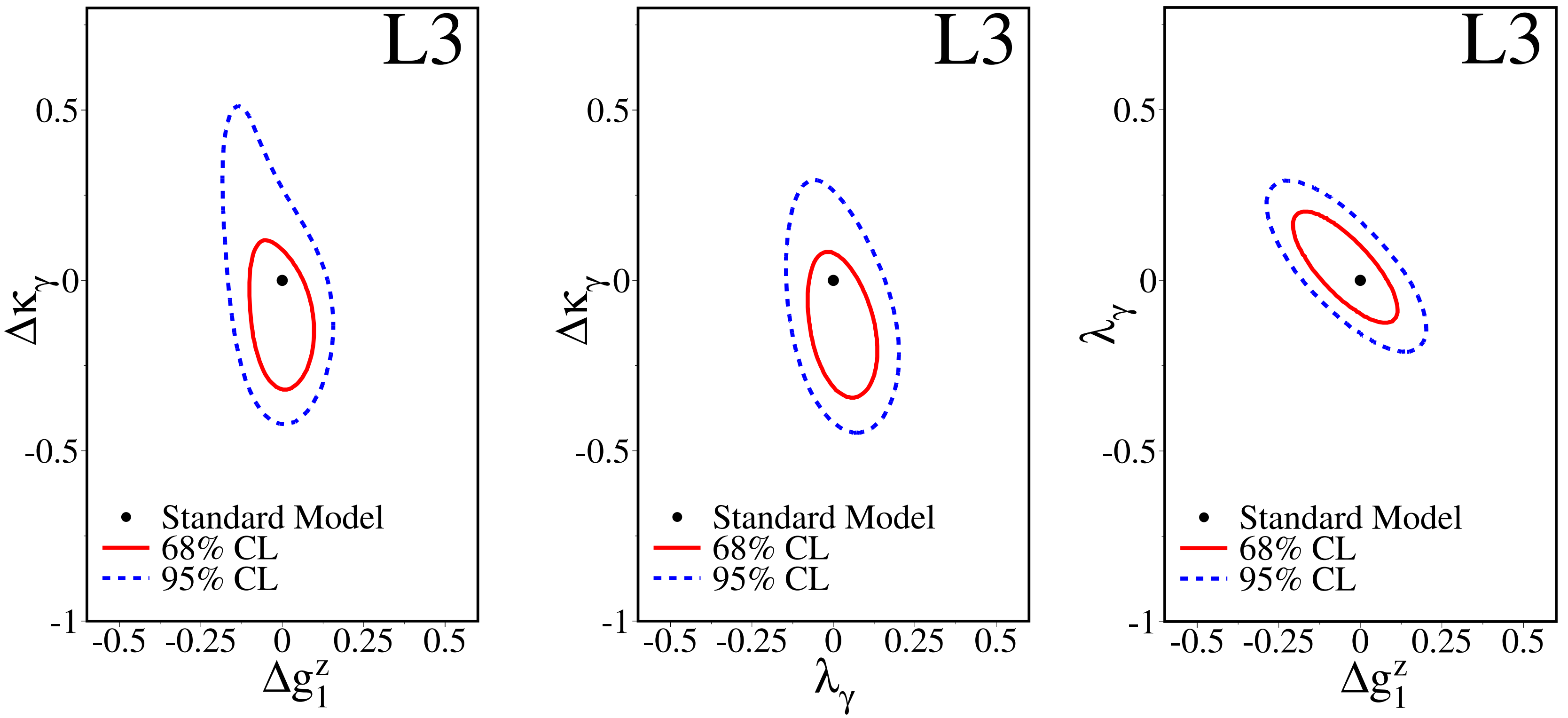
172 GeV final, 183 GeV and 189 GeV preliminary

All other couplings set to SM value. With *preliminary* estimate of systematic errors

Δg_1^z	$-0.02^{+0.07}_{-0.07} \pm 0.03$
$\Delta\kappa_\gamma$	$-0.12^{+0.14}_{-0.12} \pm 0.08$
λ_γ	$0.00^{+0.07}_{-0.07} \pm 0.03$

2-D fits: contour plots

Third coupling set to SM.



Δg_1^z	$0.00^{+0.07}_{-0.07}$		$\Delta\kappa_\gamma$	$-0.14^{+0.17}_{-0.14}$		Δg_1^z	$-0.05^{+0.11}_{-0.11}$
$\Delta\kappa_\gamma$	$-0.13^{+0.17}_{-0.14}$		λ_γ	$0.03^{+0.08}_{-0.08}$		λ_γ	$0.04^{+0.12}_{-0.11}$
	$\rho = -0.21$			$\rho = -0.34$			$\rho = -0.78$

Optimal Observables method

As an alternative approach, the Optimal Observables method was used.

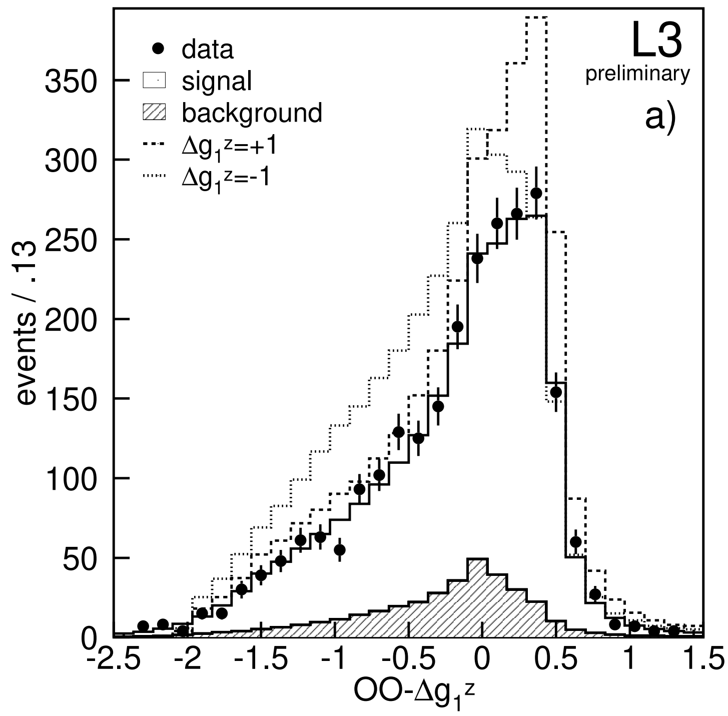
$$\frac{d\sigma(\Psi)}{d\Omega} = c_0(\Omega) + c_1(\Omega)\psi + c_2(\Omega)\psi^2$$

Define:

$$\mathcal{O}_1 = \frac{c_1(\Omega)}{c_0(\Omega)}$$

$$\mathcal{O}_2 = \frac{c_2(\Omega)}{c_0(\Omega)}$$

If $\psi \sim 0$ then $\mathcal{O}_2$ can be neglected and $\mathcal{O}_1$ carries all the information describing the event ($\rightarrow$ Optimal Observable).

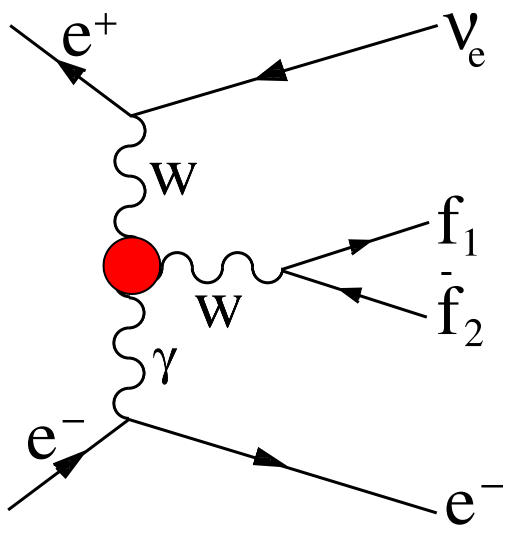


Results are compatible with the other method:

Δg_1^z	$-0.01^{+0.07}_{-0.07}$
$\Delta\kappa_\gamma$	$-0.18^{+0.18}_{-0.15}$
λ_γ	$-0.07^{+0.08}_{-0.07}$

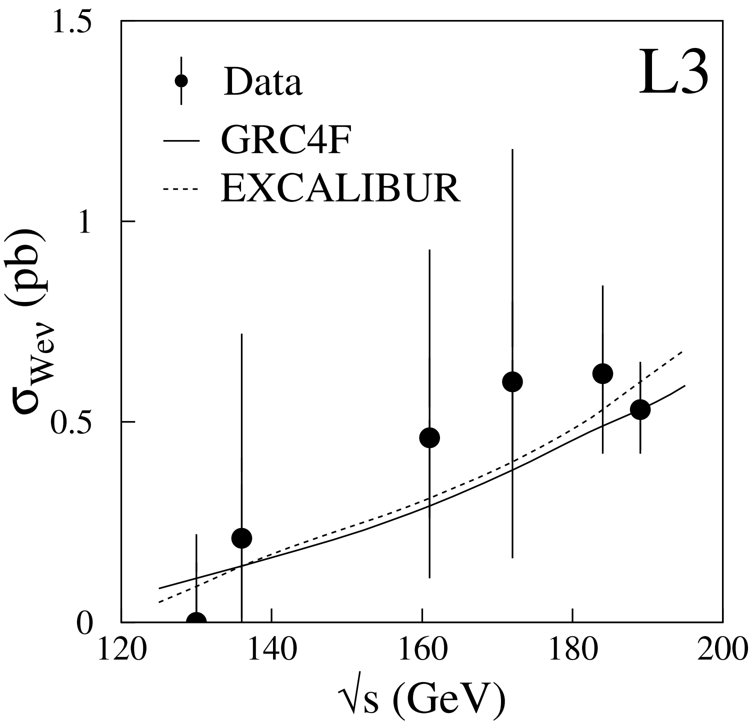
189 GeV data

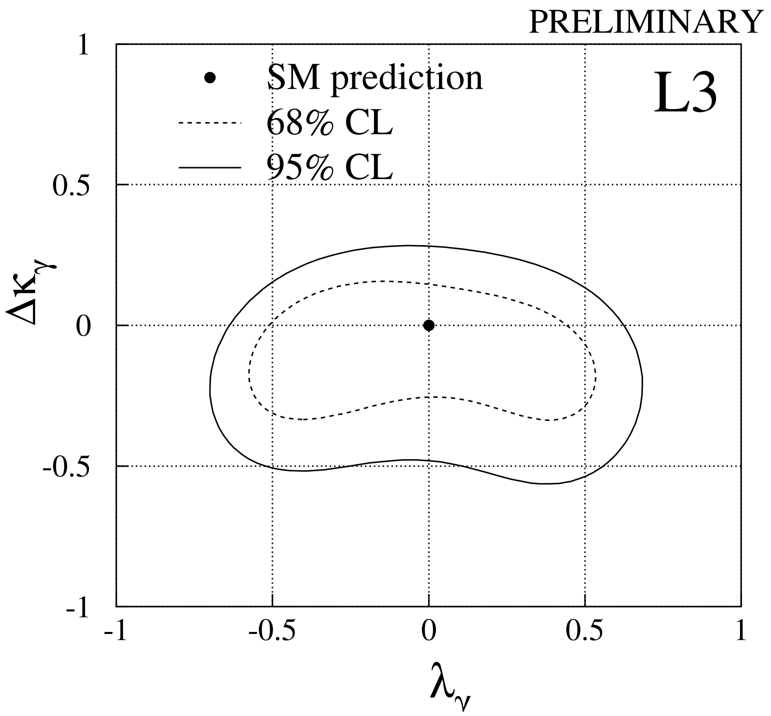
Single W



← is one of the dominant diagrams in single W production: allows to disentangle $WW\gamma$ from WWZ couplings.

- Final state electron (positron) produced at very low polar angle $\Longrightarrow$ not detected
- Hadronic final state: low signal to background ratio $(1/5)$
- Leptonic final states: low statistics
- WW background is coupling dependent





Result of 2-D fit (95% C.L.) :

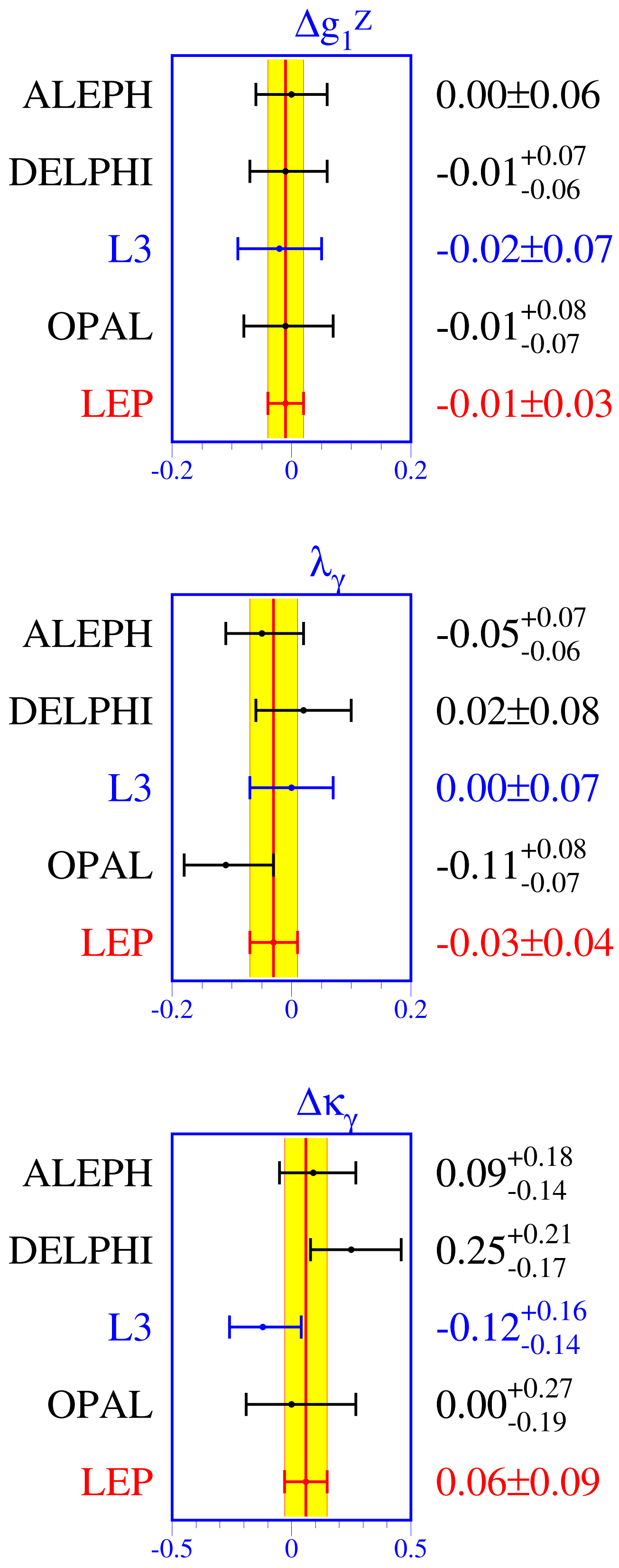
$$-0.42 < \Delta\kappa_\gamma < 0.22 \quad -0.64 < \lambda_\gamma < 0.61$$

Other LEP experiments

1-D fits, data up to 183 GeV

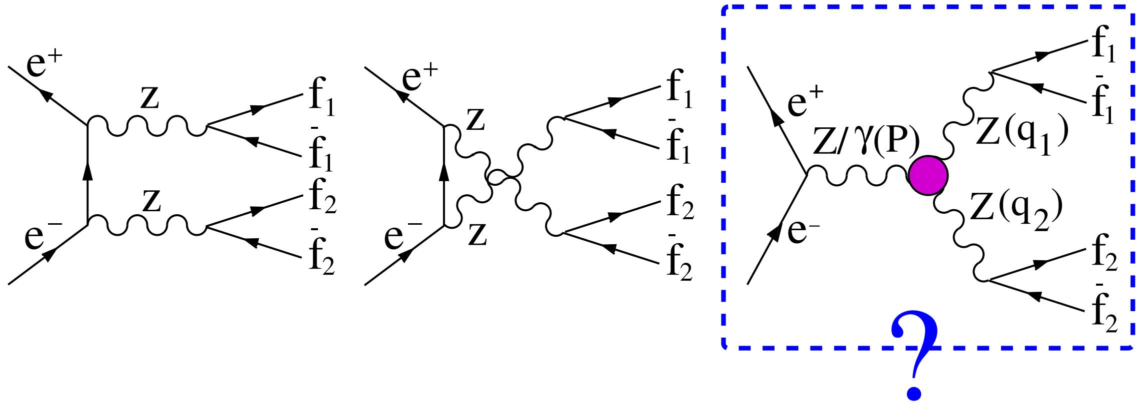
ALEPH	$-2.6 < \Delta\kappa_\gamma < 0.5$	95% C.L.
	$-1.6 < \lambda_\gamma < 1.6$	95% C.L.
DELPHI	$-1.13 < \lambda_\gamma < 1.14$	95% C.L.
	$\Delta\kappa_\gamma = 0.26^{+0.41}_{-0.50}$	1σ

Combined LEP results (1-D fits)



ZZ anomalous couplings

Look for Anomalous Couplings also in Z-pair production.
introduce a ZZV vertex (Z's on shell)



The most general vertex (Bose symmetric and EM gauge invariant):

$$\Gamma^{\alpha\beta\mu}_{\mathrm{ZZV}}(q_1, q_2, P) = \frac{s - m_{\mathrm{V}}^2}{m_{\mathrm{Z}}^2}\left(i f_4^{\mathrm{ZZV}}\left(P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}\right) + i f_5^{\mathrm{ZZV}} \epsilon^{\mu\alpha\beta\rho}(q_1 - q_2)_\rho\right)$$

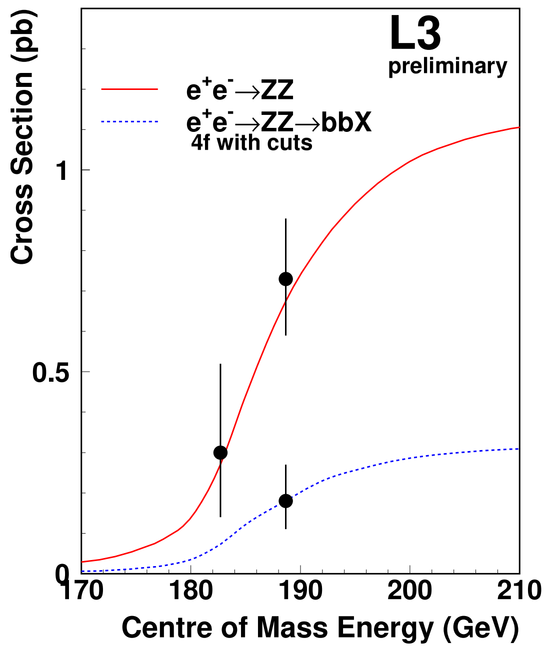
- f_4^{ZZV} leads to CP violation
- f_5^{ZZV} is P-violating but CP Conserving

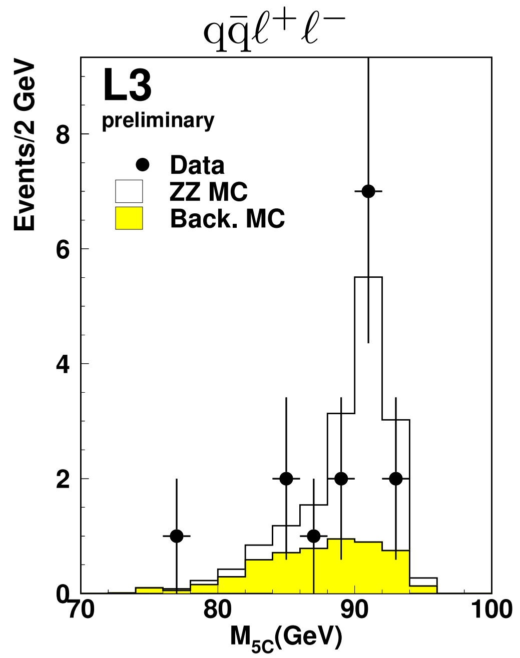
Effects of the anomalous couplings:

- Change of total ZZ cross section
- Modification in the angular distribution of the Z's
- Change in the polarisation of the Z's

Experimental Signature of the ZZ channels:

$q\bar{q}q'\bar{q}'$	4 hadronic jets
$q\bar{q}\nu\bar{\nu}$	2 hadronic jets + missing energy
$q\bar{q}\ell^+\ell^-$	2 hadronic jets + 2 leptons
$\ell^+\ell^-\nu\bar{\nu}$	2 leptons + missing energy
$\ell^+\ell^-\ell'^+\ell'^-$	4 leptons





Fit Results (95% C.L.)

$$-1.9 \le f_4^Z \le 1.9 \qquad -4.9 \le f_5^Z \le 4.7$$
$$-1.1 \le f_4^\gamma \le 1.1 \qquad -3.0 \le f_5^\gamma \le 2.9$$

couplings from $Z\gamma$ final state

$e^+e^- \rightarrow Z\gamma$: another set of 8 anomalous couplings can be tested. The most general ZγV vertex (Zγ on shell):

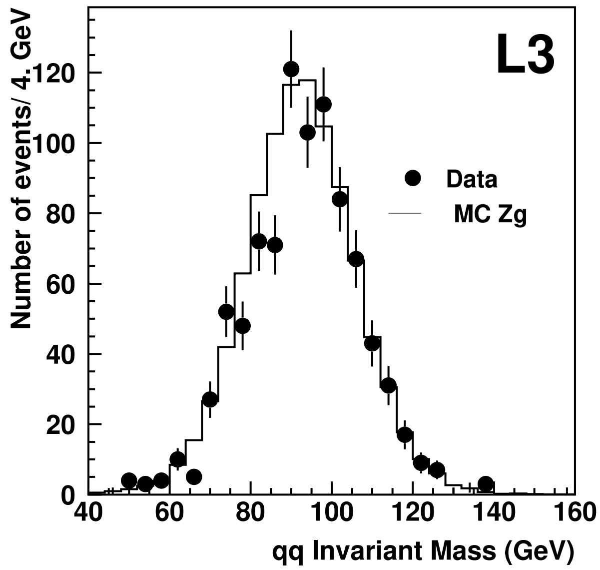
$$\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1, q_2, P) = \frac{s - m_V^2}{m_Z^2}\left[h_1^V\left(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}\right) + \frac{h_2^V}{m_Z^2}P^\alpha\left(P \cdot q_2 g^{\mu\beta} - q_2^\mu P^\beta\right) + h_3^V \epsilon^{\mu\alpha\beta\rho} q_{2\rho} - \frac{h_4^V}{m_Z^2} P^\alpha \epsilon^{\mu\beta\rho\sigma} P_\rho q_{2\sigma}\right]$$

- h_1^V and h_2^V are CP-odd

In the Standard Model, Zγ produced through t-channel electron exchange: signature is an almost monoenergetic photon.

2 subchannels studied, at 189 GeV:

- $e^+e^- \rightarrow q\bar{q}\gamma(\gamma)$
- $e^+e^- \rightarrow \nu\bar{\nu}\gamma(\gamma)$



$-0.09 < h_1^Z < 0.20$	$-0.09 < h_1^\gamma < 0.08$
$-0.12 < h_2^Z < 0.06$	$-0.05 < h_2^\gamma < 0.07$
$-0.16 < h_3^Z < 0.15$	$-0.09 < h_3^\gamma < 0.07$
$-0.09 < h_4^Z < 0.10$	$-0.05 < h_4^\gamma < 0.06$
DELPHI (183 GeV)	$\lvert h_{30}^Z\rvert < 0.55$ $\lvert h_{30}^\gamma\rvert < 0.34$

1-D fits (95% CL)

Conclusions.

- Measurement of Trilinear Gauge Couplings is a direct test of the gauge structure of the electroweak theory.
- LEP: precision of the order of 3-9 % on the measurement of WWV couplings. Expected sensitivity at the end of LEP2: 2-5%.
- First results on neutral current couplings.
- No deviations from the Standard Model were observed.