Measurements of Quartic Gauge Boson Couplings

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for the LEP Experiments

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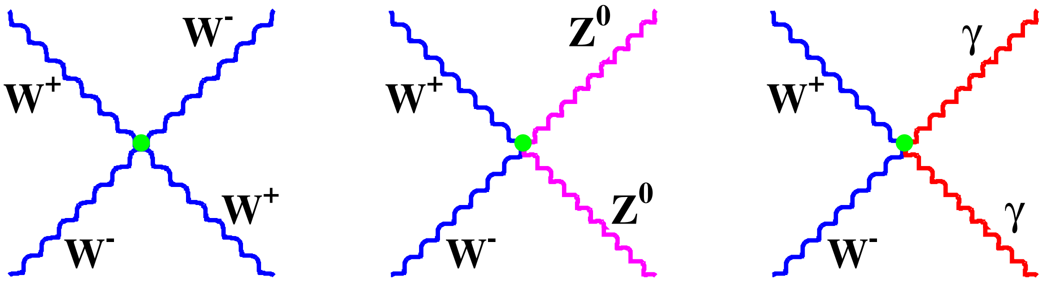
- Introduction to Quartic Gauge boson Couplings
- The Experimental Results on QGCs at LEP 2

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



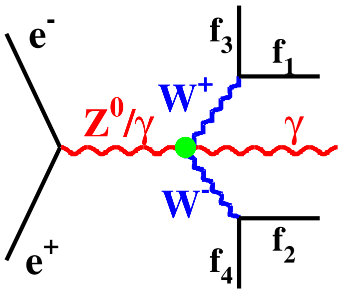
- **TGC**s test the **Non-Abelian structure of the SM**
  ➥ **Form Factors**
- **QGC**s insight in **Spontaneous Symmetry Breaking**
  ➥ **Contact Interactions**

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 $VVV'\gamma$

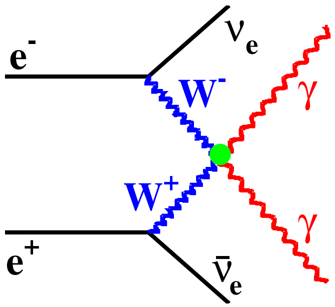
The Experimental Analyses at LEP



$$e^+e^- \longrightarrow W^+W^-\gamma$$

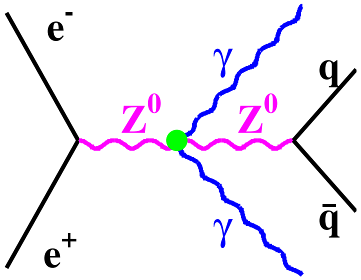
	L3	$\sqrt{s} = 189$ GeV	$\mathcal{L}_{int} \simeq 180\ \mathrm{pb}^{-1}$
❇	OPAL	$\sqrt{s} = 189$ GeV	$\mathcal{L}_{int} \simeq 180\ \mathrm{pb}^{-1}$

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



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

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



$$e^+e^- \longrightarrow Z^0\gamma\gamma$$

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

The Formalism

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

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

- keep ONLY terms not leading to TGCs

→ 11 independent Lorentz Invariant Structures

→ 2 → $\mathrm{WW}\gamma\gamma$

2 → $\mathrm{ZZ}\gamma\gamma$

Commonly used Lagrangian

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

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

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

→ "Equal strength" for $\mathrm{WW}\gamma\gamma$ and $\mathrm{ZZ}\gamma\gamma$ couplings
(not a necessary assumption)

Λ = Scale of New Physics results in GeV^{-2}

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

$$a_n/\Lambda^2 \quad \Longrightarrow \mathrm{WWZ}\gamma \text{ vertex}$$

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

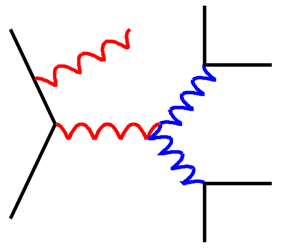
Final states analysed: $qql\nu\gamma$ **and** $qqqq\gamma$ $(l = e,\ \mu,\ \tau)$

Signature of (Anomalous) QGCs

➥ **excess of high energy γ in WW events at low $|\cos\theta|$**

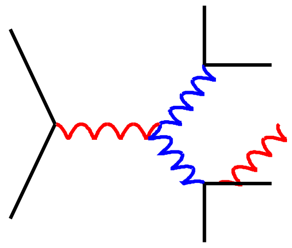
23 SM diagrams for $qql\nu\gamma$ at $\mathcal{O}(\alpha)$
(3 more for $qqqq\gamma$)

ISR (dominant)



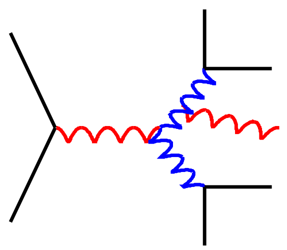
γ **at high** $|\cos\theta|$
$M_{f_1 f_2} \sim M_W$

FSR

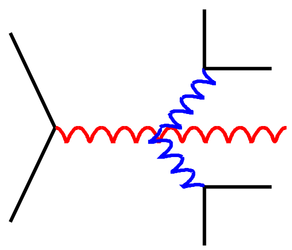


γ **close to the fermion**
$M_{f_1 f_2 \gamma} \sim M_W$

WR (small)



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



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

+ t-channel diagrams and crossed diagrams

$e^+e^- \longrightarrow W^+W^-\gamma$ *Signal definition*

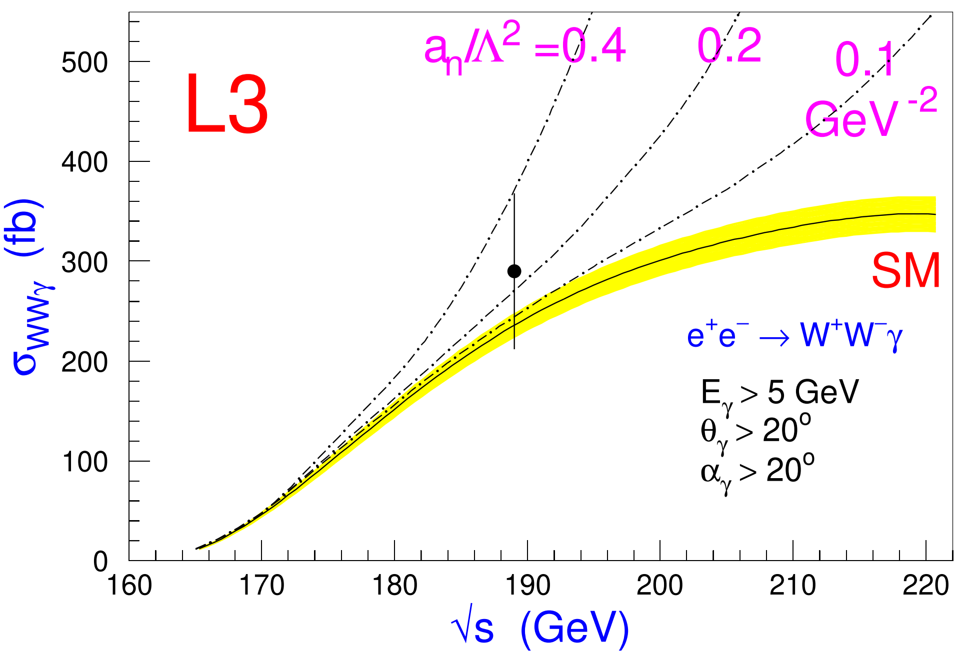
Standard WW selection + **Search for Isolated γ**

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

Signal definitions similar but not identical

cut	OPAL	L3
E_γ	>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

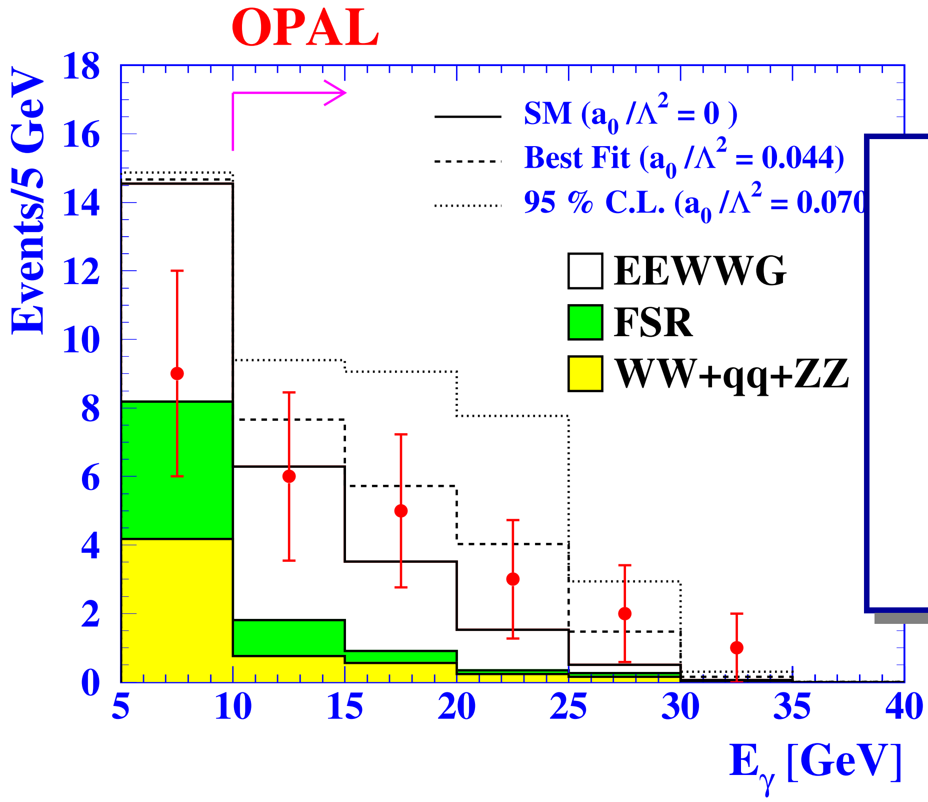
L3 $\hat{\sigma}_{WW\gamma} = 290 \pm 80(stat) \pm 16(syst)$ fb



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

MC predictions ➜ 85-102 fb

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



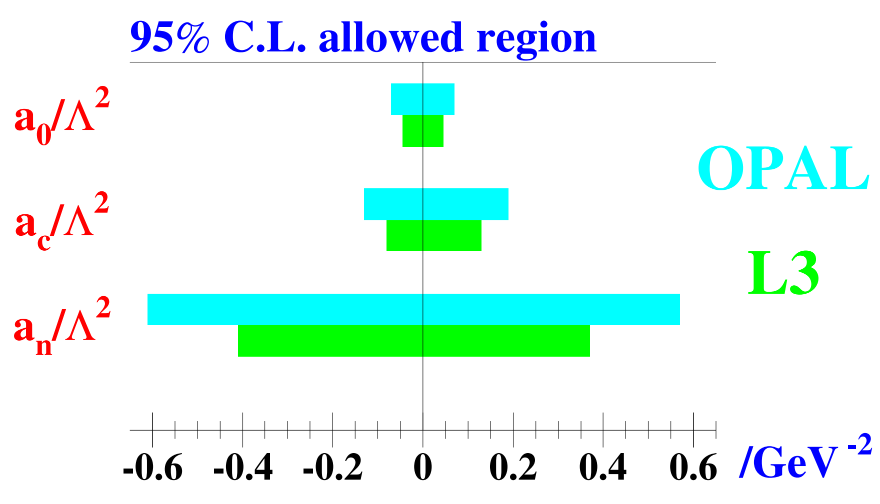
a_0, a_c, a_n
from a fit to

$(E_\gamma, \cos\theta_\gamma)$
OPAL

E_γ
L3

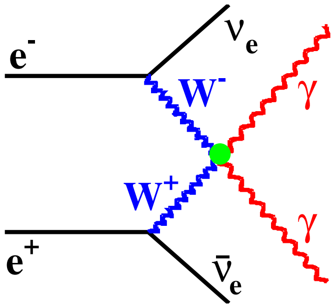
Theoretical predictions

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



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

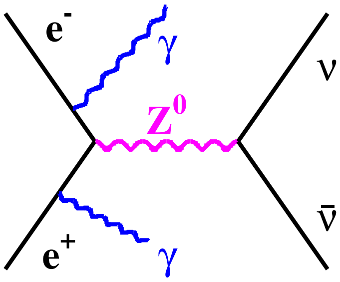
Anomalous QGCs in WW fusion



Event topology

two acoplanar photons

sensitive to a_0 and a_c



Standard Model Background

doubly-radiative return to the Z^0

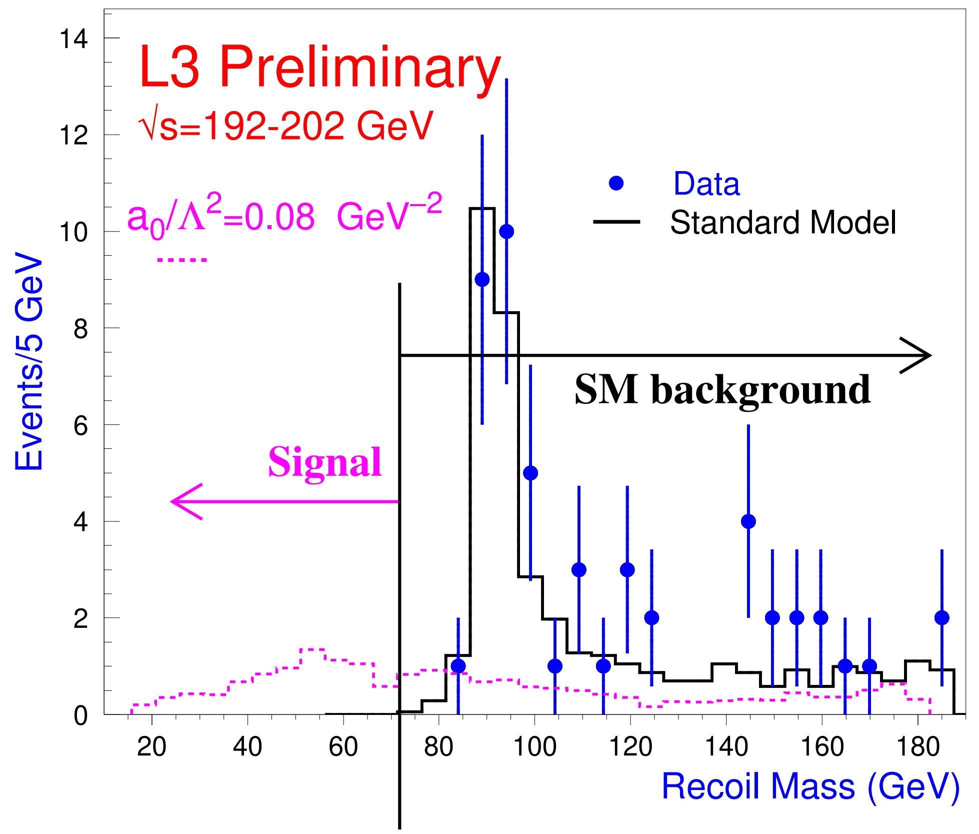
Theoretical predictions

- **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 γs
  KORALZ exponentiated $\mathcal{O}(\alpha^2)$
  agreement within 3%

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

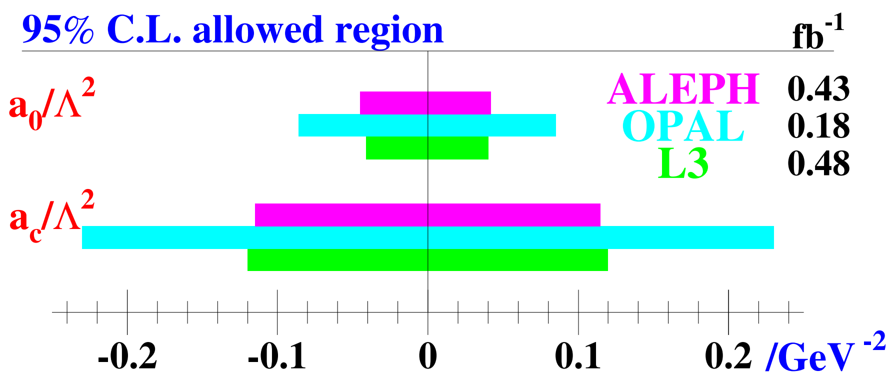
$e^+e^- \longrightarrow \nu\bar{\nu}\gamma\gamma$

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



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

➥



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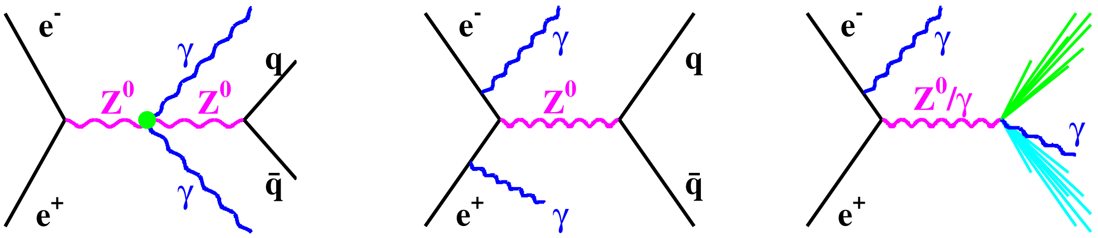
$e^+e^- \to Z^0\gamma\gamma$

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

AQGC signal **SM background**

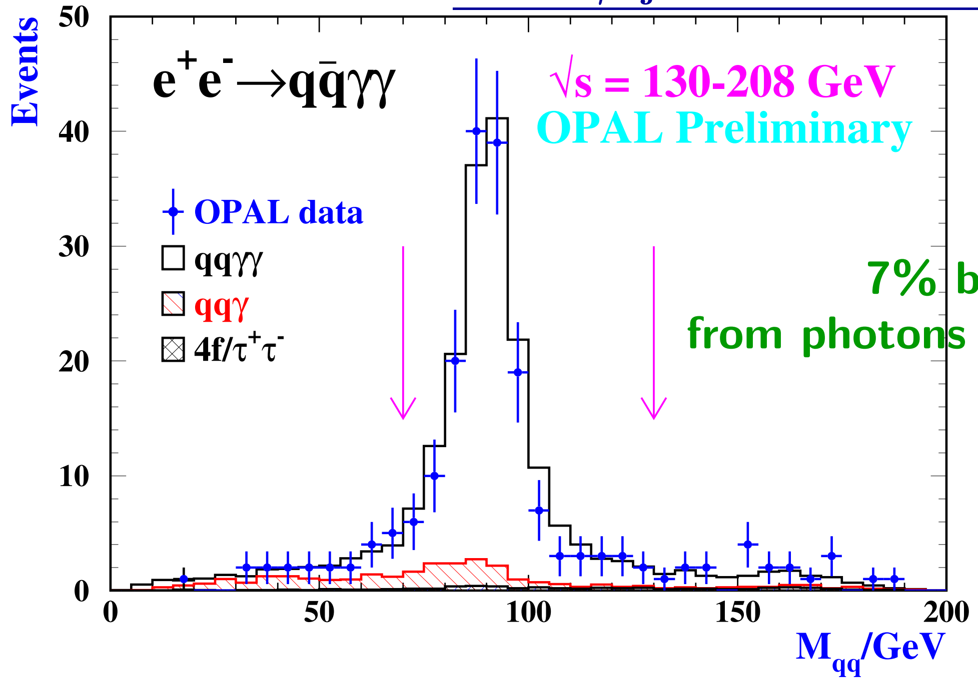
dominant



❇ **Event selection** ≥ 2 **Isolated γ in multihadronic events** ❇

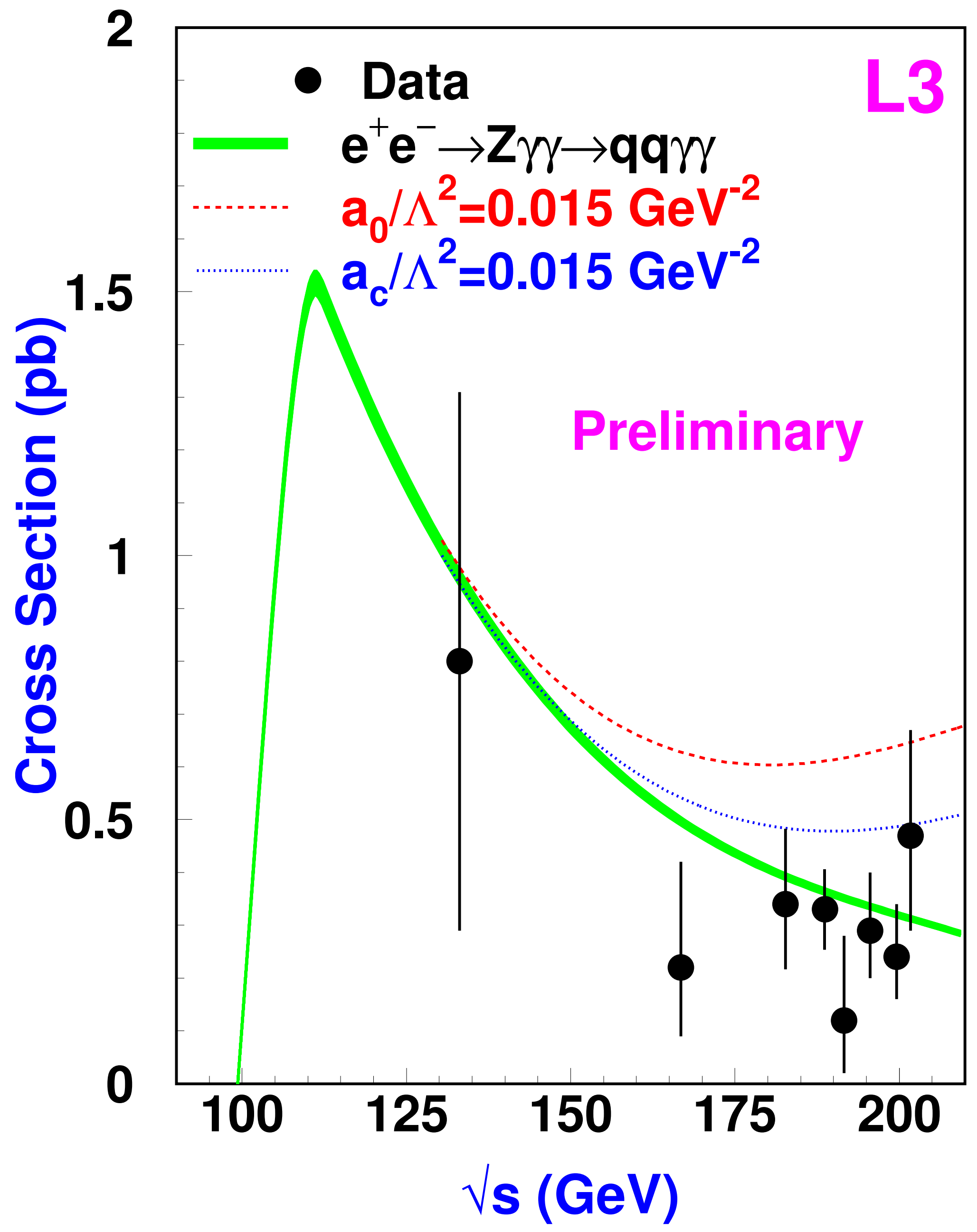
Signal definition

	OPAL	L3
E_{γ_1}, E_{γ_2}	> 5 GeV	> 5 GeV
$\lvert\cos\theta_{\gamma_{1,2}}\rvert$	< 0.95	< 0.97
$M_{q\bar{q}}$	80-120 GeV	$M_Z \pm 2\Gamma_Z$
$\cos\theta_{\gamma-\mathrm{jet}}$	< 0.9	



7% background from photons in the jets

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



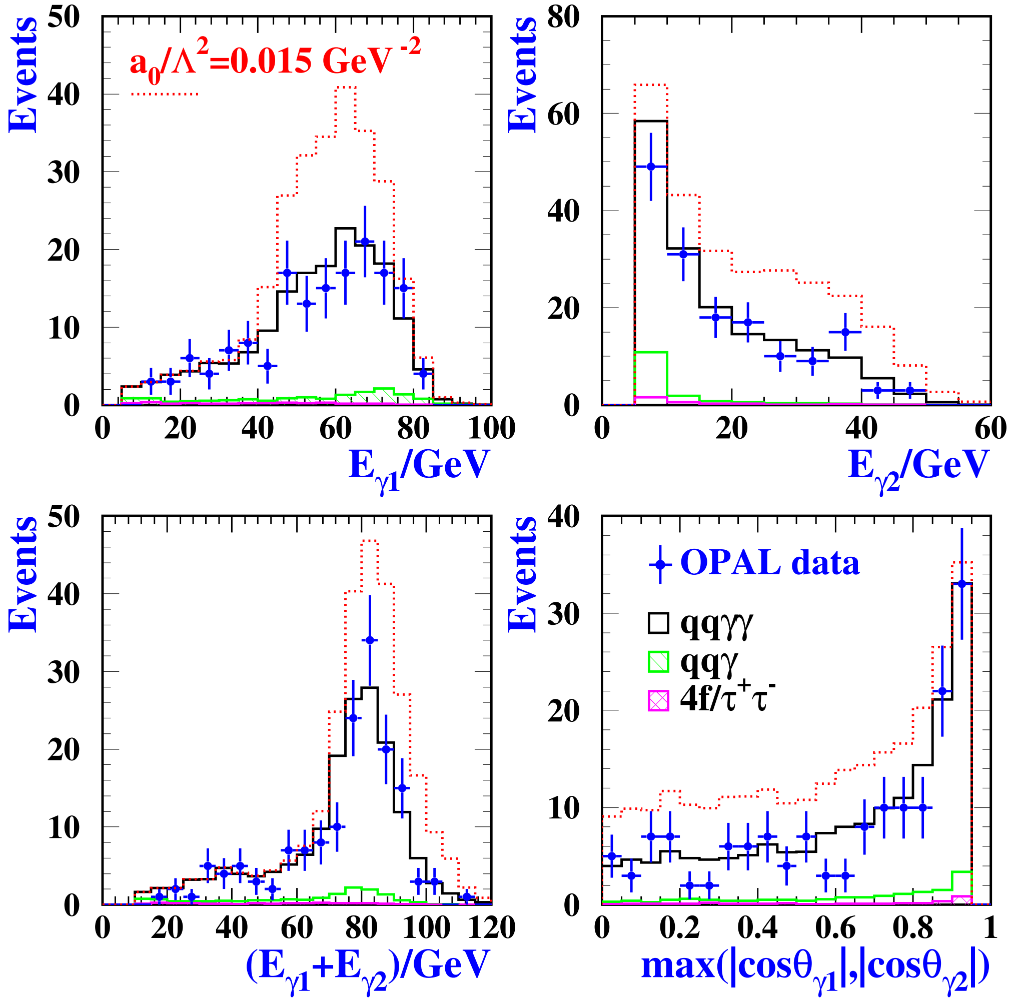
- Standard Model prediction → KK2f
- Signal EEZGG
  (Stirling, Werthenbach)
  AQGCs + SM doubly-radiative return to Z^0

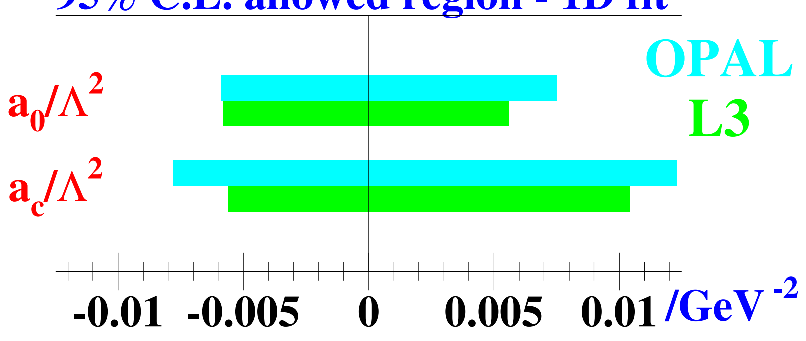
$e^+e^- \longrightarrow Z^0\gamma\gamma$

Fit method binned maximum likelihood fit

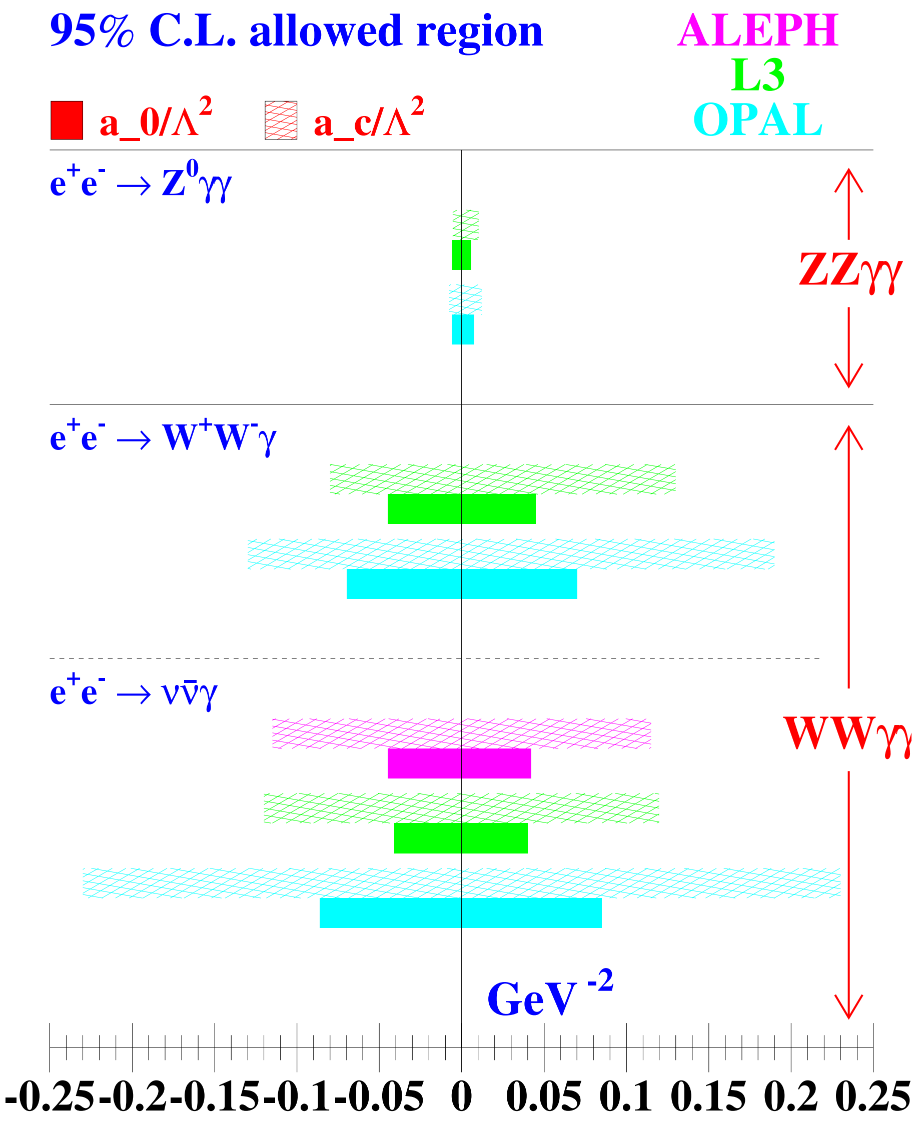
at each energy point

- **OPAL** $(E_{\gamma_2}, \max|\cos\theta_\gamma|)$
- **L3** (E_{γ_2})





LEP Combined Results



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

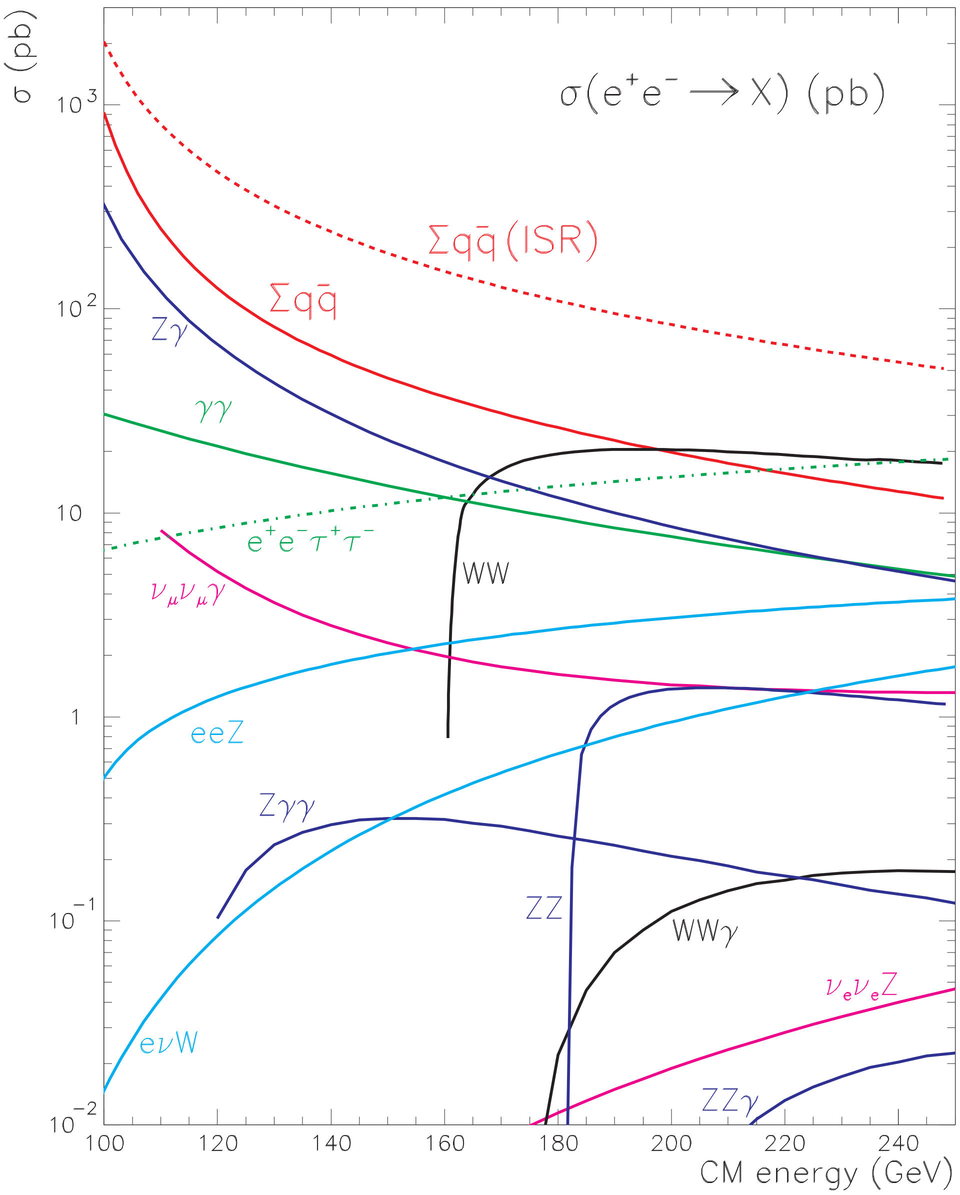
$$-0.0049 < a_0/\Lambda^2 < 0.0056$$
$$-0.0054 < a_c/\Lambda^2 < 0.0098$$

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

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$\gamma\gamma$
$\lvert a_0/\Lambda^2\rvert <$	~ 0.04	~ 0.006
$\lvert a_c/\Lambda^2\rvert <$	~ 0.1	~ 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 ~ 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 $\mathrm{WW}\gamma$, $Z\gamma\gamma$ 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