Triple and Quartic Gauge Couplings at LEP

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on behalf of the LEP collaborations

- Overview of Couplings Between Gauge Bosons
- LEP2 Measurements
  - Charged TGC's
  - QGC's
  - Neutral TGC's
- Summary and Outlook

Couplings Between Gauge Bosons

- Within the Standard Model
  - Electroweak interactions mediated by γ, Z^0, $W^\pm$
  - $SU(2)_L \times U(1)_Y$ gauge group structure
  - Non-Abelian group $\Rightarrow$ gauge bosons couplings
- Beyond the Standard Model
  - W sub-structure (technicolour?)
  - Loops of 'new physics' particles (MSSM?)

	TGC	QGC
Charged	γWW, ZWW	$(WWWW)$, $(WWZZ)$, $WWZ\gamma$, $WW\gamma\gamma$
Neutral	ZZZ, $ZZ\gamma$, $Z\gamma\gamma$, $(\gamma\gamma\gamma)$	$(ZZZZ)$, $(ZZZ\gamma)$, $ZZ\gamma\gamma$, $(Z\gamma\gamma\gamma)$, $(\gamma\gamma\gamma\gamma)$

SM Coupling

SM Coupling but negligible at LEP2

Zero in SM

Charged Triple Gauge Couplings

- Lorentz invariance and $U(1)_{em}$
  $\Rightarrow$ 7 γWW + 7 ZWW independent parameters

- C and P invariance
  $\Rightarrow$ 3 γWW + 3 ZWW independent parameters

- Charge of $W^{\pm}$ known
  $\Rightarrow$ 2 γWW + 3 ZWW independent parameters

$$\{\kappa_\gamma,\, \lambda_\gamma,\, g_1^Z,\, \kappa_Z,\, \lambda_Z\}$$

- Use $SU(2) \times U(1)$ operators
- Assume new physics scale is high

$$\left.\begin{array}{rcl} \kappa_Z & = & g_1^Z - (\kappa_\gamma - 1)\tan^2\theta_W \\ \lambda_Z & = & \lambda_\gamma \end{array}\right\}$$

$\Rightarrow$ 3 independent parameters

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

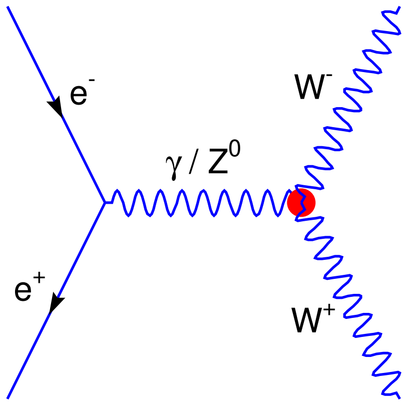
- Magnetic dipole moment

$$\mu_W = \frac{e}{2m_W}(1 + \kappa_\gamma + \lambda_\gamma)$$

- Electric quadrupole moment

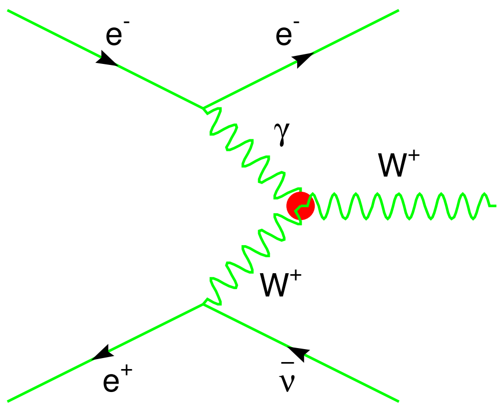
$$q_W = \frac{e}{m_W^2}(\kappa_\gamma - \lambda_\gamma)$$

cTGC physics at LEP2

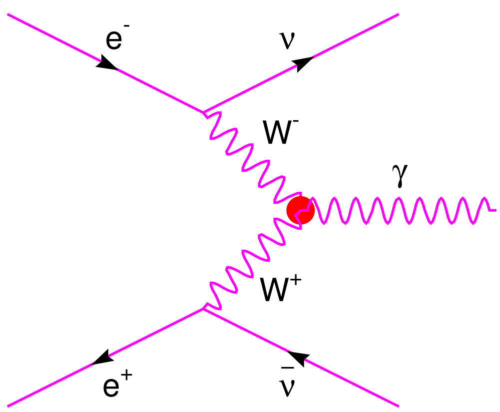


W pair $(g_1^Z, \kappa_\gamma, \lambda_\gamma)$

- $qqqq$
- $ql\nu$
- $l\nu l\nu$



Single W
$(\kappa_\gamma\ \lambda_\gamma\ )$



Single γ
$(\kappa_\gamma\ \lambda_\gamma)$

cTGC Measurements at LEP2

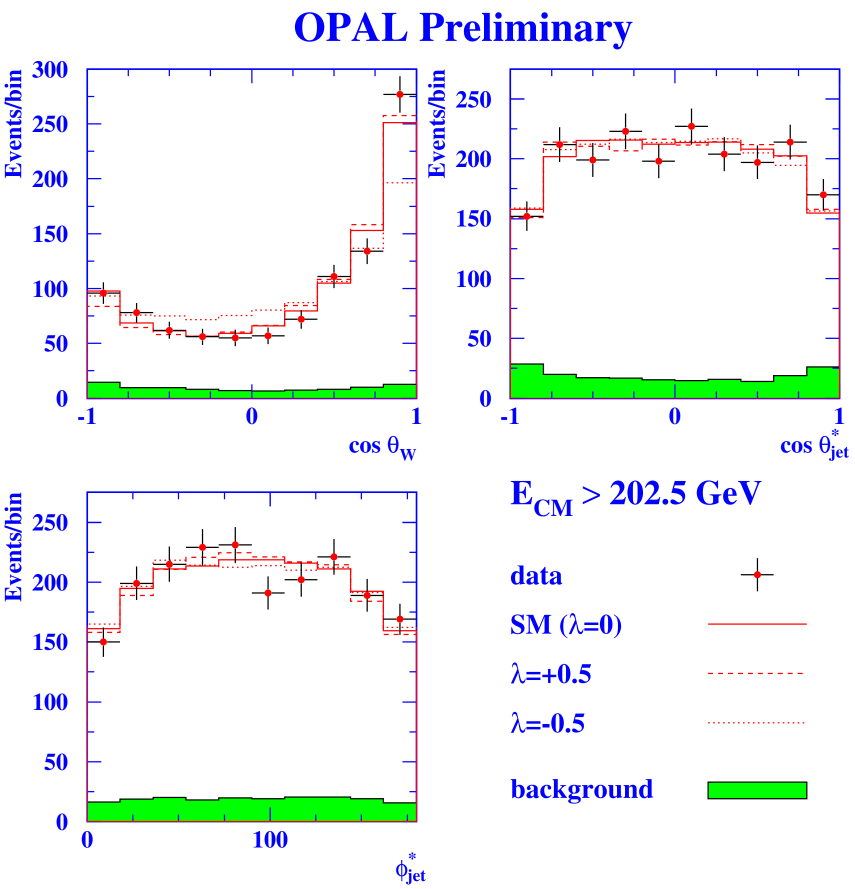
	ALEPH	DELPHI	L3	OPAL
$WW \to qqqq$	$\times$	$\times$		$\times$
$WW \to ql\nu$	$\times$	$\times$	$\times$	$\times$
$WW \to l\nu l\nu$	$\times$			$\times$
single W	$\times$	$\times$	$\times$	$\times$
single γ	$\times$			$\times$

	ALEPH	DELPHI	L3	OPAL
g_1^Z	$1.022^{+0.033}_{-0.033}$	$1.002^{+0.041}_{-0.043}$	$0.952^{+0.053}_{-0.048}$	$0.987^{+0.037}_{-0.036}$
κ_γ	$0.967^{+0.091}_{-0.088}$	$0.966^{+0.106}_{-0.106}$	$0.892^{+0.099}_{-0.095}$	$0.925^{+0.087}_{-0.082}$
λ_γ	$0.010^{+0.034}_{-0.034}$	$0.013^{+0.048}_{-0.045}$	$-0.030^{+0.057}_{-0.054}$	$-0.065^{+0.036}_{-0.035}$

Errors not symmetric in general
Some systematic errors correlated

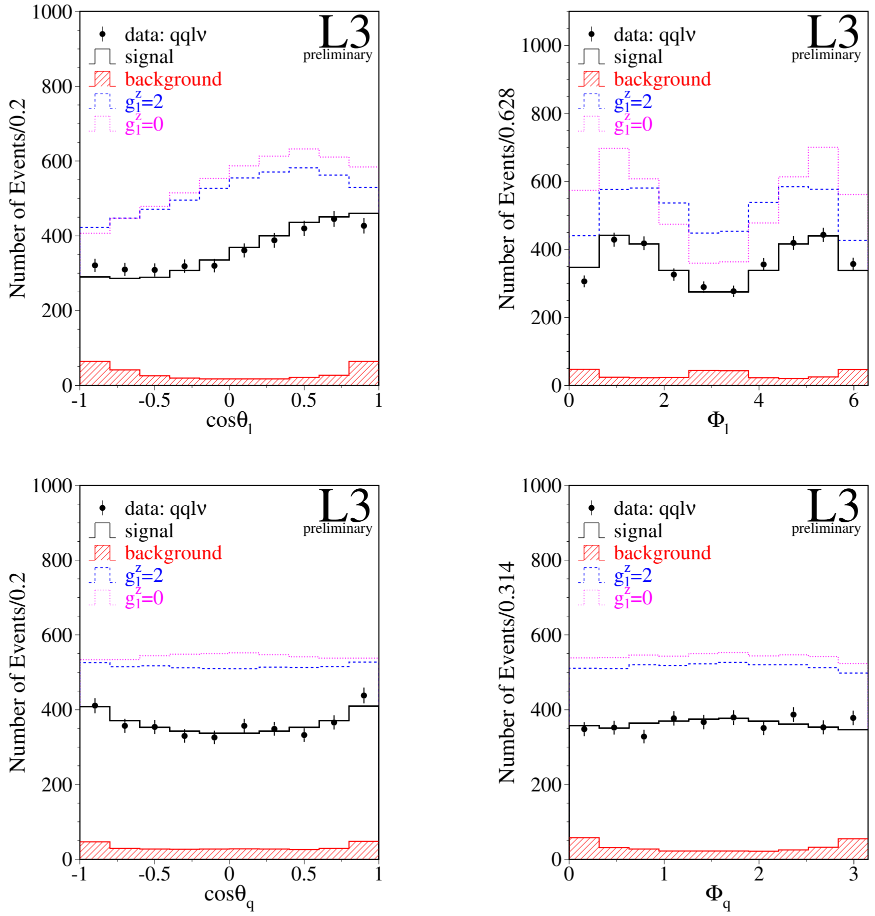
Combine log likelihood curves

Examples of WW Angular Distributions



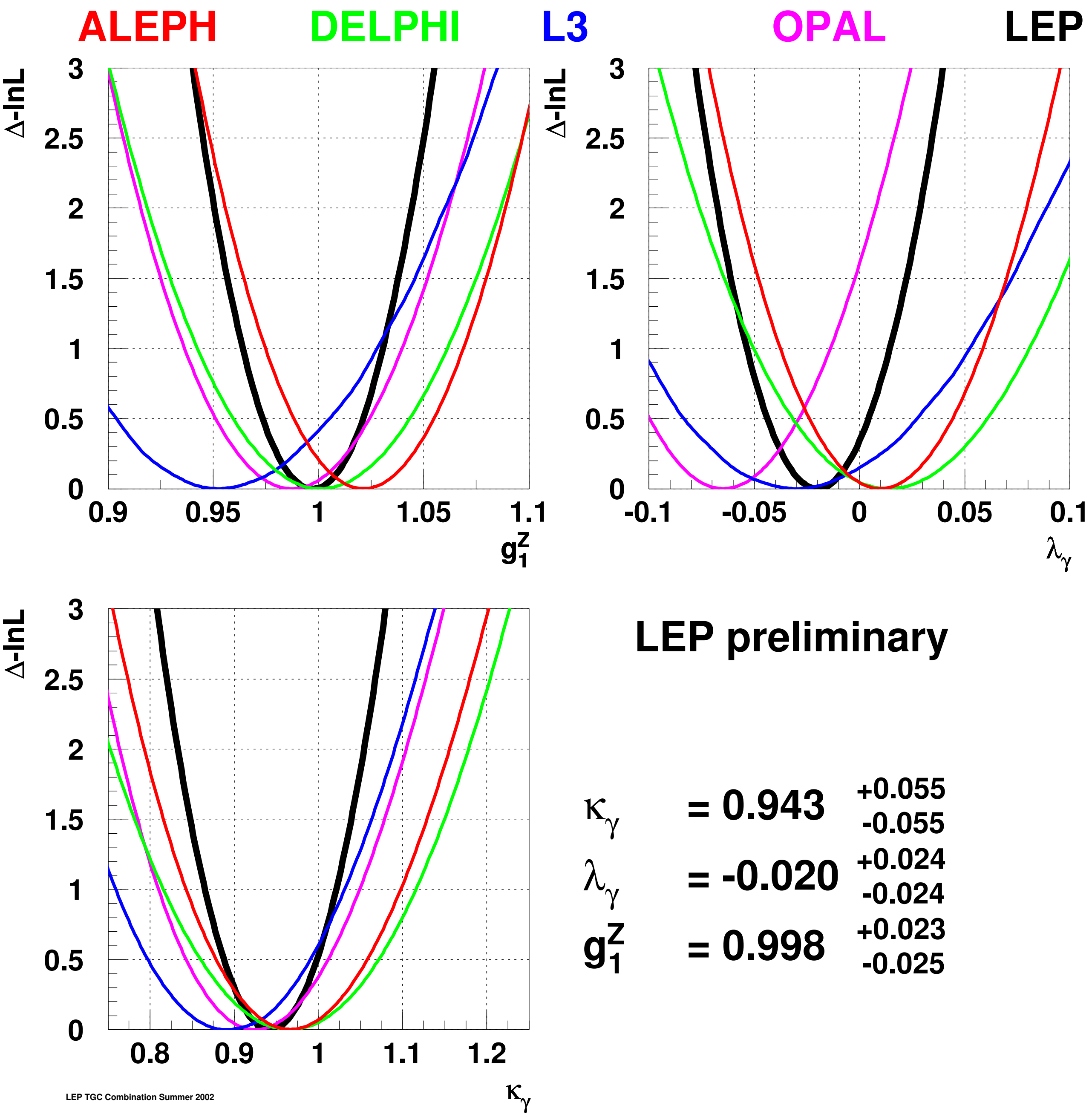
qqqq

- Jet assignment ambiguity
- Folded decay distributions



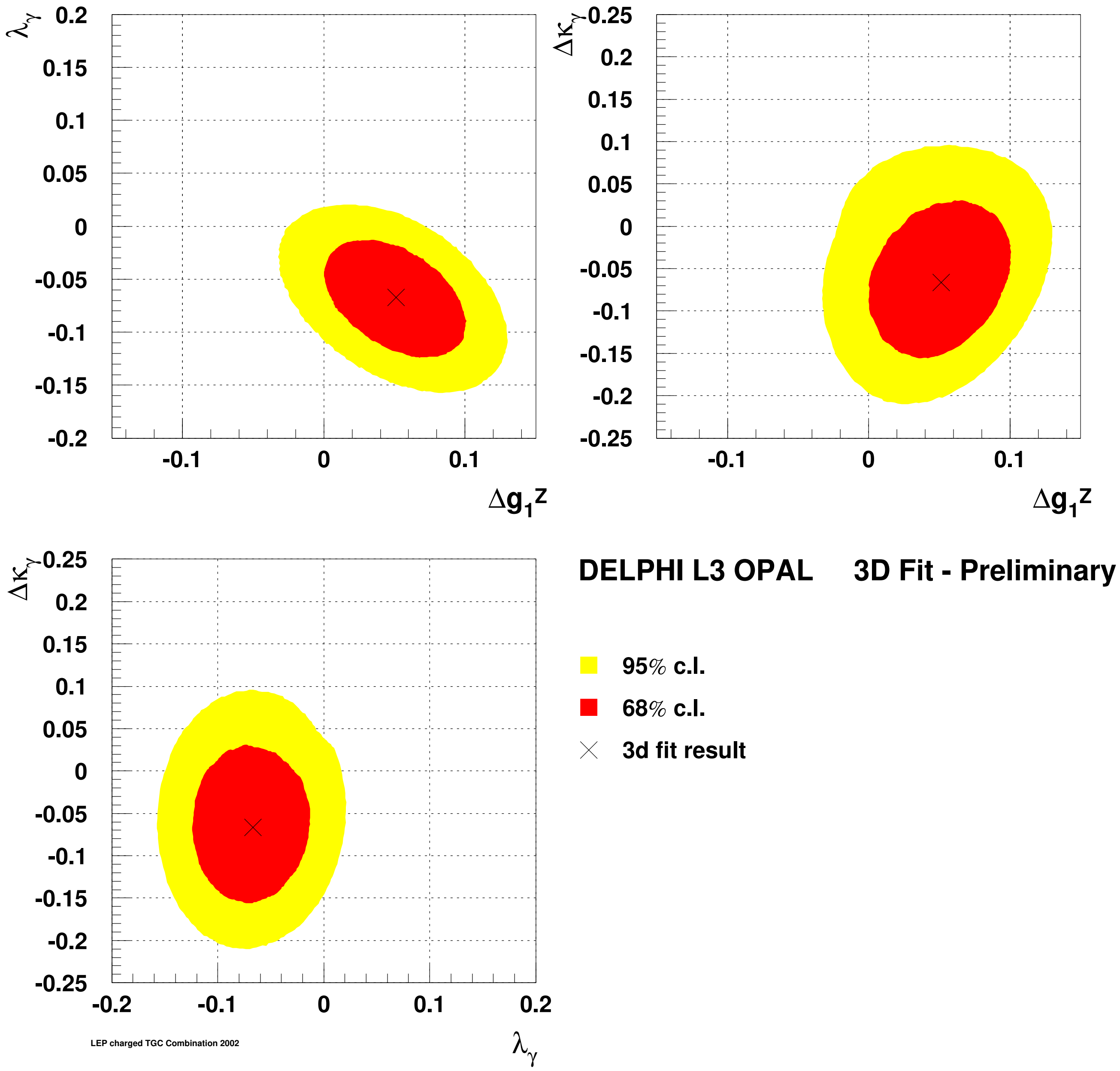
qqlν

LEP combined cTGC Results



- Theory uncertainty for $\mathcal{O}(\alpha_{em})$ corrections gives largest contribution to systematic error

LEP combined cTGC Results - 3D fits



$$\kappa_\gamma = 0.933^{+0.061}_{-0.059}$$

$$\lambda_\gamma = -0.067^{+0.036}_{-0.038}$$

$$g_1^Z = 1.051^{+0.031}_{-0.032}$$

Quartic Gauge Couplings

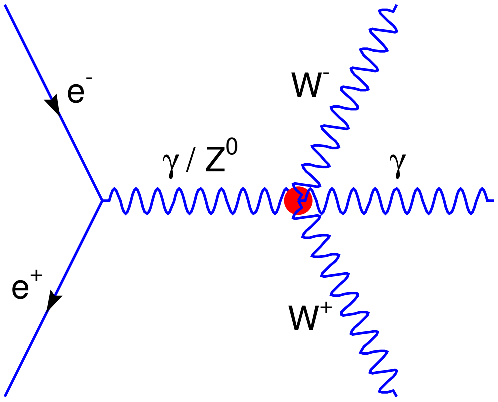
- Consider 'genuine' quartic gauge couplings
- Assume
  - Lorentz invariance
  - $U(1)_{em}$
  - Use $SU(2) \times U(1)$ operators
  - New physics scale is high (dim-6 operators)

$\Rightarrow$ 2 $WW\gamma\gamma$ + 2 $ZZ\gamma\gamma$ + 1 $WWZ\gamma$ parameters

$$\{a_0^W, a_c^W, a_0^Z, a_c^Z, a_n\}$$

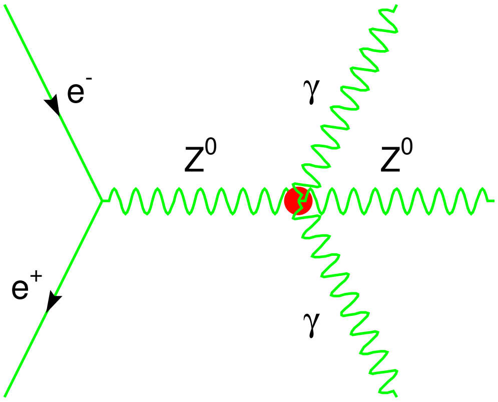
- a_n is CP violating

QGC physics at LEP2



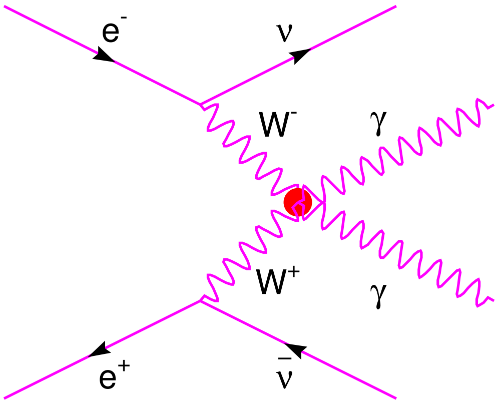
$WW\gamma$ $(a_0^W,\ a_c^W,\ a_n)$

- $qqqq\gamma$
- $qql\nu\gamma$



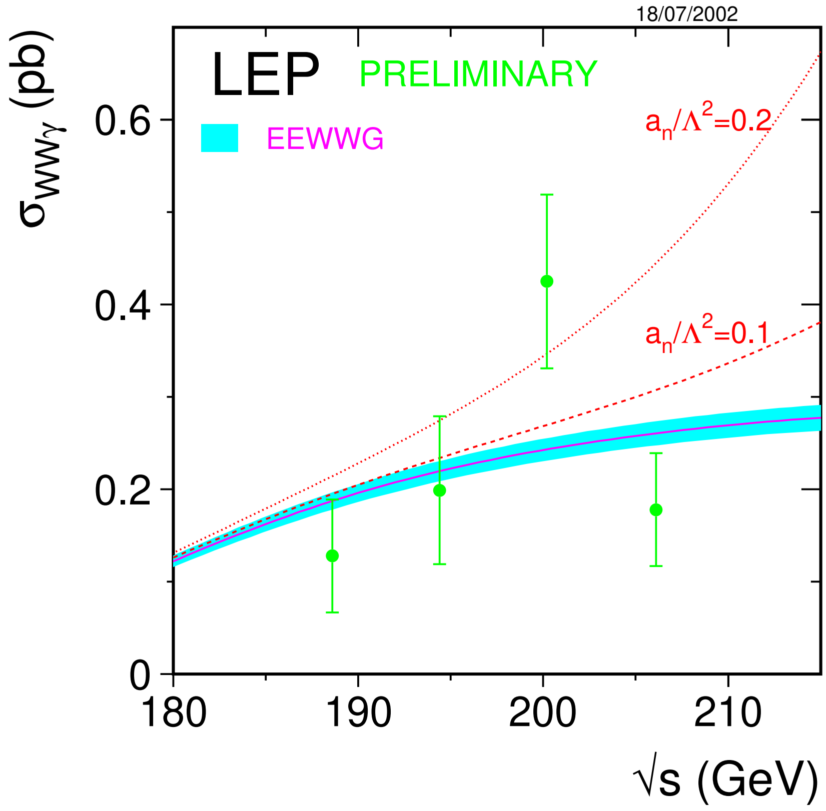
$Z\gamma\gamma$ $(a_0^Z,\ a_c^Z)$

- $qq\gamma\gamma$
- $\nu\nu\gamma\gamma$



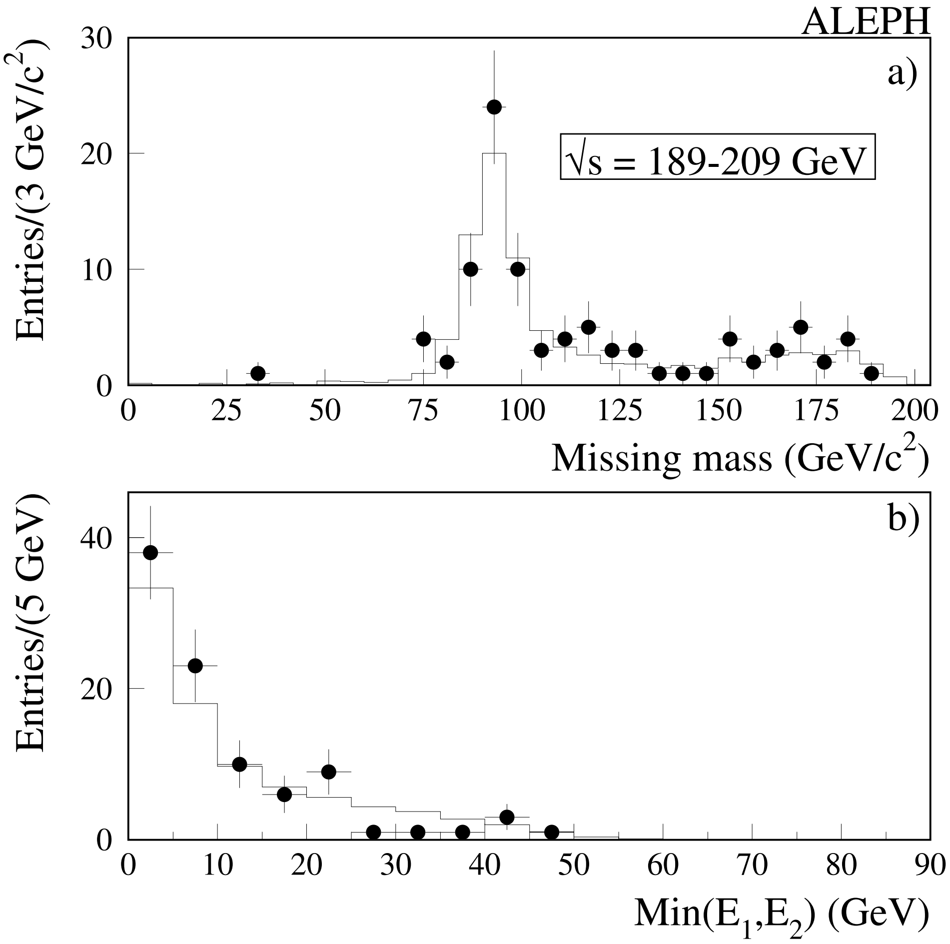
$\nu\nu\gamma\gamma$ $(a_0^W,\ a_c^W)$

a_0^W, a_c^W and a_n Measurements



$WW\gamma$

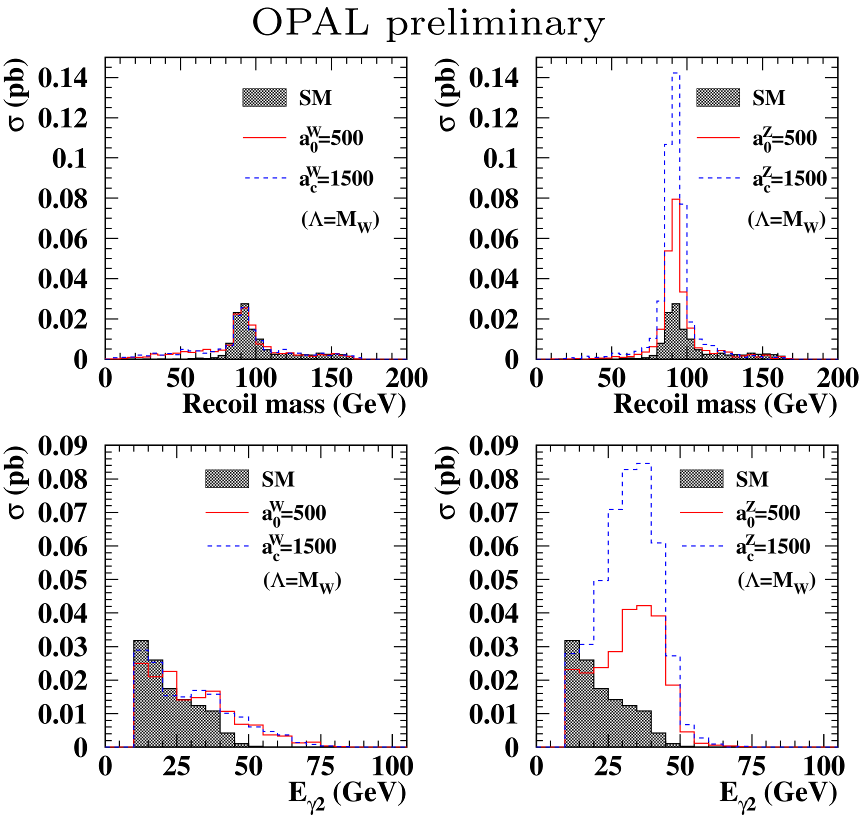
- Hard, isolated γ



$\nu\nu\gamma\gamma$

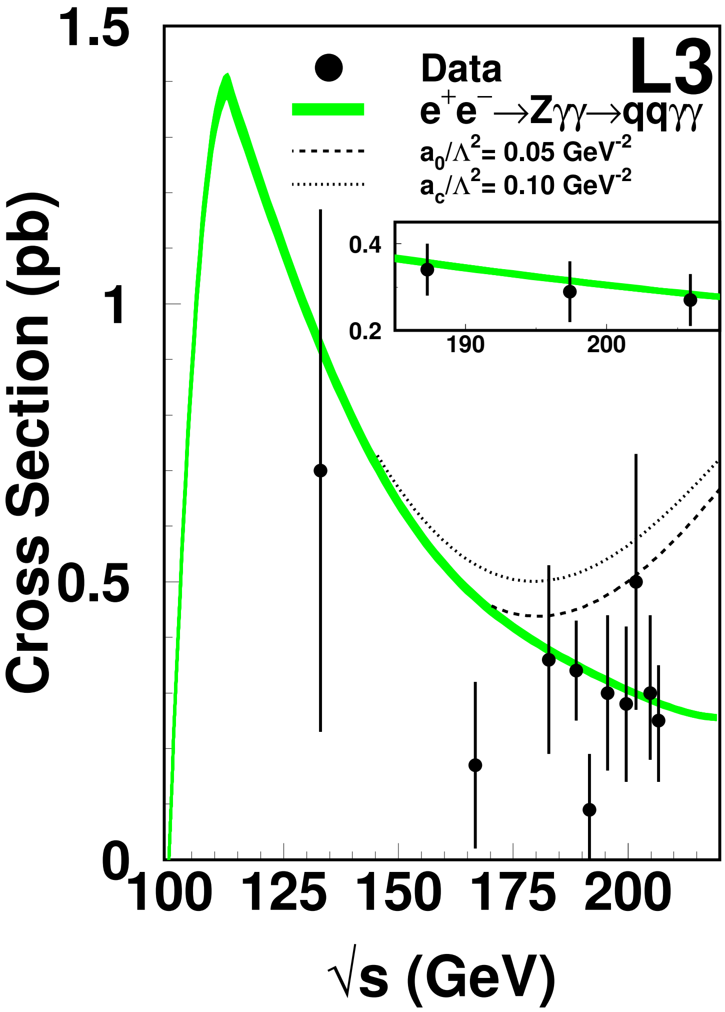
- Radiative return

a_0^Z and a_c^Z Measurements



$\nu\nu\gamma\gamma$

$qq\gamma\gamma$

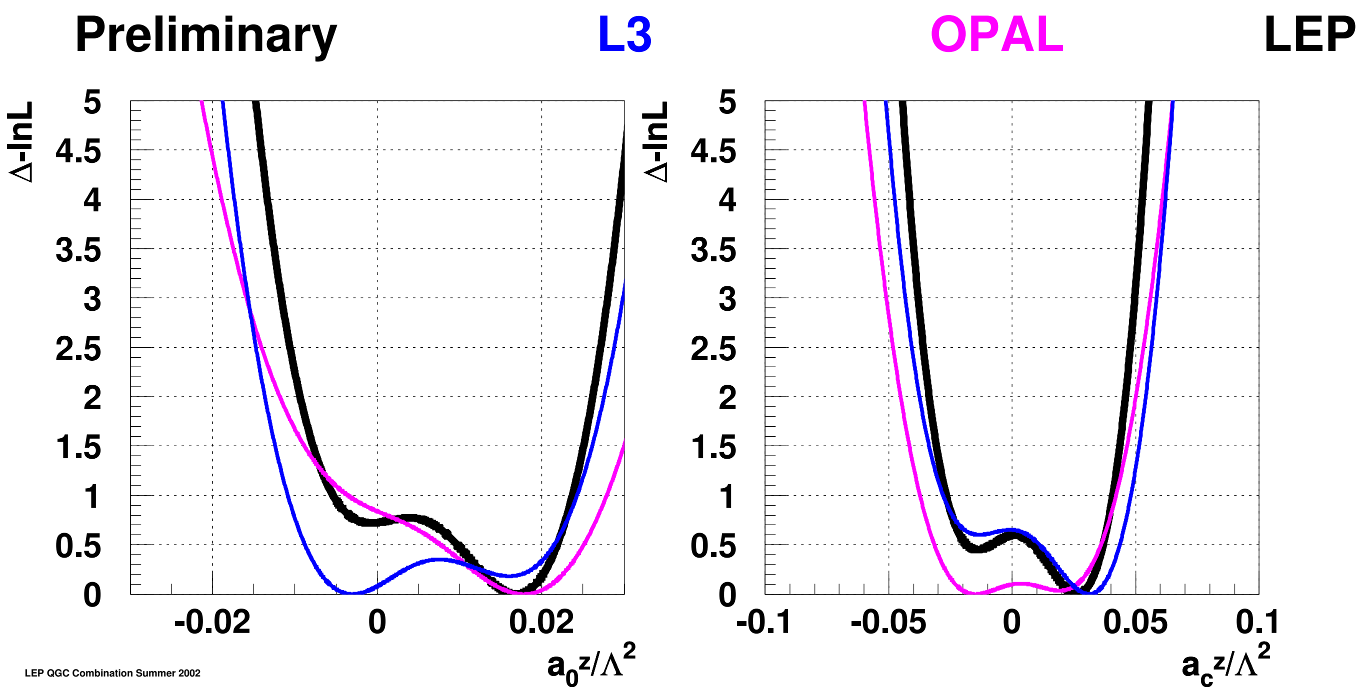


LEP Combined QGC Results

- 95% confidence level limits

	DELPHI	L3	OPAL
a_0^W	$[-0.018, 0.018]$	$[-0.015, 0.015]$	$[-0.054, 0.052]$
a_c^W	$[-0.057, 0.030]$	$[-0.048, 0.026]$	$[-0.15, 0.14]$
a_n	$[-0.16, 0.12]$	$[-0.14, 0.13]$	$[-0.61, 0.57]$

Combination expected soon



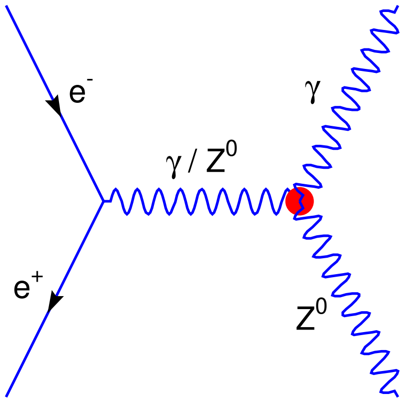
	L3	OPAL	LEP Combined
a_0^Z	$[-0.037, 0.054]$	$[-0.045, 0.050]$	$[-0.033, 0.046]$
a_c^Z	$[-0.014, 0.027]$	$[-0.012, 0.031]$	$[-0.009, 0.026]$

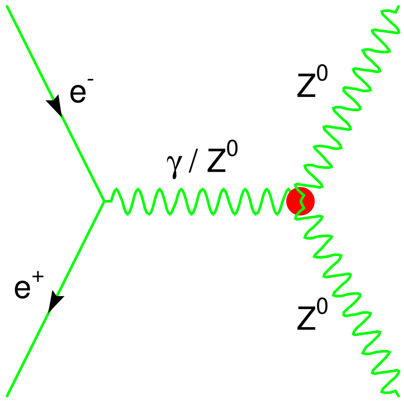
Neutral Triple Gauge Couplings

- Assume
  - Lorentz invariance
  - $U(1)_{em}$
  - Bose symmetry

$\Rightarrow$ $4\ Z\gamma\gamma^* + 4\ Z\gamma Z^* + 2\ ZZ\gamma^* + 2\ ZZZ^*$ parameters

	CP even	**CP** odd
$Z\gamma\gamma^*$	h_3^γ, h_4^γ	h_1^γ, h_2^γ
$Z\gamma Z^*$	h_3^Z, h_4^Z	h_1^Z, h_2^Z
$ZZ\gamma^*$	f_5^γ	f_4^γ
ZZZ^*	f_5^Z	f_4^Z





- $qq\gamma$
- $\nu\nu\gamma$

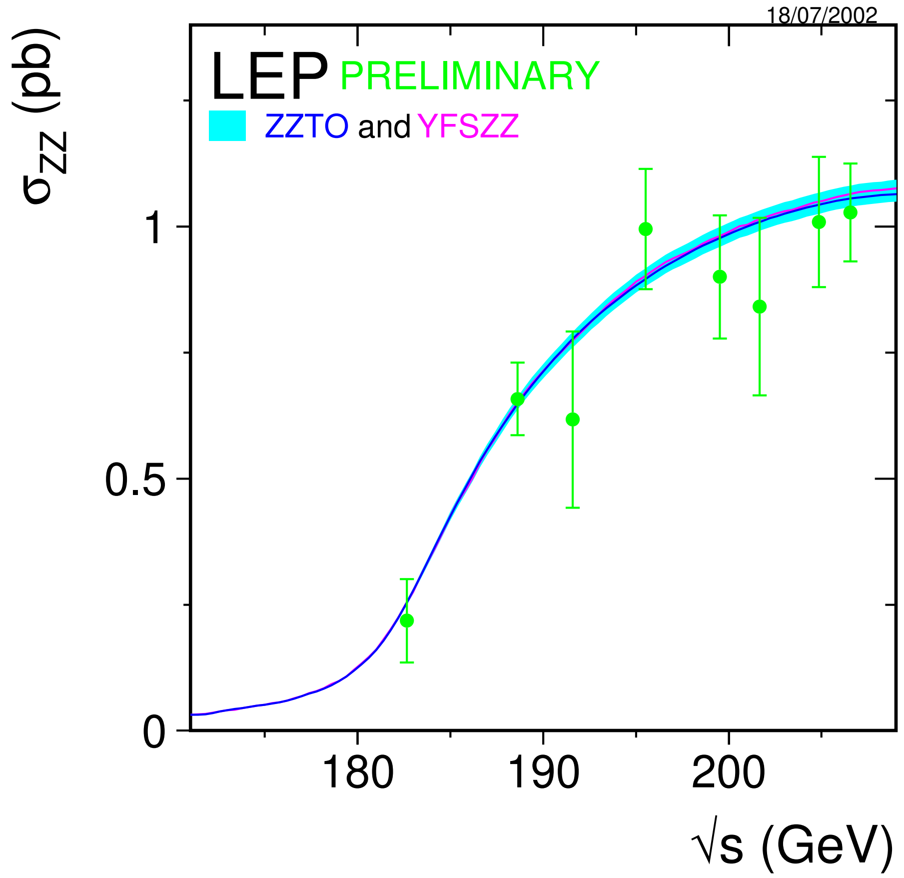
- all 4f decay modes

LEP Combined nTGC Results

- 95% confidence level limits

h_1^γ	[-0.056, +0.055]
h_2^γ	[-0.045, +0.025]
h_3^γ	[-0.049, +0.008]
h_4^γ	[-0.002, +0.034]

h_1^Z	[-0.13, +0.13]
h_2^Z	[-0.078, +0.071]
h_3^Z	[-0.20, +0.070]
h_4^Z	[-0.05, +0.012]



f_4^γ	[-0.17, +0.19]
f_5^γ	[-0.36, +0.40]

f_4^Z	[-0.31, +0.28]
f_5^Z	[-0.36, +0.39]

Conclusion

- Preliminary GC results from LEP
  (CERN-EP / 2002-091)
- All values consistent with SM
- cTGC
  - Expect reductions in $\mathcal{O}(\alpha_{em})$ systematic
  - CP violating cTGC measurements ongoing
- QGC
  - Combination of a_0^W, a_c^W and a_n
- nTGC
- Future for GC physics
  - Final LEP combinations soon
  - Tevatron, LHC, NLC, ...