W Couplings and Spin Density Matrix

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On behalf of the LEP experiments

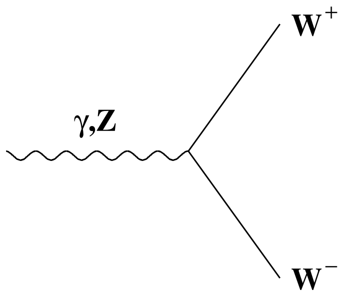
- Introduction
- Charged Triple Gauge Couplings
- Spin Density Matrix
- Neutral Triple Gauge Couplings
- Quartic Gauge Couplings
- Conclusions

$XXXVIII^{th}$ Rencontres de Moriond

Introduction

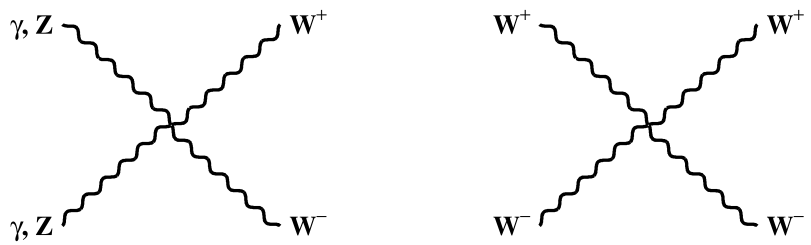
SM : non-Abelian $SU(2)_L \otimes U(1)_Y$ gauge structure
⇨ interactions between charged($W^{\pm}$) and neutral(Z, γ) gauge bosons at tree level

cTGC's



⇓
directly observed at LEP

cQGC's



⇓
$WWWW$, $WWZZ$: not at LEP
$WW\gamma\gamma$, $WWZ\gamma$: negligible at LEP

Physics beyond the SM :
- nTGC's : ZZZ, $ZZ\gamma$, $Z\gamma\gamma$
- nQGC's : $ZZ\gamma\gamma$

cTGC's : constraints

Most general Lorentz-invariant Lagrangian including $WWV (V = \gamma, Z)$

$\boxed{\text{14 parameters}}$

$\swarrow$ $\searrow$

8 CP-conserving	Assuming	6 CP-violating
$g_1^V,\ \lambda_V,\ \kappa_V$ $g_5^V\ (\not{C}, \not{P})$	C & P conservation $U(1)_{em},\ SU(2)_L \otimes U(1)_Y$	$\tilde{\lambda}_V,\ \tilde{\kappa}_V (\not{P})$ $g_4^V\ (\not{C})$

$\boxed{\Rightarrow \text{3 free parameters : } g_1^Z,\ \kappa_\gamma,\ \lambda_\gamma}$

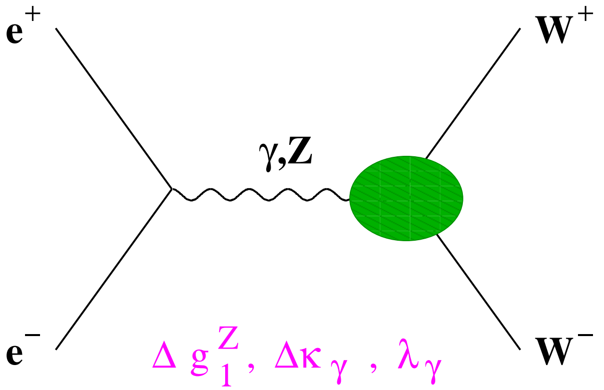
SM : $g_1^Z = 1,\ \kappa_\gamma = 1,$ all others $= 0$ $\qquad \lambda_\gamma = \lambda_Z \qquad \Delta\kappa_Z = \Delta g_1^Z + \Delta\kappa_\gamma tan^2\theta_w$

$$Q_{el}^W = \frac{-e}{2m_W^2}(\kappa_\gamma - \lambda_\gamma) \qquad \mu_{mag}^W = \frac{e}{2m_W}(1 + \kappa_\gamma + \lambda_\gamma)$$

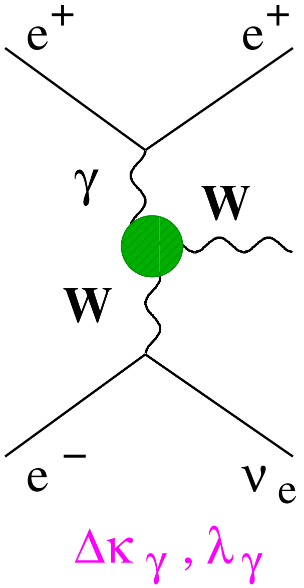
Anomalous coupling $\Longleftrightarrow$ deviation from SM coupling
$\Longleftrightarrow$ non-SM effective coupling introduced by a new physics process

cTGC's : sensitive processes

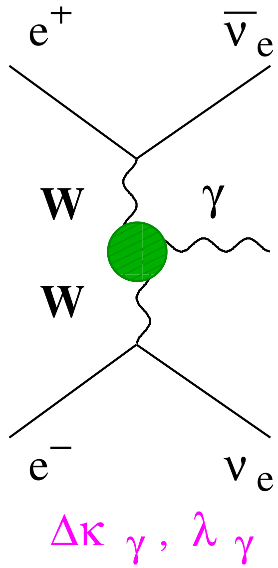
$e^+e^- \to W^+W^-$
W-pair production



$e^+e^- \to We\nu_e$
single W production



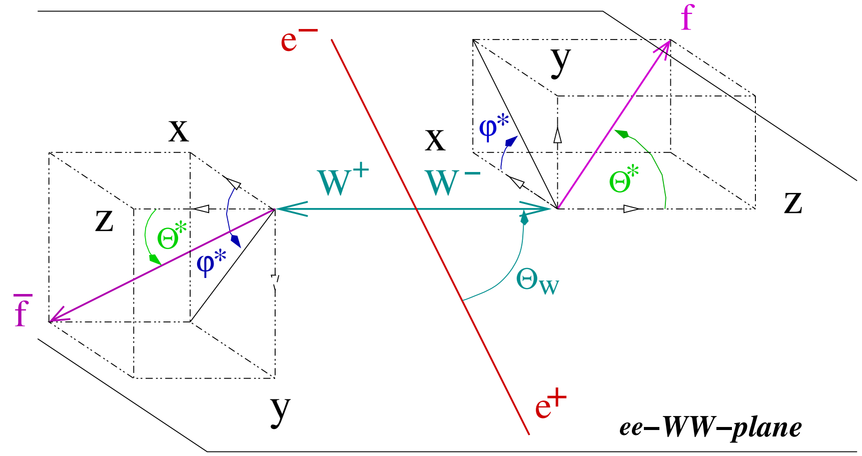
$e^+e^- \to \nu_e\bar{\nu}_e\gamma$
single γ production

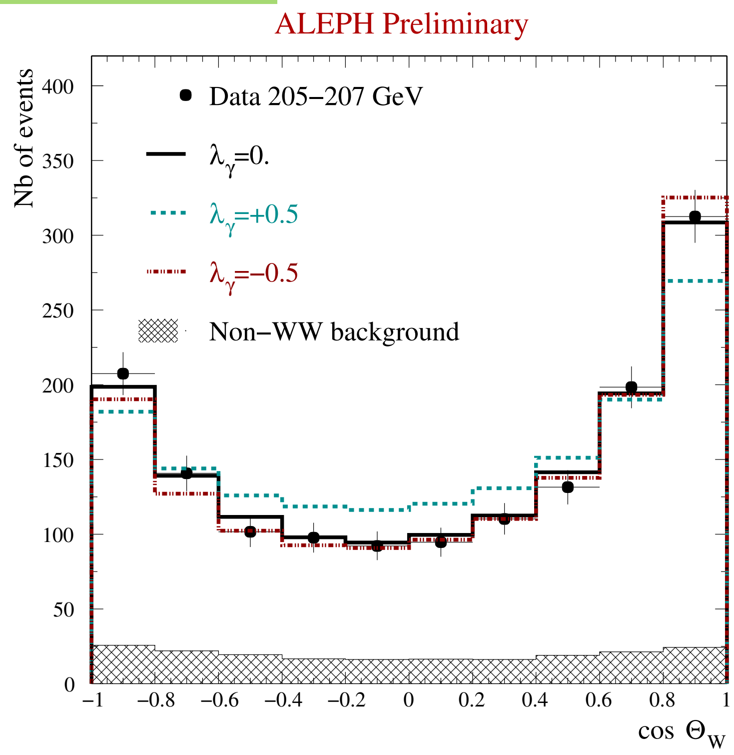


Single γ results not used for LEP combination

cTGC's : W-pair production

$$e^+ e^- \longrightarrow W^+ W^- \longrightarrow f_1 \bar{f}_2 f_3 \bar{f}_4$$





Anomalous coupling modifies

- ❑ σ_{tot}
- ❑ W-production ➪ $\cos\theta_W$
- ❑ W-polarisation ➪ $\cos\theta^*_{f(\bar{f})}$, $\phi^*_{f(\bar{f})}$

cTGC's : extraction methods

- total cross section : increase sensitivity
- angular distributions : 3 strategies

1. Maximum likelihood fit
2. Optimal observables

projects phase space angles onto 1(2) parameters/TGC

$$\frac{d\sigma(\alpha)}{d\Omega} = c^0(\Omega) + \sum_i c_i^1(\Omega)\alpha_i + \sum_{i\leq j} c_{ij}^2(\Omega)\alpha_i\alpha_j$$

Define OO as

$$\mathcal{O}_i^1 = \frac{c_i^1(\Omega)}{c^0(\Omega)} \qquad \mathcal{O}_{ij}^2 = \frac{c_{ij}^2(\Omega)}{c^0(\Omega)}$$

χ^2-fit to OO distributions

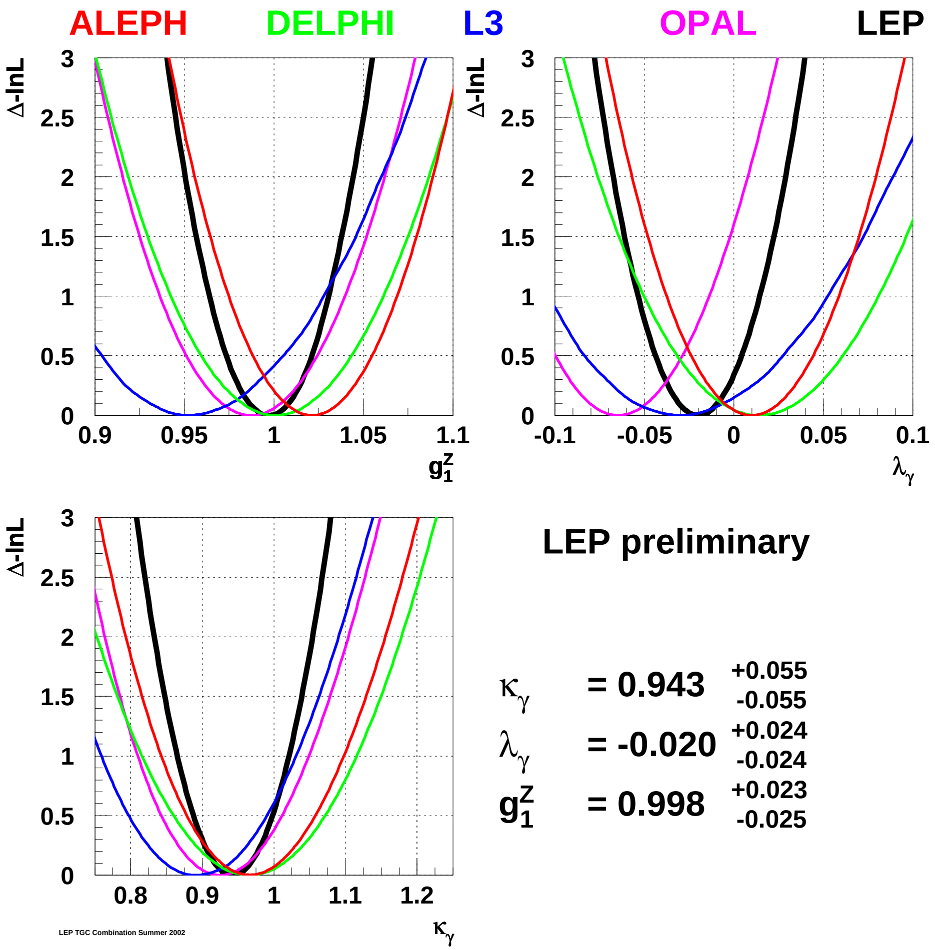
⇨ 1. and 2. only used for LEP combination

3. Spin Density Matrix method

projection operators on angular distributions +
χ^2-fit to SDM element distributions

⇨ direct limits on CP-violating couplings

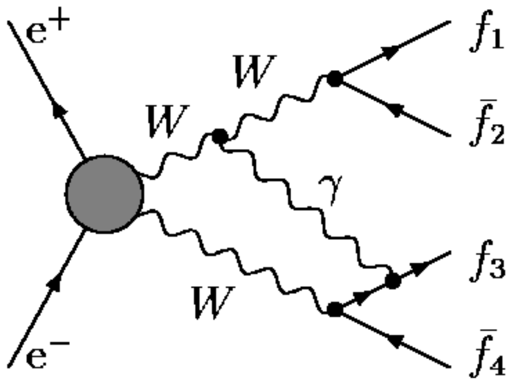
cTGC's : LEP combination one-parameter fit



Source Systematic Uncertainty	g_1^Z	λ_γ	κ_γ
$\mathcal{O}(\alpha)$ corrections	.015	.015	.039
Hadronisation	.004	.002	.004
Bose-Einstein correlation	.005	.004	.009
Colour reconnection	.005	.004	.010
σ_{WW} prediction	.003	.005	.014
$\sigma_{single\ W}$ prediction			.011

- WW and single W combined
- all W-decay channels, only $q\bar{q}l\nu$ for L3
- all LEP2 data, 189-209 GeV for Delphi

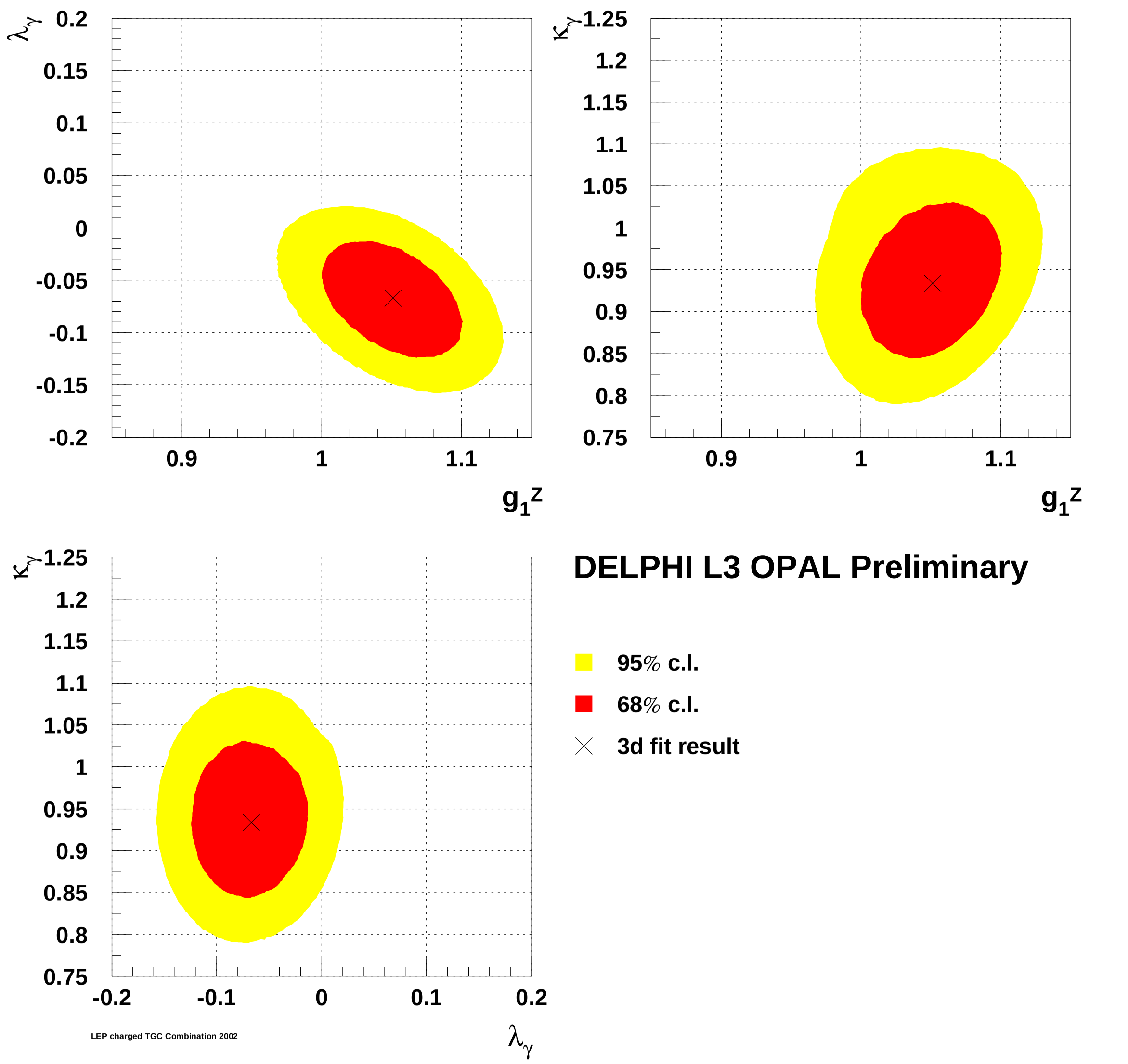
cTGC's : Double Pole Approximation (DPA)



$\mathcal{O}(\alpha)$ corrections : largest contribution to systematic uncertainty

- virtual $\mathcal{O}(\alpha)$ radiative corrections between W and initial and final state particles in resonant W-pair production
- DPA introduces 0.7% slope in $\cos\theta_W$
- full difference DPA-no DPA taken as systematic uncertainty
  ➩ studies are going on among LEP experiments

cTGC's : LEP combination three-parameter fit



⇨ agreement with the SM prediction

Spin Density Matrix

Theoretically
(G. Gournaris, D. Schildknecht, F.M. Renard, Phys. Lett. B263 (1991))

$$e^+(\lambda')\ e^-(\lambda) \ \rightarrow \ W^+(\tau_2)\ W^-(\tau_1) \ \rightarrow \ 4\ f$$

- $e^\pm$: $\lambda,\ \lambda' = \pm 1/2,\ \lambda = -\lambda'\ (m_e \approx 0)$
- $W^\pm$: $\tau_1, \tau_2 = \pm 1$ transverse polarisation (T)

  0 longitudinal polarisation (L)

Two particle SDM

$$\rho_{\tau_1 \tau_1' \tau_2 \tau_2'}(s, cos\theta_W) \equiv \frac{\sum_\lambda F^\lambda{}_{\tau_1 \tau_2}\ (F^\lambda{}_{\tau_1' \tau_2'})^\star}{\sum_{\lambda,\tau_1,\tau_2} |F^\lambda{}_{\tau_1 \tau_2}|^2}$$

➪ $\sum$ over all possible helicities of the W^+ : $81 \rightarrow 9$ elements

Spin Density Matrix

Single particle SDM

$$\rho^{W^-}_{\tau_1 \tau_1{}'}(s, cos\theta_{W^-}) \equiv \sum_{\tau_2} \rho_{\tau_1 \tau_1{}' \tau_2 \tau_2}(s, cos\theta_{W^-})$$

- diagonal elements (real) : ⇨ probability to produce a W^- with $\tau_1 = -1,\ 0$ or $+1$

- off-diagonal elements (complex) :

CPT-invariance ⇨ $Im\ (\rho^{W^-}_{\tau\tau'}) + Im\ (\rho^{W^+}_{-\tau-\tau'}) = 0$

CP-invariance ⇨ $Im(\rho^{W^-}_{\tau\tau'})$ - $Im\ (\rho^{W^+}_{-\tau-\tau'}) = 0$

Spin Density Matrix

Experimentally

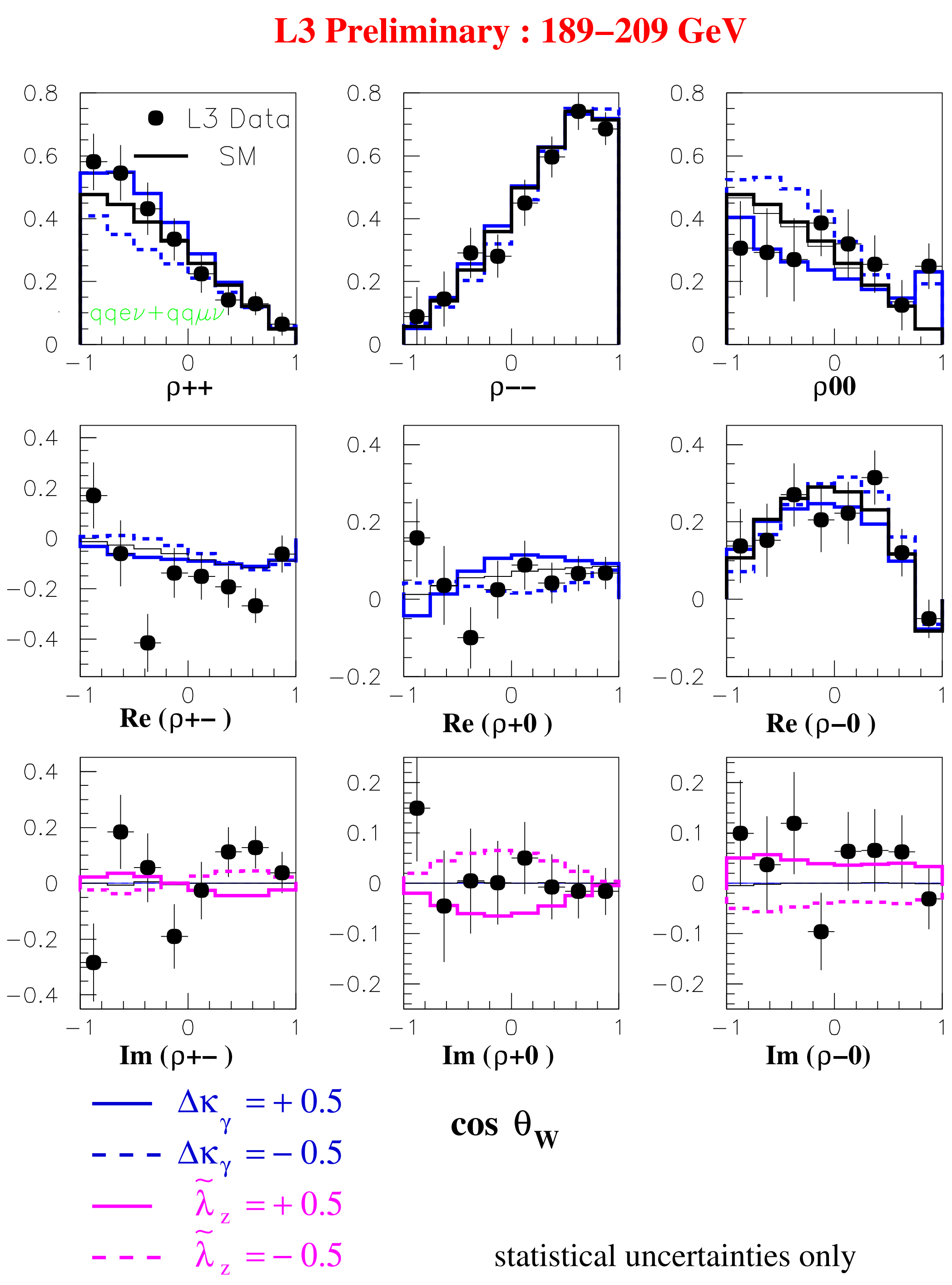
- divide in 8 bins of $\cos\ \theta_W$
- apply projection operators Λ on the events bin k

$$\rho_{\tau\tau'}{}^{W^\pm}(k) = \frac{1}{N_k}\sum_{i=1}^{N_k}\Lambda^{W^\pm}{}_{\tau\tau'}(cos\ \theta^\star_f, \phi^\star_f)_i$$

$$\boxed{\begin{gathered}
\Lambda_{\pm\pm}{}^{W^-} = \Lambda_{\mp\mp}{}^{W^+} = (1/2)(5\ cos^2\theta^\star_f \mp 2\ cos\theta^\star_f - 1) \\
\Lambda_{00}{}^{W^-} = \Lambda_{00}{}^{W^+} = 2 - 5\ cos^2\theta^\star_f \\
\Lambda_{+-}{}^{W^-} = \Lambda_{+-}{}^{W^+} = 2e^{-2i\phi^\star_f} \\
\Lambda_{\pm 0}{}^{W^-} = -(\Lambda_{\mp 0}{}^{W^+})^\star = (-8/3\pi\sqrt{2})(1 \mp 4\ cos\theta^\star_f)e^{\mp i\phi^\star_f}
\end{gathered}}$$

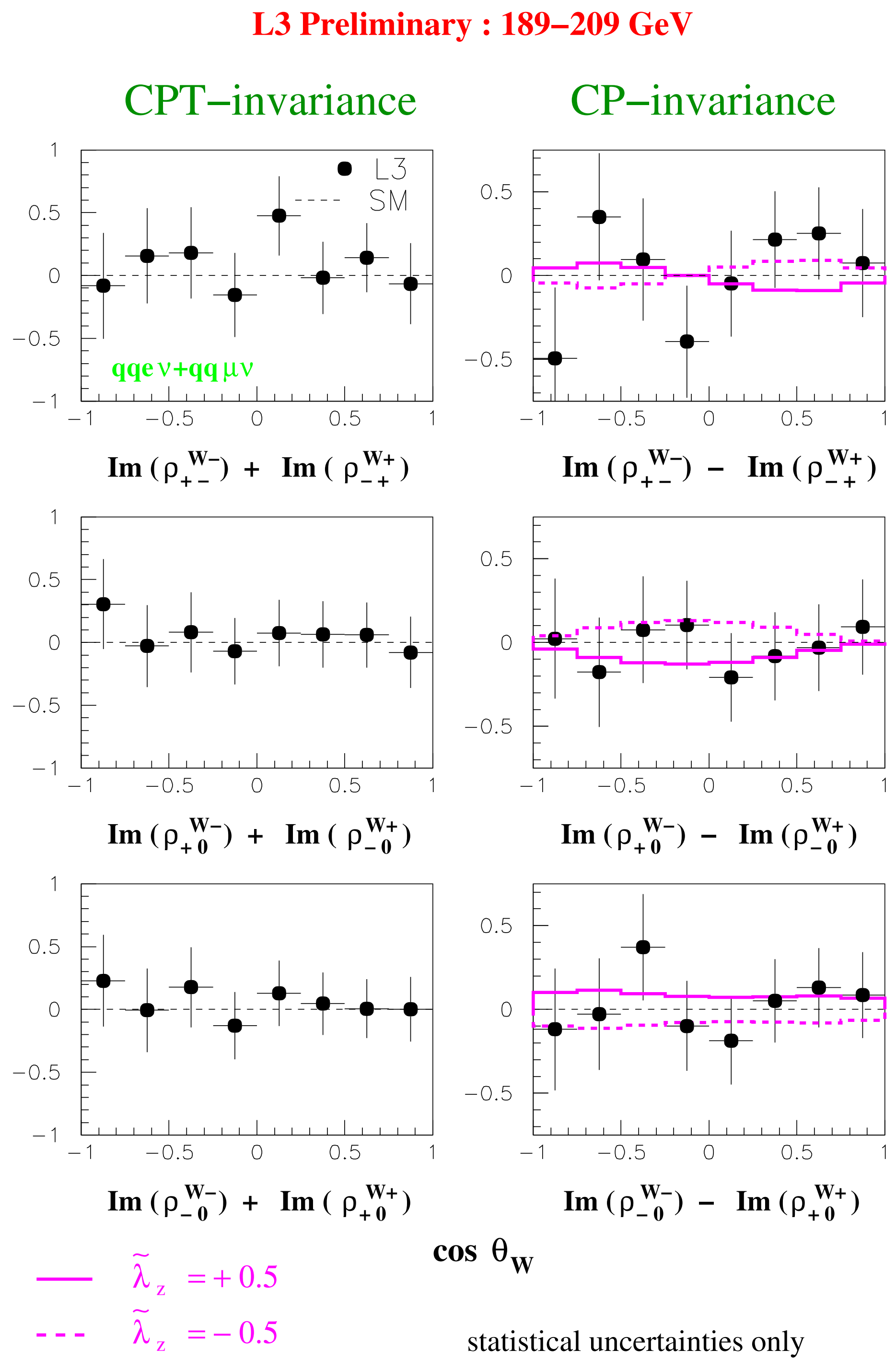
- correct data events for background contamination, detector acceptance and resolution
  ⇨ direct comparison with SM prediction

Spin Density Matrix : distributions



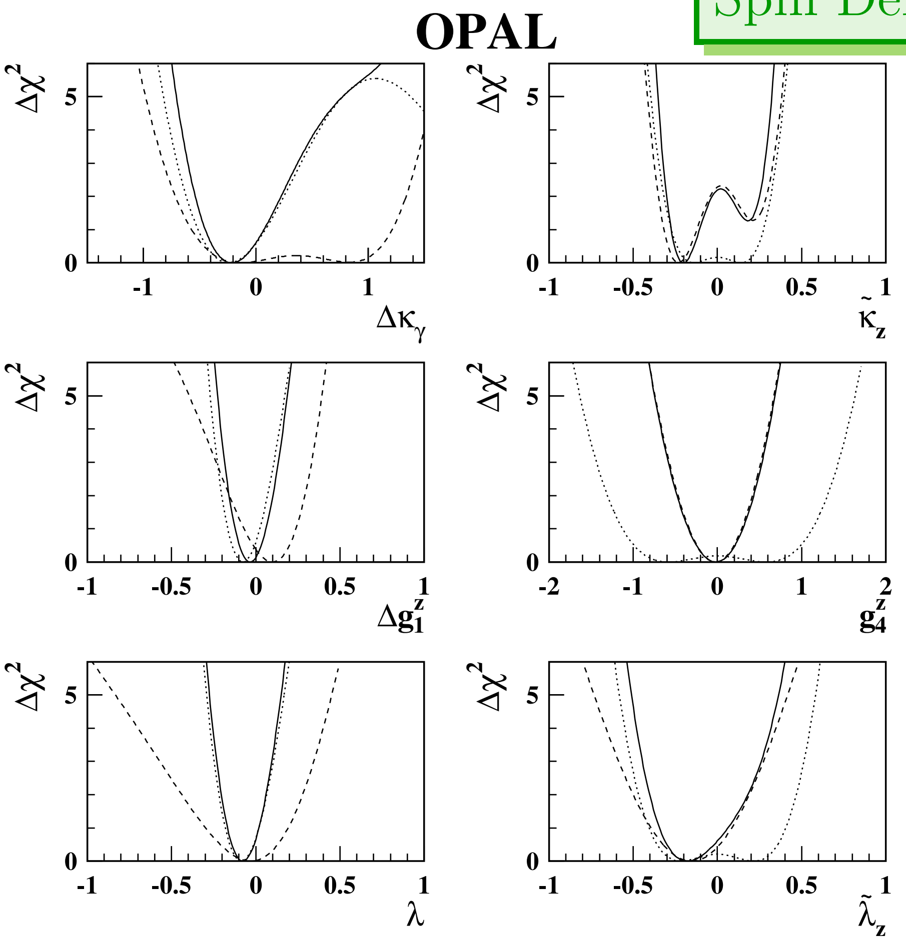
⇨ good agreement with SM prediction

Spin Density Matrix : CP(T)-test



⇨ good agreement with CPT- and CP- invariance at tree level

Spin Density Matrix



Opal 189 GeV $q\bar{q}l\nu$ data
$g_1^Z = 0.97\,^{+.09}_{-.09}$
$\lambda_\gamma = -0.08\,^{+.10}_{-.09}$
$\kappa_\gamma = 0.78\,^{+.29}_{-.24}$
$g_4^Z = -0.01\,^{+.32}_{-.33}$
$\tilde{\lambda}_Z = -0.18\,^{+.24}_{-.16}$
$\tilde{\kappa}_Z = -0.20\,^{+.10}_{-.07}$

- Opal : results $\sqrt{s} = 189 - 209$ GeV for this summer
- Delphi, L3 : extraction CP-violating coupling using SDM method going on ...
- Aleph : CP-violating couplings from maximum likelihood fit

W-polarisation

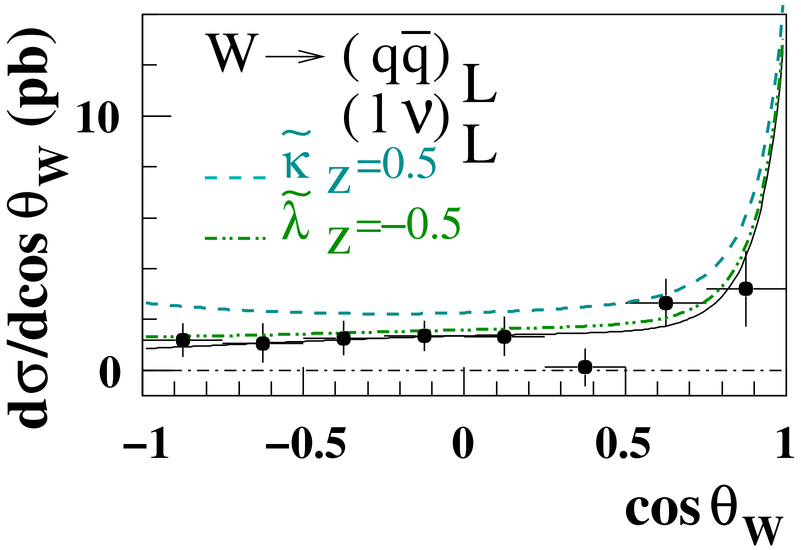
- longitudinally polarised W's $\Leftrightarrow$ spontaneous symmetry breaking

- W-boson : 3 helicity states (+1), (0), (-1)
  ➪ $\neq$ angular distributions decay products

- Opal : integrate

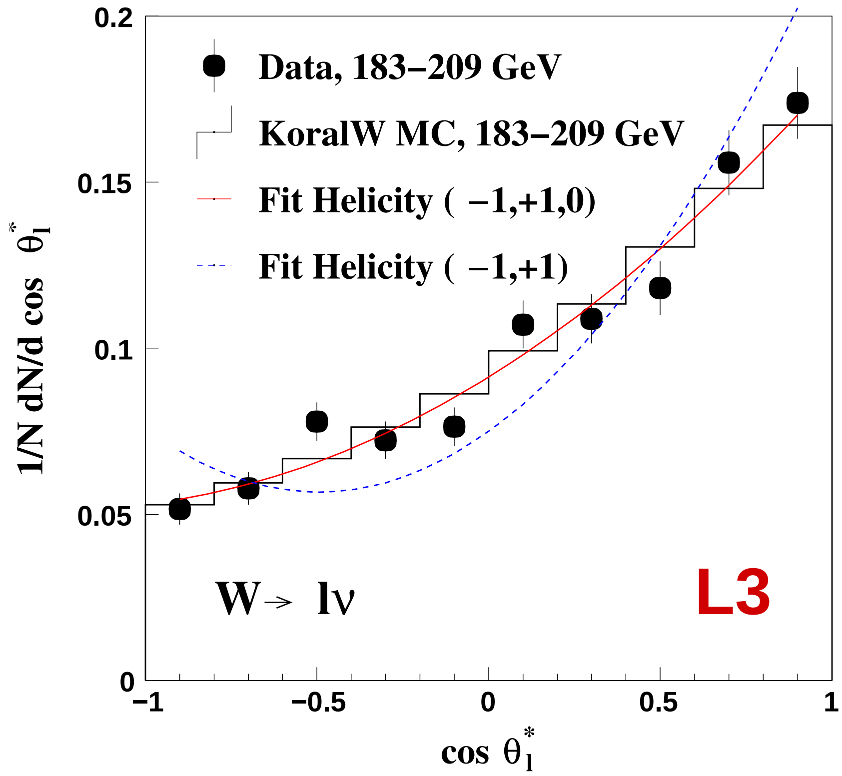
$$\frac{d\sigma_L}{d\cos\theta_W} = \rho_{00}\frac{d\sigma}{d\cos\theta_W}$$

OPAL – 189 GeV



W-polarisation

- L3 : direct fit analytical helicity distributions to $\cos\theta_q^*$, $\cos\theta_l^*$ in $q\bar{q}l\nu$ events

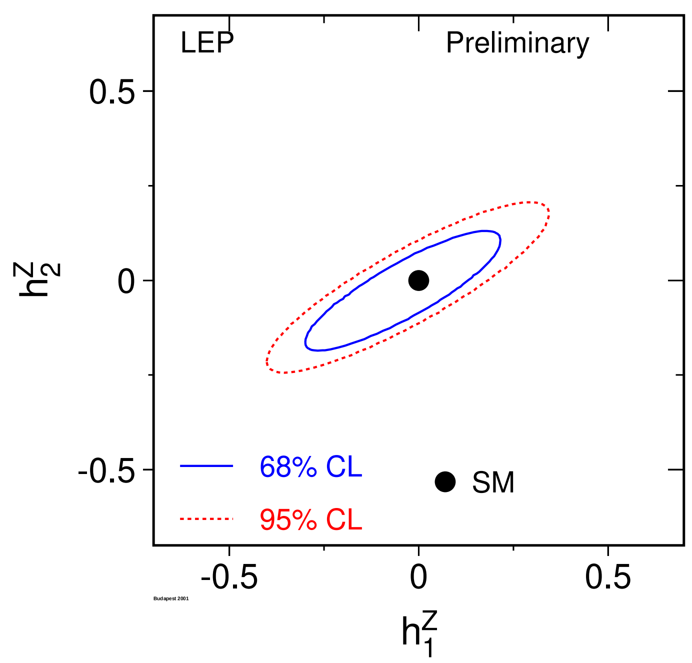


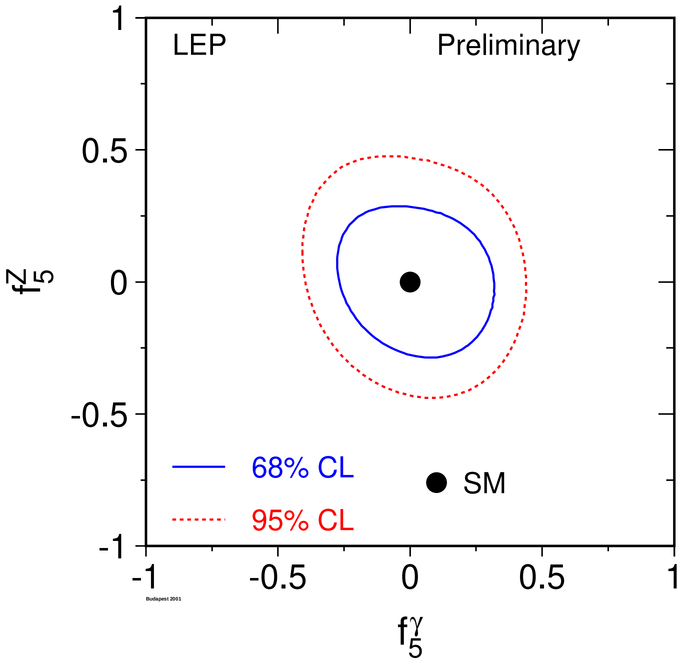
Fraction longitudinally polarised W's	
L3 (183-209 GeV) SM	$0.218 \pm 0.027 \pm 0.016$ 0.241
Opal (189 GeV) SM	$0.210 \pm 0.033 \pm 0.016$ 0.257

⇨ direct confirmation longitudinal W-polarisation

Neutral TGC's

- nTGC's : $e^+e^- \to Z\gamma,\ ZZ$





LEP 1-parameter fit results

95% CL	$V=Z$	$V=\gamma$
f_4^V	[-.31 ; .28]	[-.17 ; .19]
f_5^V	[-.36 ; .39]	[-.36 ; .40]
h_1^V	[-.13 ; .13]	[-.06 ; .06]
h_2^V	[-.08 ; .07]	[-.05 ; .03]
h_3^V	[-.20 ; .07]	[-.05 ; -.01]
h_4^V	[-.05 ; .12]	[-.002 ; .034]

⇨ agreement with SM prediction

Quartic Gauge Couplings

- cQGC's : $e^+e^- \longrightarrow W^+W^-\gamma,\ \nu\bar{\nu}\gamma\gamma$

95 % CL (GeV^{-2})	a_0^W/Λ^2	a_c^W/Λ^2	a_n^W/Λ^2
Delphi ($WW\gamma$)	[-.018 ; .018]	[-.057 ; .030]	[-.16 ; .12]
L3 ($WW\gamma$ & $\nu\bar{\nu}\gamma\gamma$)	[-.015 ; .015]	[-.048 ; .026]	[-.14 ; .13]
Opal ($\nu\bar{\nu}\gamma\gamma$, $WW\gamma$)	[-.054 ; .052]	[-.15 ; .14]	[-.61; .57]

(all LEP 2 Data, Opal $WW\gamma$ only 189 GeV Data)

LEP-combination expected soon

- nQGC's : $e^+e^- \longrightarrow Z\gamma\gamma$

95 % CL (GeV^{-2})	a_0^Z/Λ^2	a_c^Z/Λ^2
L3-Opal Combined	[-.009 ; .026]	[-.033 ; .046]

(all LEP 2 Data)

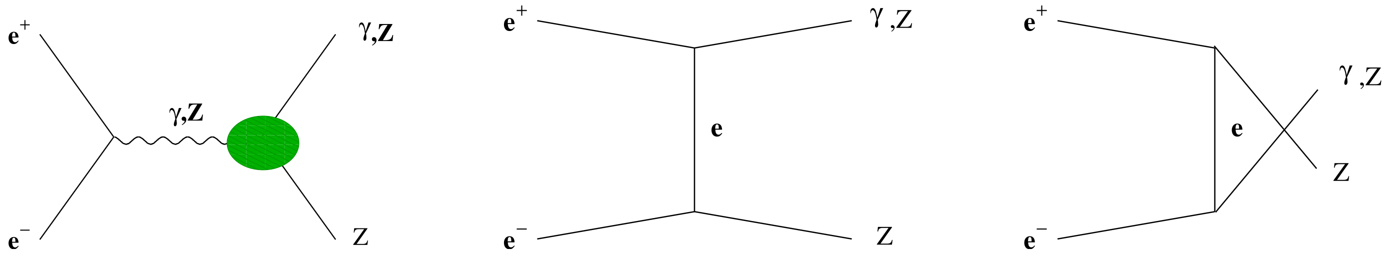
➩ all measured QGC's agree with SM prediction

Conclusions

- all gauge boson couplings measured at LEP are in agreement with the SM expectation
- direct confirmation existence longitudinally polarised W gauge bosons and non-Abelian $SU(2)_L \otimes U(1)_Y$ gauge structure of the SM
- all LEP2 data analysed, finalising systematic uncertainty due to $\mathcal{O}(\alpha)$ corrections
- expected combined LEP precision $\approx .020$ for g_1^Z and λ_γ,
  $\approx .040 - .045$ for κ_γ
- TGC analysis almost in final stage for publication
- soon new results CP- violating couplings using SDM method

nTGC's : $e^+e^- \to ZZ,\ Z\gamma$

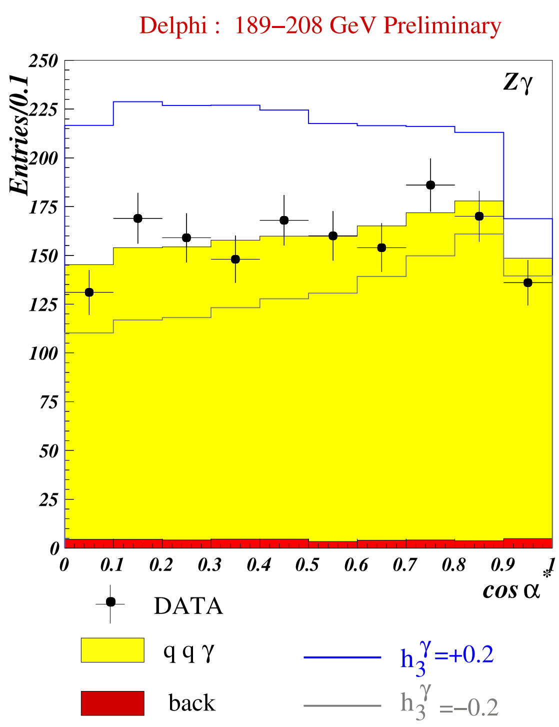
SM background

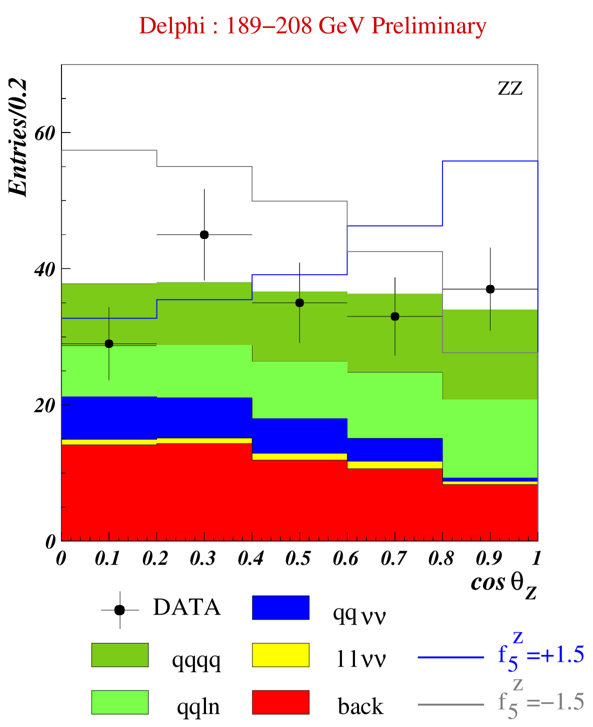


Most general Lorentz-invariant Lagrangian including $VVZ(V = \gamma, Z)$ vertices

12 parameters : $h_1^V,\ h_2^V,\ h_3^V,\ h_4^V,\ f_4^V,\ f_5^V \overset{\mathrm{SM}}{=} 0$ at tree level

Determination : angular distributions + σ_{tot}





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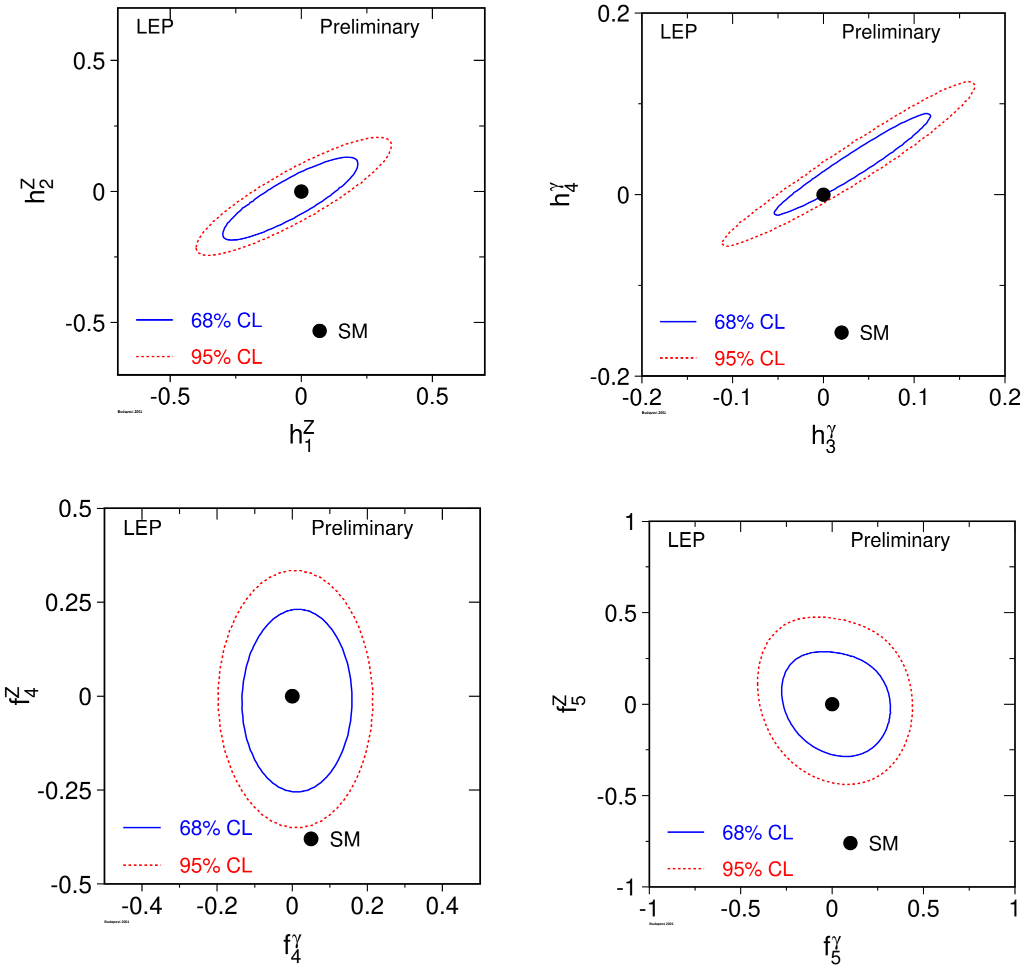

➪ agreement with SM prediction

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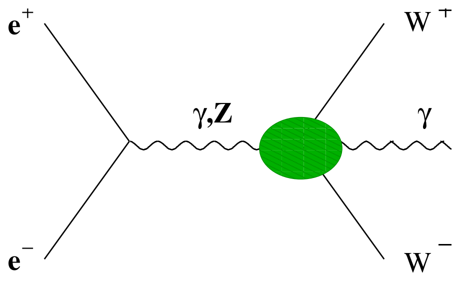
cQGC's : $e^+e^- \to W^+W^-\gamma$

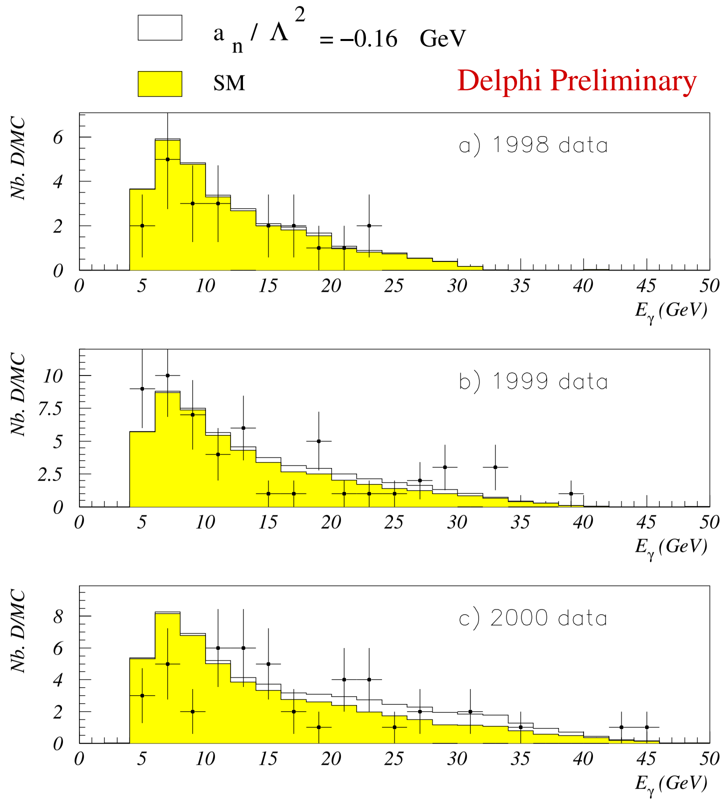


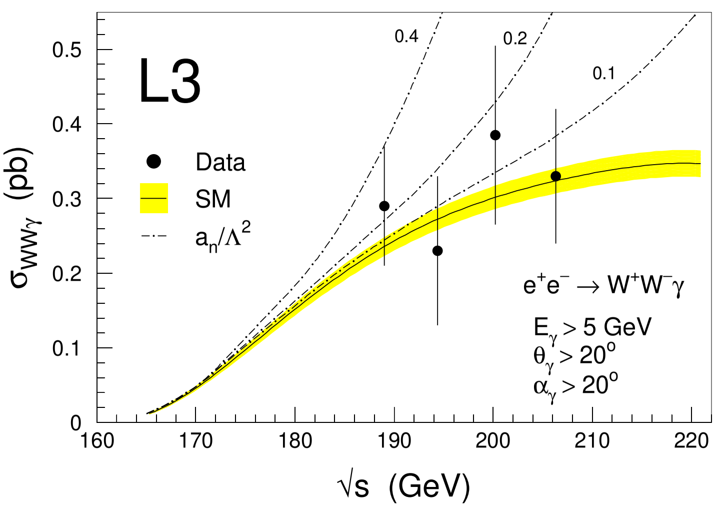
SM background : ISR, FSR, W photon radiation...

SM cQGC contribution too small to be seen at LEP
⇨ look for cQGC's at new physics scale Λ

a_0^W/Λ^2, a_c^W/Λ^2, a_n^W/Λ^2

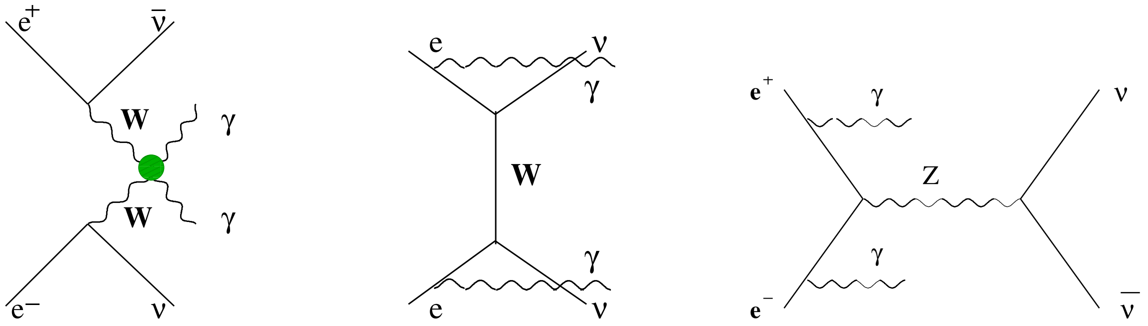
Determination : fit to E_γ + σ_{tot}





cQGC's : $e^+e^- \longrightarrow \nu\bar{\nu}\gamma\gamma$

SM background



SM cQGC contribution too small to be seen at LEP
➩ look for cQGC's at new physics scale Λ

$$a_0^W/\Lambda^2,\ a_c^W/\Lambda^2$$

Determination : fit to E_γ, two-photon recoil mass + σ_{tot}

➩ LEP combination expected soon

95 % CL (GeV^{-2})	a_0^W/Λ^2	a_c^W/Λ^2	a_n^W/Λ^2
Delphi ($WW\gamma$)	[-.018 ; .018]	[-.057 ; .030]	[-.16 ; .12]
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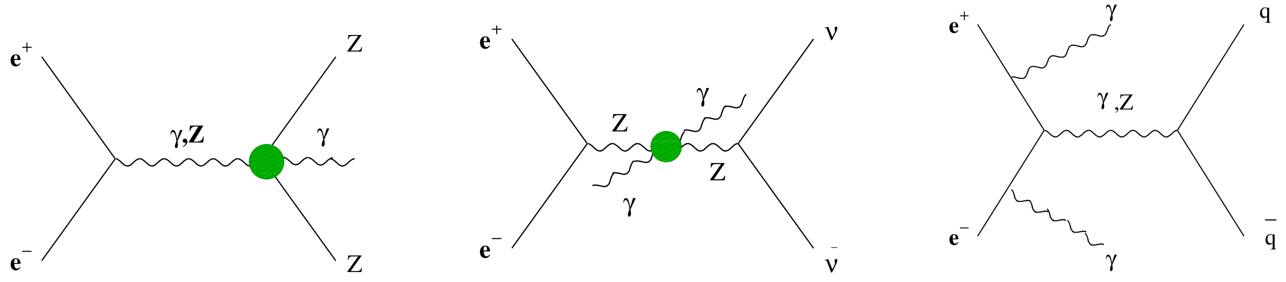
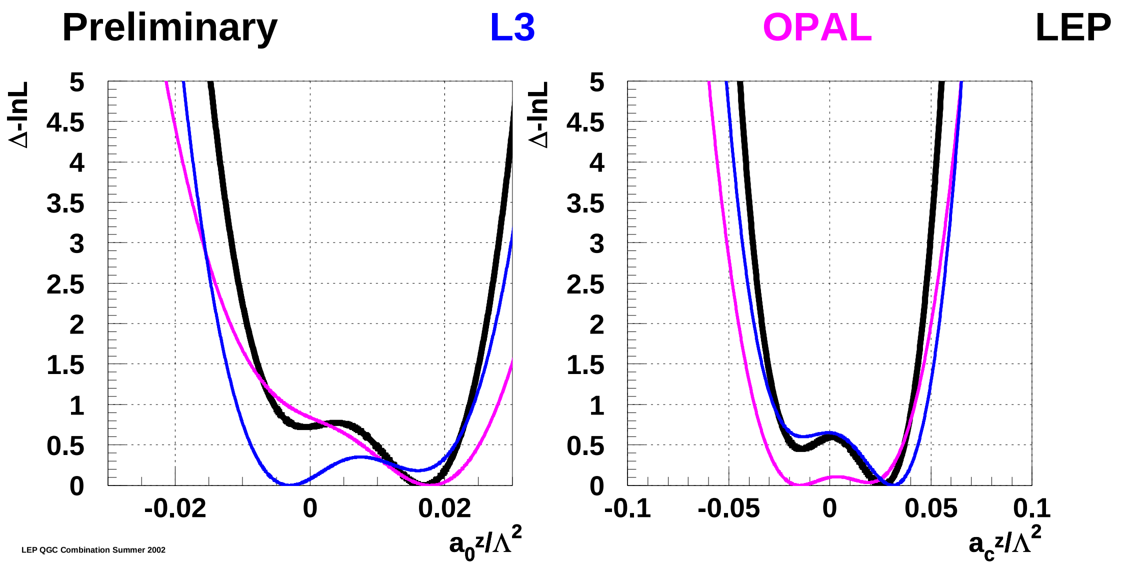


➩ look for nQGC's at new physics scale Λ

a_0^Z/Λ^2, a_c^Z/Λ^2

Determination : fit to E_γ and two-photon recoil mass + σ_{tot}



95 % CL (GeV^{-2})	a_0^Z/Λ^2	a_c^Z/Λ^2
L3-Opal Combined	[-.009 ; .026]	[-.033 ; .046]

➩ all measured QGC's agree with SM prediction