Charged Current Gauge Couplings

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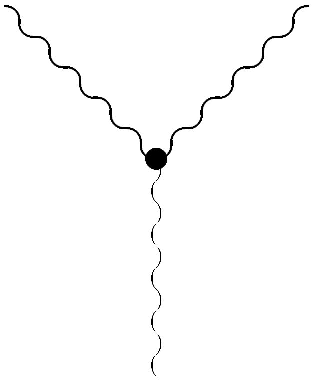
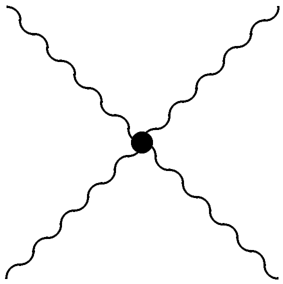




OUTLINE

- Theoretical Background
- TGCs from WW
- WW Spin Density Matrix, W-polarization, $\not{C}\not{P}$ TGCs
- TGCs from single W, single γ
- QGCs
- Conclusions and Outlook

Theoretical Background

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

Gauge invariance dictates:

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

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

$$\begin{aligned} \mathcal{L}_W &= -\tfrac{1}{4}\mathbf{W}^{\mu\nu} \cdot \mathbf{W}_{\mu\nu} \\ &= -\tfrac{1}{4}(\partial_\mu \mathbf{W}_\nu - \partial_\nu \mathbf{W}_\mu) \cdot (\partial^\mu \mathbf{W}^\nu - \partial^\nu \mathbf{W}^\mu) \quad \text{K.E.} \\ &\quad + \tfrac{g}{2}(\partial_\mu \mathbf{W}_\nu - \partial_\nu \mathbf{W}_\mu) \cdot (\mathbf{W}^\mu \times \mathbf{W}^\nu) \quad \text{TGC} \\ &\quad - \tfrac{g^2}{4}(\mathbf{W}_\mu \times \mathbf{W}_\nu) \cdot (\mathbf{W}^\mu \times \mathbf{W}^\nu) \quad \text{QGC} \end{aligned}$$

To test the SM, we should

a) measure the effect of the SM TGC & QGC terms

b) search for other, non-SM TGC & QGC terms.

The effect of the SM QGC term is too small at presently available energies & statistics.

Triple Gauge Couplings

General expression for the WWV (V=γ,Z) effective Lagrangian:

$$
\begin{array}{rcl}
i\mathcal{L}_{eff}^{WWV} & = & g_{WWV}[g_1^V V^\mu \left(W^-_{\mu\nu} W^{+\nu} - W^+_{\mu\nu} W^{-\nu}\right) \\
 & + & \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} \\
 & + & \frac{\lambda_V}{m_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu} \\
\not C, \not P & + & i g_5^V \epsilon_{\mu\nu\rho\sigma} \left((\partial^\rho W^{-\mu}) W^{+\nu} - W^{-\mu}(\partial^\rho W^{+\nu})\right) V^\sigma \\
\not C & + & i g_4^V W^-_\mu W^+_\nu \left(\partial^\mu V^\nu + \partial^\nu V^\mu\right) \\
\not P & - & \frac{\hat\kappa_V}{2} W^-_\mu W^+_\nu \epsilon^{\mu\nu\rho\sigma} V^{\rho\sigma} \\
\not P & - & \frac{\hat\lambda_V}{2m_W^2} W^-_{\rho\mu} W^{+\mu}_{\ \ \nu} \epsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}]
\end{array}
$$

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

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

Standard Model values: $g_1^V = 1$, $\kappa_V = 1$

Anomalous couplings:

Δg_1^V=g_1^V-1, $\Delta\kappa_V$=κ_V-1, λ_V, g_5^V, g_4^V, $\hat\kappa_V$, $\hat\lambda_V$

Physics interpretation:

$q_W = e g_1^\gamma$	charge
$\mu_W = \frac{e}{2m_W}(g_1^\gamma + \kappa_\gamma + \lambda_\gamma)$	mag. dipole moment
$Q_W = -\frac{e}{m_W^2}(\kappa_\gamma - \lambda_\gamma)$	elec. quadr. moment
$d_W = \frac{e}{2m_W}(\hat{\kappa}_\gamma + \hat{\lambda}_\gamma)$	elec. dipole moment
$\hat{Q}_W = -\frac{e}{m_W^2}(\hat{\kappa}_\gamma - \hat{\lambda}_\gamma)$	mag. quadr. moment

Constraints:

QED Gauge invariance: $g_1^\gamma = 1$, $g_5^\gamma = 0$

Custodial SU(2): $\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_w$

$$\lambda_Z = \lambda_\gamma$$
$$\hat{\kappa}_Z = -\hat{\kappa}_\gamma \tan^2\theta_w$$
$$\hat{\lambda}_Z = \hat{\lambda}_\gamma$$

We are left with 8 TGCs:

4 CP-conserving: $\Delta\kappa_\gamma$, λ_γ, Δg_1^z, g_5^Z

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

Quartic Gauge Couplings

Consider only genuine anomalous QGCs which do not contribute to triple gauge vertices:

$$\mathcal{L}_6^0 = -\frac{e^2}{16}\frac{a_0^W}{\Lambda^2} F^{\mu\nu} F_{\mu\nu} \vec{W}^\alpha \cdot \vec{W}_\alpha$$

$$\mathcal{L}_6^c = -\frac{e^2}{16}\frac{a_c^W}{\Lambda^2} F^{\mu\alpha} F_{\mu\beta} \vec{W}^\beta \cdot \vec{W}_\alpha$$

$$\mathcal{L}_6^n = -\frac{e^2}{16}\frac{a_n^W}{\Lambda^2} \epsilon_{ijk} W_{\mu\alpha}^{(i)} W_\nu^{(j)} W^{\alpha,(k)} F^{\mu\nu}$$

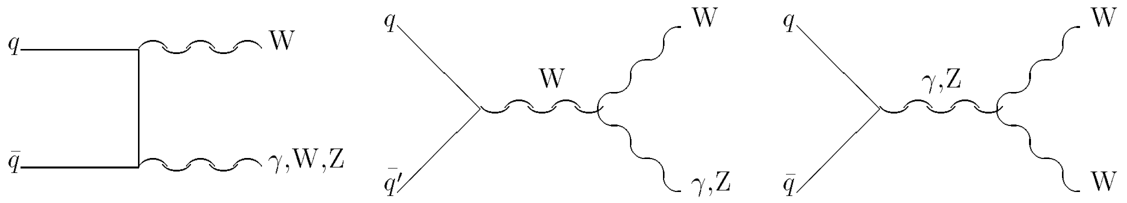
$(W_\mu^{(3)} = Z^\mu / \cos\theta_w)$

$\mathcal{L}_6^0$, $\mathcal{L}_6^c$ are WW$\gamma\gamma$ terms (CP-conserving)

$\mathcal{L}_6^n$ is WWZγ term (CP-violating)

If LEP Did Not Exist...

TGC limits from the Tevatron using di-boson final states



Measure σ_{tot} for these processes, where the outgoing bosons have high p_T.

$\Longrightarrow$ $\sqrt{\hat{s}_{q\bar{q}}} \approx 500$ GeV

Obtain limits for TGC and correct them for the $q^2 = \hat{s}$ dependence to $q^2 = 0$, using dipole form factor:

$$TGC(q^2) = \frac{TGC(0)}{(1+q^2/\Lambda_{FF}{}^2)^2}$$

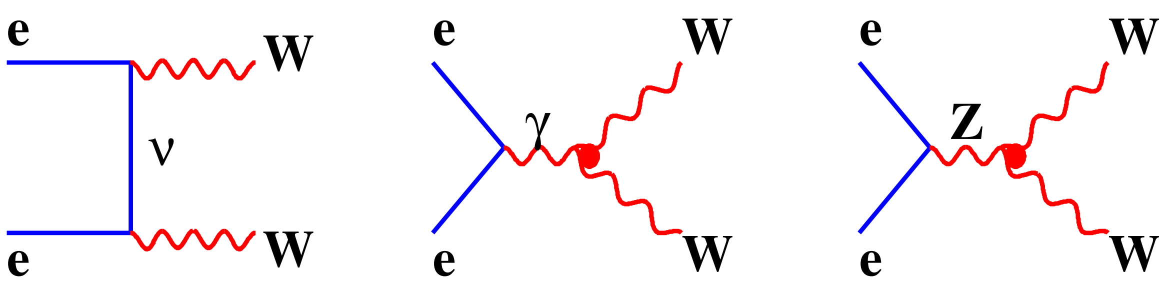
with some arbitrary Λ_{FF} value (typically, Λ_{FF}=1 – 2 TeV).

Best D0 results for Λ_{FF}=1.5 TeV (1999):

$\Delta\kappa_\gamma = -0.03 \pm 0.30, \qquad \lambda_\gamma = 0.00 \pm 0.10$

No results on $\not{C}\not{P}$ TGCs, no QGCs!

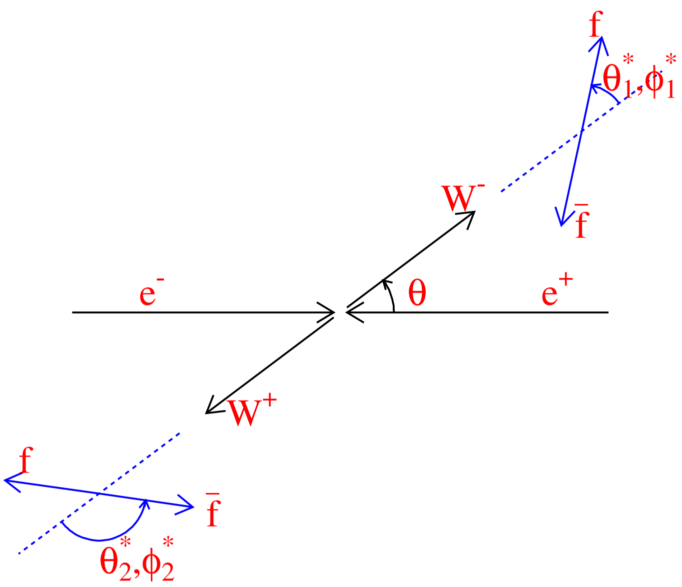
TGCs from W-pairs



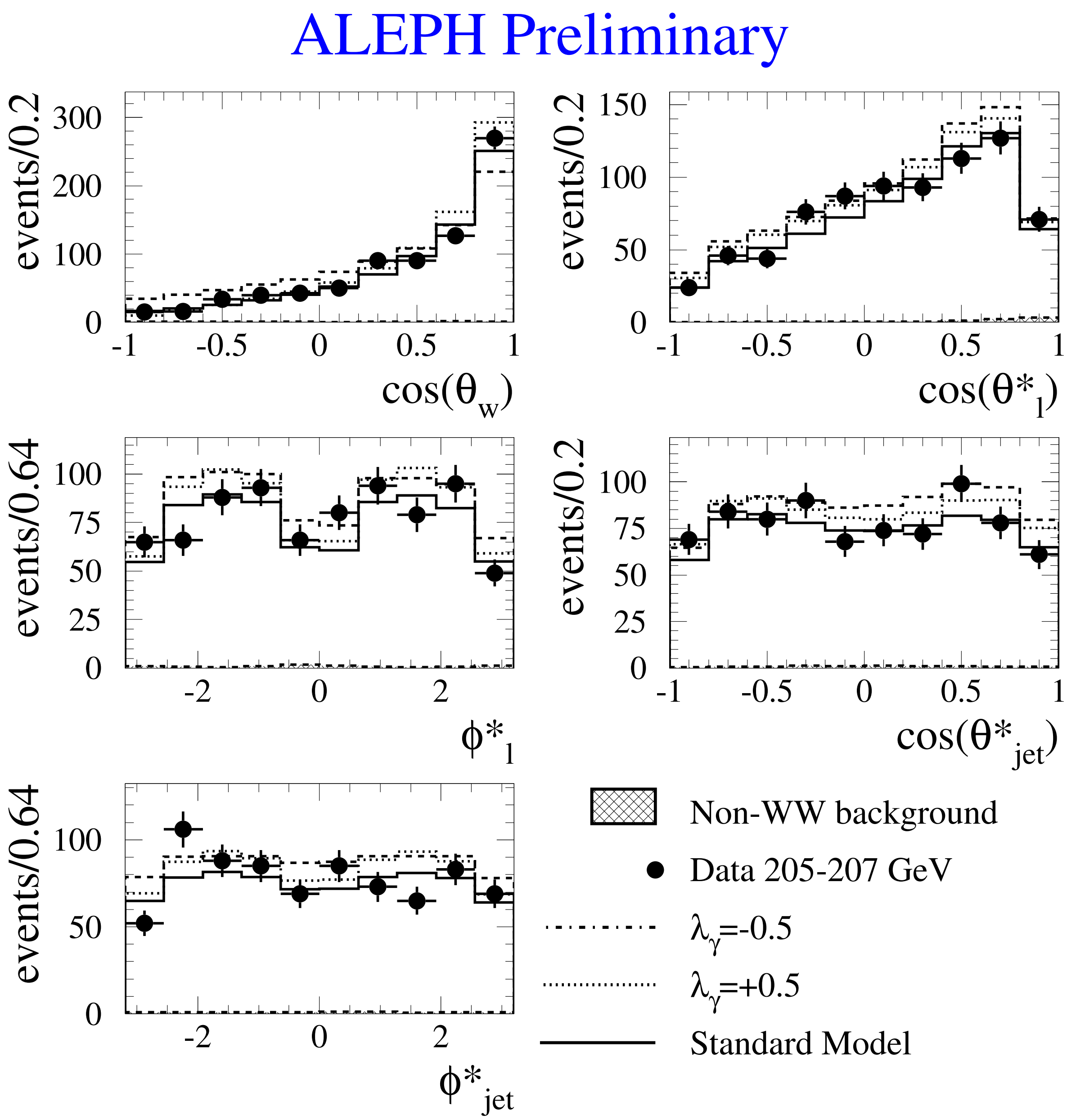
Sensitivity to TGCs is expected in:

- Total event rate
- W scattering angle, θ_W
- W helicity through W decay angles $(\theta_1^*,\ \phi_1^*,\ \theta_2^*,\ \phi_2^*)$

Some ambiguity in measuring these 5 angles, depending on final state.



Angular Distributions:



TGC Extraction

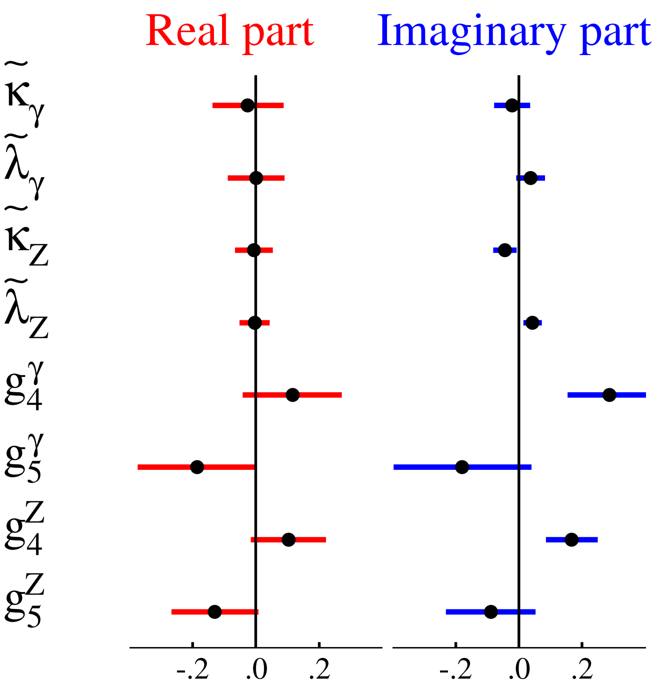
Three different strategies:

- multi-dimensional phase-space fit; AL
- project all info into Optimal Observables ADLO
- spin density matrix elements DO

Multi-dimensional fits:

L3: Maximum Likelihood fit in 5D phase-space

ALEPH: Unbinned Maximum Likelihood fit:
Convolving analytic differential cross-section with ISR function, detector resolution and efficiency correction.



Optimal Observables (OOs)

$$\frac{d\sigma}{d\Omega} = S^{(0)}(\Omega) + \sum_i \alpha_i \cdot S_i^{(1)}(\Omega) + \sum_{i,j} \alpha_i \alpha_j \cdot S_{ij}^{(2)}(\Omega)$$

α_i – TGC's

$\Omega = (\cos\theta_W, \cos\theta_1^*, \phi_1^*, \cos\theta_2^*, \phi_2^*)$ – ph.-space point

$\mathcal{O}_i^{(1)} = S_i^{(1)}(\Omega)/S^{(0)}(\Omega) \qquad \mathcal{O}_{ij}^{(2)} = S_{ij}^{(2)}(\Omega)/S^{(0)}(\Omega)$

All the relevant info is included in $\mathcal{O}_i^{(1)}$, $\mathcal{O}_{ij}^{(2)}$.

... but for n TGCs there are $n + n(n+1)/2$ OOs!

DELPHI: multi-dimensional clustering technique, but still allows only ≤ 2 TGCs to vary in the fit.

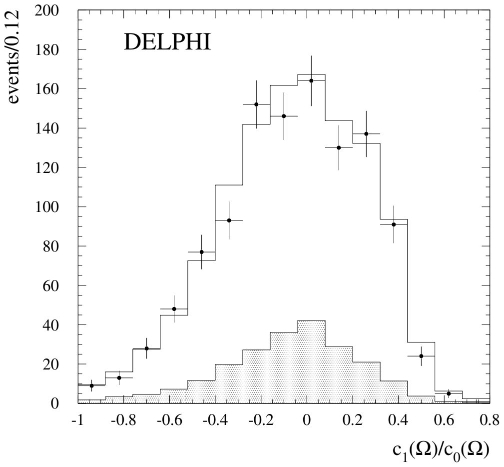
Other alternative: Apply small α approximations:

- use only the mean values of the OOs;

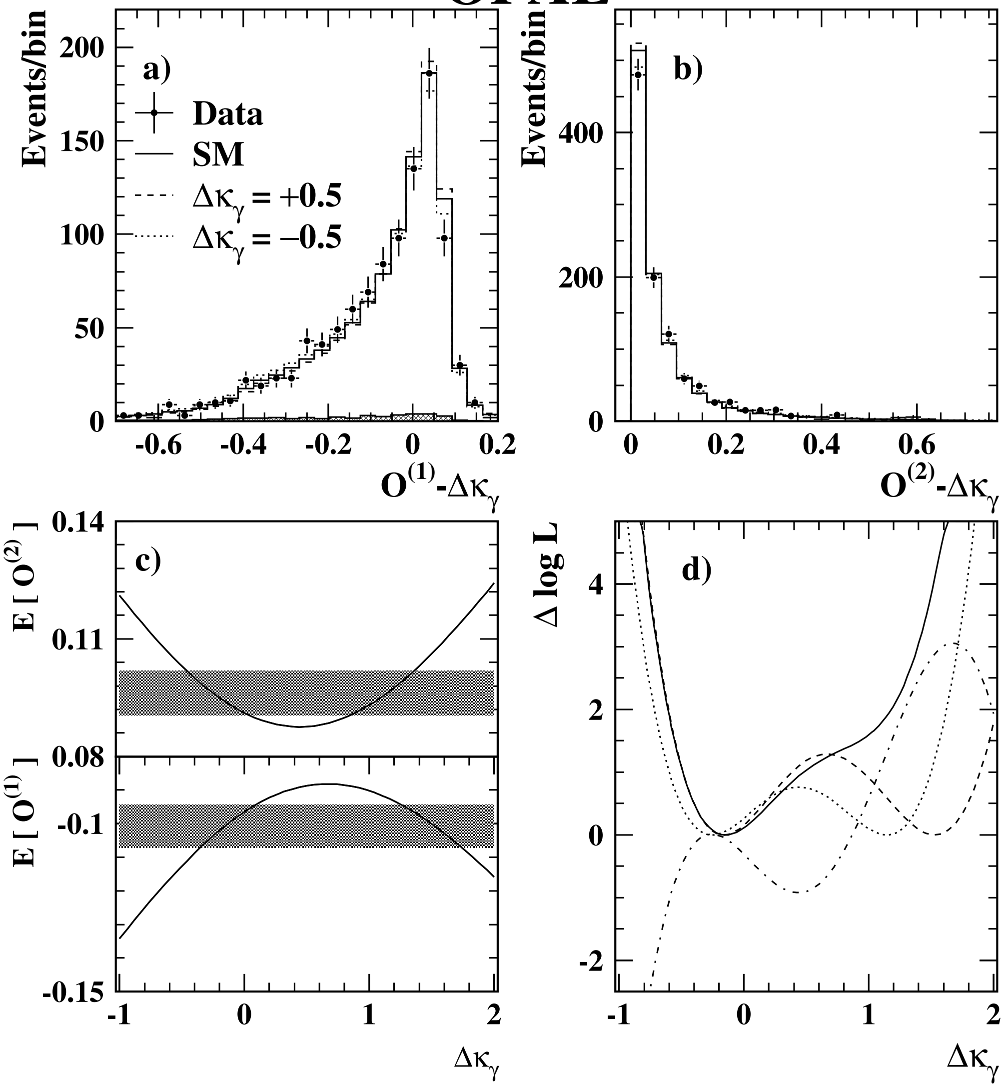
OPAL, ALEPH

- use only $\mathcal{O}_i^{(1)}$ with iterative procedure.

ALEPH, DELPHI for $\mathrm{q\bar{q}q\bar{q}}$ channel 2D fits


DELPHI
events/0.12
c1(Ω)/c0(Ω)

OPAL


a)
Data
SM
Δκγ = +0.5
Δκγ = −0.5
Events/bin
O(1)-Δκγ
b)
Events/bin
O(2)-Δκγ
c)
E [O(2)]
E [O(1)]
Δκγ
d)
Δ log L
Δκγ

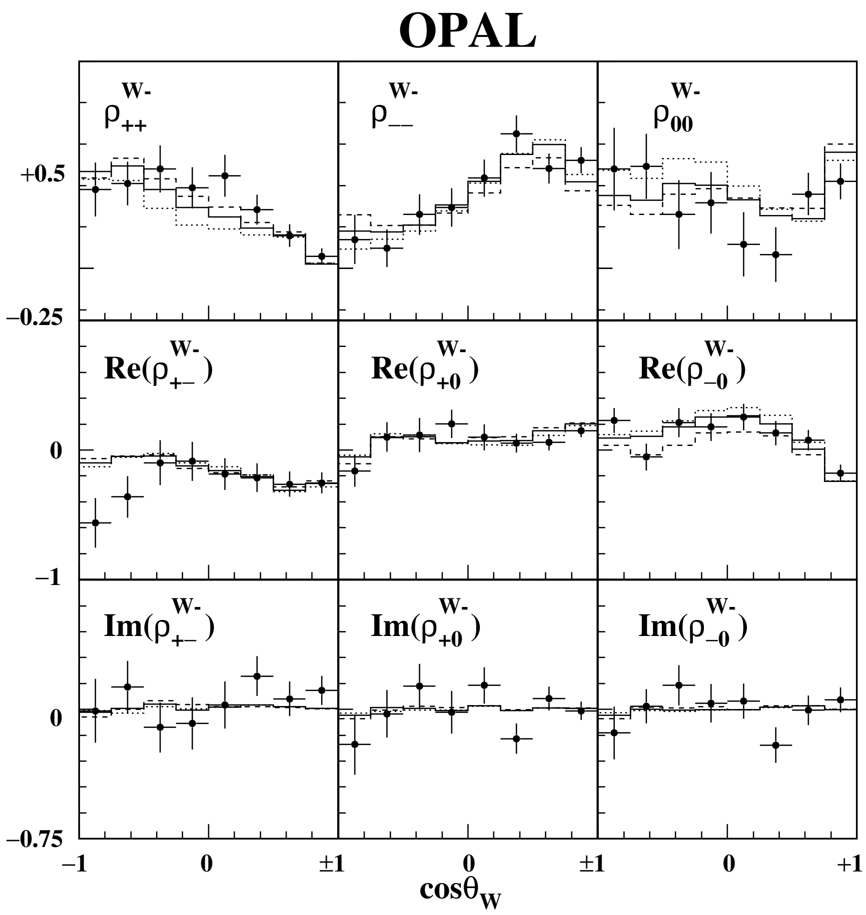
Spin Density Matrix (SDM)

$$\rho_{\tau_-\tau'_-\tau_+\tau'_+}(s,\cos\theta_{\mathrm{W}}) = \frac{\sum_\lambda F^{(\lambda)}_{\tau_-\tau_+}(F^{(\lambda)}_{\tau'_-\tau'_+})^*}{\sum_{\lambda\tau_+\tau_-}|F^{(\lambda)}_{\tau_-\tau_+}|^2}$$

$F^{(\lambda)}_{\tau_-\tau_+}$ – helicity amplitudes

λ=e$^-$ helicity $\quad$ $\tau^\pm$=W$^\pm$ helicity

One W SDM: $\quad \rho^{W^-}_{\tau_-\tau'_-} = \sum_{\tau_+} \rho_{\tau_-\tau'_-\tau_+\tau_+}$



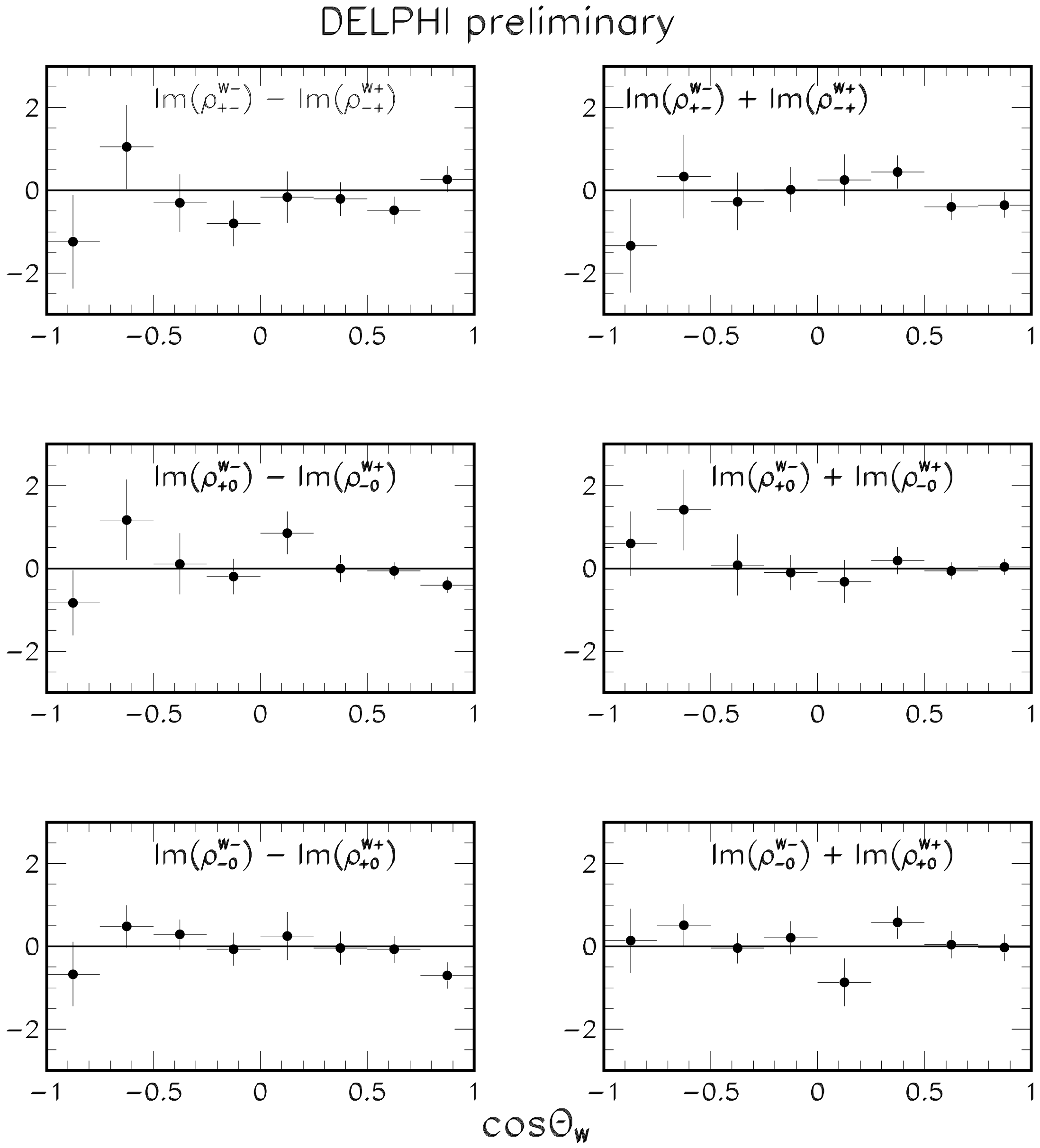
CPT invariance at tree level: $\rho^{W-}_{\tau_1\tau_2} = (\rho^{W+}_{-\tau_1-\tau_2})^*$

CP invariance: $\rho^{W-}_{\tau_1\tau_2} = \rho^{W+}_{-\tau_1-\tau_2}$

OPAL uses sensitivity to $\not{C}\not{P}$ TGCs to obtain:

$\hat{\kappa}_Z = -0.20^{+.10}_{-.07}$ $\hat{\lambda}_Z = -0.18^{+.24}_{-.16}$

$g_4^Z (= g_4^\gamma) = -0.02^{+.32}_{-.33}$ (189 GeV data)



W-Polarization

OPAL uses SDM: (189 GeV data)

	Data	SM
$\sigma_T/\sigma_{\rm tot}$	$0.790 \pm .033 \pm .016$	0.743
$\sigma_L/\sigma_{\rm tot}$	$0.210 \pm .033 \pm .016$	0.257
$\sigma_{TT}/\sigma_{\rm tot}$	$0.781 \pm .090 \pm .033$	0.572
$\sigma_{LL}/\sigma_{\rm tot}$	$0.201 \pm .072 \pm .018$	0.086
$\sigma_{TL}/\sigma_{\rm tot}$	$0.018 \pm .147 \pm .038$	0.342

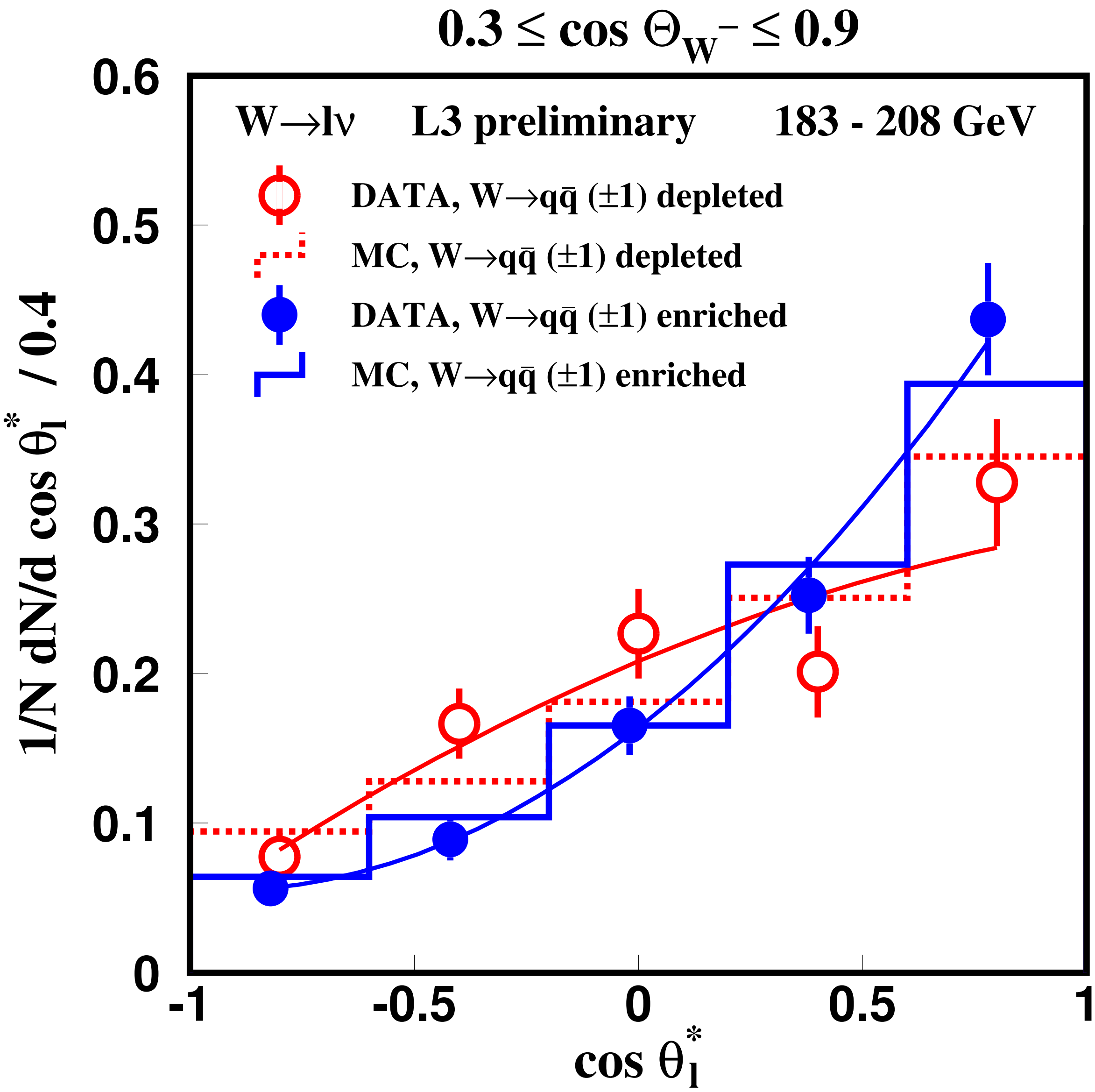
L3 uses $\cos\theta^*$ distribution: (206 GeV data)

	Data	SM
$\sigma_-/\sigma_{\rm tot}$	$0.647 \pm .066$	0.623
$\sigma_+/\sigma_{\rm tot}$	$0.137 \pm .034$	0.157
$\sigma_L/\sigma_{\rm tot}$	$0.216 \pm .053$	0.220

L3 also finds evidence (3.6σ) for WW spin correlations, looking at $\cos\theta^*_l$ distribution for samples where the other W (decaying hadronically) is enriched or depleted in W_T

enriched: $(0.66 < |\cos\theta^*_q| < 1)$

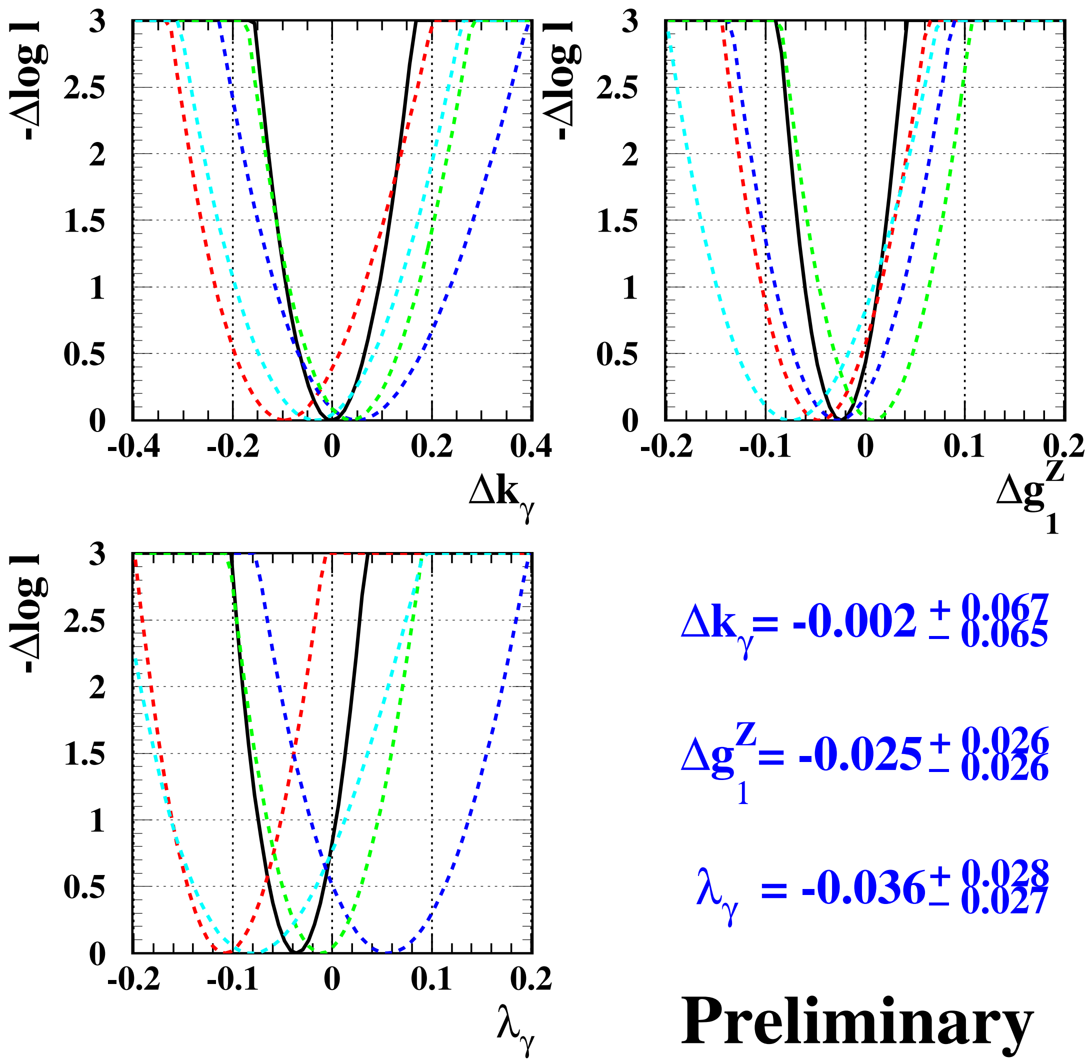
depleted: $(0 < |\cos\theta^*_q| < 0.33)$



Last Year TGC Results

$E_{\mathrm{CM}} \leq 202$ GeV

ALEPH + DELPHI + L3 + OPAL



$\Delta k_\gamma = -0.002 ^{+0.067}_{-0.065}$

$\Delta g_1^Z = -0.025 ^{+0.026}_{-0.026}$

$\lambda_\gamma = -0.036 ^{+0.028}_{-0.027}$

Preliminary

New Monte Carlo Programs

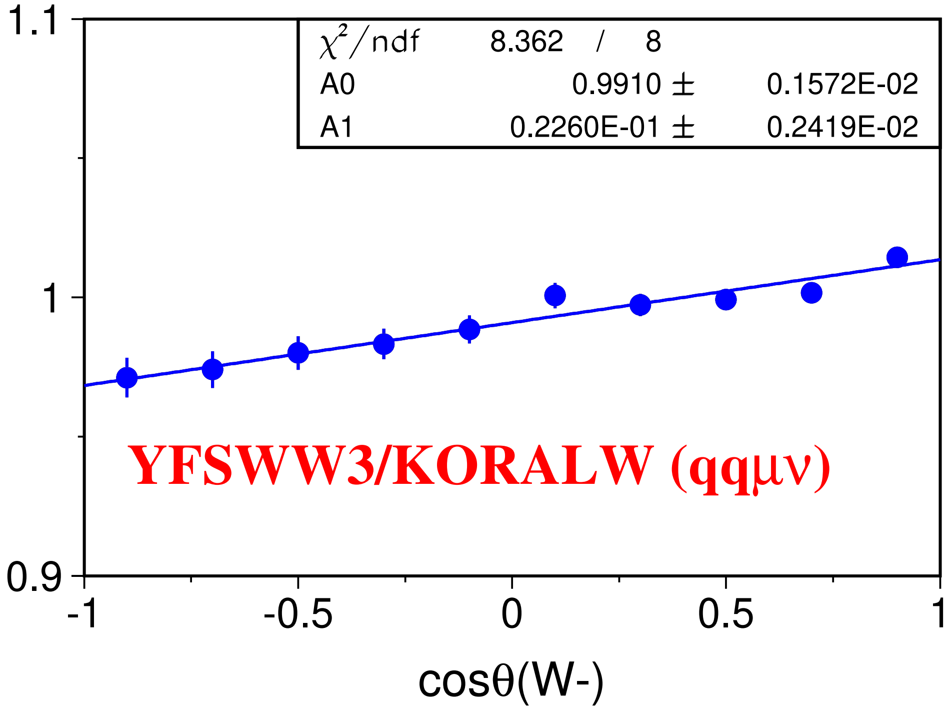
A) RacoonWW (A.Denner et al., hep-ph/0006307)
B) YFSWW3 (S.Jadach et al., hep-ph/0103163)

$\mathcal{O}(\alpha)$ treatment based on double pole approximation and screened Coulomb corrections.

Very good agreement between RacoonWW and YFSWW3.

- $\sigma_{\rm tot}$ is $\approx 2.5\%$ lower than old MC
- $\cos\theta_W$ is 1–2% steeper than old MC

189 GeV

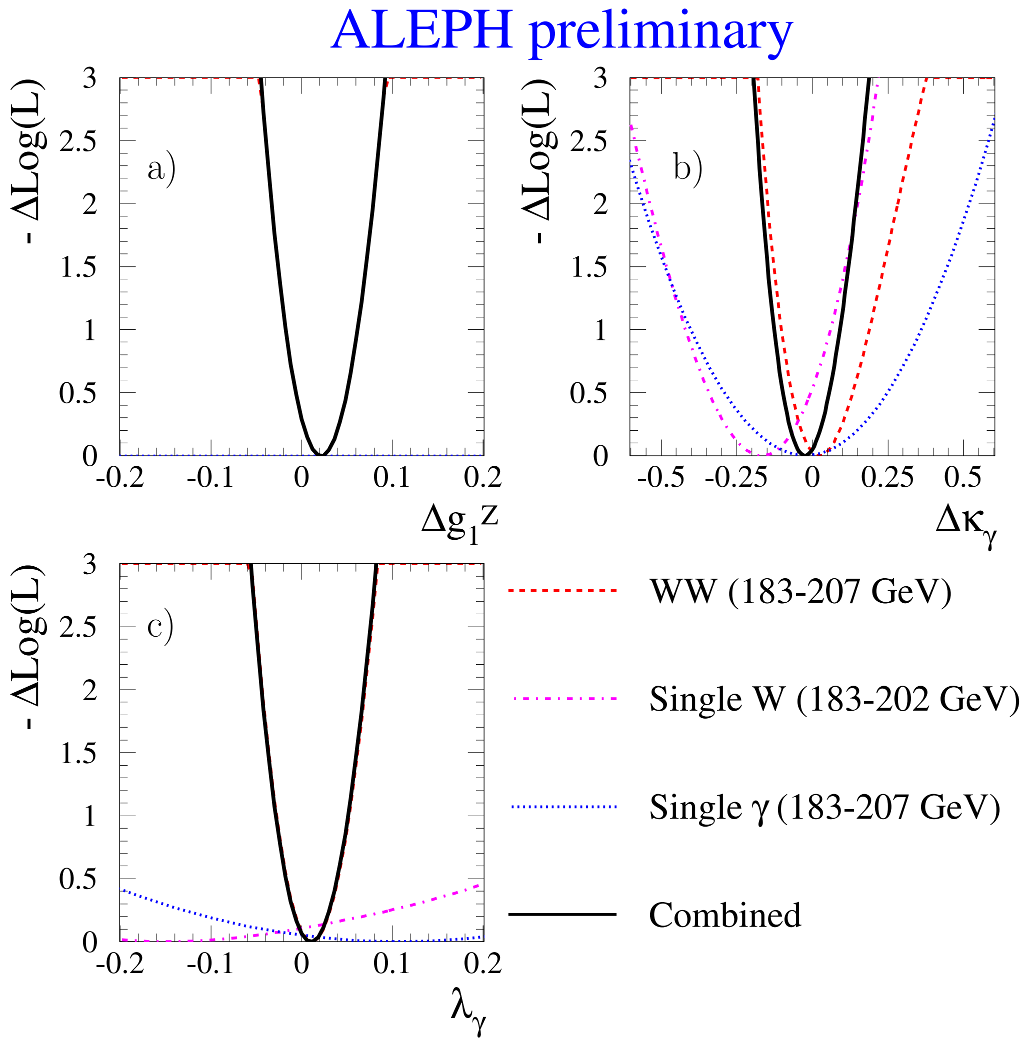


New TGC Results

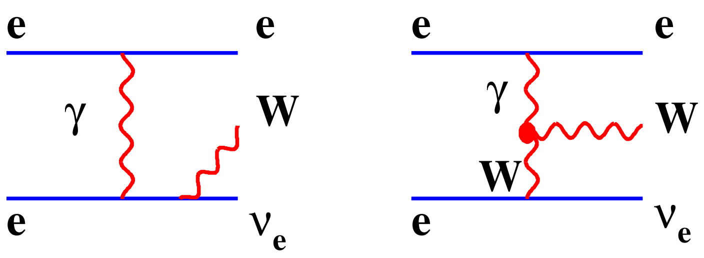
ALEPH has TGC results based on new MCs:

Reweight existing KORALW samples with YFSWW3/KORALW correction
Include the full effect (40–50% of full error) in syst.

This effect is still under study by LEP experiments.
⟹ No other new results, no LEP comb. in 2001.



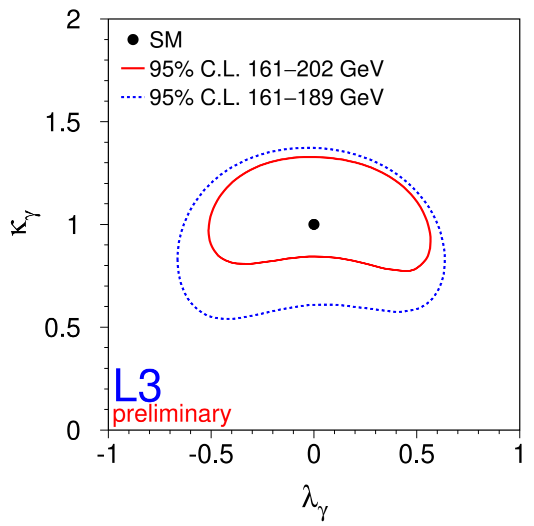
TGC from Single W



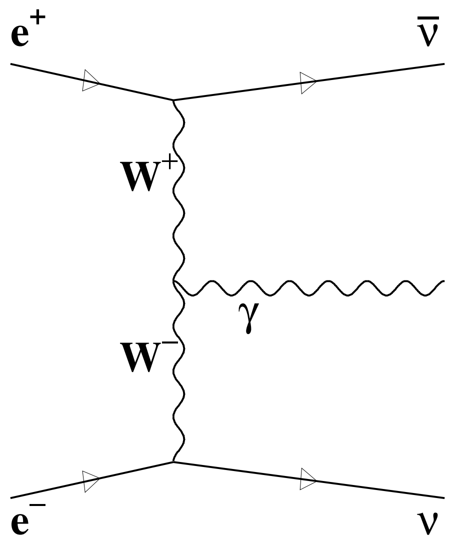
Sensitive only to WWγ coupling, but high ($\approx$ 50%) backgr. (WW events) sensitive also to WWZ coupl.

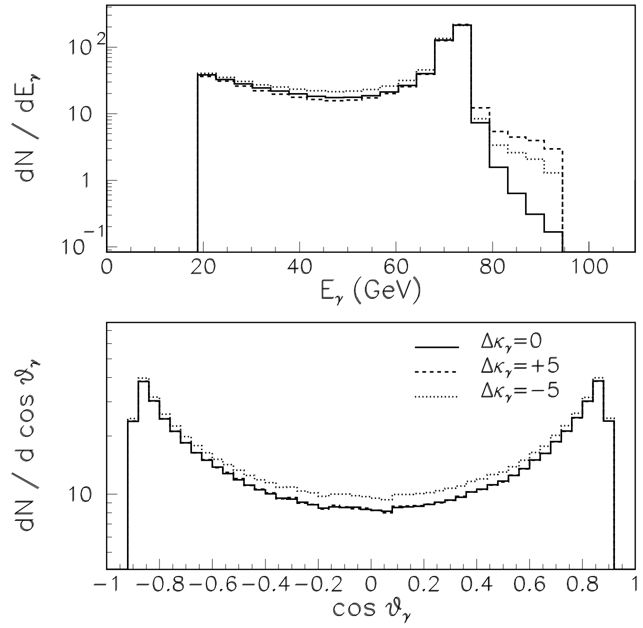
Use mainly event rate & some diff. distr. info

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



TGC from Single γ





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

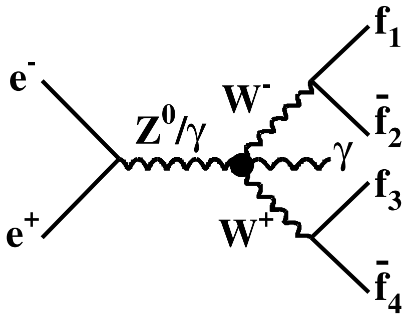
Use event rate and E_γ, $\cos\theta_\gamma$ distributions.

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

Measurement of QGCs

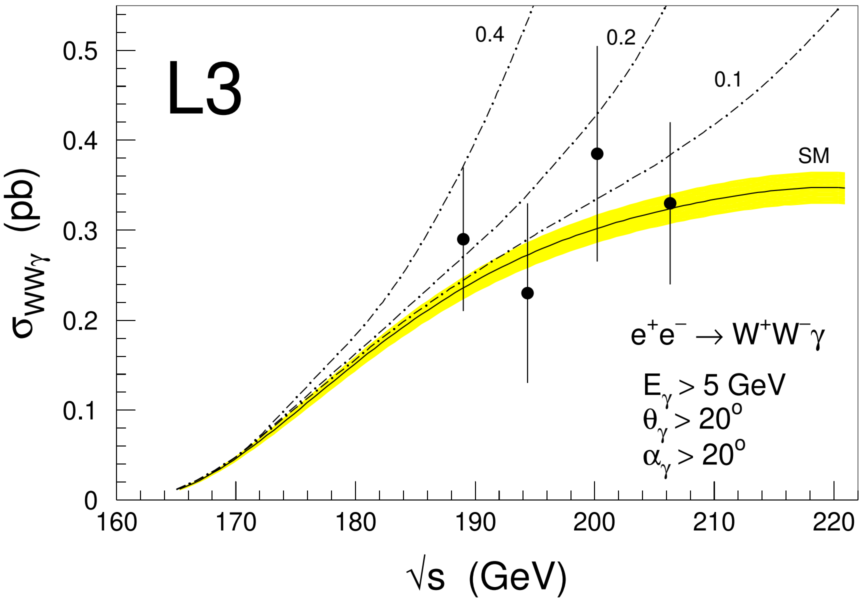
WWγ Final States

L3, OPAL



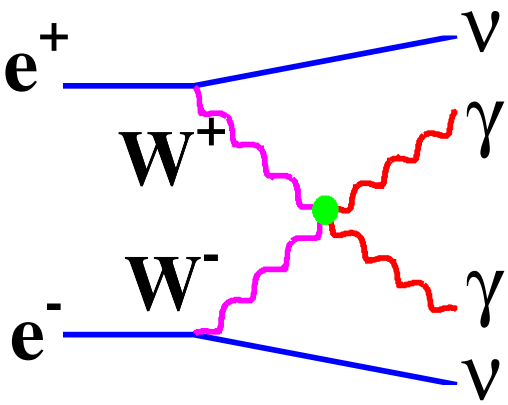
Most sensitivity for energetic central γ

Experiment	L3	OPAL
Data sample	189–208 GeV	189 GeV
Observ. used	E_γ	$E_\gamma, \cos\theta_\gamma$
a_0^W/Λ^2	[–0.017, 0.017]	[–0.070, 0.070]
a_c^W/Λ^2	[–0.026, 0.052]	[–0.13, 0.19]
a_n^W/Λ^2	[–0.014, 0.013]	[–0.61, 0.57]

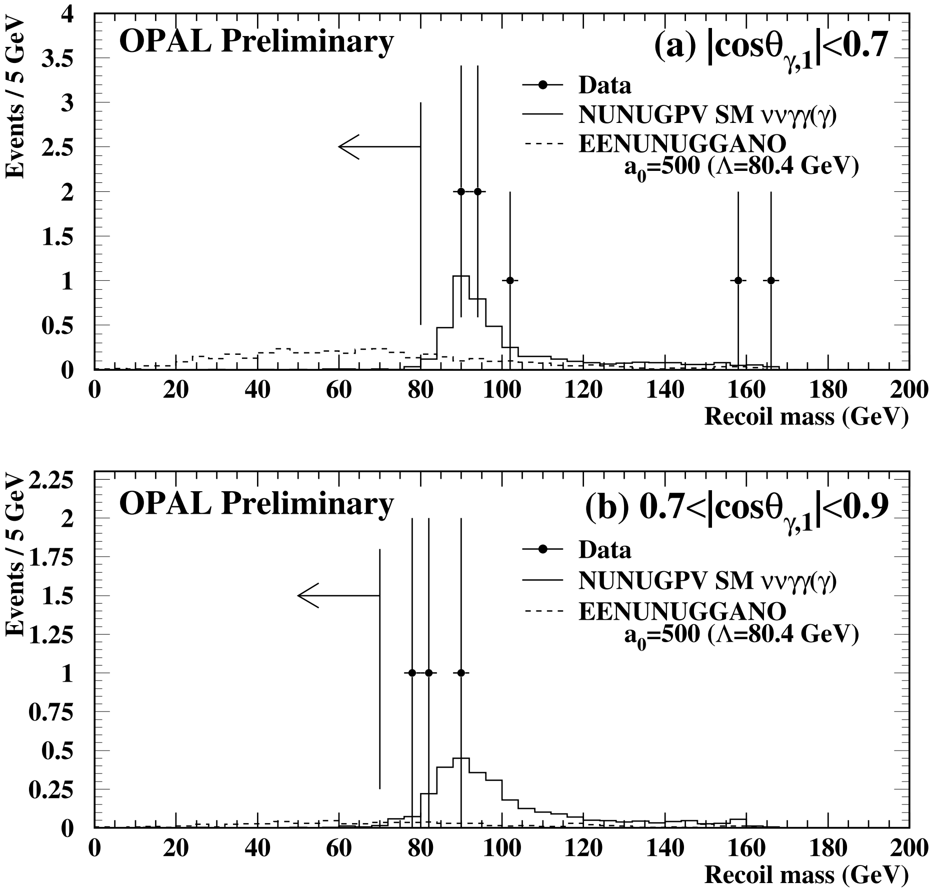


$\nu\bar{\nu}\gamma\gamma$ Final States

ALEPH, L3, OPAL



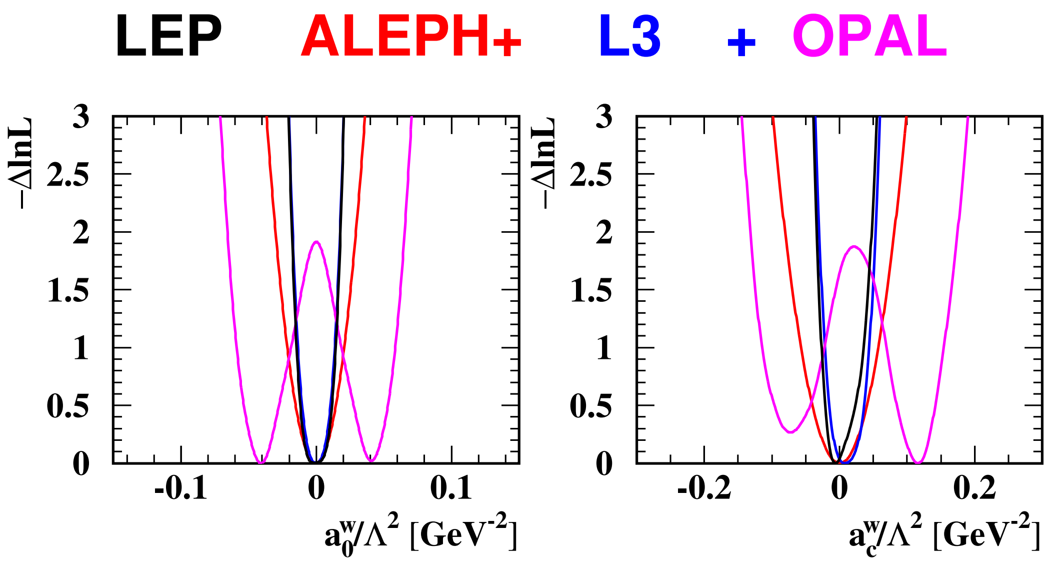
Cut on recoil mass ($M_{\nu\overline{\nu}}$) to reject $Z\gamma\gamma$ events:

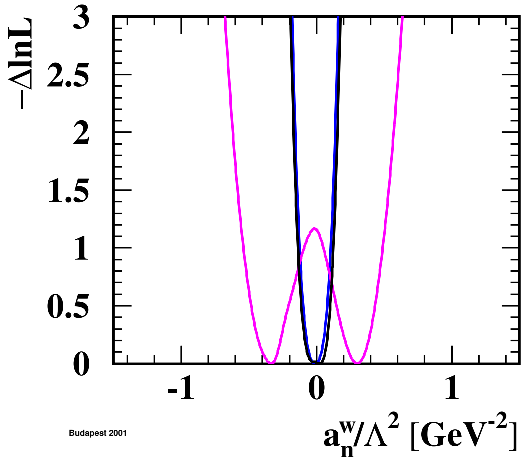


Exp.	ALEPH	L3	OPAL
Data	189-208 GeV	189-208 GeV	189 GeV
a_0^W/Λ^2	[−0.029, 0.026]	[−0.032, 0.031]	[−0.086, 0.085]
a_c^W/Λ^2	[−0.080, 0.075]	[−0.09, 0.09]	[−0.23, 0.23]

Combined QGC Results

	a_0^W/Λ^2	a_c^W/Λ^2	a_n^W/Λ^2
ALEPH	[–0.029, 0.029]	[–0.079, 0.080]	
L3	[–0.017, 0.017]	[–0.03, 0.05]	[–0.15, 0.14]
OPAL	[–0.065, 0.065]	[–0.13, 0.17]	[–0.61, 0.57]
LEP	[–0.018, 0.018]	[–0.033, 0.047]	[–0.17, 0.15]





WWγ+ννγγ:

a_0^w/Λ^2	[-0.02,0.02]
a_c^w/Λ^2	[-0.03,0.05]

WWγ:

a_n^w/Λ^2	[-0.17,0.15]

Conclusions and Outlook

- Charged TGCs measurements are performed at LEP using WW, single W and single γ final states.

- Ongoing studies to understand the effects of new $\mathcal{O}(\alpha)$ MC generators.

- Expected precision of the combined LEP results is: 0.060, 0.025, 0.025 for $\Delta\kappa_\gamma$, Δg_1^z, λ_γ respectively.
$\approx$ 4–5 times better than without LEP

- Study of W decay angles:
  - Spin density matrix elements
  - W polarization
  - Search for $\not{C}\not{P}$ in W production

- Limits on anomalous charged QGCs obtained at LEP using WWγ and $\nu\bar{\nu}\gamma\gamma$ final states.
Limits will improve once all LEP data is included.

- So far, all anomal. couplings are consistent with 0.
$\Longrightarrow$ SM still survives!