# Measurements of Quartic Gauge Boson Couplings

Stefania Spagnolo
CLRC Rutherford Appleton Laboratory
**for the LEP Experiments**

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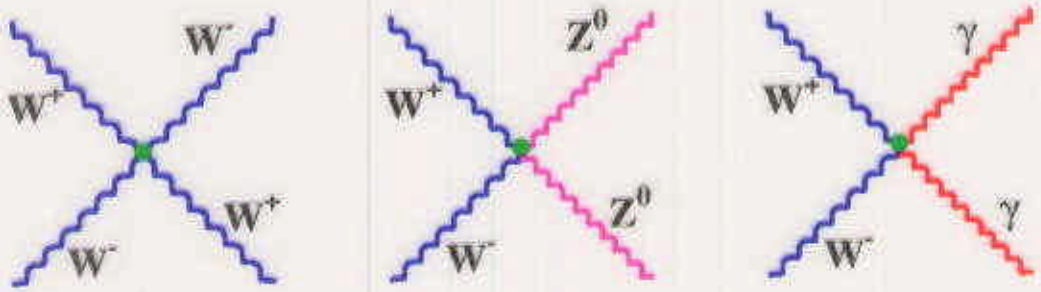
- Introduction to Quartic Gauge boson Couplings
- The Experimental Results on QGCs at LEP 2

Abstracts n. 147, 286, 505, 520, 572

# QGCs - Introduction

**Standard Model** gauge symmetry
➠ **TGC** and **QGC** (with definite strengths)

**The Quartic Vertices in the SM**

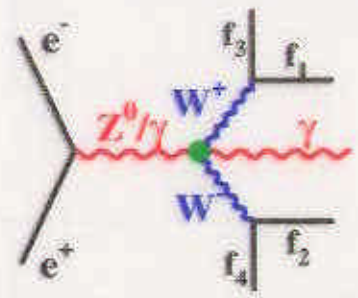



- **TGC**s test the **Non-Abelian structure of the SM**
  ➥**Form Factors**
- **QGC**s insight in **Spontaneous Symmetry Breaking**
  ➥**Contact Interactions**

**Anomalies in QGCs → Heavy New Particle exchange**

➥ **Parametrize unknown New Physics effects with "effective" couplings/Lagrangians**

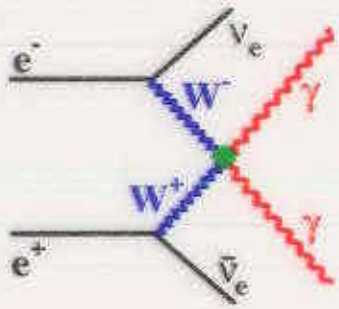
While waiting for next **Linear Collider** ...
.... **QGCs at LEP 2 in $VVV'\gamma$**




## $e^+e^- \to W^+W^-\gamma$

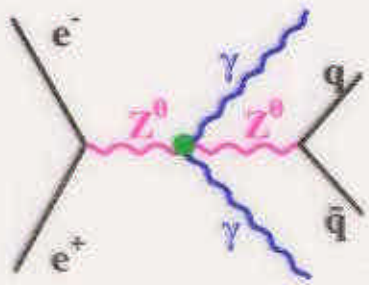
| | | | |
|---|---|---|---|
| | L3 | $\sqrt{s} = 189$ GeV | $\mathcal{L}_{int} \simeq 180$ pb$^{-1}$ |
| ❄ | OPAL | $\sqrt{s} = 189$ GeV | $\mathcal{L}_{int} \simeq 180$ pb$^{-1}$ |

❄ pioneering QGC study at LEP 2 - EPS-PH 1999




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

| | | |
|---|---|---|
| ALEPH | 189 GeV $\leq \sqrt{s} \leq$ 202 GeV | $\mathcal{L}_{int} \simeq 430$ pb$^{-1}$ |
| L3 | 183 GeV $\leq \sqrt{s} \leq$ 202 GeV | $\mathcal{L}_{int} \simeq 480$ pb$^{-1}$ |
| OPAL | $\sqrt{s} = 189$ GeV | $\mathcal{L}_{int} \simeq 180$ pb$^{-1}$ |




## $e^+e^- \to Z^0\gamma\gamma$

| | | |
|---|---|---|
| L3 | 130 GeV $\leq \sqrt{s} \leq$ 202 GeV | $\mathcal{L}_{int} \simeq 500$ pb$^{-1}$ |
| OPAL | 130 GeV $\leq \sqrt{s} \leq$ 208 GeV | $\mathcal{L}_{int} \simeq 580$ pb$^{-1}$ |

# The Formalism

## The general $VVV'\gamma$ vertex (Bélanger *et al.* 2000)

**C, P and $U(1)_{em}$ + dim. 6 operators only**

➽ keep ONLY terms not leading to TGCs

➥ 11 independent Lorentz Invariant Structures

➥ $2 \to$ $WW\gamma\gamma$

$2 \to$ $ZZ\gamma\gamma$

## Commonly used Lagrangian

C, P, $U(1)_{em}$, $SU(2)_c$ (Bélanger, Boudjema 1992)

$$\mathcal{L}_6^0 = -\frac{e^2}{16}\frac{a_0}{\Lambda^2} F^{\mu\nu} F_{\mu\nu}\, \vec{W}^\alpha \,.\, \vec{W}_\alpha \quad \propto \quad \mathcal{V}_0^{WW\gamma\gamma} + \mathcal{V}_0^{ZZ\gamma\gamma}$$

$$\mathcal{L}_6^c = -\frac{e^2}{16}\frac{a_c}{\Lambda^2} F^{\mu\alpha} F_{\mu\beta}\, \vec{W}^\beta \,.\, \vec{W}_\alpha \quad \propto \quad \mathcal{V}_c^{WW\gamma\gamma} + \mathcal{V}_c^{ZZ\gamma\gamma}$$

➥ "Equal strength" for $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings

(not a necessary assumption)

$\Lambda$ = Scale of New Physics results in $GeV^{-2}$

CP violating, $U(1)_{em}$, $SU(2)_c$ (Eboli *et al.* 1994; Leil, Stirling 1994)

$a_n/\Lambda^2 \implies WWZ\gamma$ vertex

# $e^+e^- \to W^+W^-\gamma$

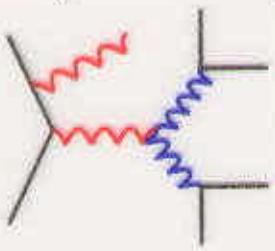
**Final states analysed:** $qql\nu\gamma$ **and** $qqqq\gamma$ $\quad (l = e,\ \mu,\ \tau)$

**Signature of (Anomalous) QGCs**

➨ **excess of high energy** $\gamma$ **in WW events at low** $|\cos\theta|$

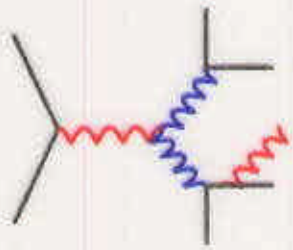
**23 SM diagrams for** $qql\nu\gamma$ **at** $\mathcal{O}(\alpha)$
**(3 more for** $qqqq\gamma$ **)**

**ISR (dominant)**



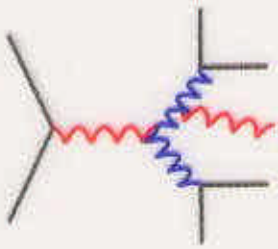
$\gamma$ **at high** $|\cos\theta|$
$M_{f_1 f_2} \sim M_W$

**FSR**

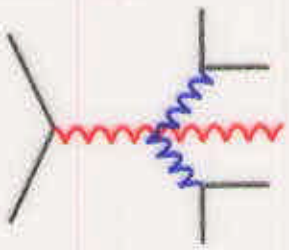


$\gamma$ **close to the fermion**
$M_{f_1 f_2 \gamma} \sim M_W$

**WR (small)**



**QGC (negligible ...**
**... unless** $a_0,\ a_c,\ a_n \neq 0$**)**



$\gamma$ $|\cos\theta| \sim$ **isotropic**
$M_{f_1 f_2} \sim M_W$

**+** $t$**-channel diagrams and crossed diagrams**

# $e^+e^- \to W^+W^-\gamma$ *Signal definition*

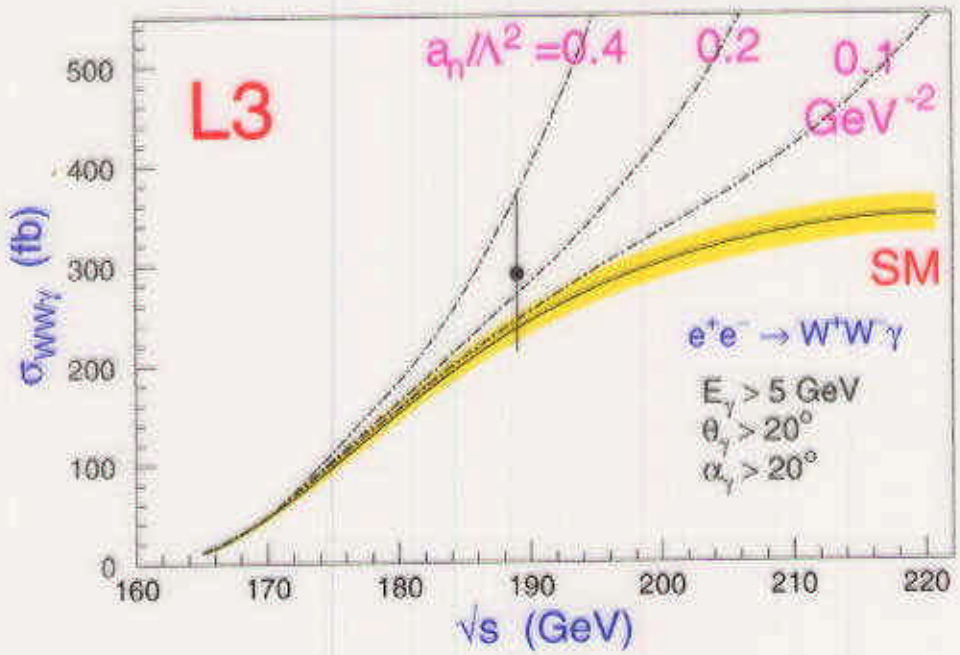
**Standard WW selection + Search for Isolated $\gamma$**

**OPAL - L3** $\sqrt{s} = 189$ GeV $\sim 180$ pb$^{-1}$

**Signal definitions similar but not identical**

| cut | OPAL | L3 |
|---|---|---|
| $E_\gamma$ | >10 GeV | > 5 GeV |
| $\lvert\cos\theta_\gamma\rvert$ | < 0.9 | < 0.94 |
| $\cos\theta_{\gamma-\mathrm{fermion}}$ | < 0.9 | < 0.94 |
| $\min M_{f_i f_j}$ | > 73 GeV | |
| # of Events | 17 | 42 |

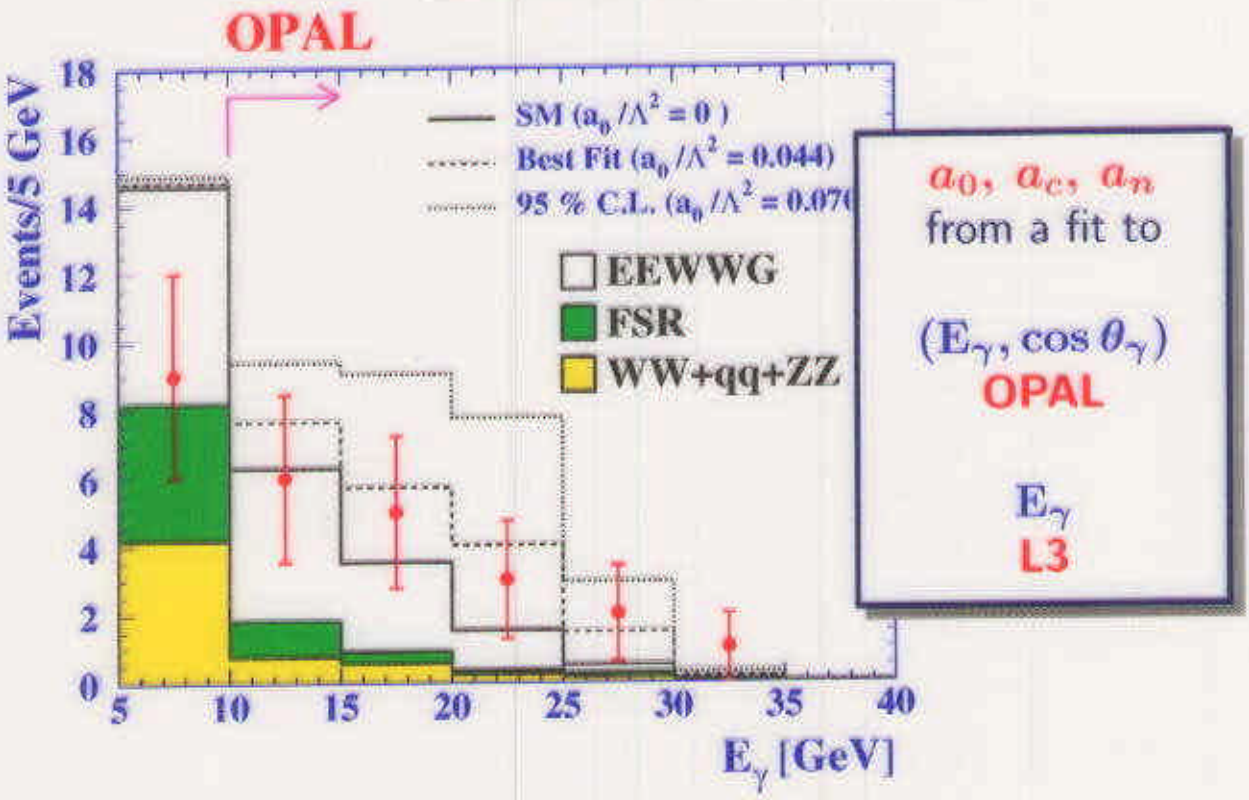
**L3** $\hat{\sigma}_{WW\gamma} = 290 \pm 80(stat) \pm 16(syst)$ fb




**OPAL** $\hat{\sigma}_{WW\gamma} = 136 \pm 37(stat) \pm 8(syst)$ fb

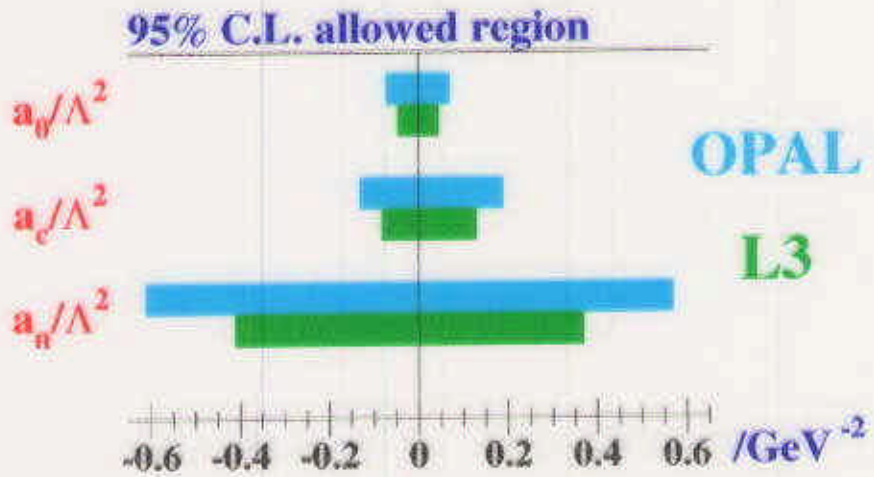
MC predictions ➜ 85-102 fb

# $e^+e^- \rightarrow W^+W^-\gamma$



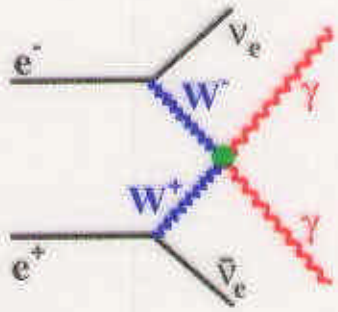

## Theoretical predictions

- EEWWG for SM (ISR+WR+QGC) and anomalous QGCs
  (Stirling, Werthenbach)
- KORALW for FSR



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

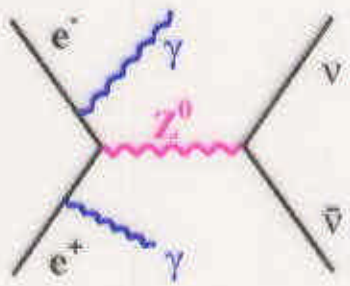
**Anomalous QGCs in WW fusion**




## Event topology

➥ two acoplanar photons

sensitive to $a_0$ and $a_c$




## Standard Model Background

➥ doubly-radiative return to the $Z^0$

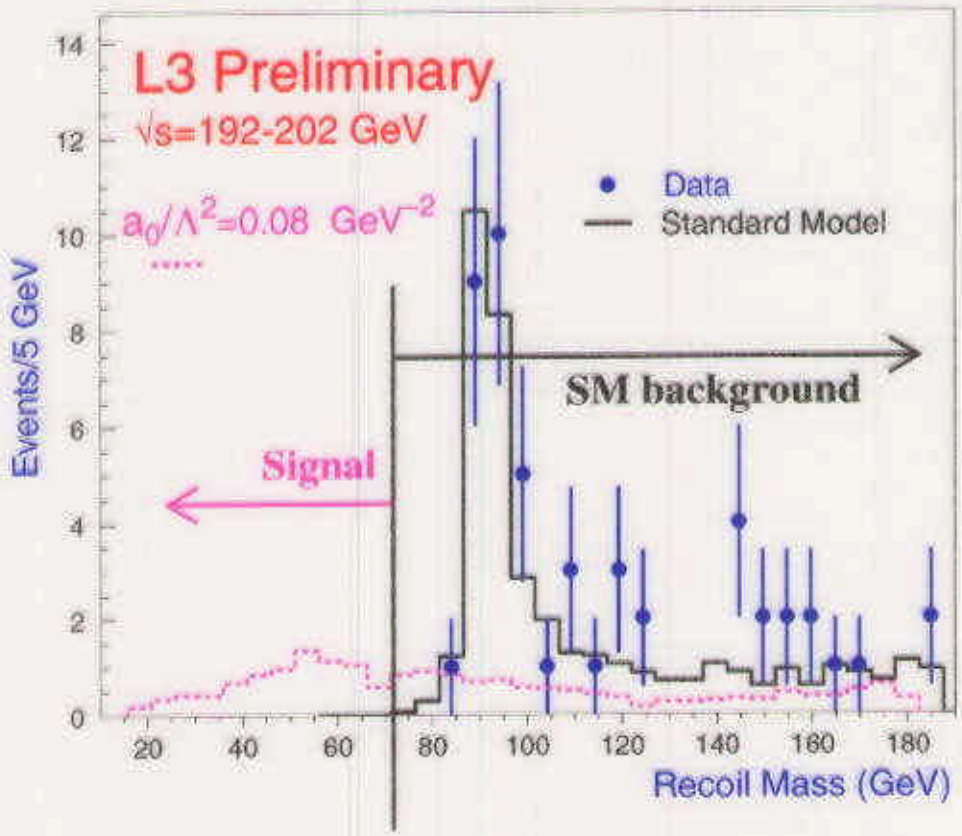
## Theoretical predictions

- EENUNUGANO for Anomalous and SM QGCs
  (Stirling, Werthenbach)
  - radiative return to the $Z^0$ not included
- SM NUNUGPV exact $\mathcal{O}(\alpha^3)$ for visible $\gamma$s
  KORALZ exponentiated $\mathcal{O}(\alpha^2)$
  agreement within 3%

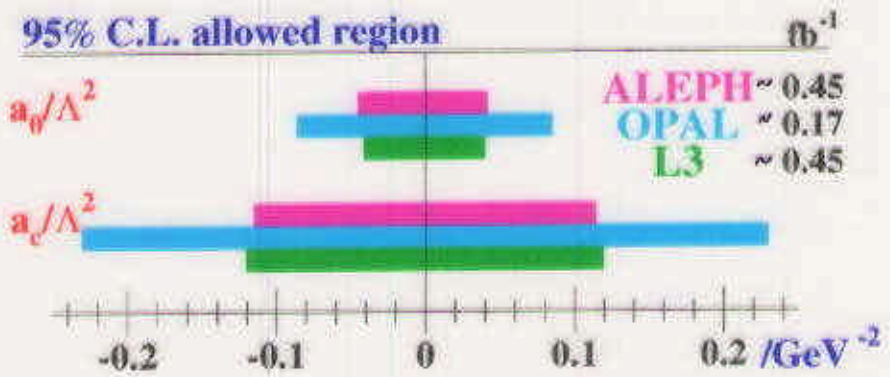
**The reduction of the $Z^0\gamma\gamma$ background is mandatory to neglect interference**

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

➥ **Reject $Z^0\gamma\gamma$ using missing mass recoiling against the two-$\gamma$ system**



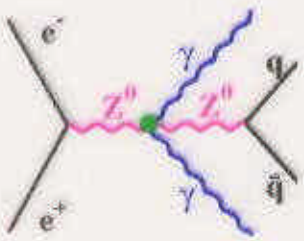

**No events observed by ALEPH, L3, OPAL**
**(with SM expectation ~ 0.1 event per experiment)**



# $e^+e^- \to Z^0\gamma\gamma$

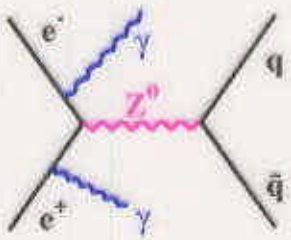
**Sensitive to $a_0$, $a_c$ in the anomalous $ZZ\gamma\gamma$ vertex**

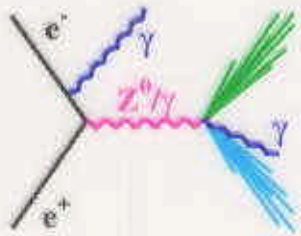
**AQGC signal**




**SM background**

dominant

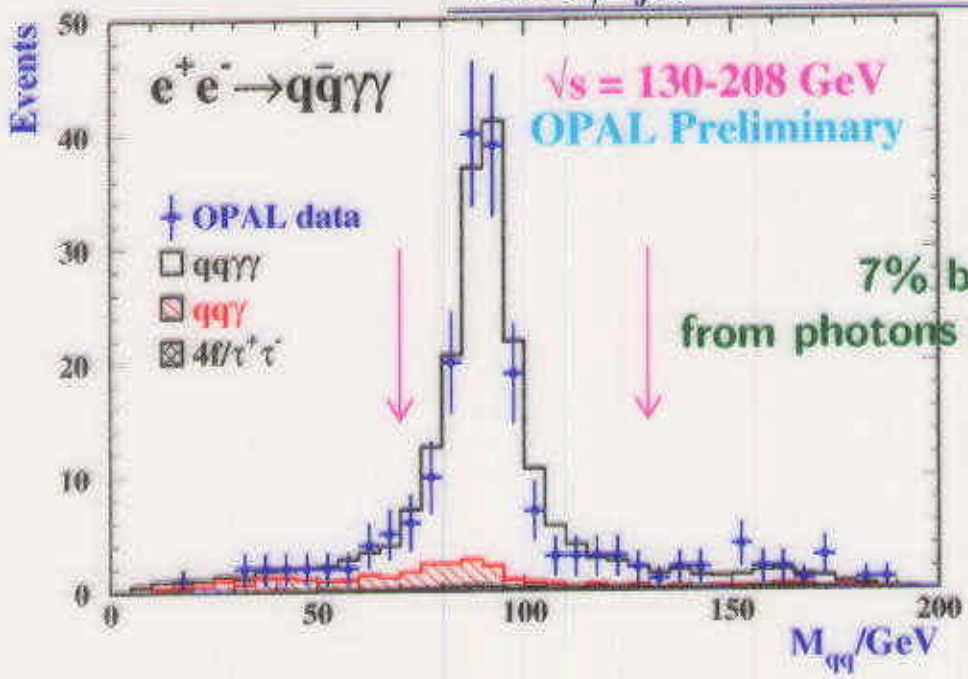



❄ **Event selection $\geq$ 2 Isolated $\gamma$ in multihadronic events** ❄

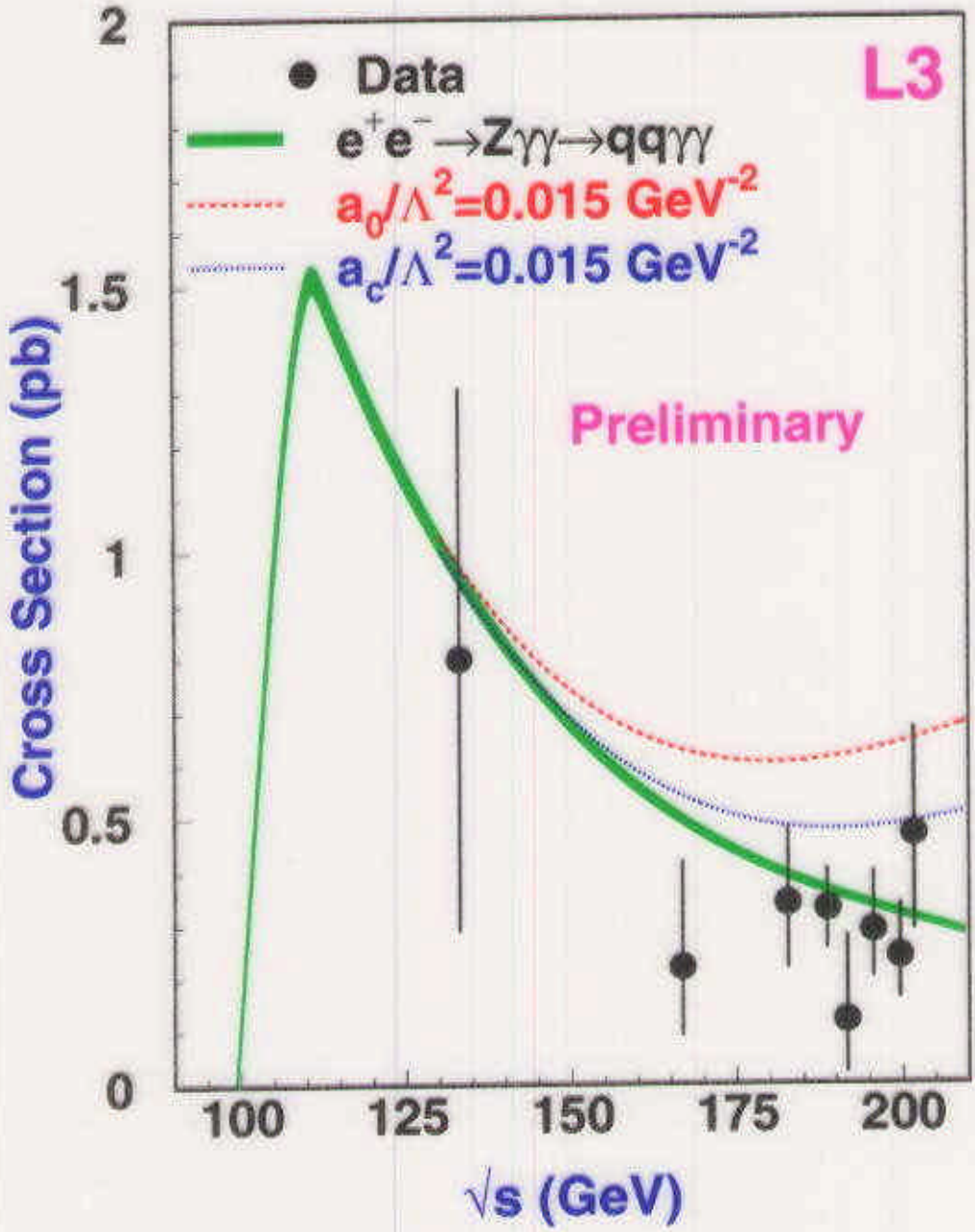
**Signal definition**

| | OPAL | L3 |
|---|---|---|
| $E_{\gamma_1}$, $E_{\gamma_2}$ | $> 5$ GeV | $> 5$ GeV |
| $\lvert\cos\theta_{\gamma_{1,2}}\rvert$ | $< 0.95$ | $< 0.97$ |
| $M_{q\bar{q}}$ | 80-120 GeV | $M_Z \pm 2\Gamma_Z$ |
| $\cos\theta_{\gamma-\text{jet}}$ | $< 0.9$ | |




**7% background from photons in the jets**

# $e^+e^- \rightarrow Z^0\gamma\gamma$



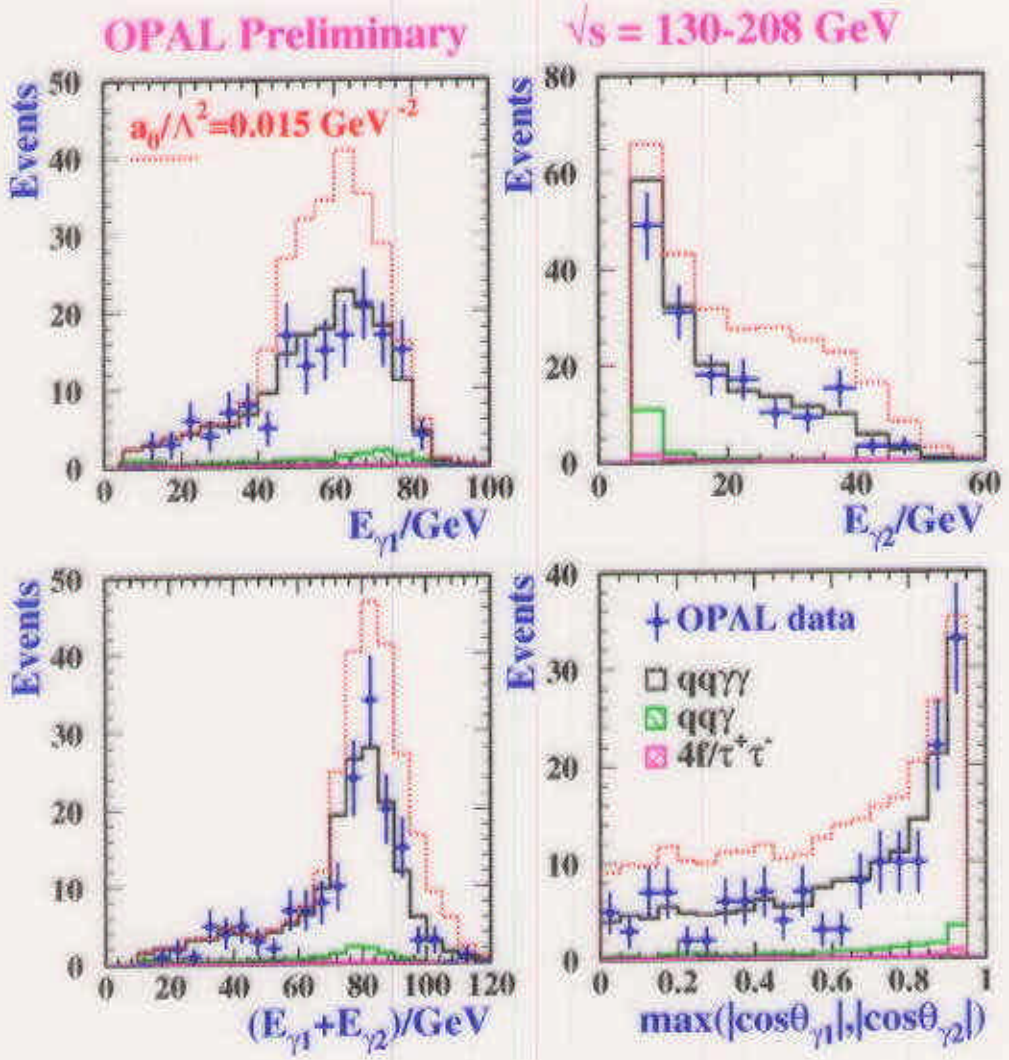

- Standard Model prediction → KK2f
- Signal EEZGG
  (Stirling, Werthenbach)
  AQGCs + SM doubly-radiative return to $Z^0$

# $e^+e^- \to Z^0\gamma\gamma$

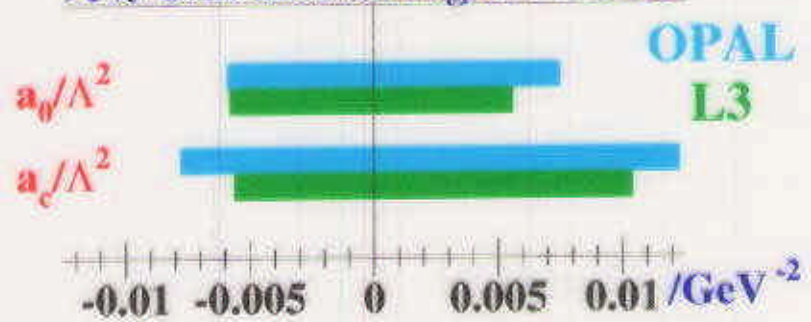
**Fit method** binned maximum likelihood fit

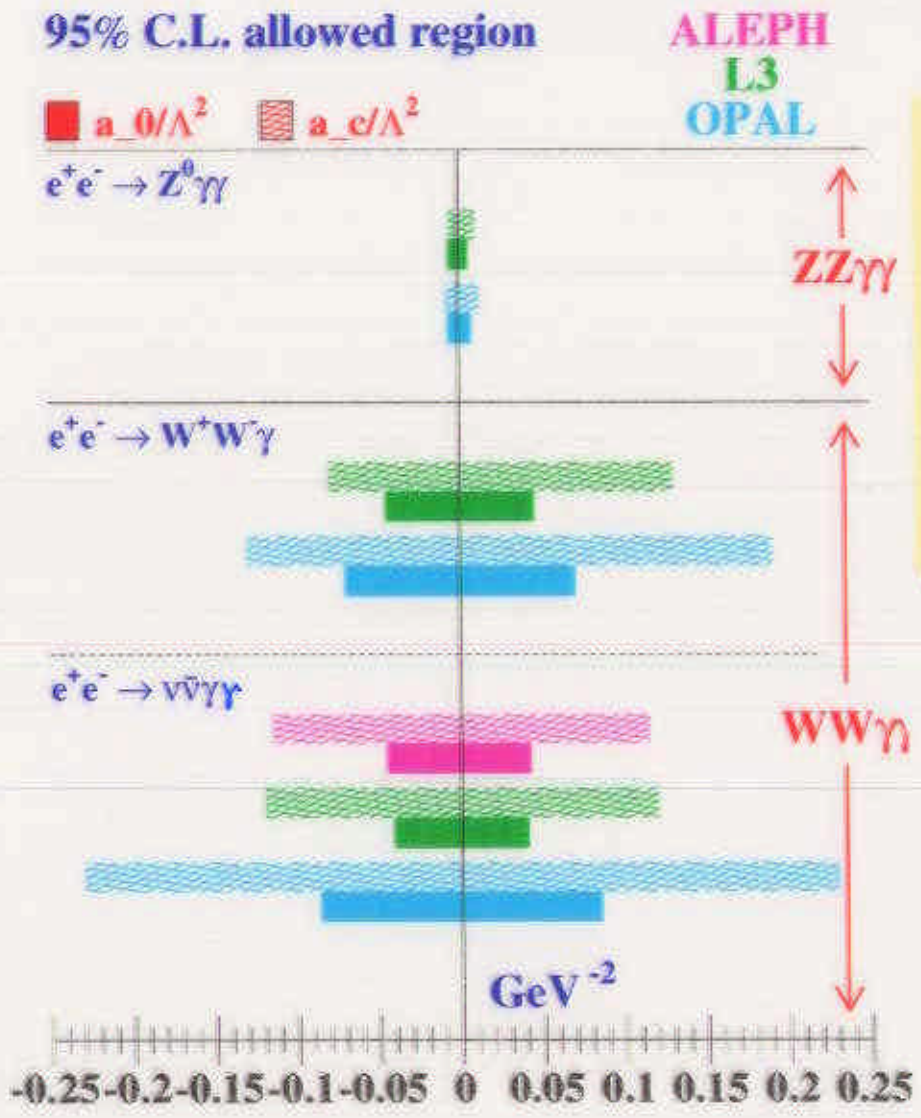
at each energy point

- **OPAL** $(E_{\gamma_2}, \max|\cos\theta_\gamma|)$
- **L3** $(E_{\gamma_1}, E_{\gamma_2})$




**95% C.L. allowed region - 1D fit**






**Combined Results**
**(all channels)**
**95% C.L. (1D fit) GeV$^{-2}$**

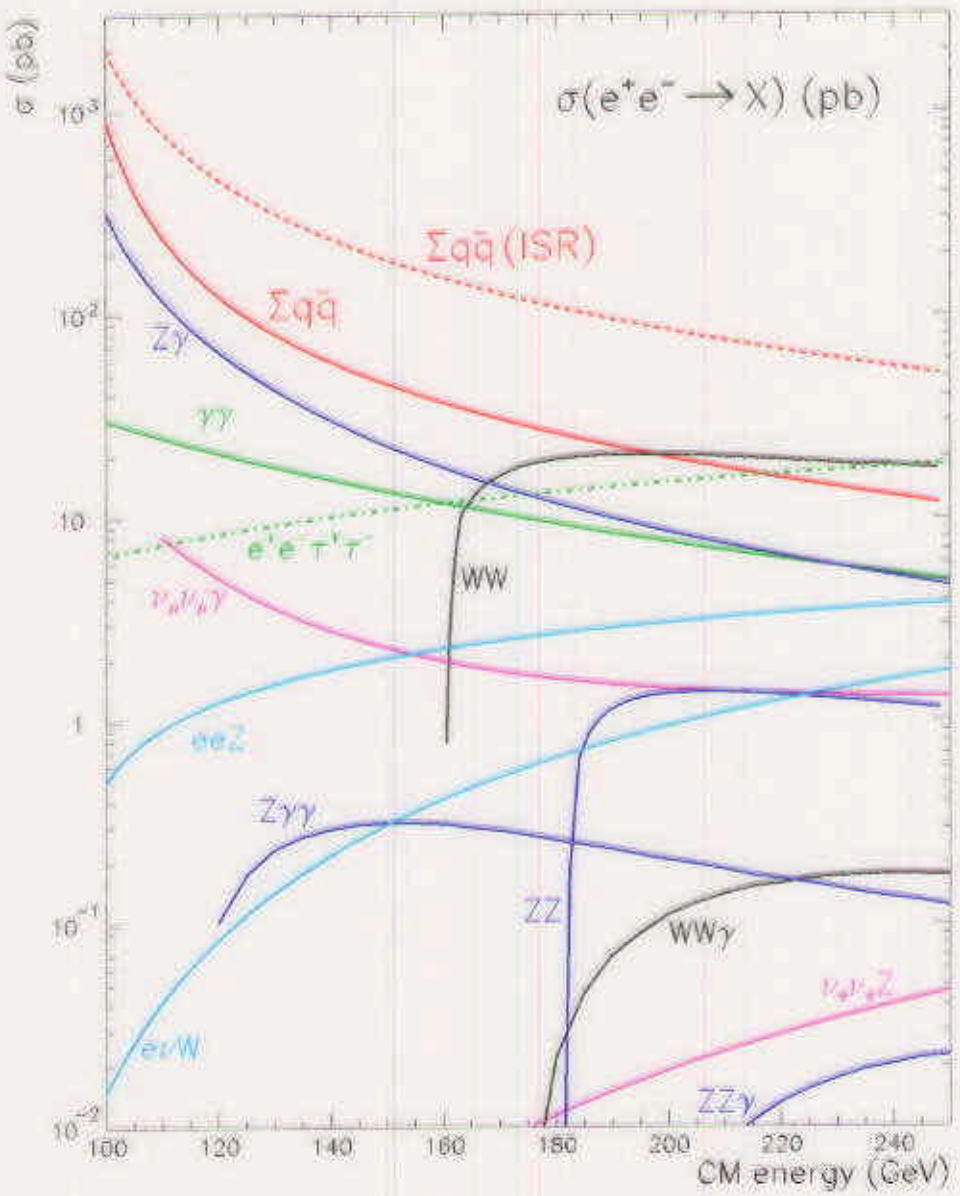
$$-0.0049 < a_0/\Lambda^2 < 0.0056$$
$$-0.0054 < a_c/\Lambda^2 < 0.0098$$

$$-0.45 < a_n/\Lambda^2 < 0.41$$

If New Physics effects
are $\neq$ in ZZ$\gamma\gamma$ and WW$\gamma\gamma$
relax constraint on equal
size of ZZ$\gamma\gamma$ and WW$\gamma\gamma$ couplings

| | WW$\gamma\gamma$ | ZZ$\gamma\gamma$ |
|---|---|---|
| $\lvert a_0/\Lambda^2\rvert <$ | $\sim 0.04$ | $\sim 0.006$ |
| $\lvert a_c/\Lambda^2\rvert <$ | $\sim 0.1$ | $\sim 0.01$ |

# LEP 2 / NLC




**First look to 3-boson production at LEP 2**

**Sensitivity to $a_0$, $a_c$ limited by low $\mathcal{L}_{int}$ and $\sqrt{s}$**

**At NLC (500 GeV, 300 fb$^{-1}$)**

**sensitivity to $a_0$, $a_c$ increases by $\sim 100$**

**access to WWWW, WWZZ**

# Conclusions

- Gauge Boson self-couplings are studied looking for anomalous contributions to the quartic vertices
- Vertices with at least one photon can be studied at LEP in $WW\gamma$, $Z\gamma\gamma$ and $\nu\bar{\nu}\gamma\gamma$ production
- One analysis at EPS-PH '99
- Seven analyses at ICHEP 2000
- The potential of the LEP 2 data set has not yet been fully exploited for QGC measurements