Electroweak Gauge Couplings at LEP

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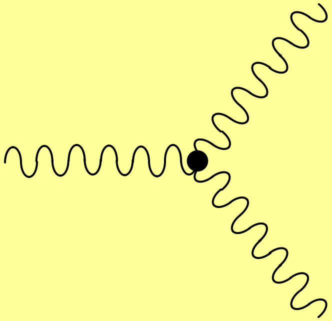
On behalf of the four LEP experiments

Outline

Triple Gauge Couplings (TGC)

Charged Current (CC): **WWγ, WWZ**

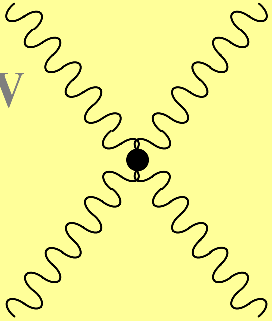
Neutral Current (NC): **Zγγ, ZZγ, ZZZ**



Quartic Gauge Couplings (QGC)

Charged Current: **W W γγ, W W Zγ, W W Z Z, W W W W**

Neutral Current: **Z γ γ γ, Z Z γ γ, Z Z Z γ, Z Z Z Z**



Only CC couplings exist in the Standard Model

W W Z Z, W W W W, Z Z Z γ, Z Z Z Z are not accessible at LEP

Gauge Couplings in the SM

Gauge Couplings are direct consequence of the non-Abelian nature of the electroweak $SU(2)\times U(1)$ theory.

Gauge invariance dictates:

$$\mathbf{W}_{\mu\nu} = \partial_\mu \mathbf{W}_\nu - \partial_\nu \mathbf{W}_\mu - g\mathbf{W}_\mu \times \mathbf{W}_\nu$$

$$\mathbf{W} = \begin{pmatrix} \left(\mathrm{W}^+ + \mathrm{W}^-\right)/\sqrt{2} \\ i\left(\mathrm{W}^+ - \mathrm{W}^-\right)/\sqrt{2} \\ \mathrm{A}\sin\theta_\mathrm{w} + \mathrm{Z}\cos\theta_\mathrm{w} \end{pmatrix}$$

$$L_W = -\tfrac{1}{4}\mathbf{W}^{\mu\nu}\cdot\mathbf{W}_{\mu\nu} =$$

$$-\tfrac{1}{4}\left(\partial_\mu \mathbf{W}_\nu - \partial_\nu \mathbf{W}_\mu\right)\cdot\left(\partial^\mu \mathbf{W}^\nu - \partial^\nu \mathbf{W}^\mu\right) \quad \textbf{K.E.}$$

$$+\tfrac{g}{2}\left(\partial_\mu \mathbf{W}_\nu - \partial_\nu \mathbf{W}_\mu\right)\cdot\left(\mathbf{W}^\mu \times \mathbf{W}^\nu\right) \quad \textbf{TGC}$$

$$-\tfrac{g^2}{4}\left(\mathbf{W}_\mu \times \mathbf{W}_\nu\right)\cdot\left(\mathbf{W}^\mu \times \mathbf{W}^\nu\right) \quad \textbf{QGC}$$

To test the SM we have to:

- measure the effect of the SM TGC and QGC terms
- search for other, non-SM, TGC and QGC terms.

The effect of the SM QGC term is too small at presently available energy and statistics.

CC Triple Gauge Couplings

General expression for the $\mathbf{WWV}$ $(\mathbf{V} = \gamma, \mathbf{Z})$ eff. Lagrangian:

$$iL_{eff}^{WWV}/g_{WWV} =$$

$$g_1^V V^\mu \left(W_{\mu\nu}^- W^{+\nu} - W_{\mu\nu}^+ W^{-\nu} \right) + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{m_W^2} V^{\mu\nu} W_\nu^{+\rho} W_{\rho\nu}^- \quad \Big\} \; C,P \text{ conserving}$$

$$+ i g_5^V \varepsilon_{\mu\nu\rho\sigma} \left(\left(\partial^\rho W^{-\mu} \right) W^{+\nu} - W^{-\mu} \left(\partial^\rho W^{+\nu} \right) \right) V^\sigma \quad \Big\} \; C,P \text{ Violating, } CP \text{ Conserving}$$

$$+ i g_4^V W_\mu^- W_\nu^+ \left(\partial^\mu V^\nu + \partial^\nu V^\mu \right) \quad \Big\} \; C \text{ violating}$$

$$- \frac{\hat{\kappa}_V}{2} \varepsilon_{\mu\nu\rho\sigma} W_\mu^- W_\nu^+ V^{\rho\sigma} - \frac{\hat{\lambda}_V}{2 m_W^2} \varepsilon^{\nu\rho\alpha\beta} W_{\rho\nu}^- W_\nu^{+\mu} V_{\alpha\beta} \quad \Big\} \; P \text{ violating}$$

$$W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu \qquad V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$$

$$g_{WW\gamma} = e \qquad g_{WWZ} = e \cot\theta_w$$

Standard Model: $g_1^V = 1$, $\kappa_V = 1$. All others vanish.

Anomalous couplings: $\Delta g_1^V = g_1^V - 1,\ \Delta\kappa_1^V = \kappa_1^V - 1,\ \lambda_V,\ g_5^V,\ g_4^V,\ \hat{\kappa}_V,\ \hat{\lambda}_V$

Physics interpretation:

$q_W = e g_1^\gamma$ charge

$\mu_W = \frac{e}{2m_W}\left(g_1^\gamma + \kappa_\gamma + \lambda_\gamma\right)$ magnetic dipole moment

$Q_W = -\frac{e}{m_W^2}\left(\kappa_\gamma - \lambda_\gamma\right)$ electric quadr. moment

$d_W = \frac{e}{2m_W}\left(\hat{\kappa}_\gamma + \hat{\lambda}_\gamma\right)$ electric dipole moment

$\hat{Q}_W = -\frac{e}{m_W^2}\left(\hat{\kappa}_\gamma - \hat{\lambda}_\gamma\right)$ magnetic quadr. moment

Constraints: QED gauge invariance: $g_1^\gamma = 1,\quad g_5^\gamma = 0$

Custodial SU(2): $\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W,\quad \lambda_Z = \lambda_\gamma$

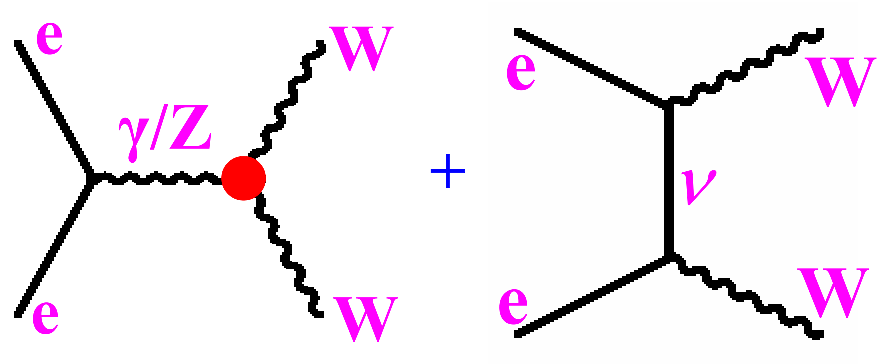
$\hat{\kappa}_Z = -\hat{\kappa}_\gamma \tan^2\theta_W,\quad \hat{\lambda}_Z = \hat{\lambda}_\gamma$

8 TGCs are left: 4 CP-conserving: $\Delta\kappa_\gamma,\ \lambda_\gamma,\ \Delta g_1^Z,\ g_5^Z$

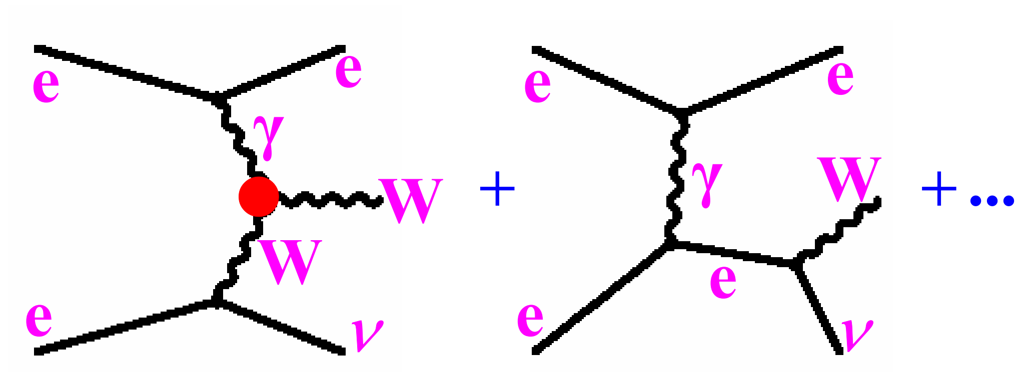
+4 CP-violating: $\hat{\kappa}_Z,\ \hat{\lambda}_Z,\ g_4^\gamma,\ g_4^Z$

LEP Physics Processes (TGC)

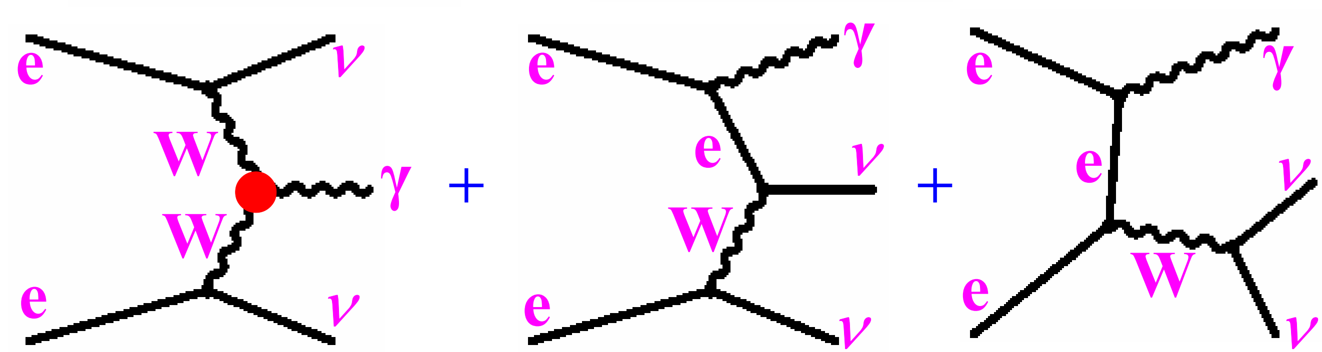
$e^+e^- \rightarrow W^+W^-$:



$e^+e^- \rightarrow We\nu$:



$e^+e^- \rightarrow \nu\bar{\nu}\gamma$:



Available Data from LEP2

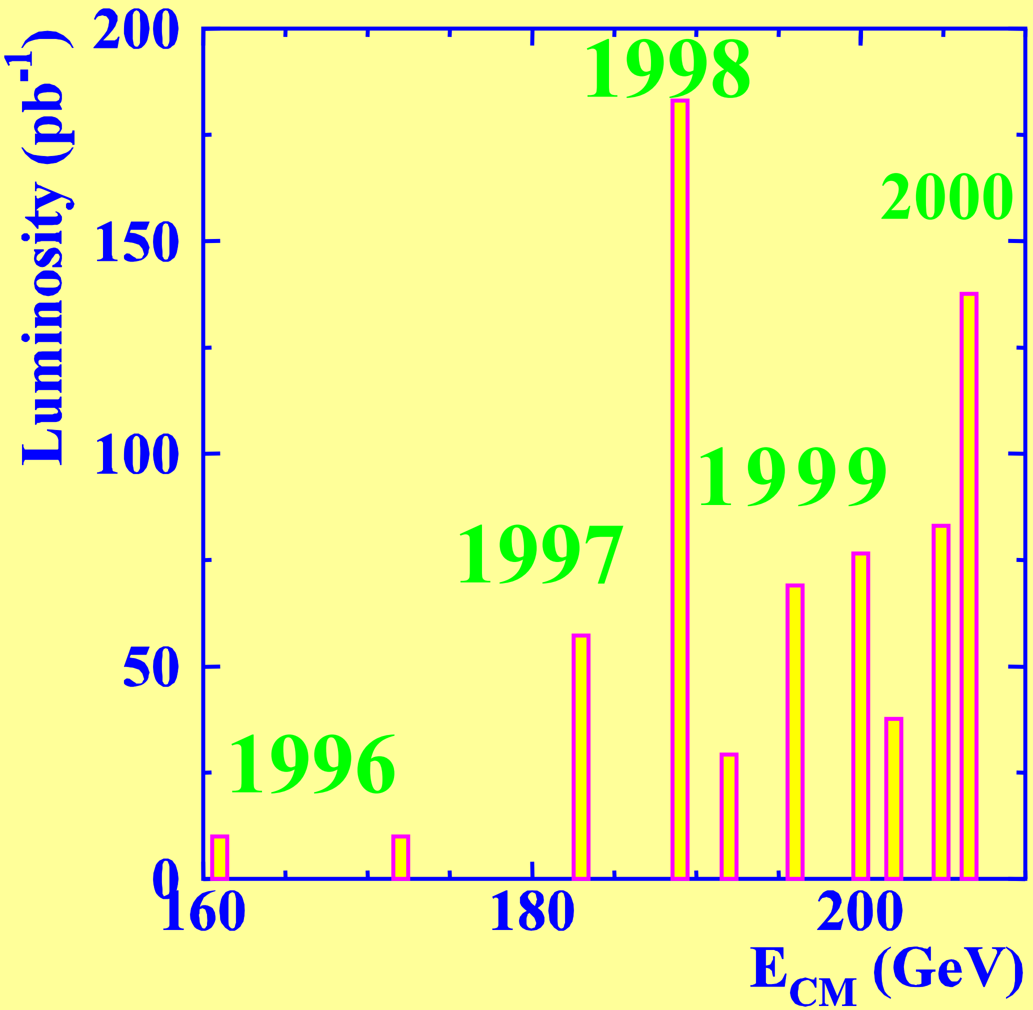
Total LEP2 luminosity:

$\simeq 700 \text{pb}^{-1}$

(per experiment)

Corresponding to:

$\simeq 10000$ W - pairs



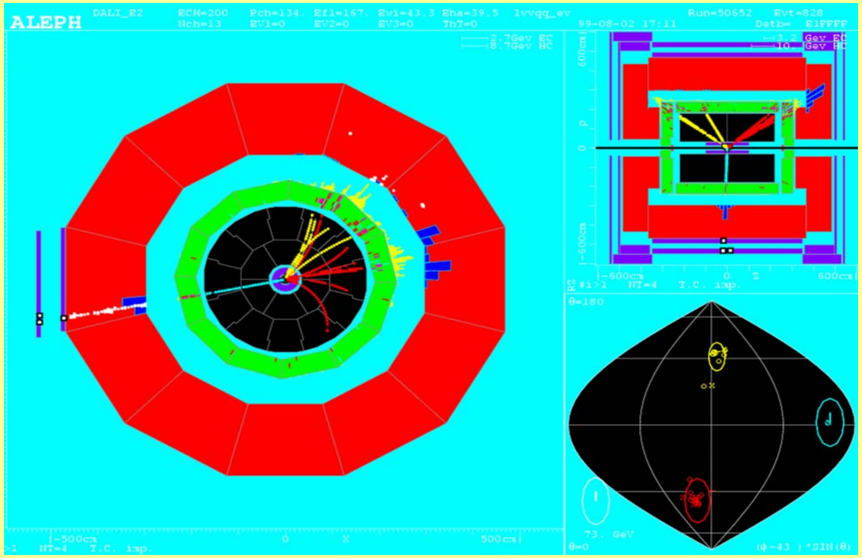
W-pair Production

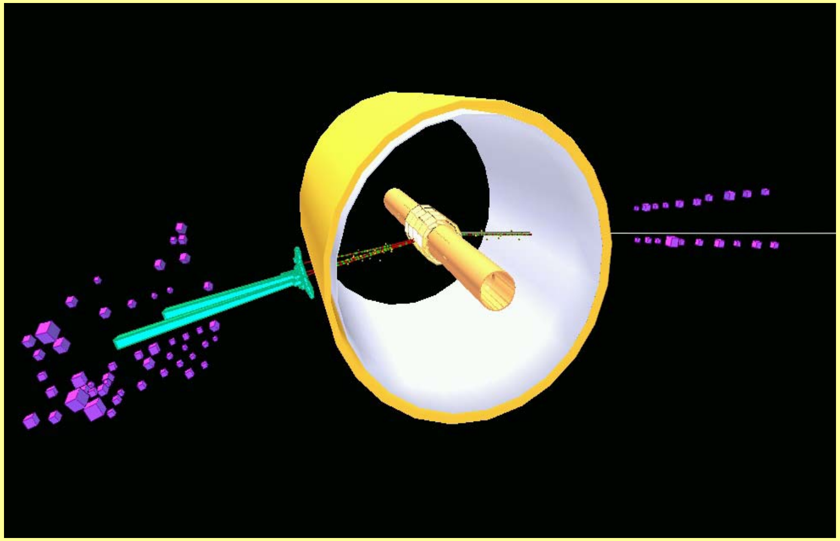
3 event topologies :

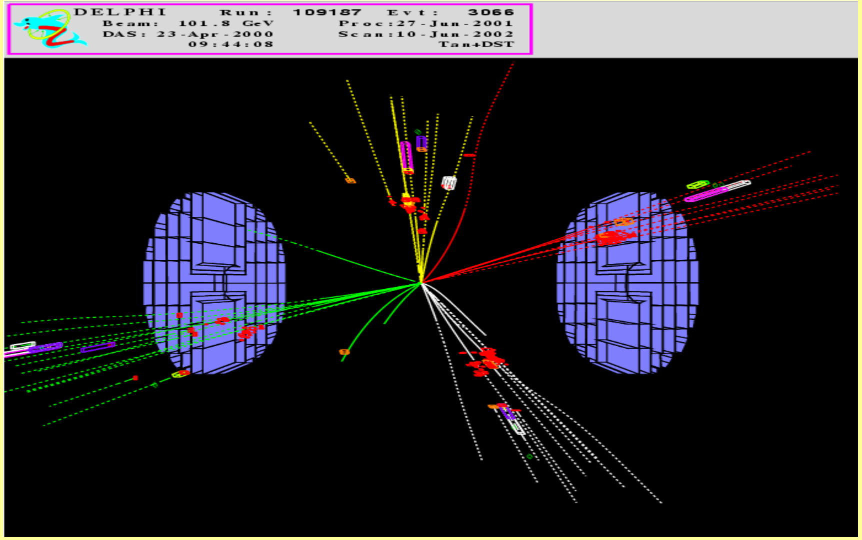
$$WW \to q\bar{q}l\nu \quad (43.9\%)$$

$$WW \to q\bar{q}q\bar{q} \quad (45.6\%)$$

$$WW \to l\bar{\nu}\bar{l}\nu \quad (10.5\%)$$







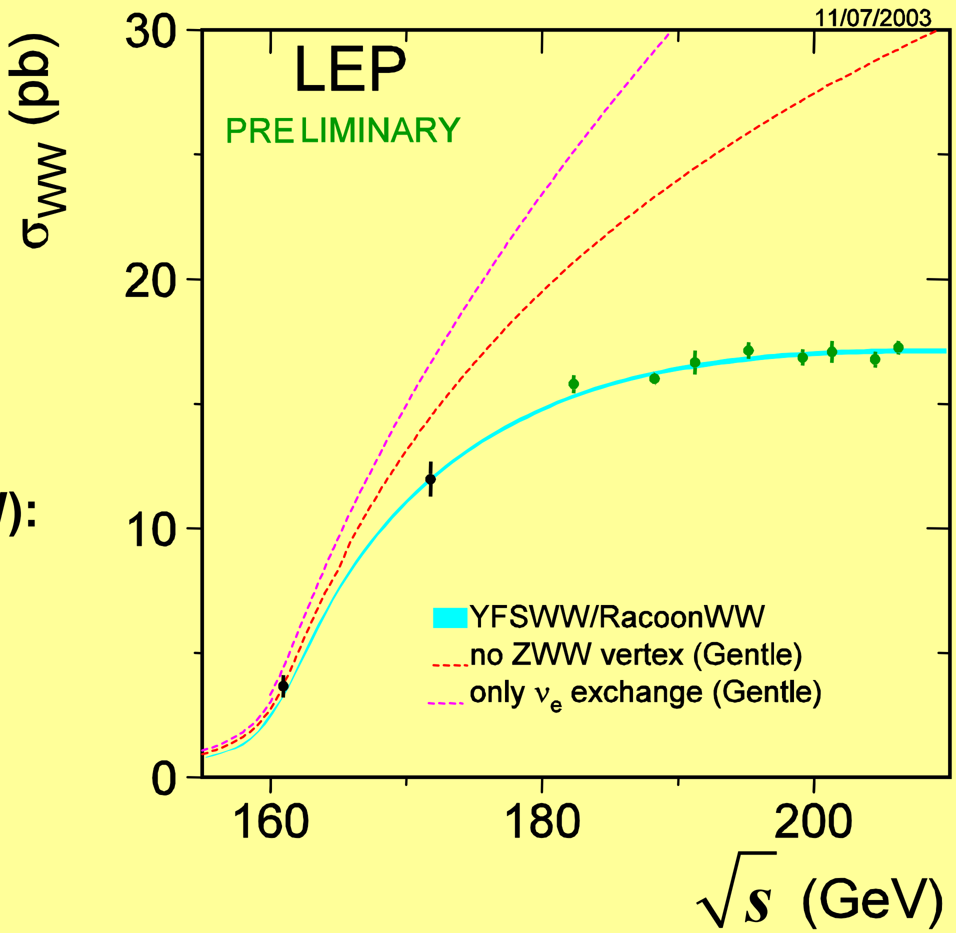
WW Cross-Section Measurement

Topology	Efficiency	Purity
$q\bar{q}q\bar{q}$	90%	80%
$q\bar{q}l\nu$	70-90%	90%
$l\bar{\nu}l\nu$	60-80%	90%

Measured σ^{WW}/Expected (YFSWW):

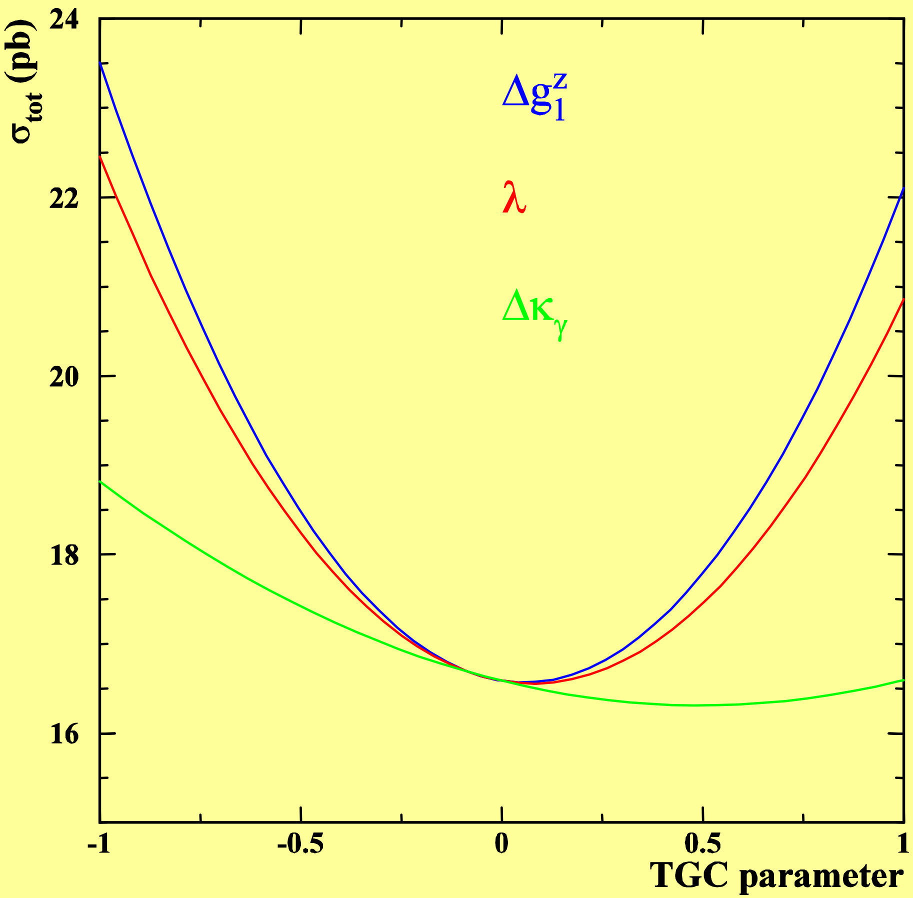
$$R^{WW} = 0.997 \pm 0.010$$

Sensitivity to TGCs is relatively weak!

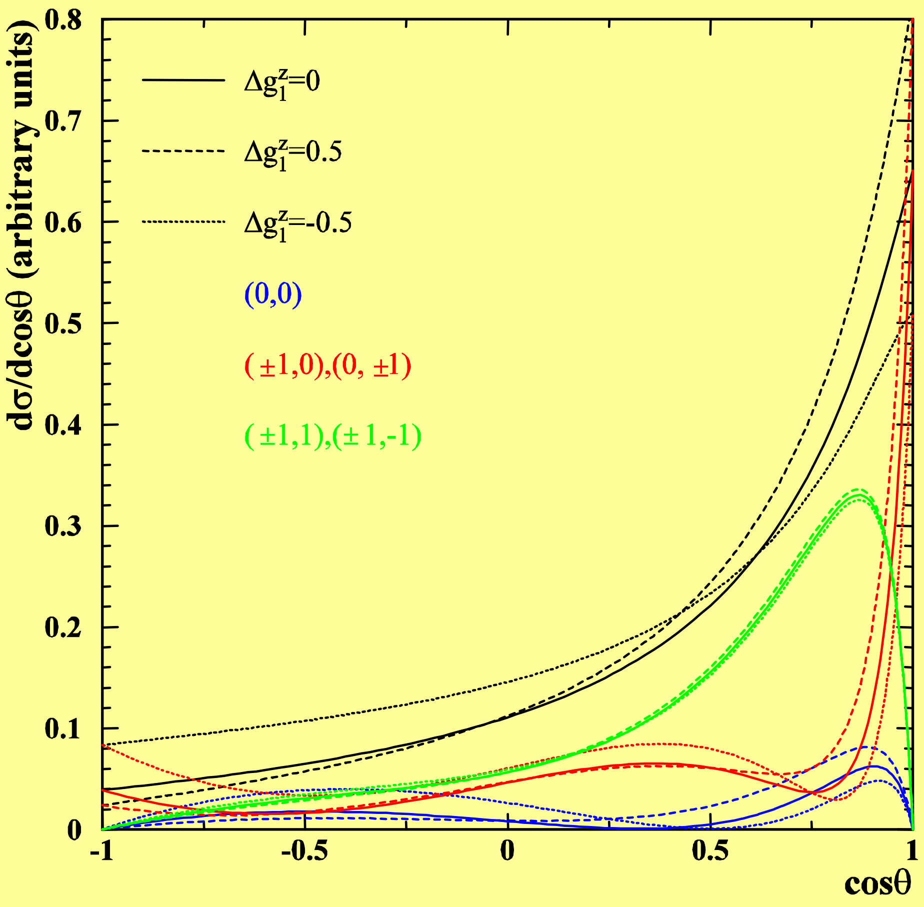


Expected TGC Dependence

Total cross-section

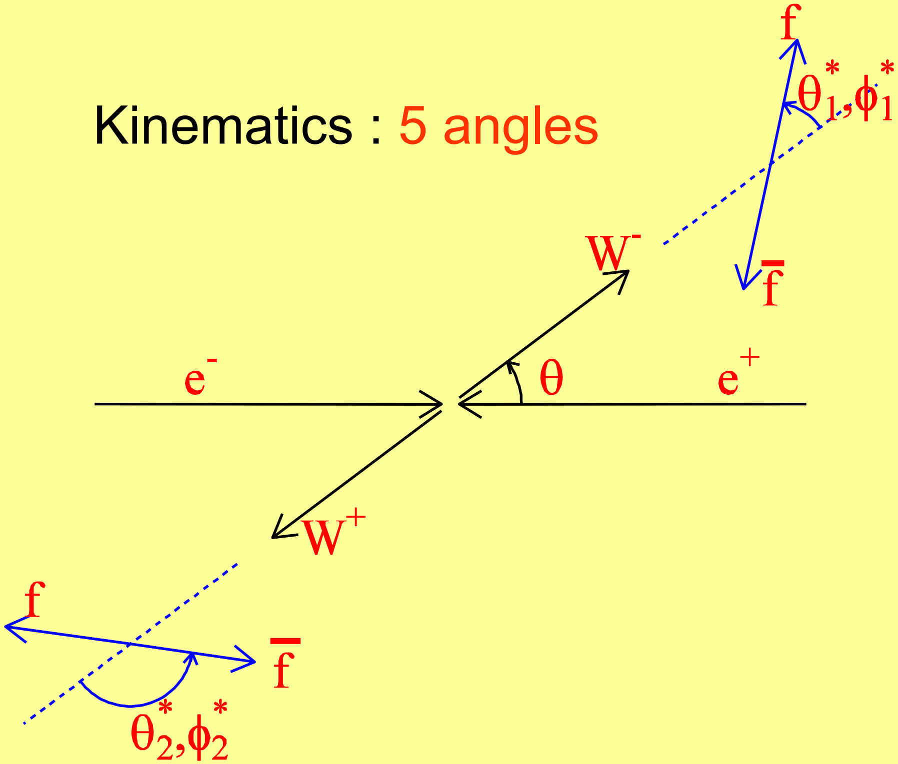


Angular distribution

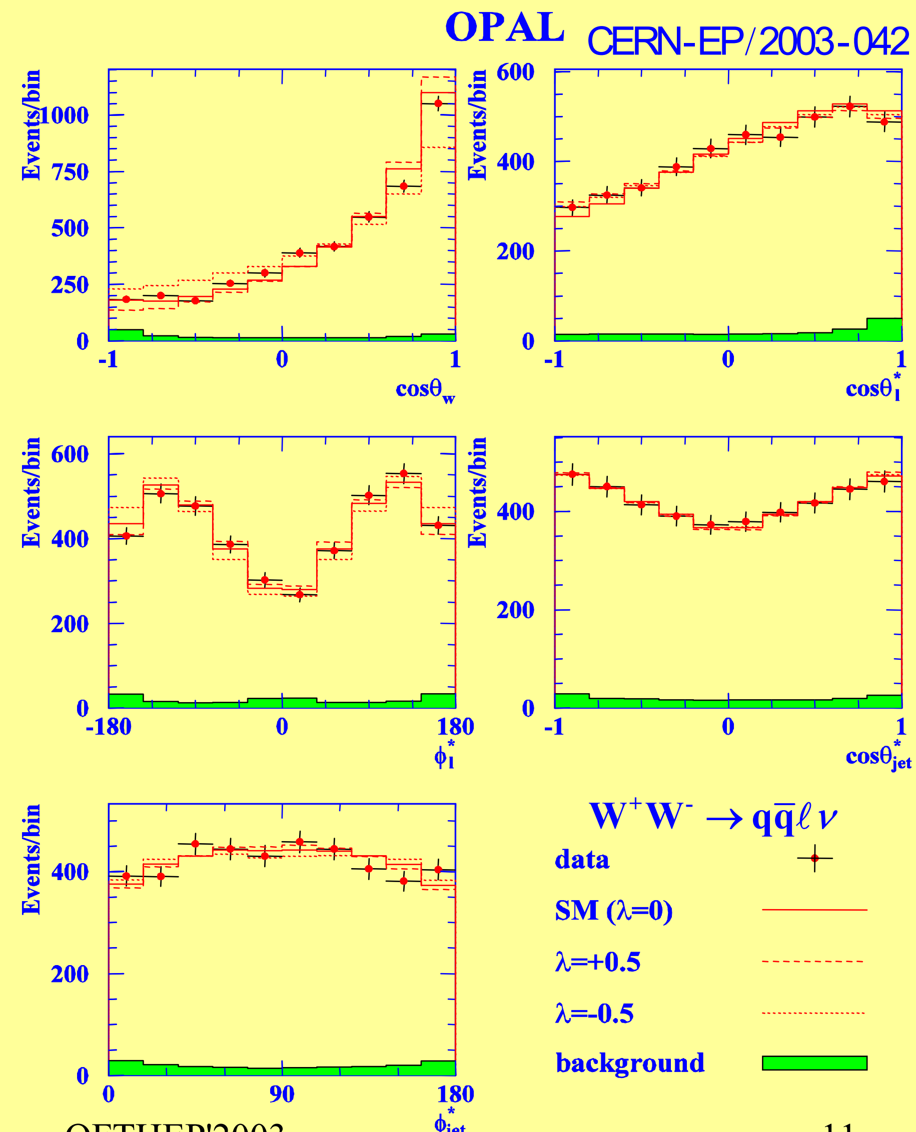


WW Angular Information

Kinematics : 5 angles



- most of the information in θ_W
- no flavor tagging
- W charge tagging in $W^+W^- \rightarrow qqqq$ channel (80%)



TGC Extraction from Angular Information

Optimal Observables (OOs), based on quadratic TGC dependence,

$$d\sigma/d\Omega = S^{(0)}(\Omega) + \sum_i \alpha_i S_i^{(1)}(\Omega) + \sum_{i,j} \alpha_i \alpha_j S_{ij}^{(2)}(\Omega) \qquad \alpha_i \text{ – TGCs}$$

$$\Omega = \left(\cos\theta_W,\ \cos\theta_1^*,\ \phi_1^*,\ \cos\theta_2^*,\ \phi_2^*\right) \text{ – phase-space point}$$

$$O_i^{(1)} = S_i^{(1)}(\Omega)/S^{(0)}(\Omega) \qquad O_{ij}^{(2)} = S_{ij}^{(2)}(\Omega)/S^{(0)}(\Omega)$$

All the relevant information is included in $O_i^{(1)},\ O_{ij}^{(2)}$

… but for *n* TGCs there are *n+n(n+1)/2* optimal observables!

$\Rightarrow$ OPAL, ALEPH apply small α approximation and use only the mean values of the optimal observables.

L3 uses full OO distributions only as a cross-check for 1 TGC fits

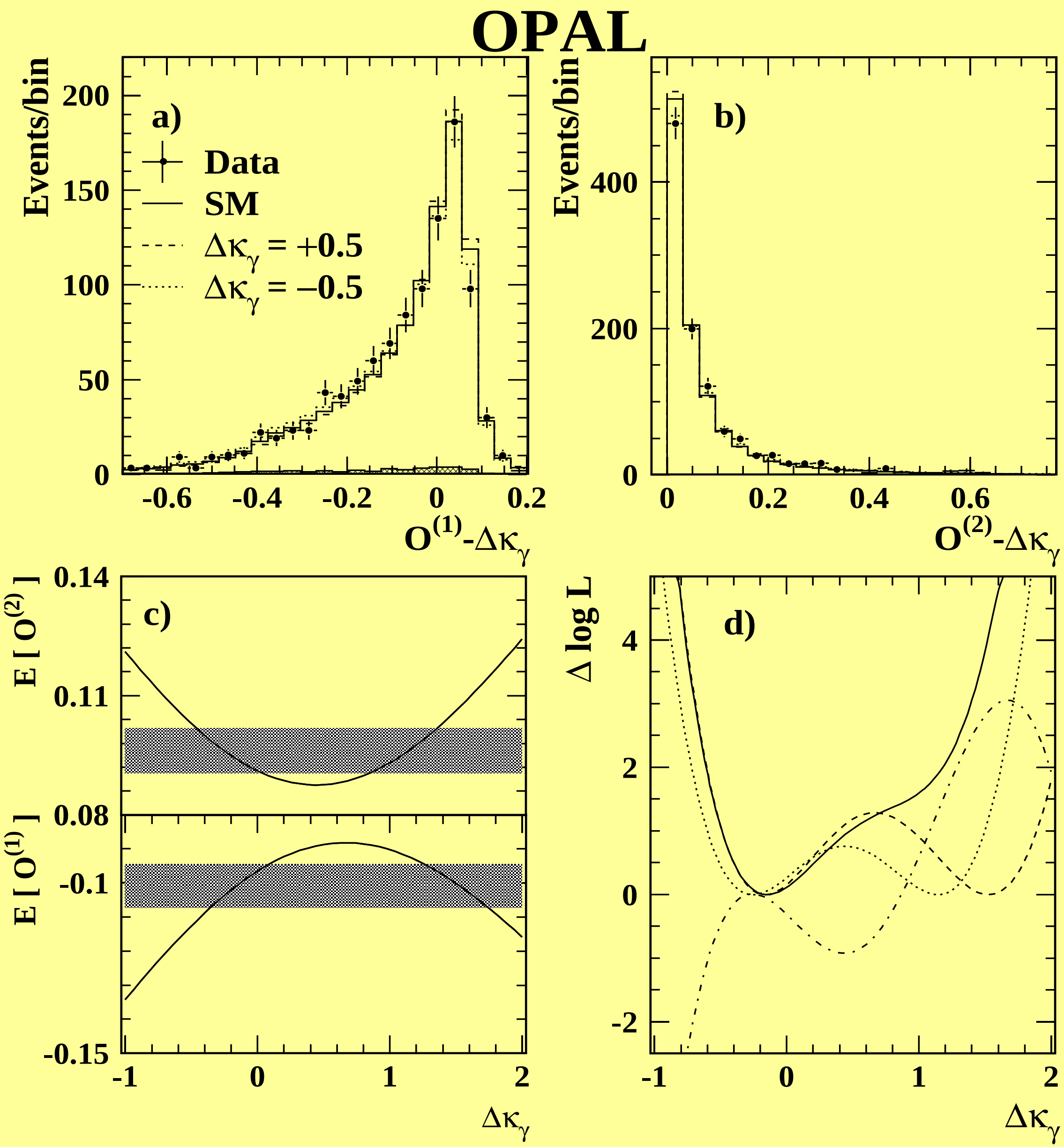
DELPHI and L3 are using binned maximum likelihood.

Example :

OO analysis of $\Delta\kappa_\gamma$

using 189 GeV data

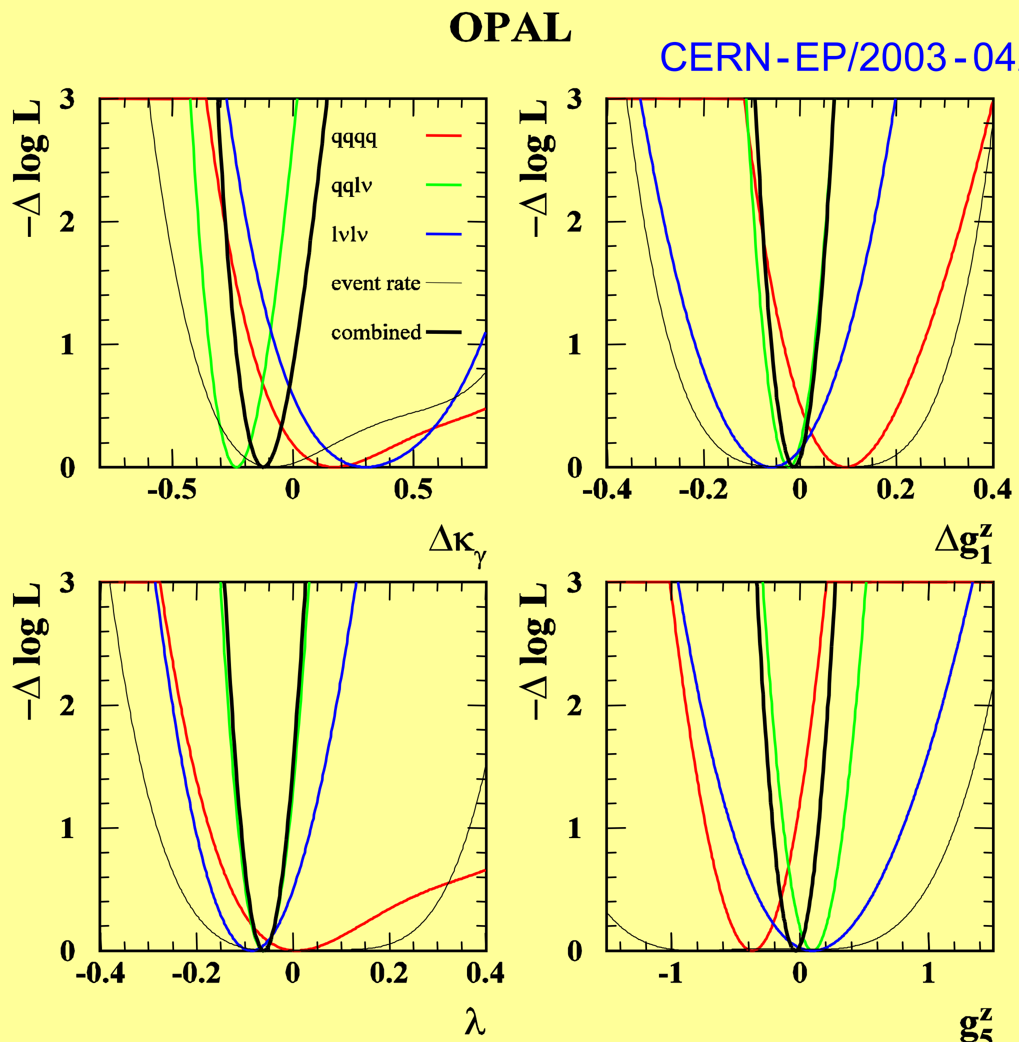
EPJ C19 (2001) 1



TGC results from W-Pairs

Systematic error sources:

CERN-EP/2003-042



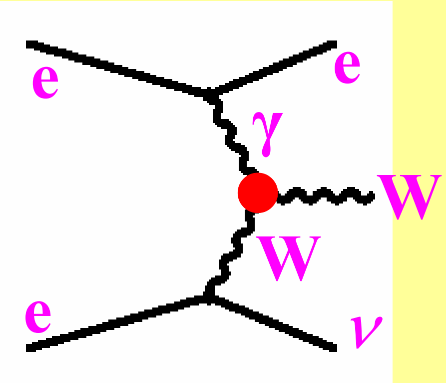
- Hadronization *
- Background
- $O(\alpha)$ correction *
- Detector simulation
- TGC matrix element
- ISR, FSR
- $\sqrt{s}$, M_W
- Bose-Einstein correlations *
- Color reconnection *
- σ_{WW} prediction *
- Luminosity
- MC statistics

*correlated between experiments

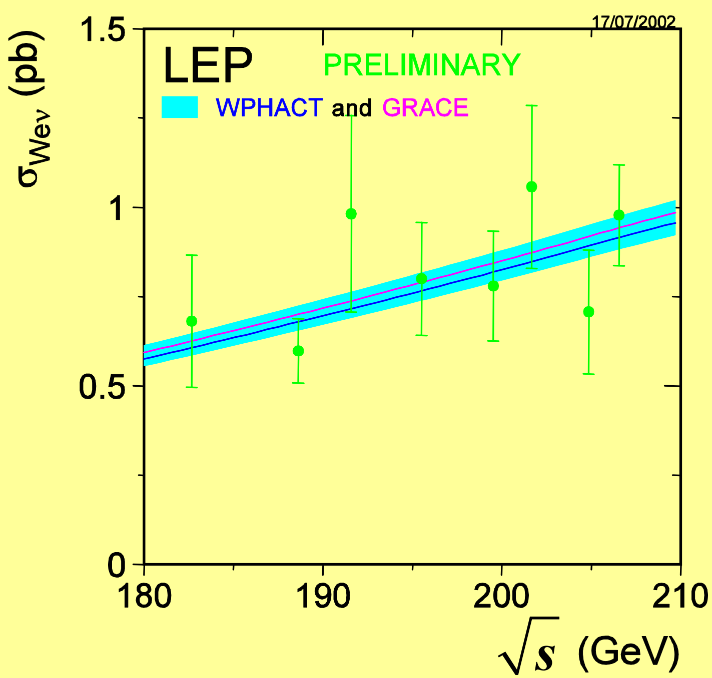
combined systematic error $\simeq (0.5-0.7)\times$stat. error

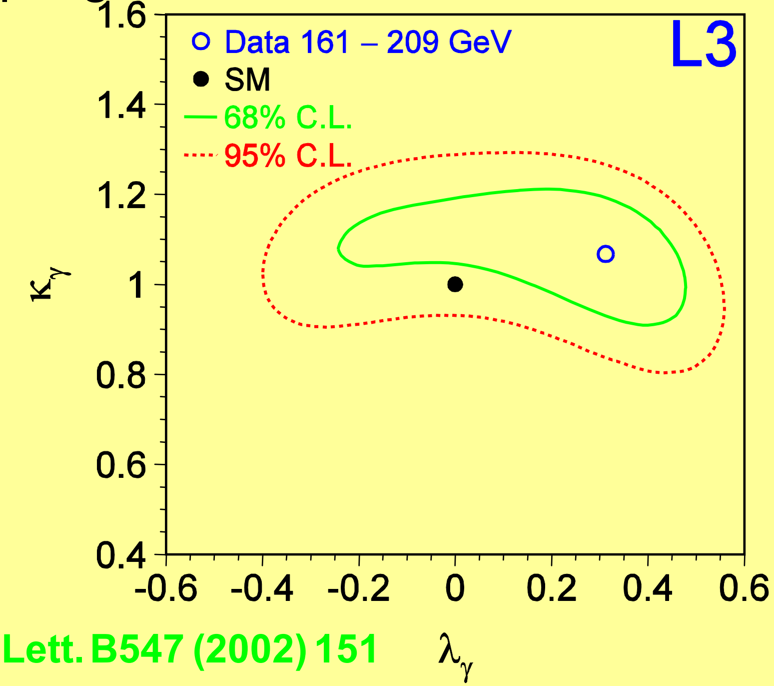
TGC from Single W Events

Final state	Fraction	Signature	Efficiency	Purity
$q\bar{q}e\nu$	67%	2 jets + $\not{E}$	$(30-50)\%$	$(20-50)\%$
$l\nu e\nu$	33%	$1\,\ell + \not{E}$	$(40-60)\%$	$(45-80)\%$



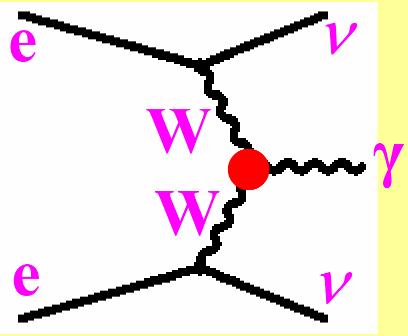
Sensitive only to WWγ coupling, but the high WW background is sensitive also to WWZ couplings.





Phys. Lett. B547 (2002) 151

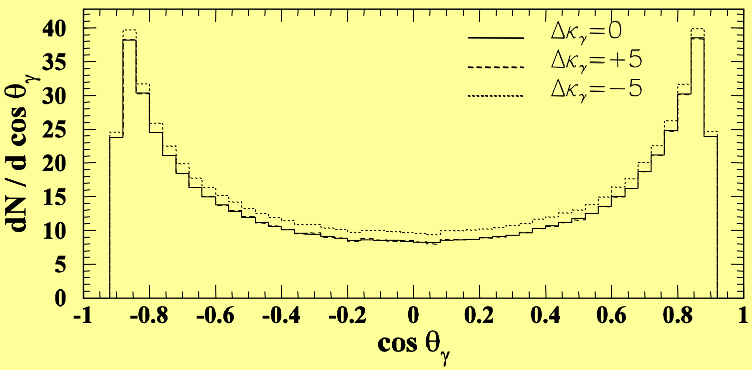
TGC from Single Photon Event

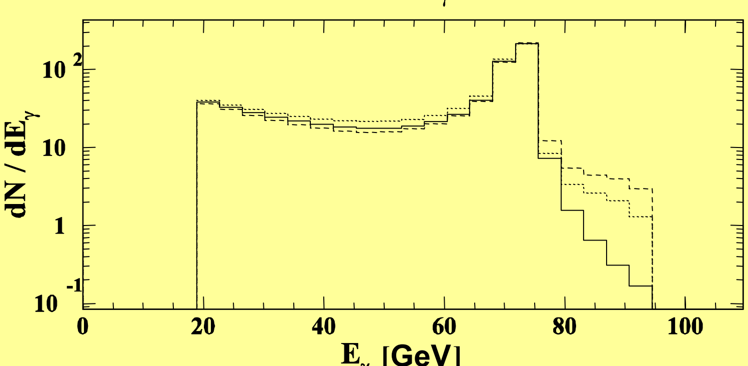


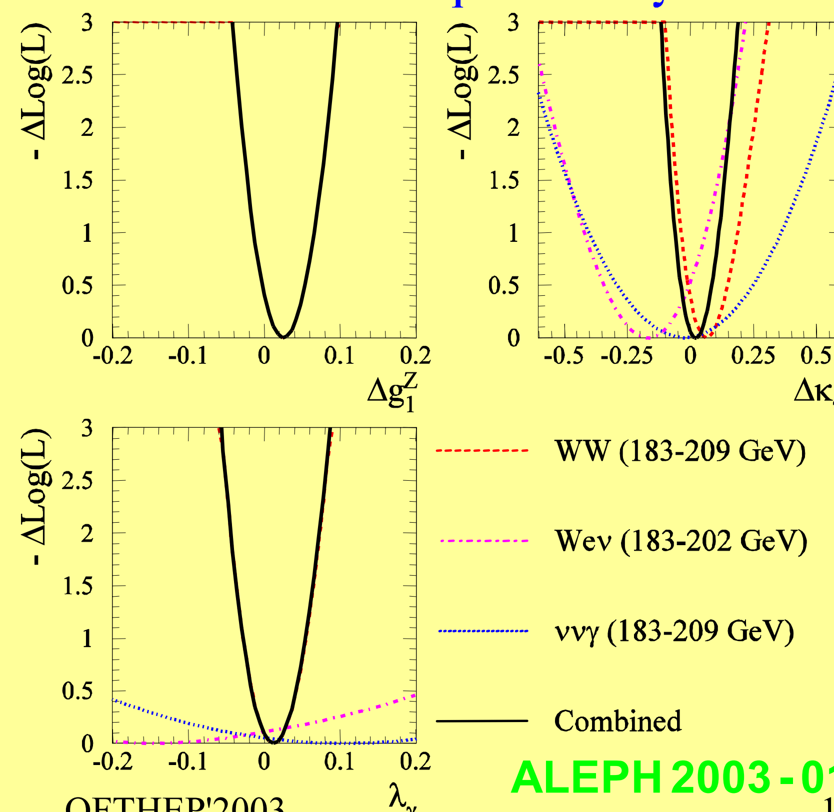
Sensitivity only to **WWγ** coupling, much lower than single W but no TGC-dependent background.

Use event-rate and E_γ, $\cos\theta_\gamma$ distributions.

ALEPH preliminary



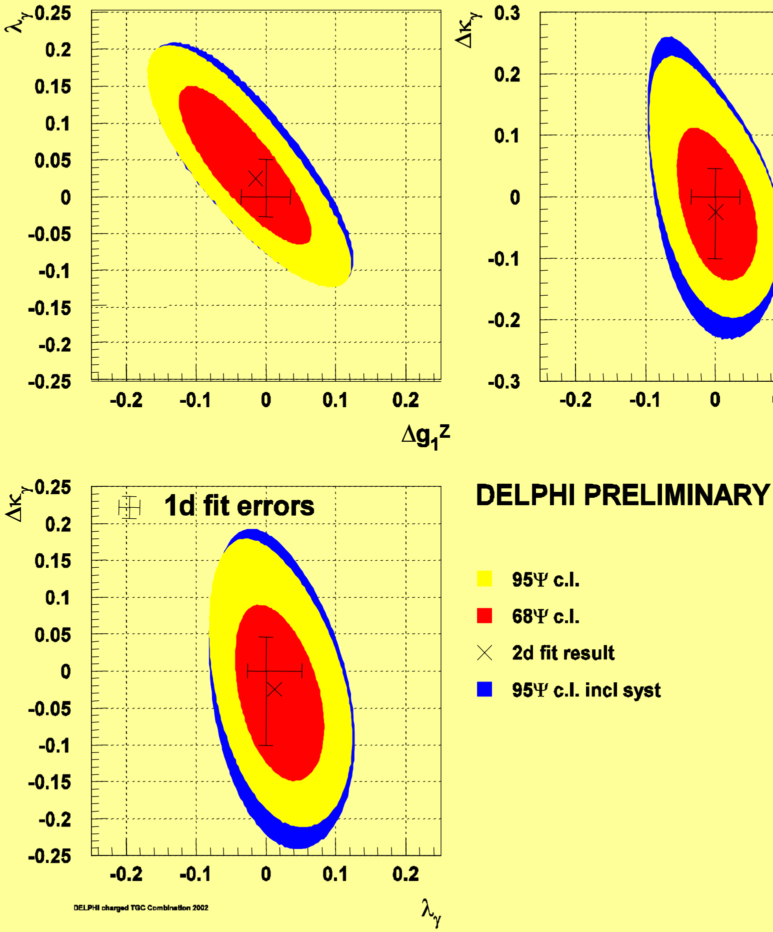




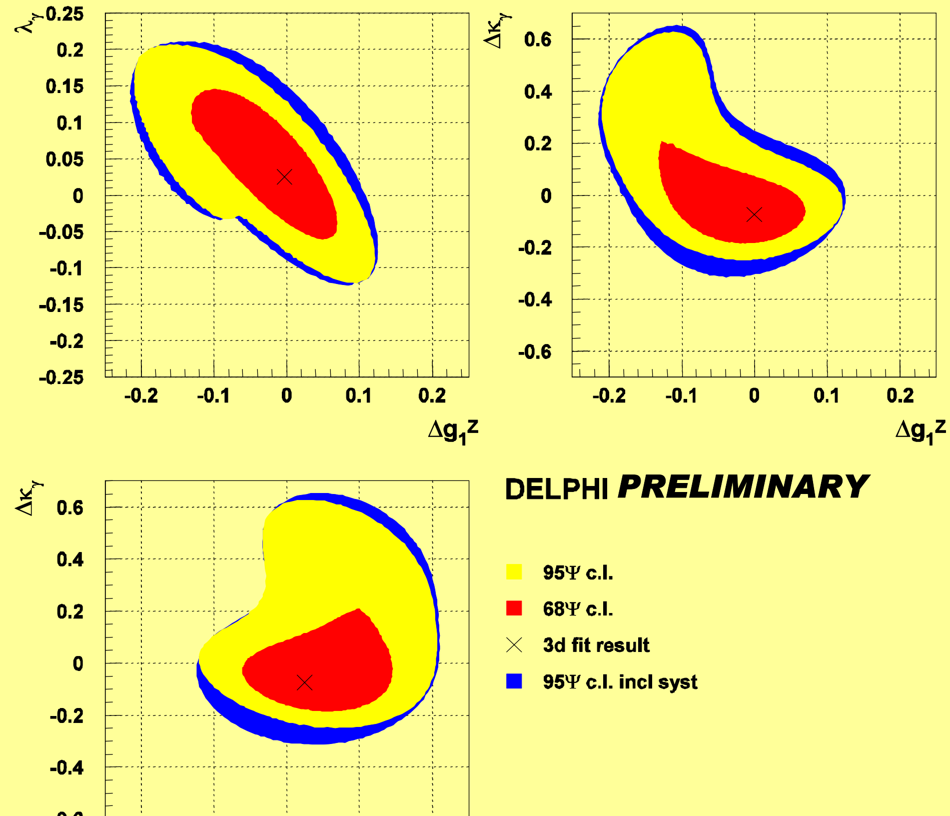
ALEPH 2003 - 015

CC TGC Results

2-parameter fits



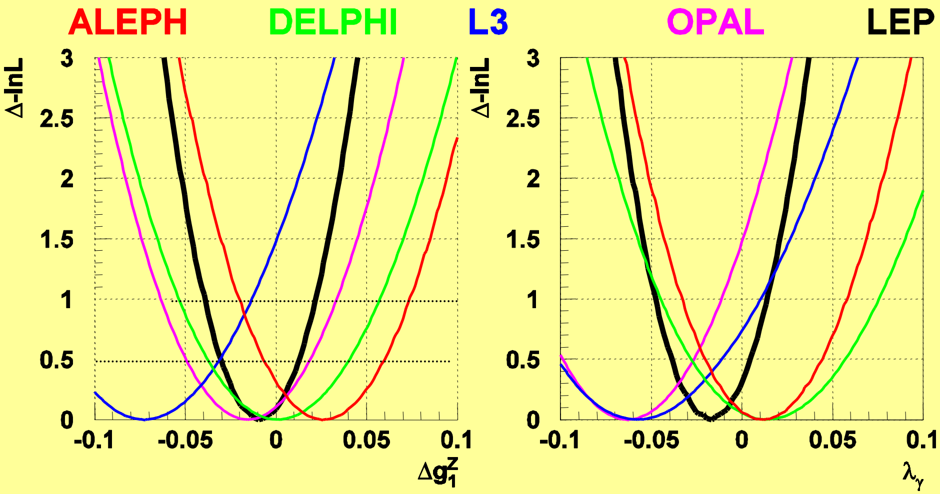
3-parameter fits

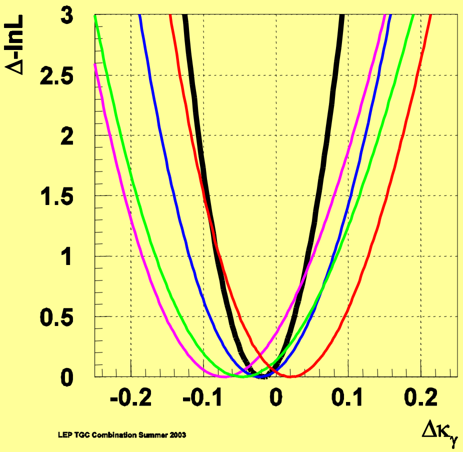


DELPHI 2003-051

Combined LEP CC TGC Results

1-parameter fits





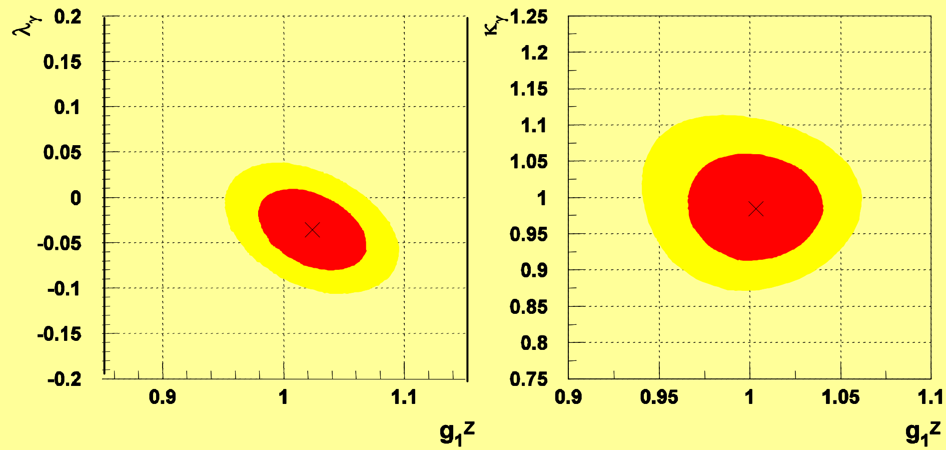
LEP preliminary

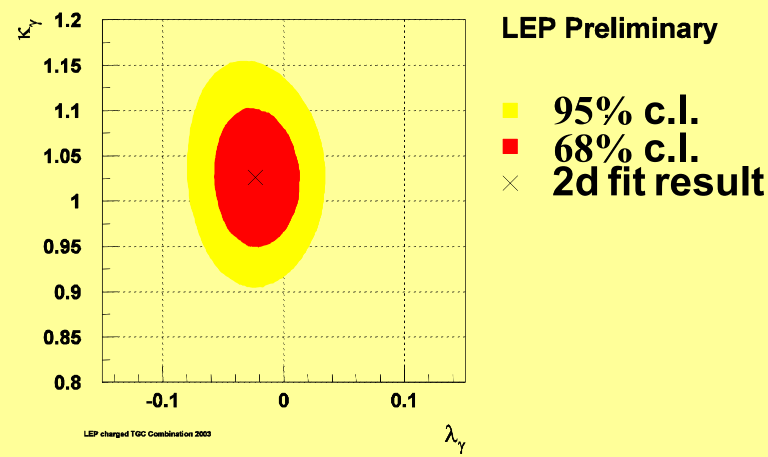
$$\Delta\kappa_\gamma = -0.016^{+0.042}_{-0.047}$$

$$\lambda_\gamma = -0.016^{+0.021}_{-0.023}$$

$$\Delta g_1^Z = -0.009^{+0.022}_{-0.021}$$

2-parameter fits

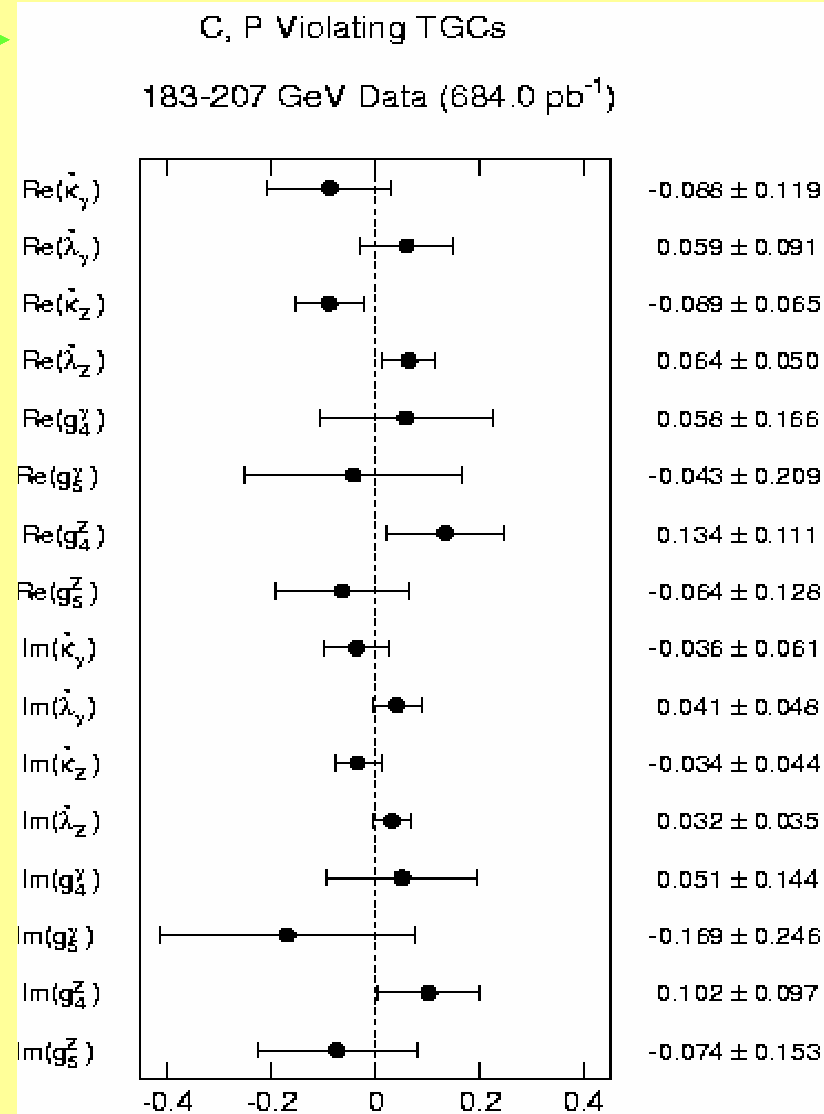




CC CP-Violating TGCs

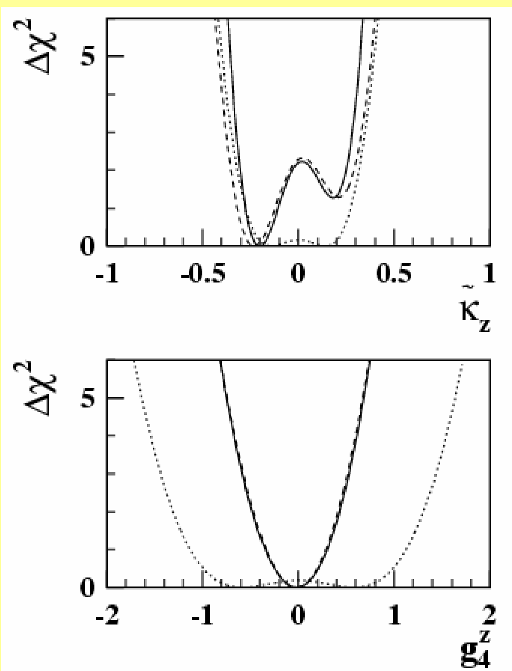
Aleph measurement (Aleph 2003-015): →

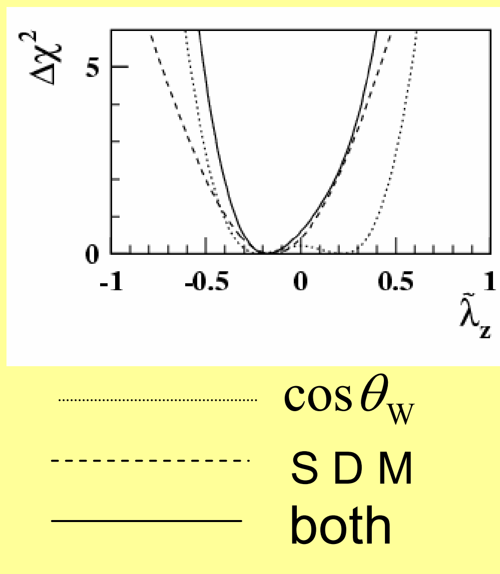
Assume no relations between the TGCs.
Fit for each coupling, assuming that all others vanish.



Opal measurement:

Use spin density matrix for 189 GeV data:



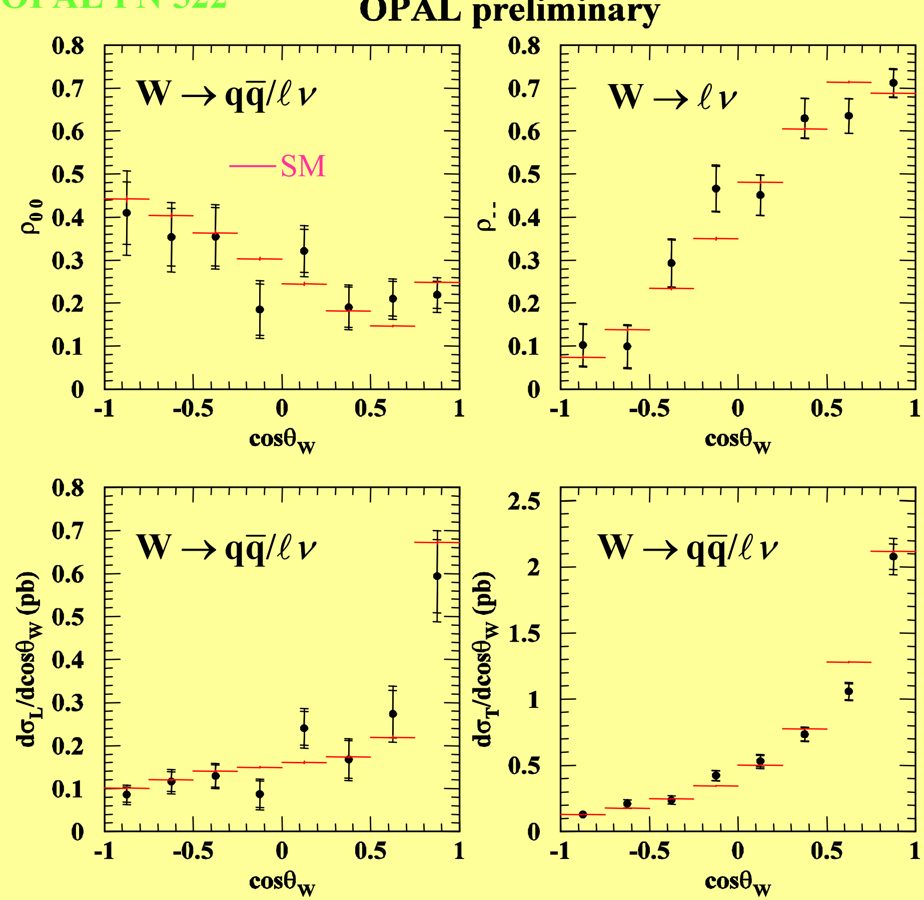


CERN-EP-2000-113

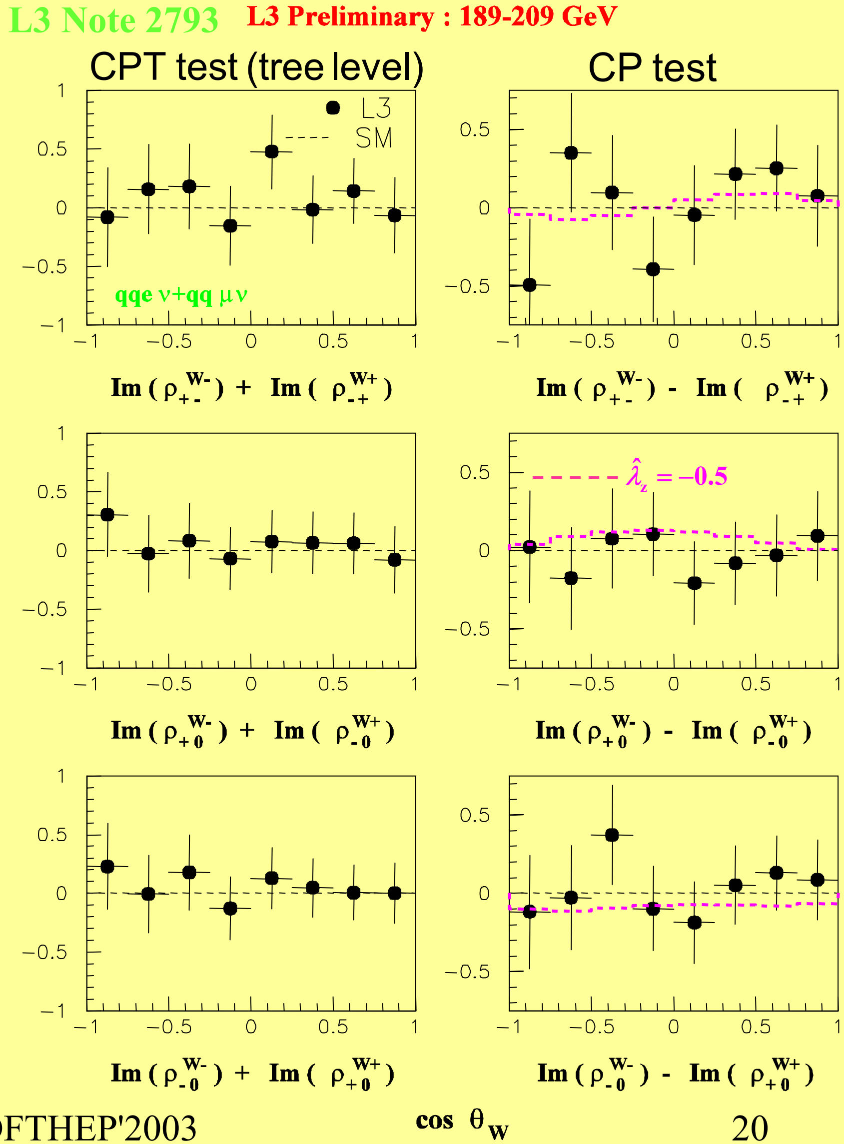
WW Spin Density Matrix (SDM)

$$\rho_{\tau_-\tau'_-}(\cos\theta_W) = \sum_{\lambda,\tau_+} F^{(\lambda)}_{\tau_-\tau_+} (F^{(\lambda)}_{\tau'_-\tau_+})^* \Big/ \sum_{\lambda,\tau_-\tau_+} \left|F^{(\lambda)}_{\tau_-\tau_+}\right|^2$$

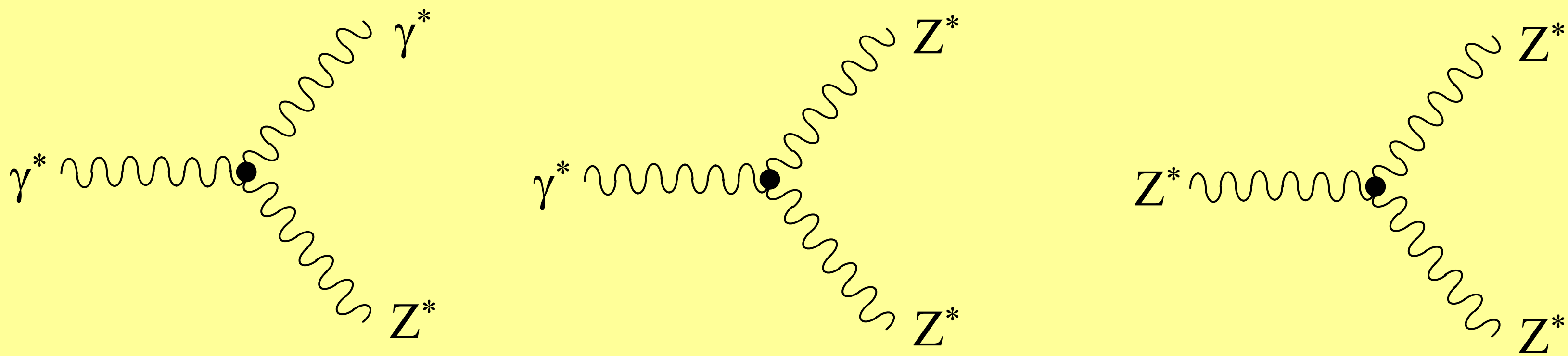
OPAL PN 522



L3 Note 2793



Neutral Triple Gauge Boson Couplings



Most general approach yields 15 CP-conserving + 29 CP-violating couplings

(Gounaris, Layssac, Renard, Phys. Rev. D62 (2000) 073013)

At LEP2 we consider only processes where the final bosons are on mass shell.

We separate :

$e^+e^- \rightarrow Z\gamma$

$\gamma^*\gamma Z, Z^*\gamma Z$

8 h-couplings →

$e^+e^- \rightarrow ZZ$

$\gamma^* ZZ, Z^* ZZ$

← 4 f-couplings

(Hagiwara, Peccei, Zeppenfeld, Hikasa, Nucl. Phys. B282 (1987) 253)

h-couplings from $e^+e^- \longrightarrow Z\gamma$

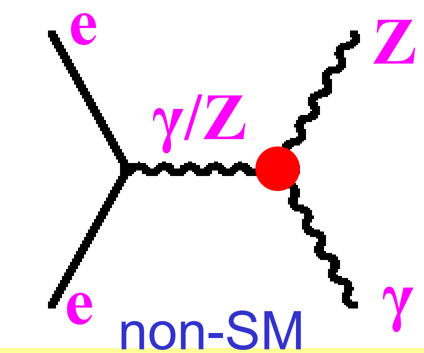
$$iΓ^{\alpha\beta\mu}_{Z\gamma V}(q_1 q_2 P) = \frac{P^2 - m_V^2}{m_Z^2} \times$$

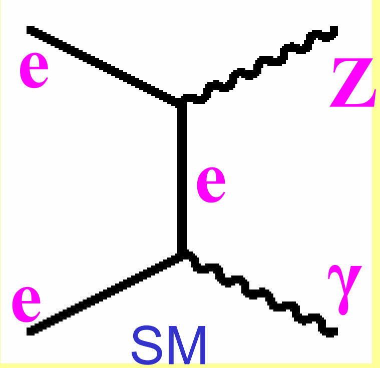
$$\{h_1^V (q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}) + \frac{h_2^V}{m_Z^2} P^\alpha (P \cdot q_2 g^{\mu\beta} - q_2^\mu P^\beta)$$

} CP-violating

$$+ h_3^V \varepsilon^{\mu\alpha\beta\nu} q_{2\nu} + \frac{h_4^V}{m_Z^2} P^\alpha \varepsilon^{\mu\beta\nu\sigma} P_\nu q_{2\sigma}\}$$

} CP-conserving



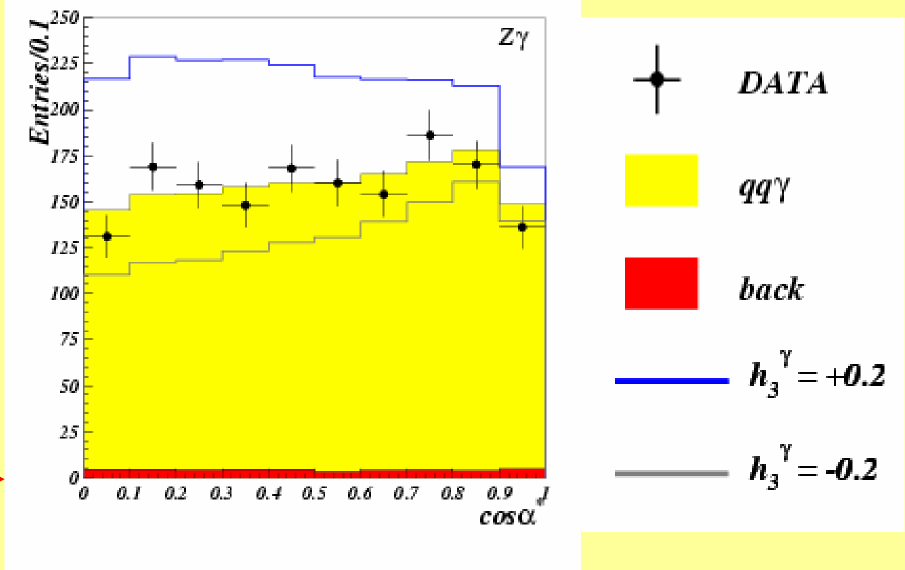


Use: $Z \rightarrow q\bar{q}, \nu\bar{\nu}$
event and angular distributions

e.g.:

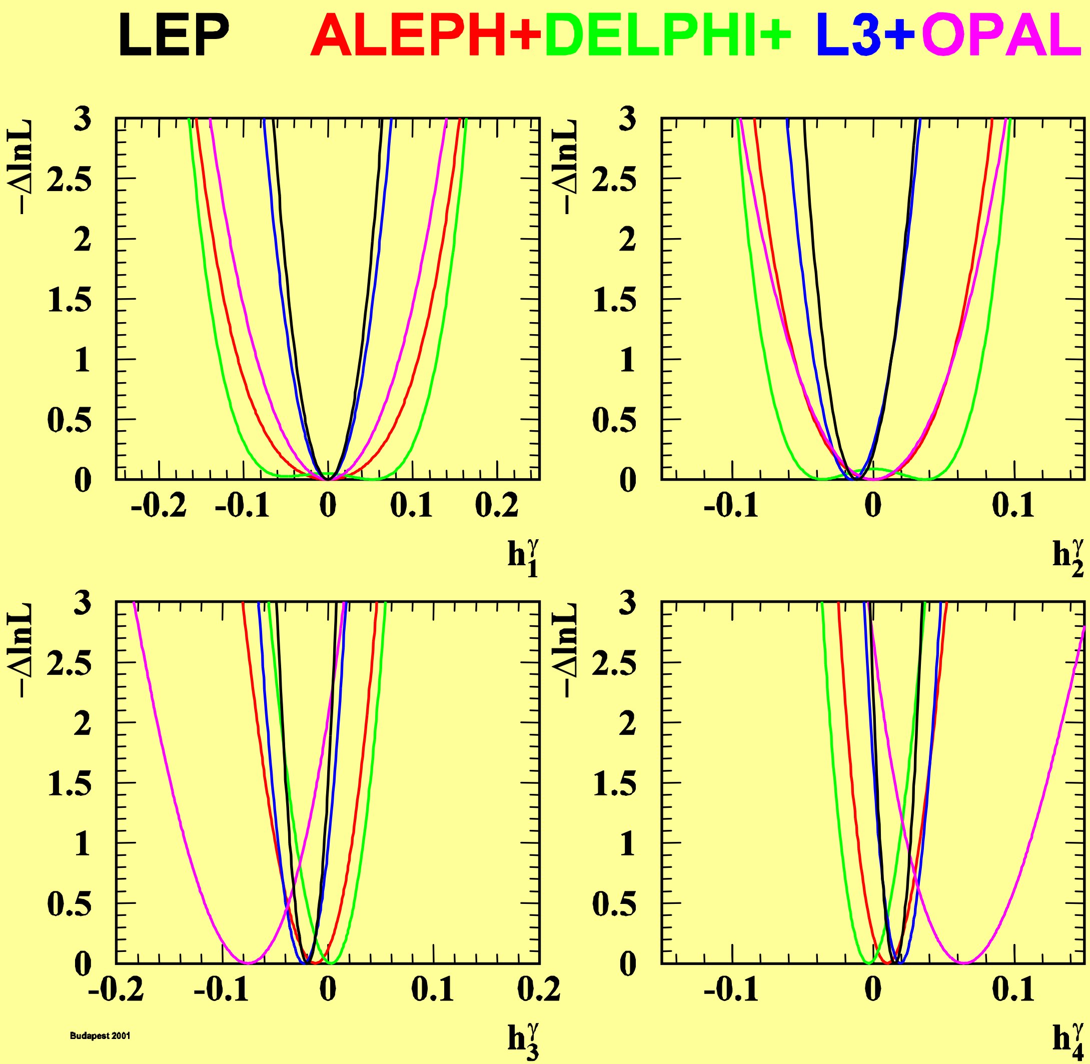
α^*- Z decay angle in its rest-frame

DELPHI 2001-097 CONF 525



h^{γ} results – 1 parameter fits

Preliminary



$-0.056 < h_1^{\gamma} < 0.055$

$-0.045 < h_2^{\gamma} < 0.025$

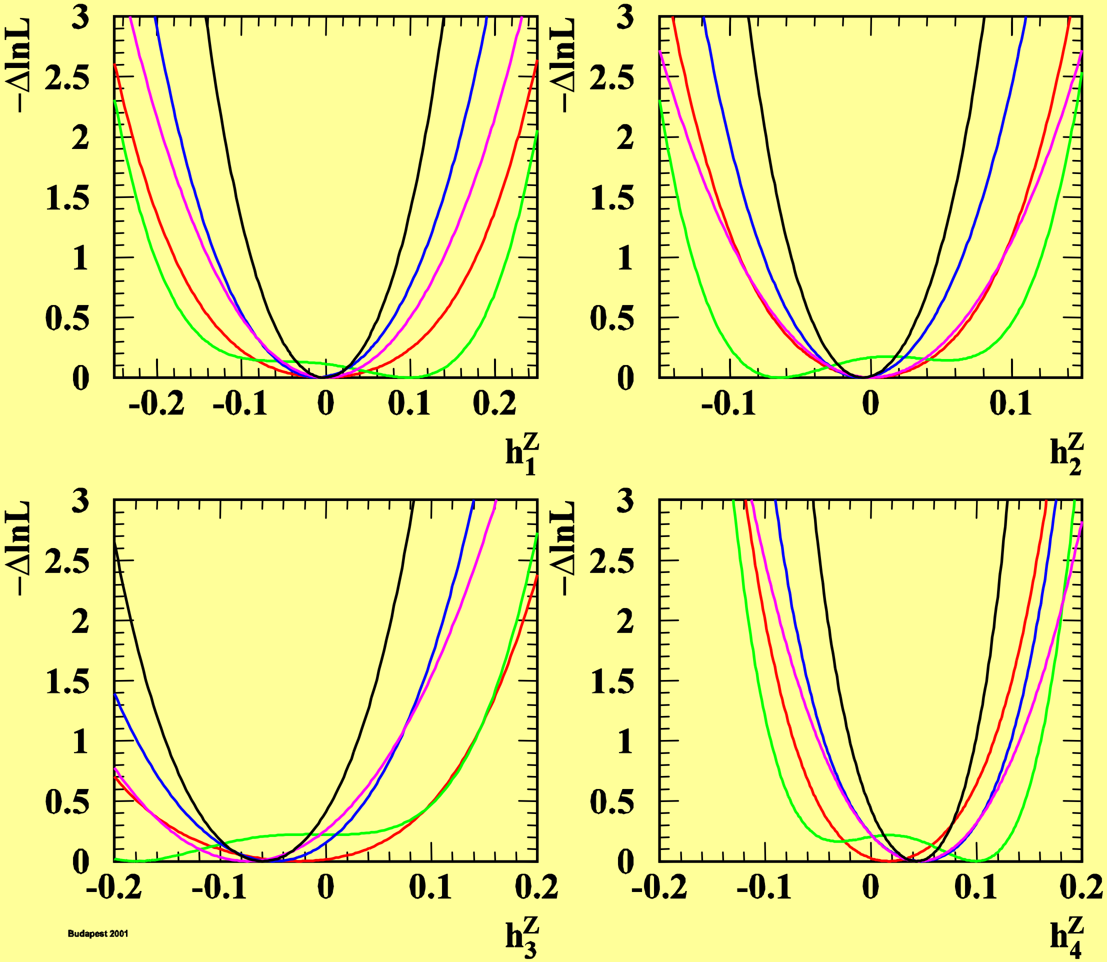
$-0.049 < h_3^{\gamma} < -0.008$

$-0.002 < h_4^{\gamma} < 0.034$

h^Z results – 1 parameter fits

Preliminary

LEP **ALEPH+DELPHI+ L3+OPAL**



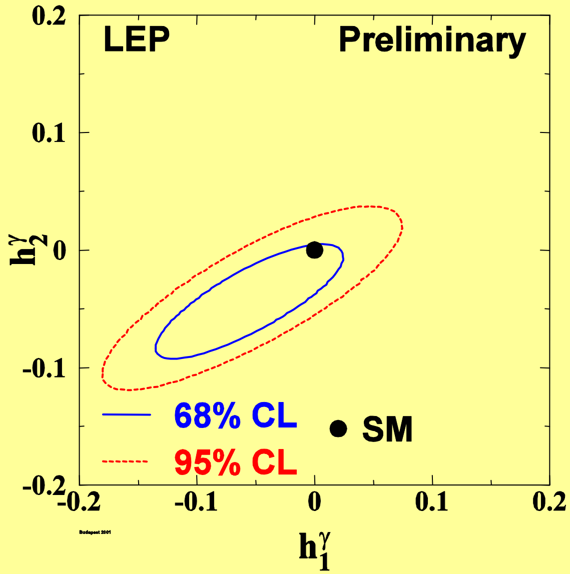
$-0.13 < h_1^Z < 0.13$

$-0.078 < h_2^Z < 0.071$

$-0.20 < h_3^Z < -0.07$

$-0.05 < h_4^Z < 0.12$

h results – 2 parameter fits



$-0.16 < h_1^\gamma < 0.05$

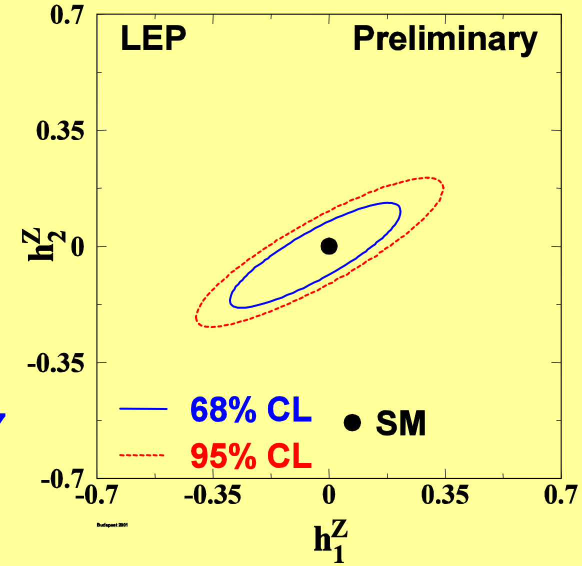
$-0.11 < h_2^\gamma < 0.02$

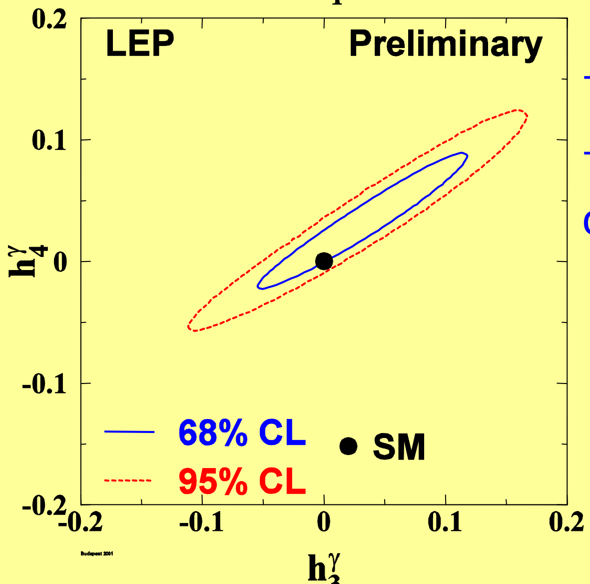
correlation = 0.79

$-0.35 < h_1^Z < 0.28$

$-0.21 < h_2^Z < 0.17$

correlation = 0.77





$-0.08 < h_3^\gamma < 0.14$

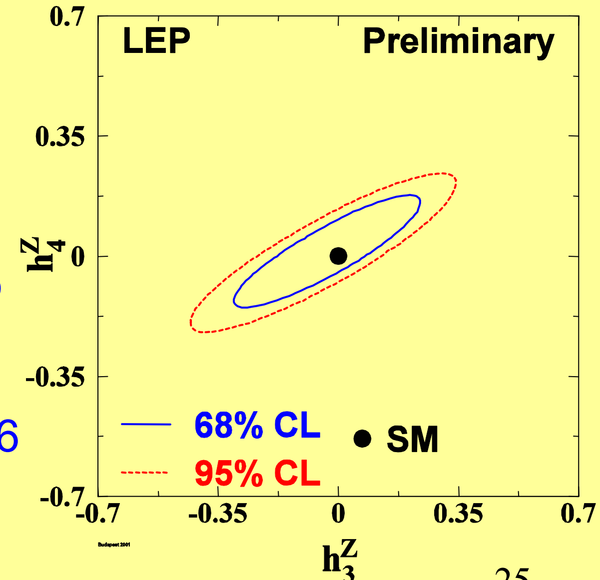
$-0.04 < h_4^\gamma < 0.11$

correlation = 0.97

$-0.37 < h_3^Z < 0.29$

$-0.19 < h_4^Z < 0.21$

correlation = 0.76

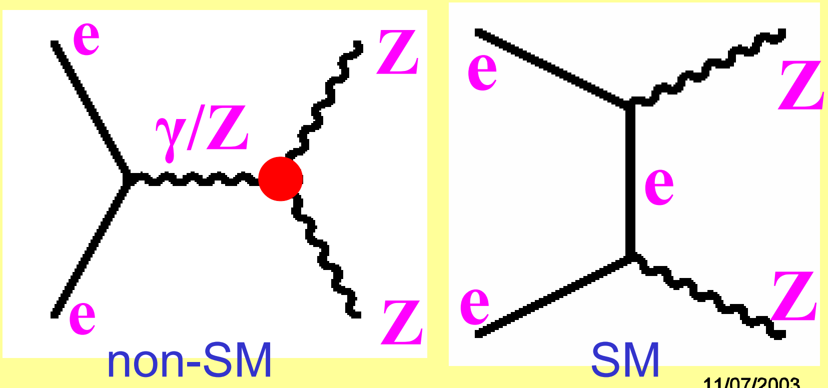


f couplings from $e^+e^- \longrightarrow ZZ$

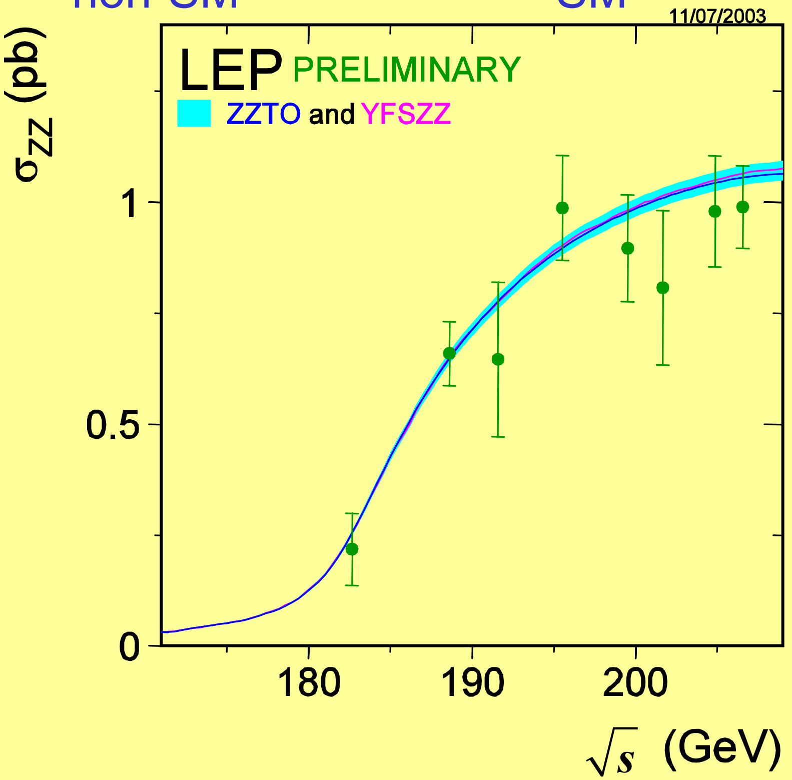
$$\Gamma^{\alpha\beta\mu}_{ZZV}(q_1,q_2,P) = \frac{P^2-m_V^2}{m_Z^2}\times$$

$$\{if_4^V(P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha})$$ CP-violating

$$+ if_5^V \varepsilon^{\mu\alpha\beta\nu}(q_1-q_2)_\nu\}$$ CP-conserving



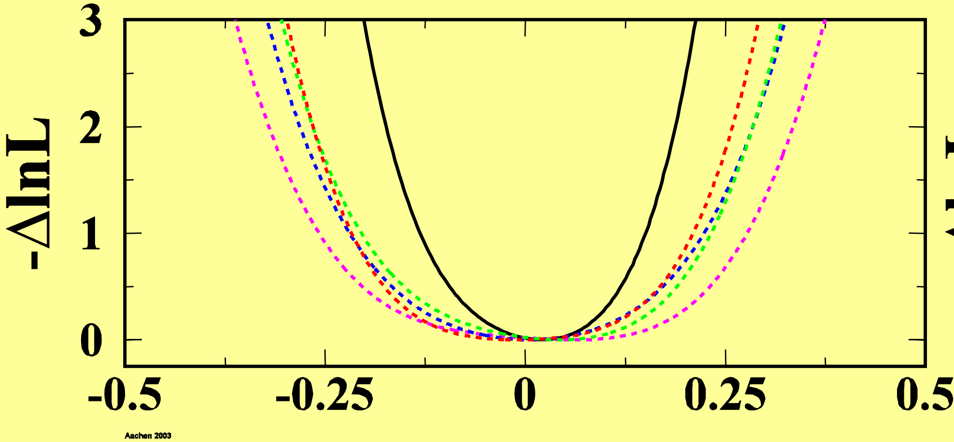
Final state	Fraction	Signature	Efficiency	Purity
$q\bar{q}q\bar{q}$	49%	4 jets	30%	(15 - 35)%
$q\bar{q}\nu\bar{\nu}$	28%	2 jets + $\not{E}$	30%	60%
$q\bar{q}l^+l^-$	14%	2 jets + 2ℓ's	(50 - 80)%	(80 - 90)%
$l^+l^-\nu\bar{\nu}$	4%	2ℓ's + $\not{E}$	30%	(45 - 55)%
$l^+l^-l^+l^-$	1%	4ℓ's	(40 - 60)%	(60 - 80)%



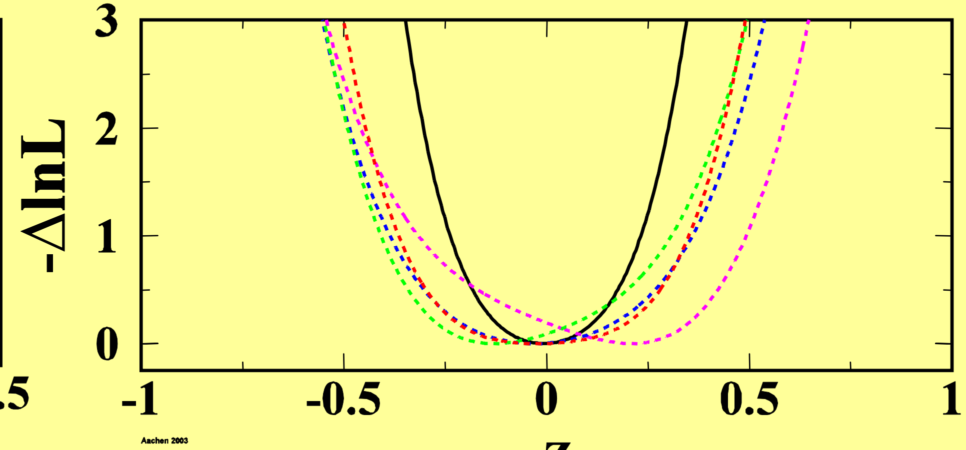
Extract anomalous couplings from total event rate and angular distributions.

f-results – 1 parameter fits

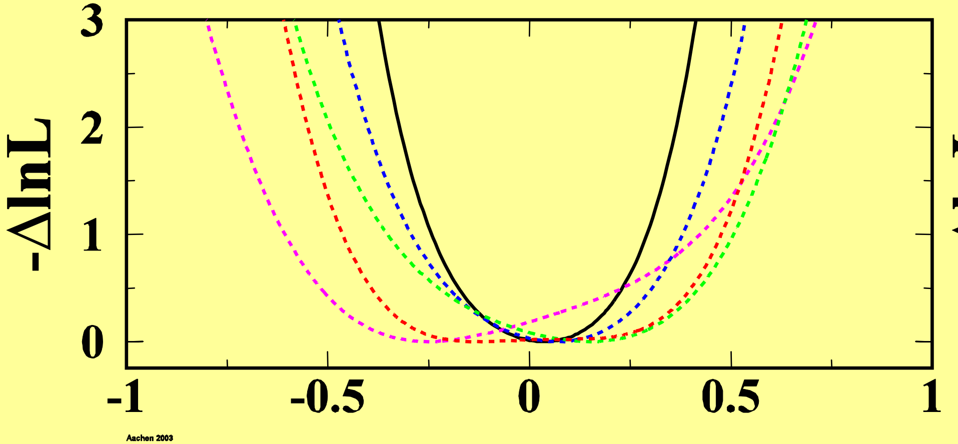
LEP **ALEPH+DELPHI+L3+OPAL**



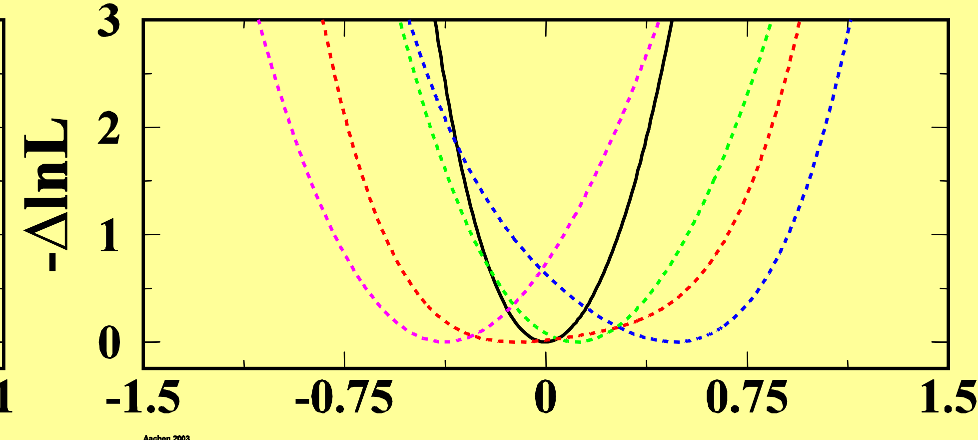
$-0.17 < f_4^{\gamma} < 0.19$



$-0.30 < f_4^{Z} < 0.30$

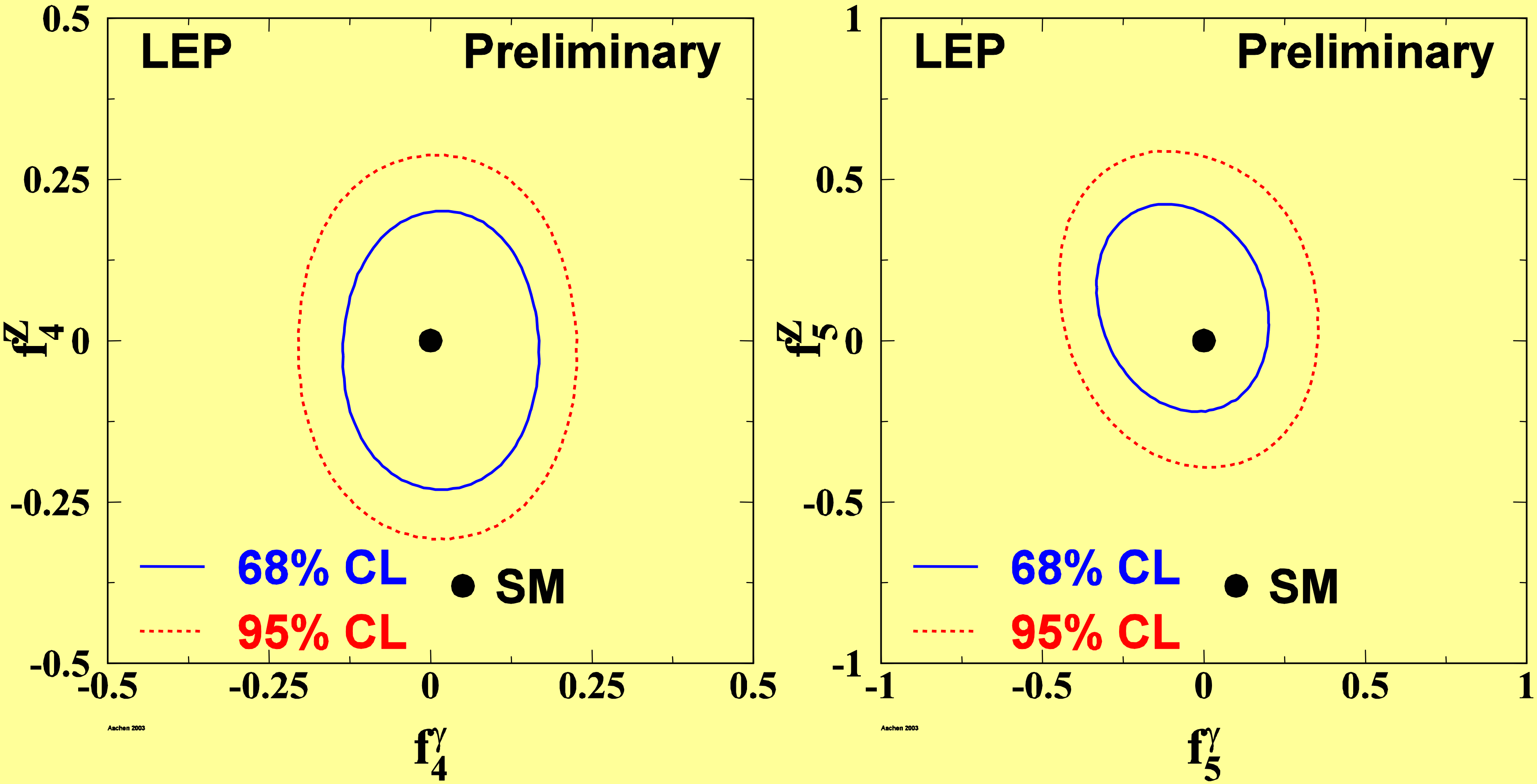


$-0.32 < f_5^{\gamma} < 0.36$



$-0.34 < f_5^{Z} < 0.38$

f-results – 2 parameter fits



Quartic Gauge Couplings

- No hope to measure SM QGCs
- Consider only anomalous couplings which are genuine QGCs – they do not contribute to triple gauge vertices.

$$L_6^0 = -\frac{e^2}{16}\frac{a_0}{\Lambda^2} F^{\mu\nu} F_{\mu\nu} \vec{W}^{\alpha} \vec{W}_{\alpha}$$

$$L_6^c = -\frac{e^2}{16}\frac{a_c}{\Lambda^2} F^{\mu\alpha} F_{\mu\beta} \vec{W}^{\beta} \vec{W}_{\alpha}$$

$WW\gamma\gamma$, $ZZ\gamma\gamma$ terms (CP - conserving)

G.Belanger, F.Boudjema Phys.Lett. B288 (1992) 201

$$L_6^n = -\frac{e^2}{16}\frac{a_n}{\Lambda^2} \vec{W}_{\mu\alpha} \cdot \left(\vec{W}_{\nu} \times \vec{W}^{\alpha} \right) F^{\mu\nu}$$

$WWZ\gamma$ term (CP - violating)

W.J.Stirling, A.Werthenbach, Phys. Lett. C14 (2000) 103

$$\left(W_{\mu}^{(3)} = Z^{\mu} / \cos\theta_w \right)$$

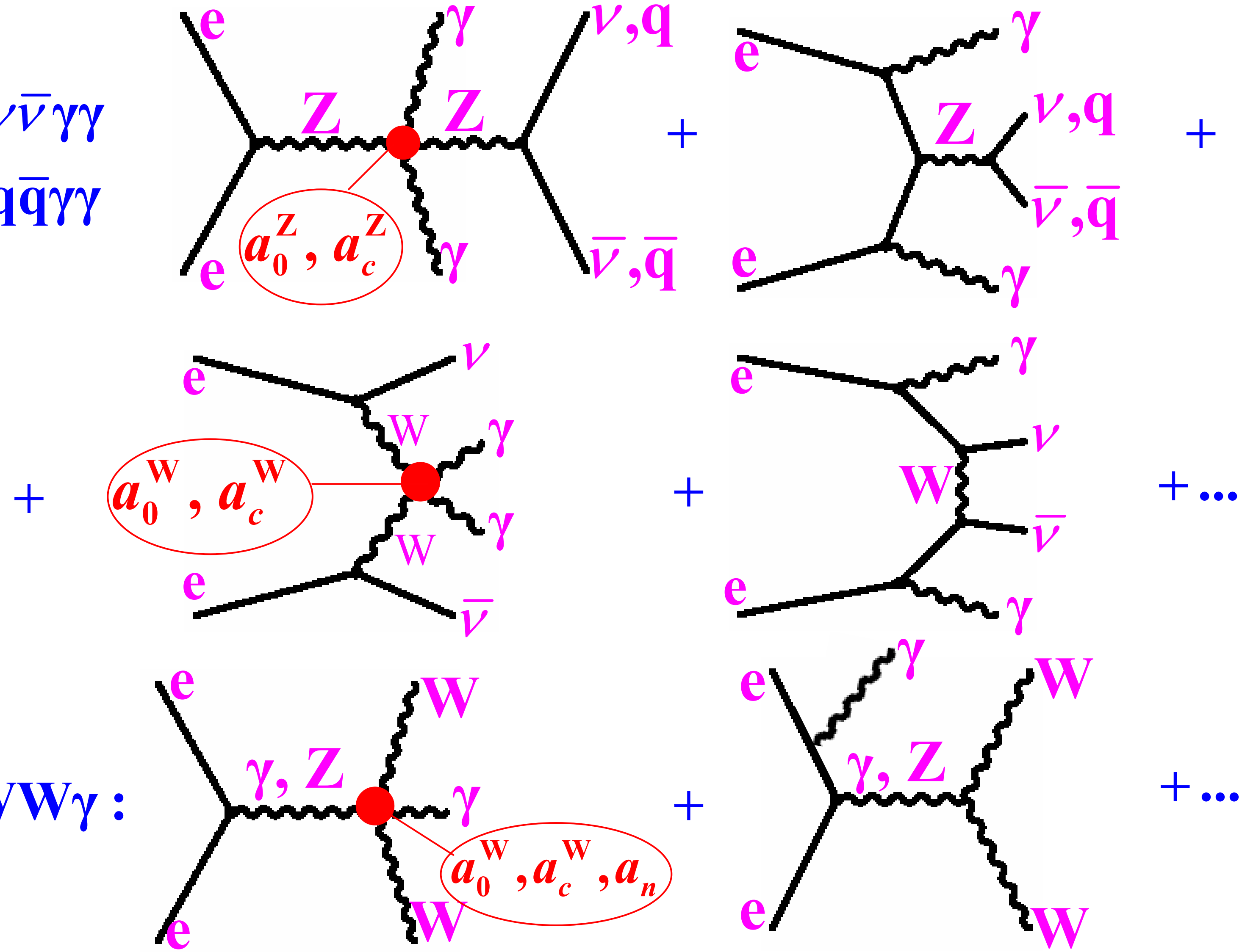
In a more general approach: (G.Belanger *et al.*, Eur.Phys.J. C13 (2000) 283)

Different couplings for $WW\gamma\gamma$ (a_0^W, a_c^W) and $ZZ\gamma\gamma$ (a_0^Z, a_c^Z)

LEP Physics Processes (QGC)

$$e^+e^- \rightarrow \begin{cases} \nu\bar{\nu}\gamma\gamma \\ q\bar{q}\gamma\gamma \end{cases}$$

$$e^+e^- \rightarrow WW\gamma :$$

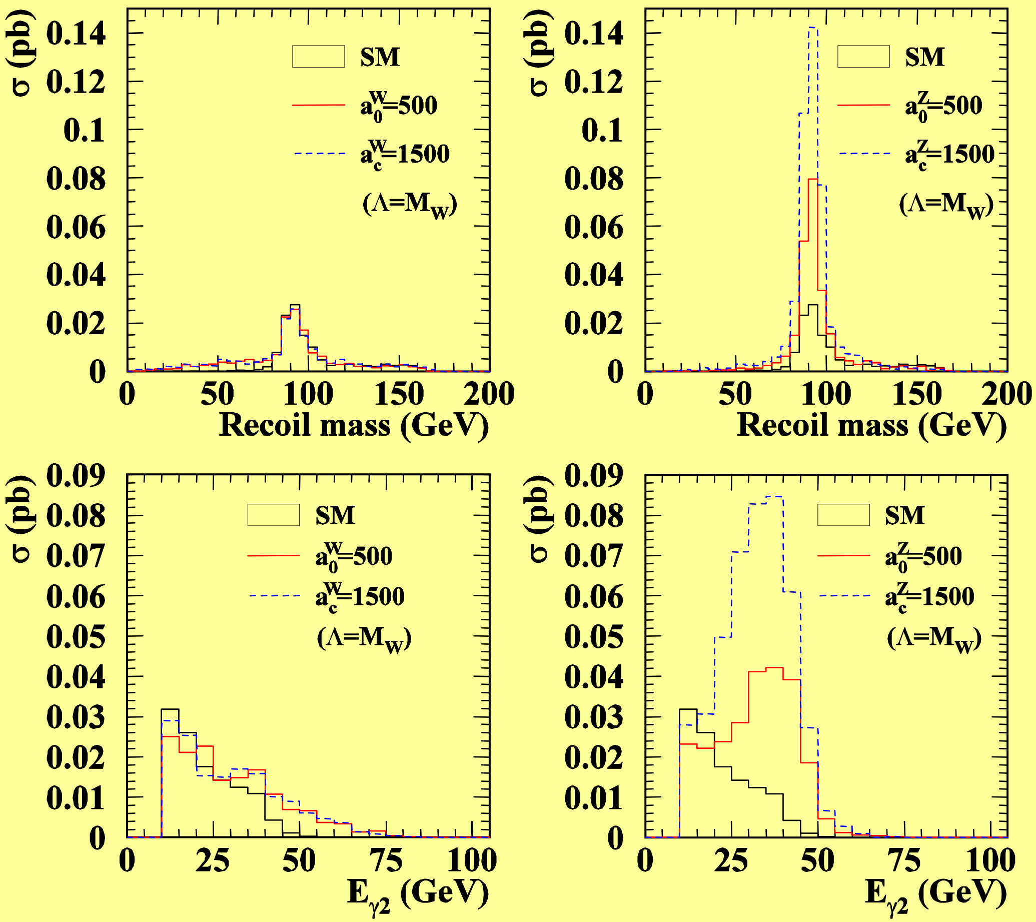


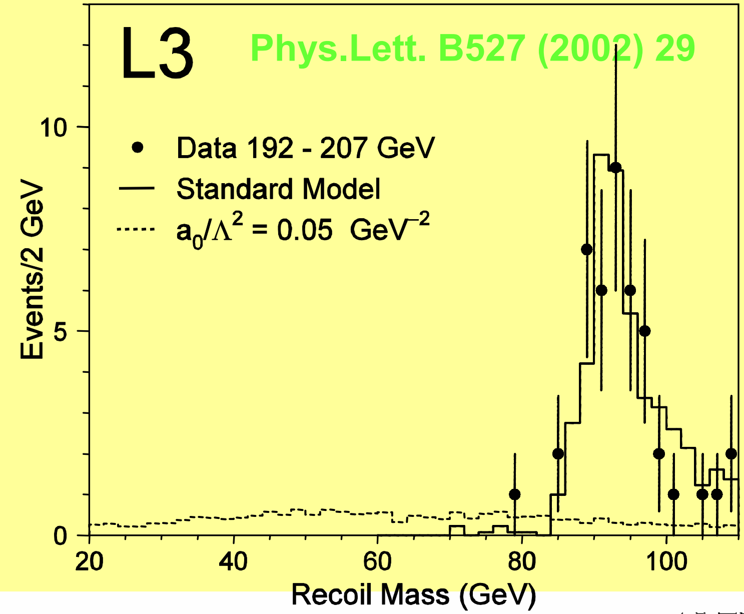
$e^+e^- \to \nu\bar{\nu}\gamma\gamma$

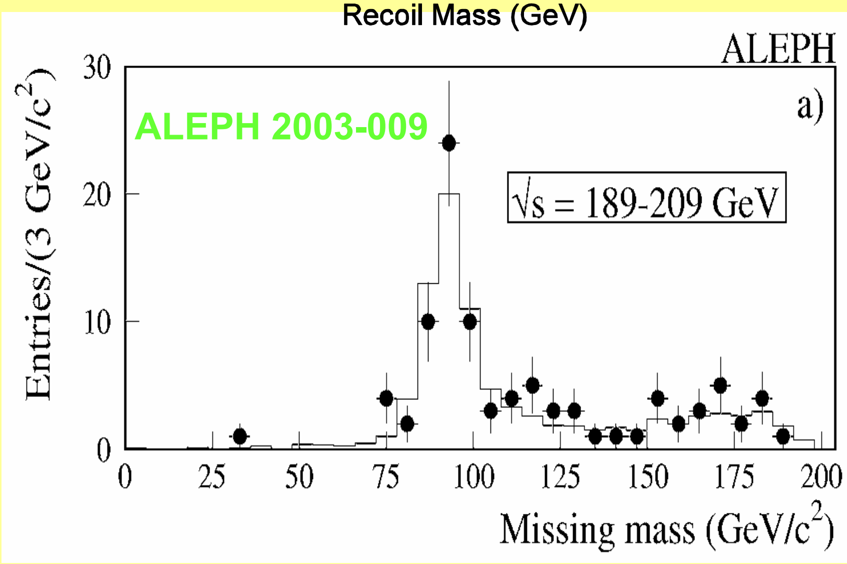
Analyses by Aleph, OPAL, L3

Sensitivity to anomalous QGC:

OPAL PN510



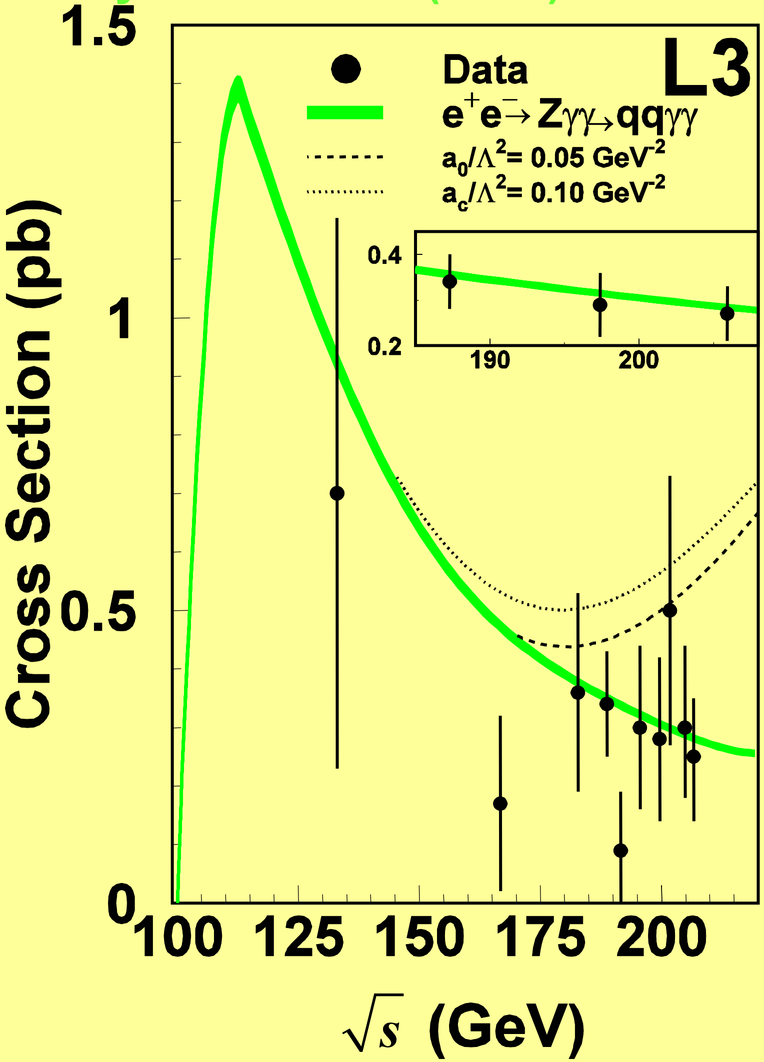


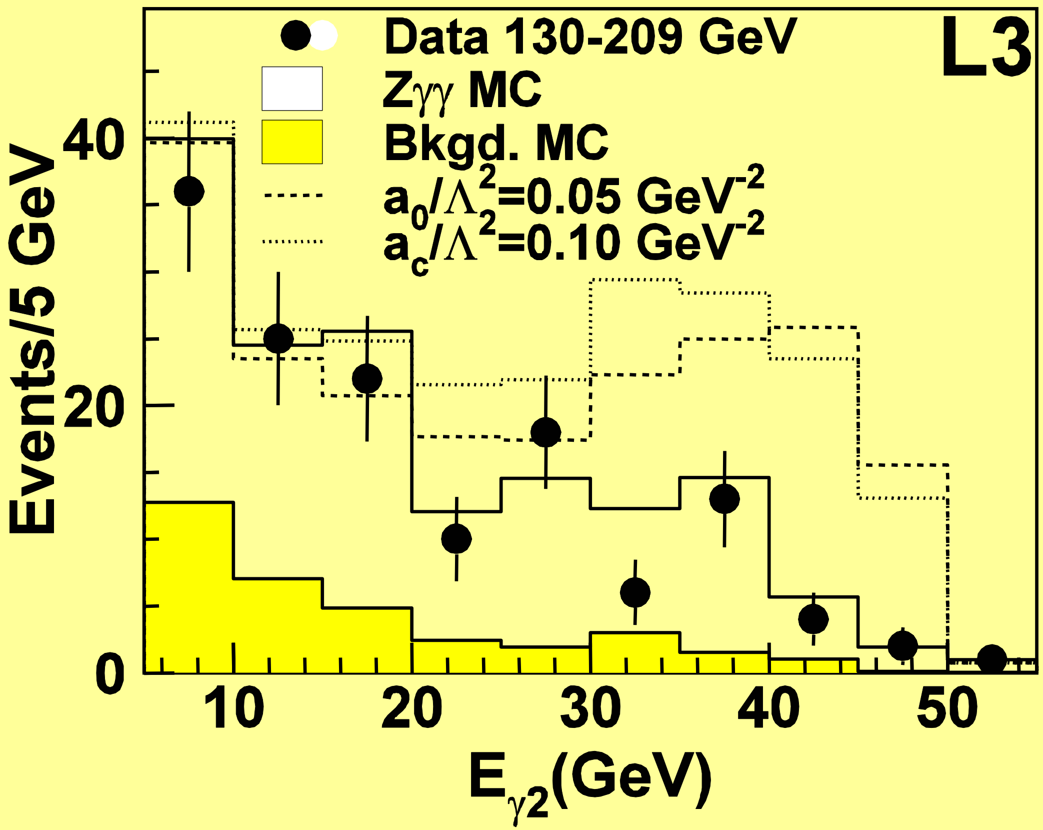


L3 analysis of $e^+e^- \to q\bar{q}\gamma\gamma$

Phys.Lett. B540 (2002) 43

Signal definition:
$E_\gamma > 5\,\mathrm{GeV}$
$|\cos\theta_\gamma| < 0.97$
$\cos\theta_{\gamma q} < 0.98$
$|\sqrt{s'} - m_Z| < 2\Gamma_Z$



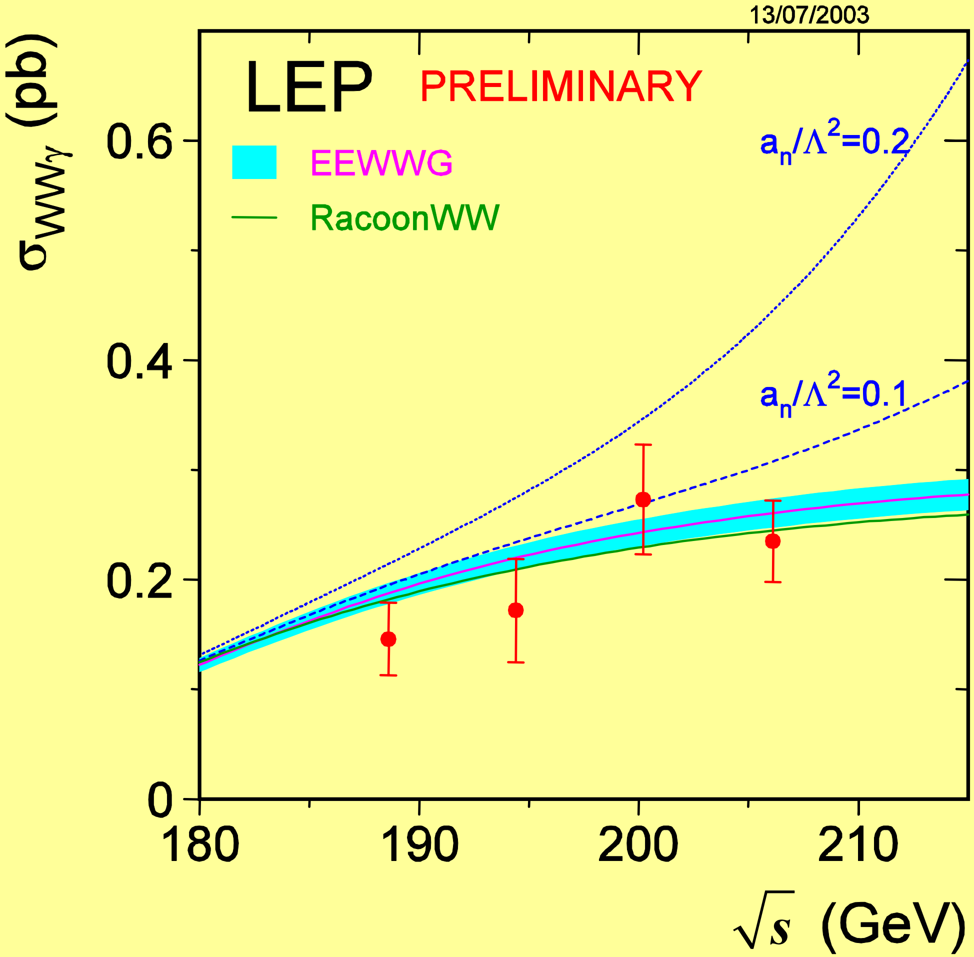


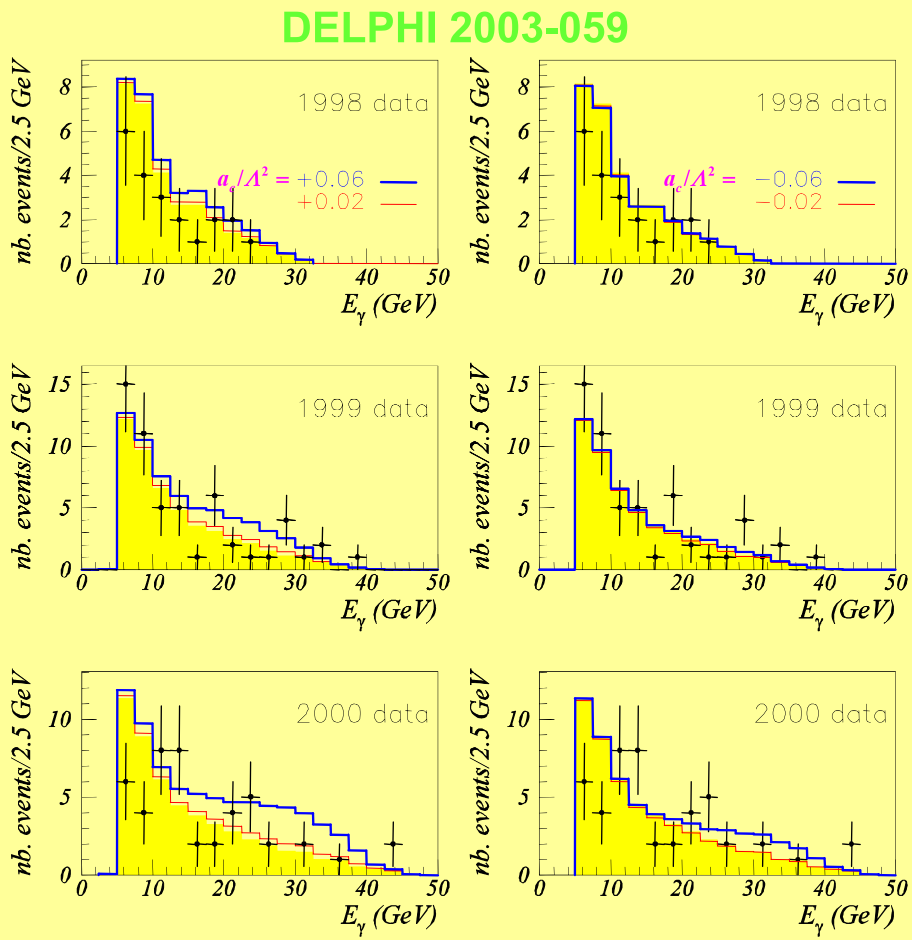
$e^+e^- \rightarrow WW\gamma$

Signal definition: $E_\gamma > 5\,\text{GeV}, \quad |\cos\theta_\gamma| < 0.95$

Analyses by Delphi, L3, Opal

$\cos\theta_{\gamma f} < 0.90 \quad |m_{ff'} - m_W| < 2\Gamma_W$





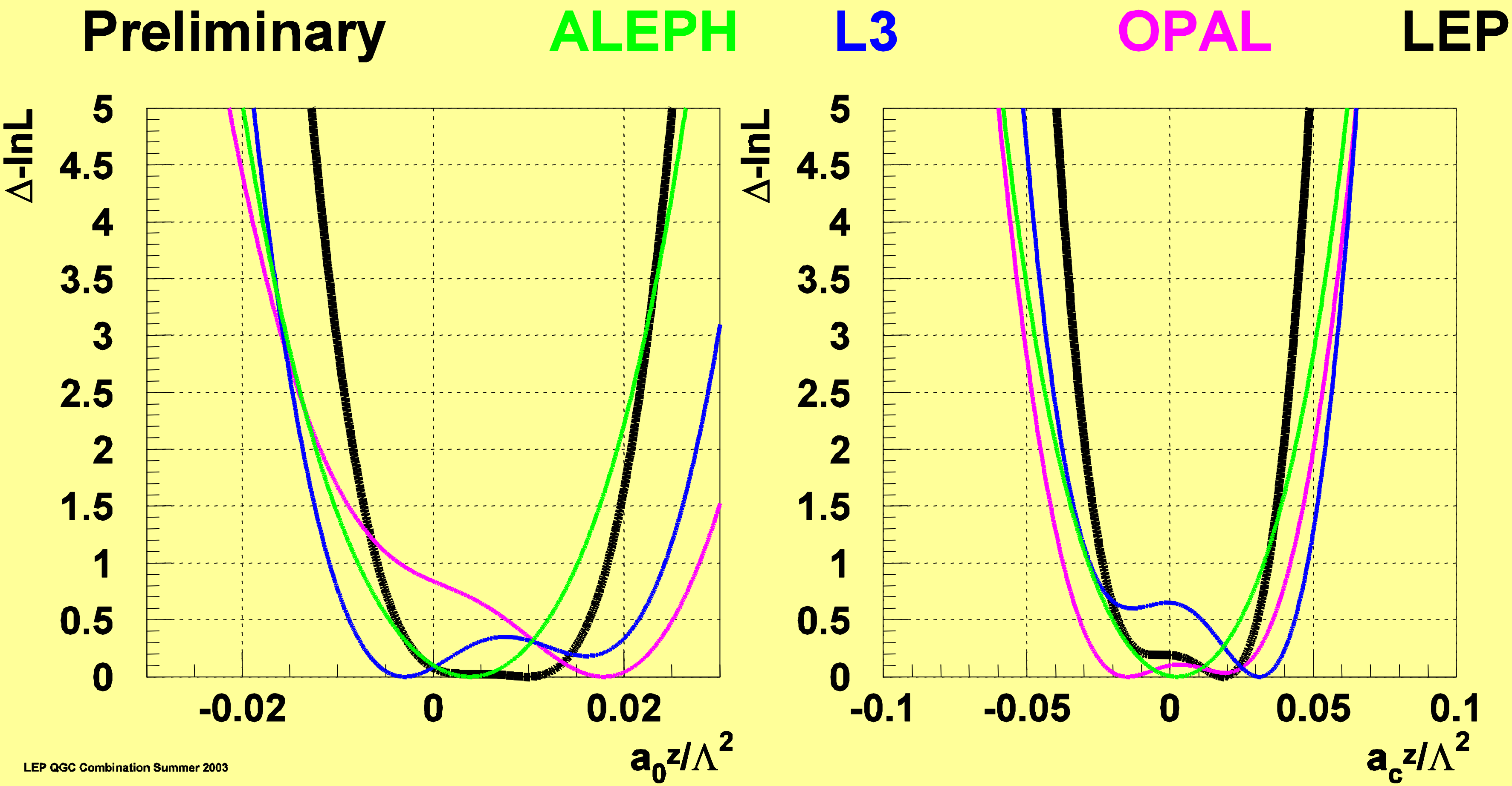
CC QGC results

No LEP combination

95% C.L. Limits in GeV^{-2}

		a_0^W/Λ^2	a_c^W/Λ^2	a_n/Λ^2
Aleph	$\nu\bar{\nu}\gamma\gamma$	[-0.060, 0.055]	[-0.099, 0.093]	
Delphi	WWγ	[-0.020, 0.020]	[-0.063, 0.032]	[-0.18, 0.14]
L3	$\nu\bar{\nu}\gamma\gamma$	[-0.031, 0.031]	[-0.090, 0.090]	
	WWγ	[-0.017, 0.017]	[-0.052, 0.026]	[-0.14, 0.13]
OPAL	$\nu\bar{\nu}\gamma\gamma$	[-0.054, 0.052]	[-0.15, 0.14]	
	WWγ	[-0.020, 0.020]	[-0.053, 0.037]	[-0.16, 0.15]

NC QGC results



$$-0.008 < a_0^Z/\Lambda^2 < 0.021\,\text{GeV}^{-2} \qquad -0.029 < a_c^Z/\Lambda^2 < 0.039\,\text{GeV}^{-2}$$

Summary

- Charged Current TGCs are measured at LEP from W-pairs, $\mathbf{We\nu, \nu\bar{\nu}\gamma}$ events with a precision of 0.02, 0.02, 0.045 for $\Delta g_1^Z, \lambda_\gamma, \Delta\kappa_\gamma$
  Other TGCs, *C*- and/or *P*-violating are also measured.
- Measurements of spin density matrix, W-polarization, (correlations), search for *CP*-violation.
- Constraints on anomalous Neutral Current TGCs:
  h-couplings from Zγ events with 95% c.l. limits $\approx \mathbf{0.05 - 0.20}$
  f-couplings from ZZ events with 95% c.l. limits $\approx \mathbf{0.20 - 0.35}$
- Constraints on anomalous CC QGCs are measured from $\mathbf{WW\gamma, \nu\bar{\nu}\gamma\gamma}$ events with 95% c.l. limits $\approx$ **0.02, 0.05, 0.15** for $a_0^W/\Lambda^2, a_c^W/\Lambda^2, a_n/\Lambda^2$
- Constraints on anomalous NC QGCs are measured from $\mathbf{q\bar{q}\gamma\gamma, \nu\bar{\nu}\gamma\gamma}$ events with 95% c.l. limits $\approx$ **0.015, 0.035** for $a_0^Z/\Lambda^2, a_c^Z/\Lambda^2$
- Results are almost final, no large improvement is expected.
- All results are (unfortunately) in agreement with the Standard Model.

Outlook

Expected TGC accuracy in future colliders: **(TESLA TDR)**