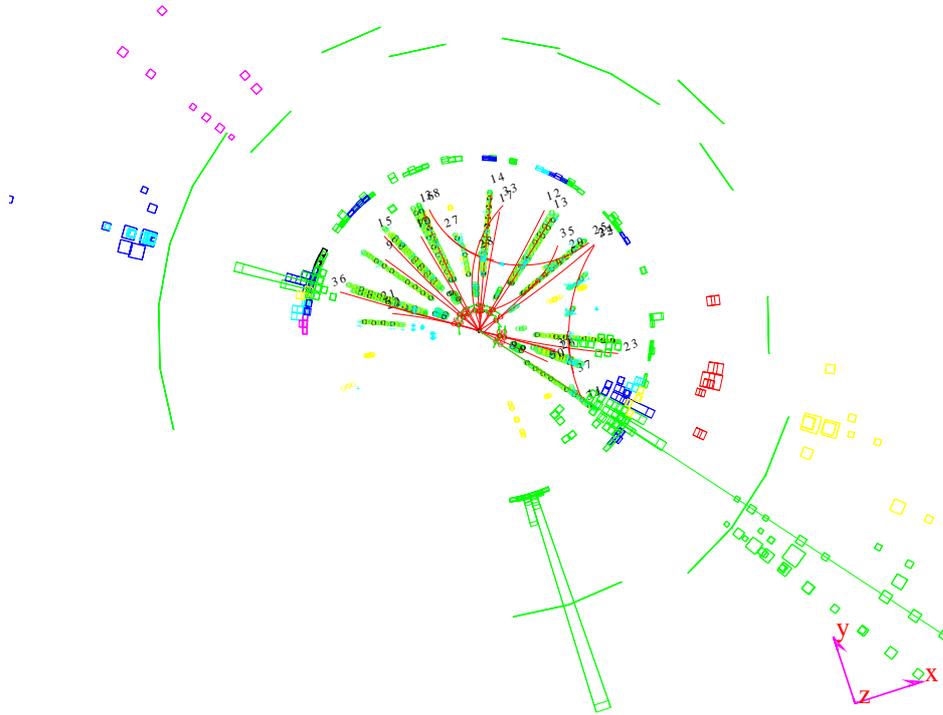


CERN WWMM Workshop

Determination of Anomalous Quartic Gauge Boson Couplings at LEP

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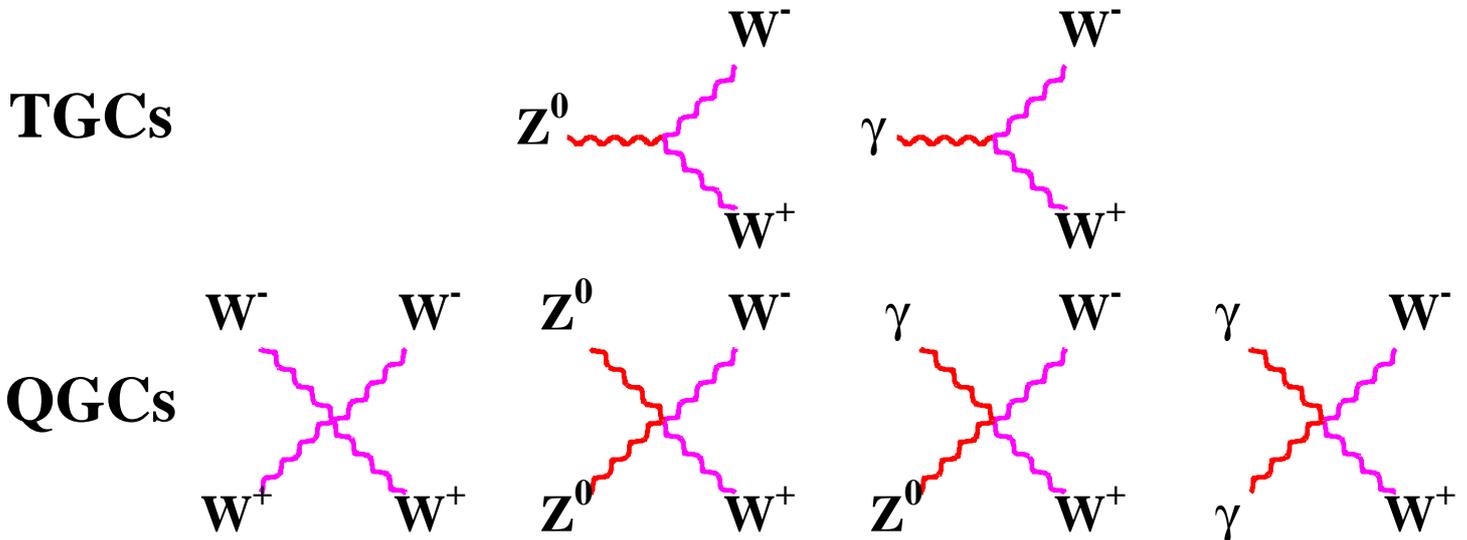


CERN, 18th April 2000

The non Abelian gauge structure of the SM electro-weak theory

⇒ Triple Gauge Boson Couplings (TGC)

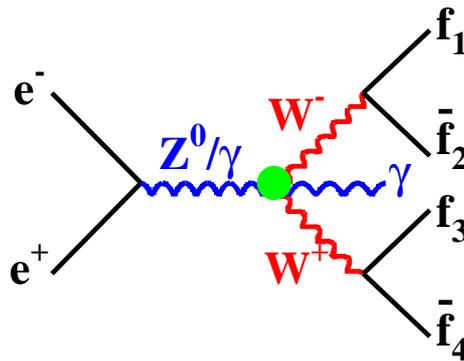
⇒ Quartic Gauge Boson Couplings (QGC)



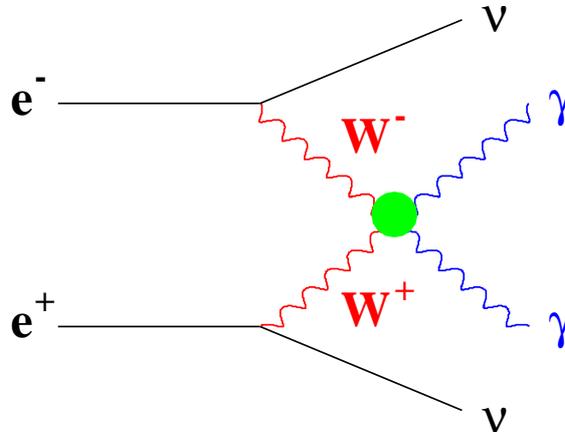
In the SM, the $SU(2) \times U(1)$ gauge invariance tightly constrains the **form** and **strength** of all these couplings. Scalar–boson couplings are also completely specified.

How to measure SM Quartic Gauge Couplings ?

- $WW\gamma$ final state production



- $\nu\bar{\nu}\gamma\gamma$ final state production



Effects in SM are very small:

at $\sqrt{s} = 200$ GeV, $\sigma_{WW\gamma} = 392$ fb (QGCs included)

$\sigma_{WW\gamma} = 402$ fb (QGCs excluded)

...about 500 pb^{-1} would be needed !! :(

• Anomalous QGCs can be parametrised by additional terms in the SM Lagrangian,

◇ Dim-4 operators:

$$\mathcal{L}_4 = -\frac{1}{4}g^2(\vec{W}_\mu \times \vec{W}_\nu)(\vec{W}^\mu \times \vec{W}^\nu), \quad \tilde{\mathcal{L}}_4 = -ie\frac{\lambda_\gamma}{M_W^2}F^{\mu\nu}W_{\mu\alpha}^\dagger W^\alpha_\nu$$

“non genuine couplings”, already constrained by TGC limits.

◇ Dim-6 operators:

$$\mathcal{L}_0 = -\frac{e^2}{16}\frac{a_0}{\Lambda^2}F^{\mu\nu}F_{\mu\nu}\vec{W}^\alpha \cdot \vec{W}_\alpha$$

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

$$\implies \gamma W^+ W^- \gamma, \gamma Z^0 Z^0 \gamma$$

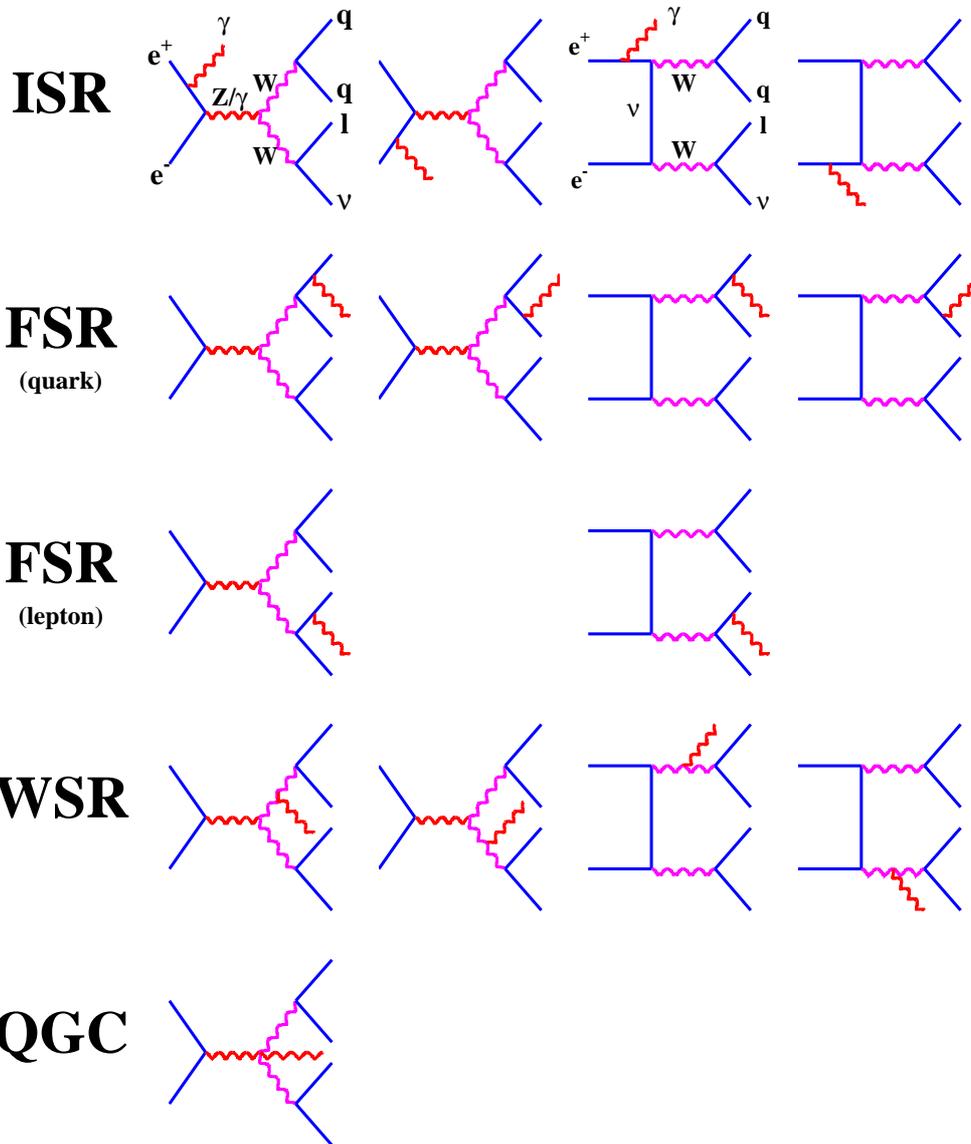
$$\mathcal{L}_n = -\frac{e^2}{16}\frac{a_n}{\Lambda^2}\epsilon_{ijk}W_{\mu\alpha}^{(i)}W_\nu^{(j)}W^{(k)\alpha}F^{\mu\nu}$$

$$\implies ZW^+W^- \gamma, \quad [\text{J.Stirling, A.Werthenbach, Phys.Lett. B466}]$$

Where Λ^2 energy scale for new physics, and

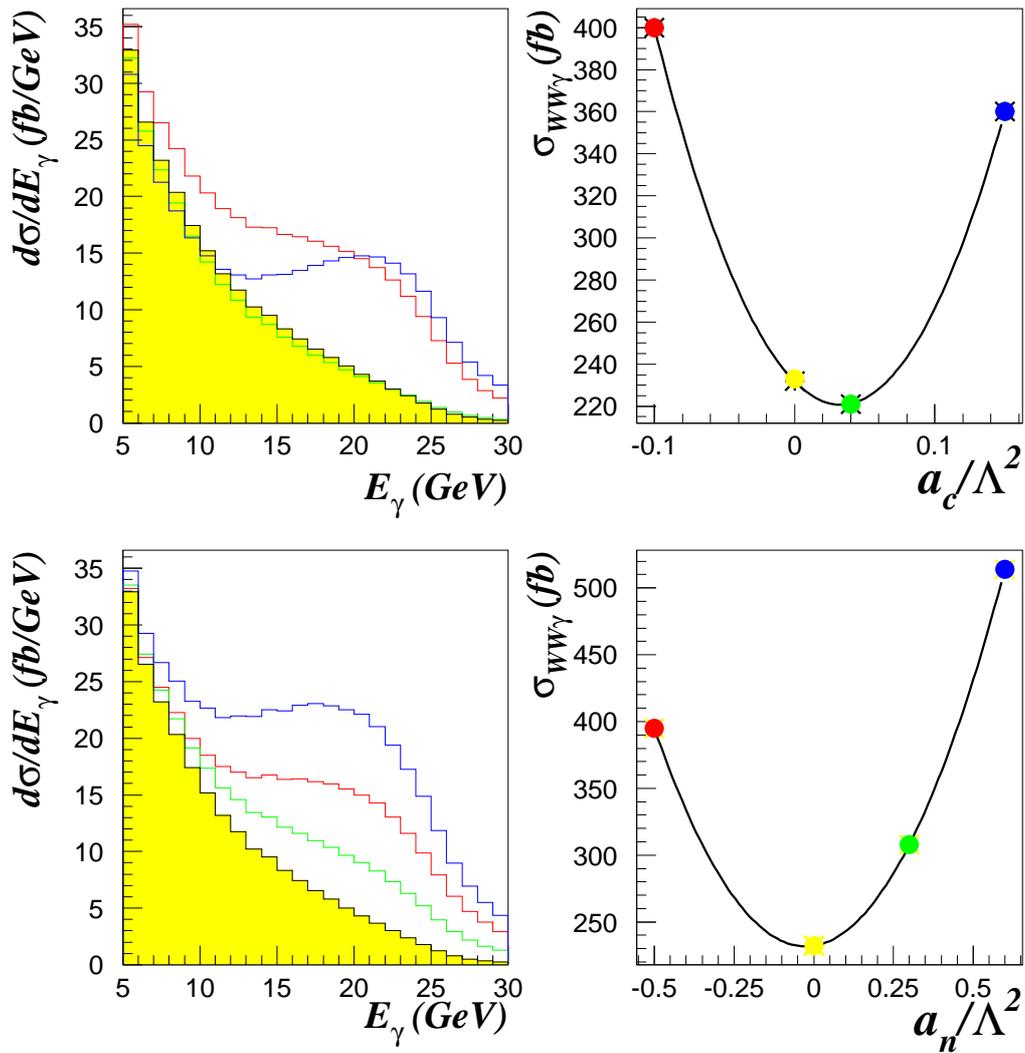
$$W_\mu = \begin{pmatrix} \frac{1}{\sqrt{2}}(W_\mu^+ + W_\mu^-) \\ \frac{i}{\sqrt{2}}(W_\mu^+ - W_\mu^-) \\ \cos\theta_w Z_\mu + \sin\theta_w A_\mu \end{pmatrix}.$$

- Photons in W-pair events may have different origins



- Available MCs :
 - EEWG includes ISR, WSR, QGC, and AQGC
 - KORALW includes ISR, FSR
 - WWF includes ISR, FSR, QGC (used in Opal analysis)

Anomalous Quartic Couplings $a_{c,n}/\Lambda^2$



Both total and differential cross sections are affected by AQC's

- $\sqrt{s} = 189 \text{ GeV}$, $\int \mathcal{L} = 183 \text{ pb}^{-1}$
- Event Selection :
 - WW Selection (no $l\nu l\nu$)
 - Isolated photon $E_\gamma > 10 \text{ GeV}$
 - Polar angle $|\cos \theta_\gamma| < 0.9$
 - Angle to the next fermion, $\cos \alpha_\gamma < 0.9$ (0.7 for $q\bar{q}\tau\nu$)

Make use of kinematic fit to reject FSR, following two hypotheses:

3–body final state $WW\gamma$

2–body final state $W(W\gamma)$

- Mass cut, $\min(M_{f_1, \bar{f}_2}, M_{f_3, \bar{f}_4}) > 74 \text{ GeV}$

\implies **17** Data Events (13.2 expected)

Selection Performance:

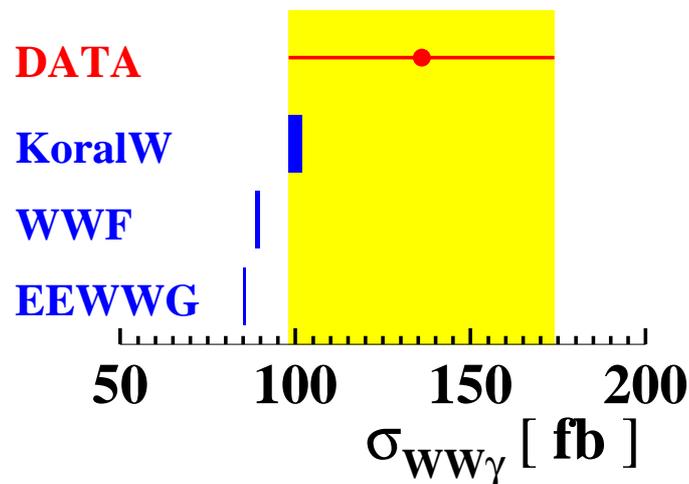
Efficiency $48.7 \pm 1.8 \%$

Accepted Bkgr $9.9 \pm 2.2 \text{ fb}$

Defined within above phase space cuts:

- $\sigma_{WW\gamma} = 136 \pm 37 \pm 8 \text{ fb}$

consistent with the SM expectation:

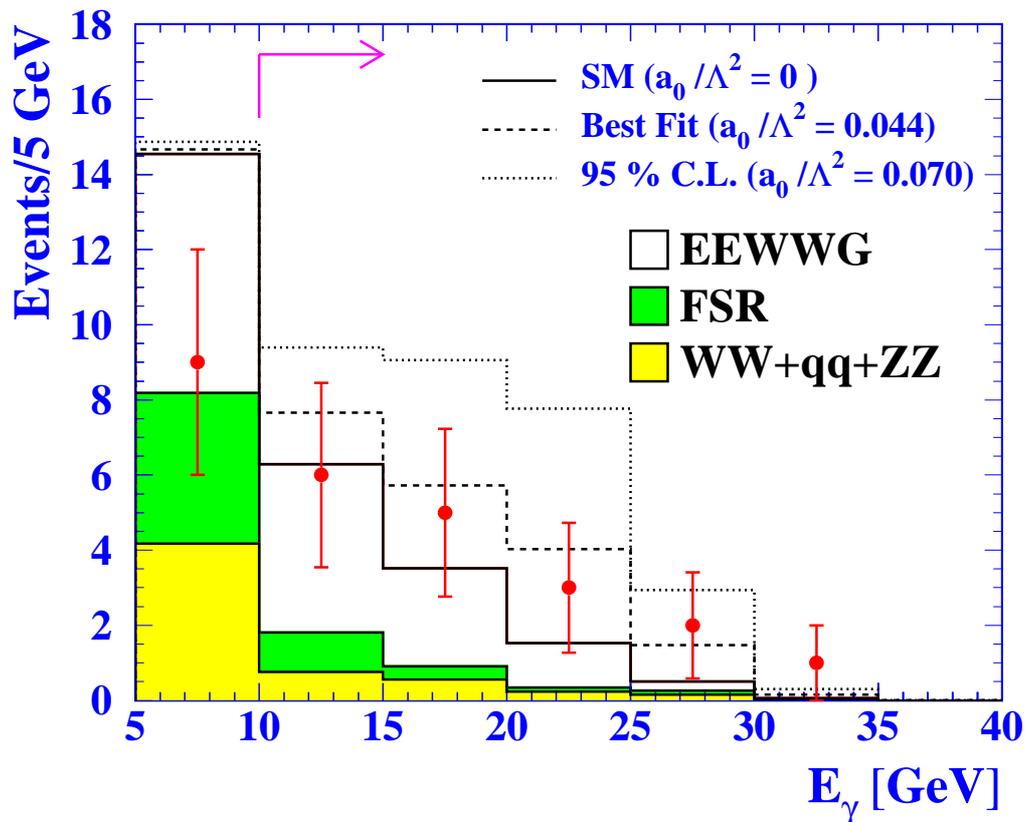


- Systematic uncertainties studied:

Source	$\Delta\sigma_{WW\gamma}$ (fb)
WW Event Selection	3.0
qq γ efficiency	0.5
Photon Identification	1.6
Kinematic fit	1.6
ECAL energy scale	1.8
ECAL energy resolution	2.8
Photons from meson decays	2.7
ISR modelling qq γ	1.9
Acceptance cuts	2.8
Four fermion events	2.0
$P_{WW\gamma}$	3.0
Total	7.7

Use E_γ spectrum shape and normalisation to constrain anomalous contribution to SM QGC diagrams

OPAL



Limits are derived at 95% C.L.

$$-0.070 \text{ GeV}^{-2} < a_0/\Lambda^2 < 0.070 \text{ GeV}^{-2}$$

$$-0.13 \text{ GeV}^{-2} < a_c/\Lambda^2 < 0.19 \text{ GeV}^{-2}$$

$$-0.61 \text{ GeV}^{-2} < a_n/\Lambda^2 < 0.57 \text{ GeV}^{-2}$$

– Expected limits are tighter ($|a_0/\Lambda^2| < 0.045 \text{ GeV}^{-2}$), slight excess of events over 15 GeV.

- $\sqrt{s} = 189 \text{ GeV}$, $\int \mathcal{L} = 176 \text{ pb}^{-1}$
- Event Selection :
 - WW Selection (no $l\nu l\bar{\nu}$)
 - Isolated photon $E_\gamma > 5 \text{ GeV}$
 - Polar angle $\theta_\gamma > 20^\circ$
 - Angle to the next fermion, $\alpha_\gamma > 20^\circ$

No kinematic fit w.r.t Opal analysis, no cuts on $M_{f,\bar{f}}$

\implies **42** Data Events (37.8 expected)

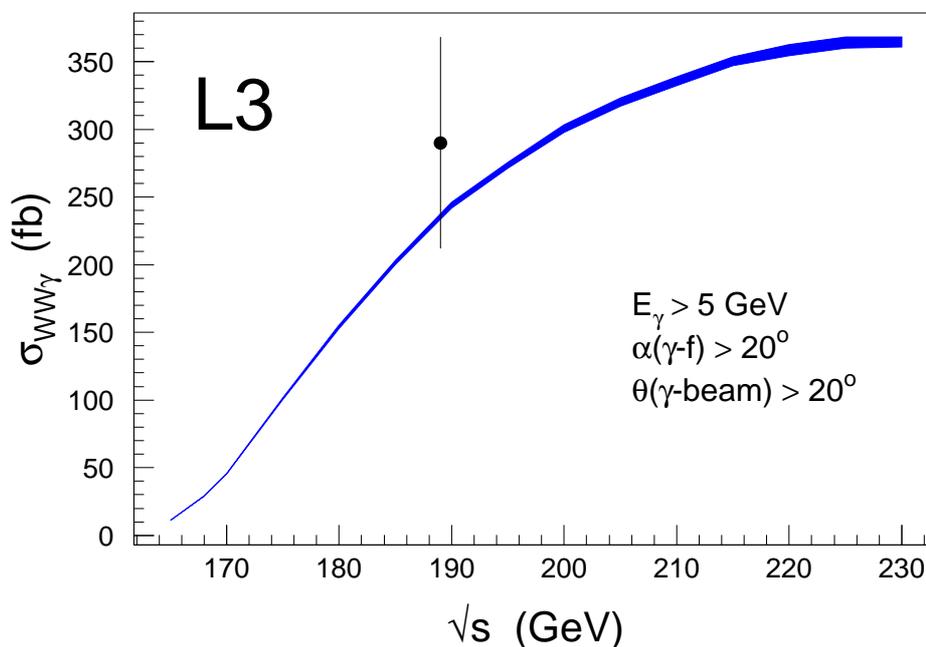
Selection Performance:

Decay Channel	Data	Efficiency	N_{exp}	FSR + Bkgr
$qqe\nu_e\gamma$	6	0.629 ± 0.033	5.85 ± 0.26	2.26 ± 0.14
$qq\mu\nu_\mu\gamma$	5	0.736 ± 0.032	6.87 ± 0.28	2.88 ± 0.17
$qq\tau\nu_\tau\gamma$	7	0.580 ± 0.030	4.63 ± 0.22	2.05 ± 0.14
$qqqq\gamma$	24	0.565 ± 0.017	20.4 ± 0.38	9.23 ± 0.26
Total	42	–	37.8 ± 0.6	16.4 ± 0.4

Defined within above phase space cuts (larger than Opal definition):

- $$\sigma_{WW\gamma} = 290 \pm 80 \pm 16 \text{ fb}$$

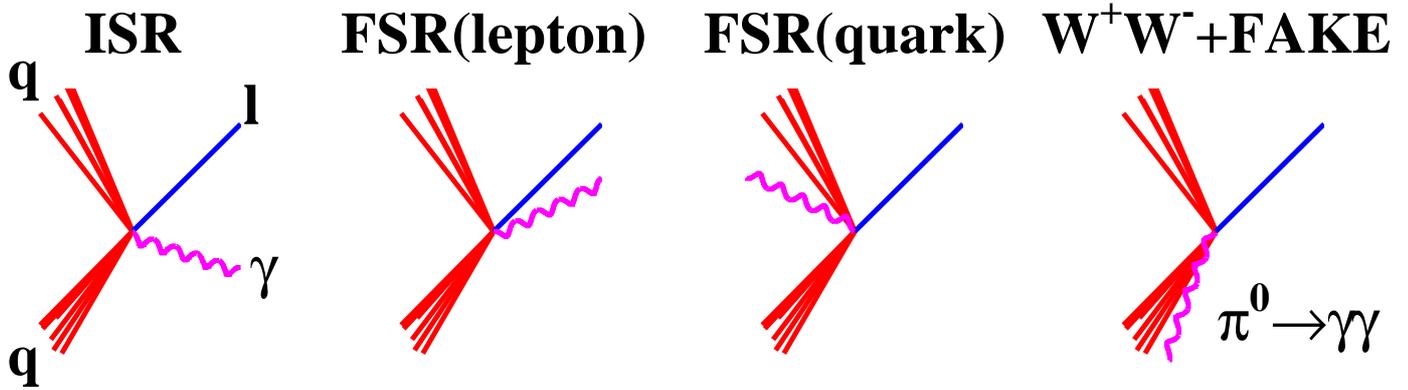
consistent with the SM expectation:



- Systematic uncertainties studied:

Source	$\Delta\sigma$ (fb)
Energy scale	3.5
Energy Resolution	4.3
Angular Resolution	< 1
Photons from meson decays	15.0
Total	16.0

Dominant source of systematic error are π^0 , η decays inside jets

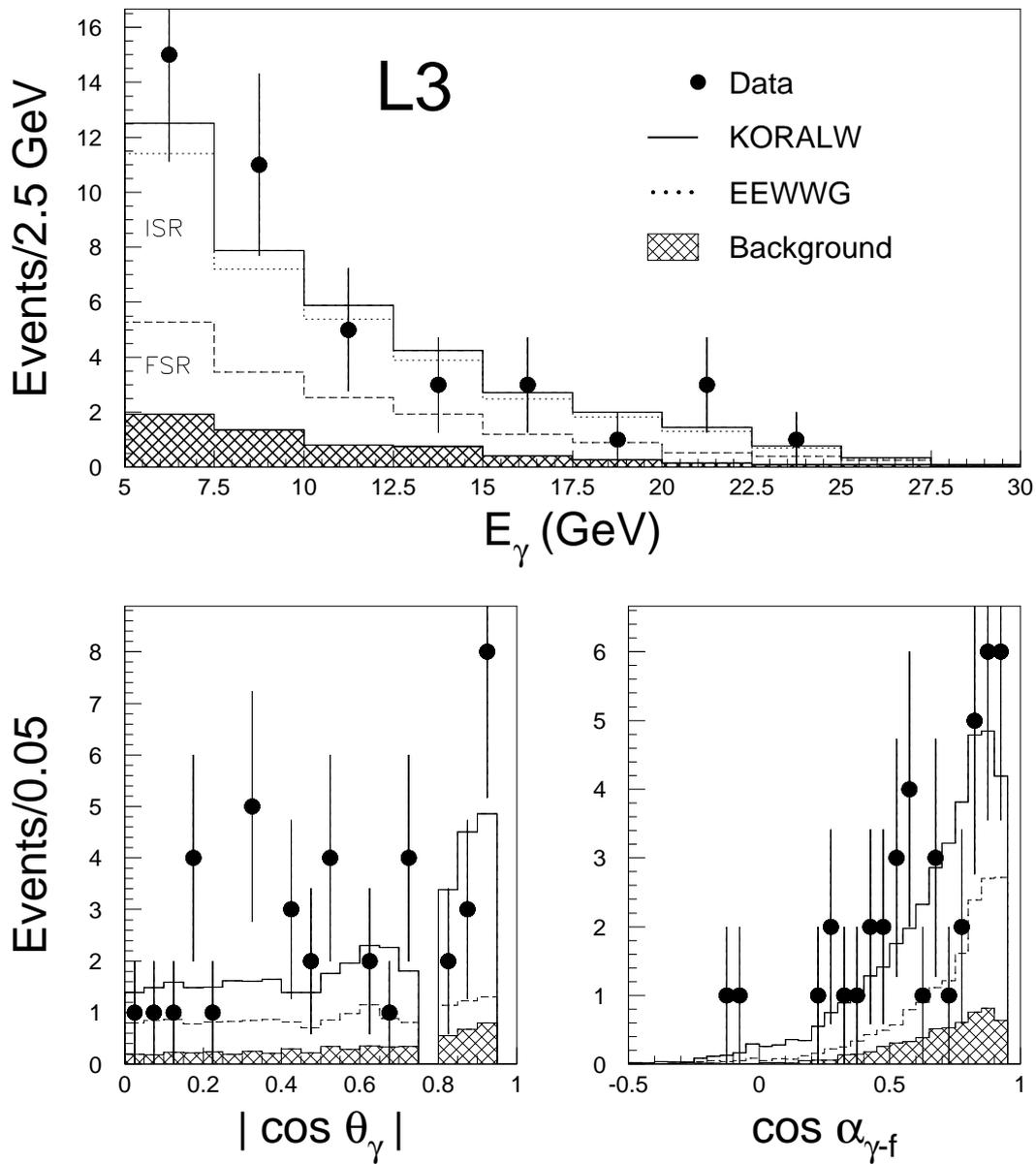


modelled by JETSET fragmentation algorithm.

\implies study $Z \rightarrow q\bar{q}\gamma$ events at $\sqrt{s} = 91$ GeV ($\mathcal{L} = 4$ pb $^{-1}$),
apply photon selection to get

$$f(E_\gamma) = N_{data}^{q\bar{q}\gamma} / N_{MC}^{q\bar{q}\gamma}$$

\longrightarrow correspondently correct E_γ spectrum.



Good agreement with SM prediction (KORALW).

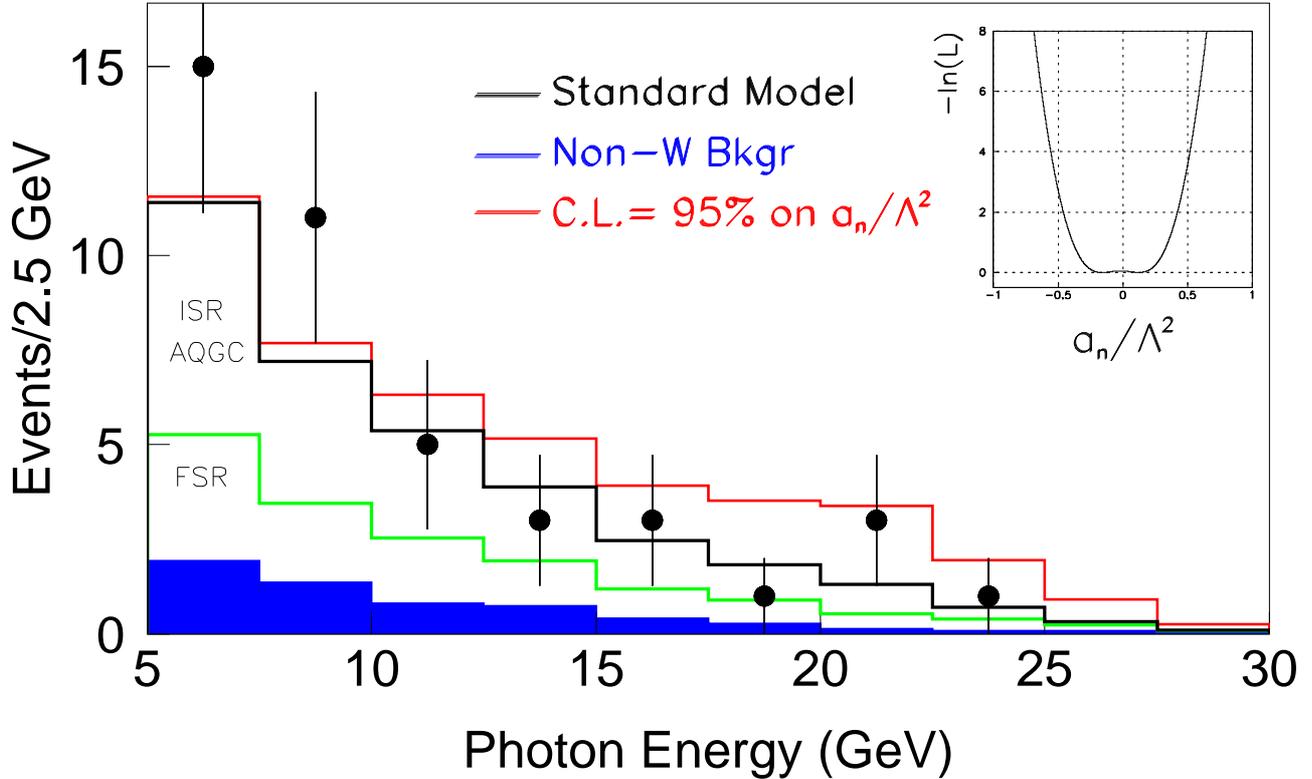
- Reweighting procedure of KORALW \rightarrow EEWWG with the ratio \mathcal{W} of the known differential E_γ distributions at generator level:

$$\mathcal{W}(E_\gamma, a_0, a_c, a_n) = \frac{d\hat{\sigma}^{\text{EEWWG}}/dE_\gamma(E_\gamma, a_0, a_c, a_n)}{d\hat{\sigma}^{\text{KORALW}}/dE_\gamma(E_\gamma, SM)}.$$

relative normalisation is taken into account.

- Equivalent to reweighting with ME
- Additional ISR collinear to beam pipe simulated with the Excalibur radiator function
- Perform maximum Likelihood 1-parameter fit on E_γ spectrum

L3 preliminary



Results:

$$a_0/\Lambda^2 = 0.017_{-0.039}^{+0.018} \pm 0.002 \text{ GeV}^{-2}$$

$$a_c/\Lambda^2 = 0.068_{-0.095}^{+0.040} \pm 0.009 \text{ GeV}^{-2}$$

$$a_n/\Lambda^2 = 0.120_{-0.330}^{+0.150} \pm 0.010 \text{ GeV}^{-2}$$

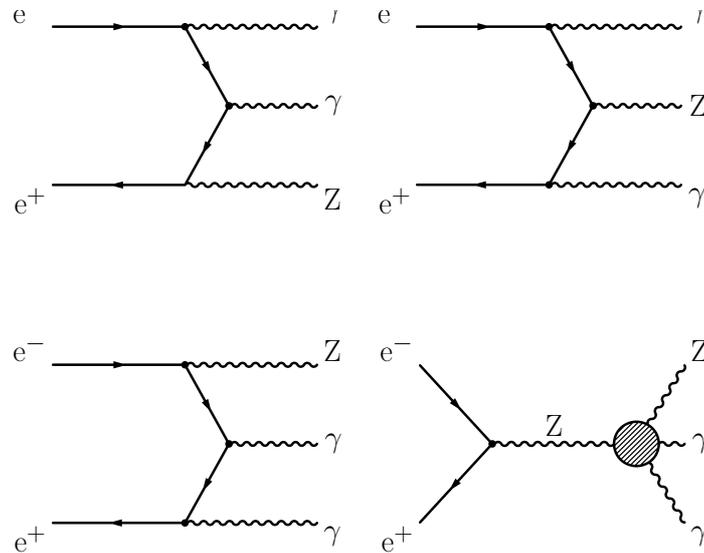
Limits at 95% C.L. ($\int e^{\ln(\mathcal{L})} da_i$) are derived:

$$-0.042 \text{ GeV}^{-2} < a_0/\Lambda^2 < 0.045 \text{ GeV}^{-2}$$

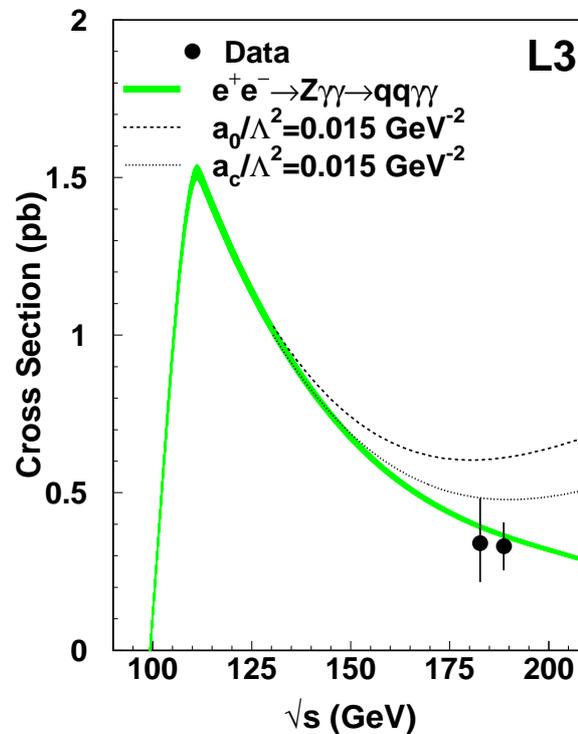
$$-0.072 \text{ GeV}^{-2} < a_c/\Lambda^2 < 0.148 \text{ GeV}^{-2}$$

$$-0.39 \text{ GeV}^{-2} < a_n/\Lambda^2 < 0.38 \text{ GeV}^{-2}$$

All results consistent with the SM value of 0.



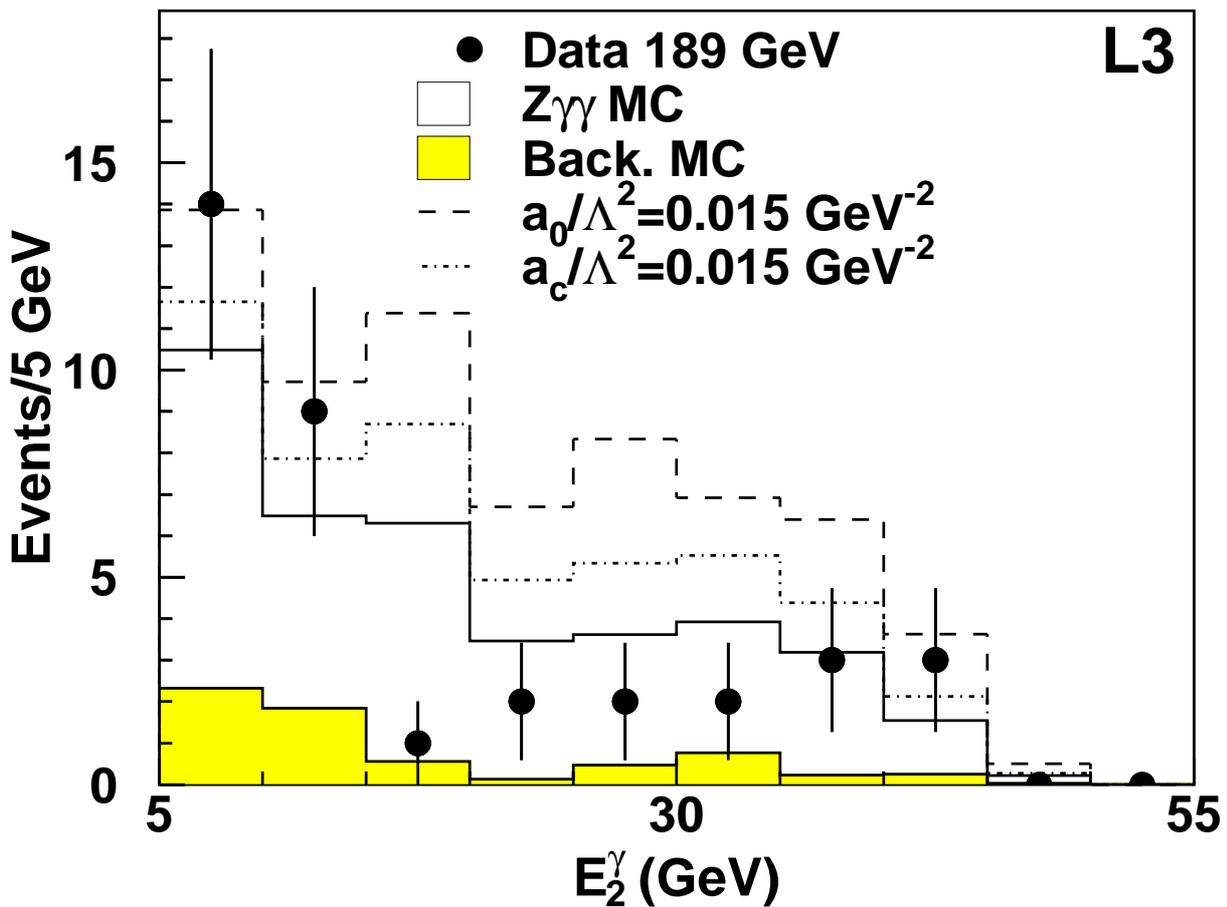
$e^+e^- \rightarrow Z\gamma\gamma$ channel probes anomalous quartic vertex $ZZ\gamma\gamma$ with couplings a_0/Λ^2 , a_c/Λ^2



Hadronic $Z\gamma\gamma$ MC events reweighted with

$$\mathcal{W}(\Omega, a_0/\Lambda^2, a_c/\Lambda^2) = \frac{|\mathcal{M}_{SM}(\Omega) + \mathcal{M}_{AQGC}(\Omega, a_0/\Lambda^2, a_c/\Lambda^2)|^2}{|\mathcal{M}_{SM}(\Omega)|^2}$$

and fitted to the observed $E_{2\gamma}$ spectrum.



One dimensional 68% C.L. measurements:

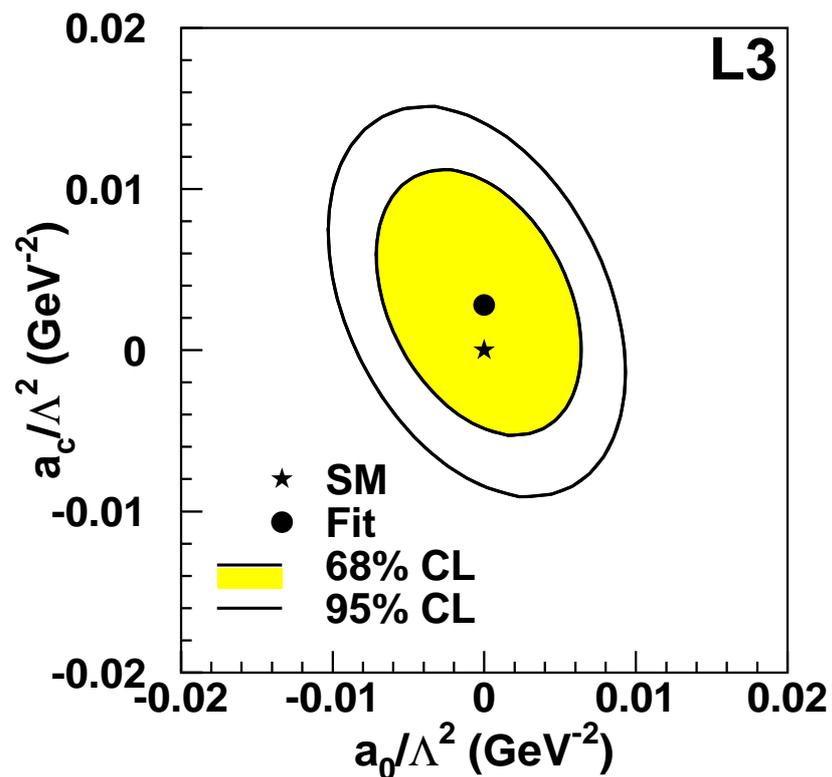
$$a_0/\Lambda^2 = 0.001 \pm 0.004 \text{ GeV}^{-2}$$

$$a_c/\Lambda^2 = 0.003 \pm 0.005 \text{ GeV}^{-2}$$

Simultaneous fit to both parameters gives 95% C.L. limits:

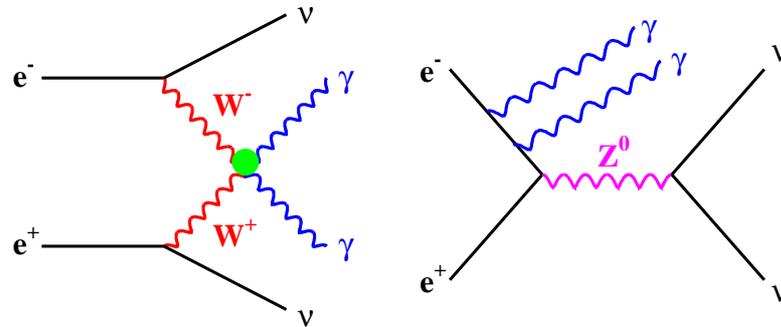
$$-0.009 \text{ GeV}^{-2} < a_0/\Lambda^2 < 0.008 \text{ GeV}^{-2}$$

$$-0.007 \text{ GeV}^{-2} < a_c/\Lambda^2 < 0.013 \text{ GeV}^{-2}$$



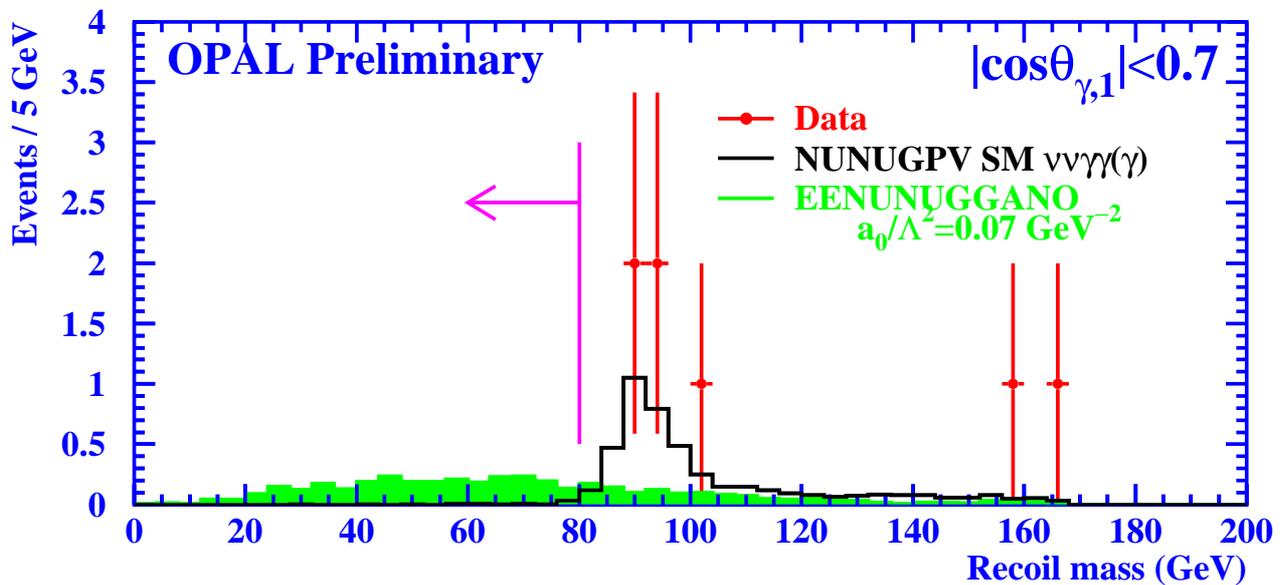
⇒ Tightest limits on a_0 and a_c .

$e^+e^- \rightarrow \nu\bar{\nu}\gamma\gamma$ also probes $WW\gamma\gamma$ vertex:



– look at **recoil mass** of the $\gamma\gamma$ system requiring (OPAL):

- $E_{1,2\gamma} > 10 \text{ GeV}$
- $|\cos\theta_{1\gamma}| < 0.7$
- $M_{\gamma\gamma} < 80 \text{ GeV}$

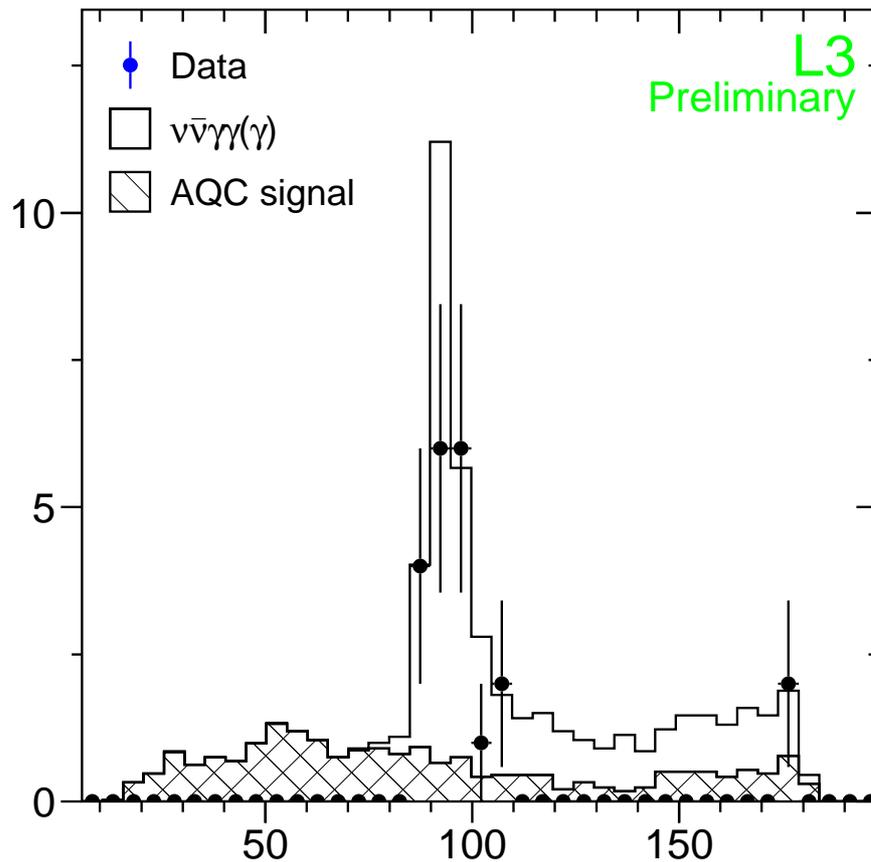


\Rightarrow **OPAL** 95% C.L. limits

$$-0.086 \text{ GeV}^{-2} < a_0/\Lambda^2 < 0.085 \text{ GeV}^{-2}$$

$$-0.023 \text{ GeV}^{-2} < a_c/\Lambda^2 < 0.023 \text{ GeV}^{-2}$$

- Both photons in Barrel :
 $M_{\gamma\gamma} < 80 \text{ GeV}$, or $(E_{1\gamma} + E_{2\gamma}) / \sqrt{s} > 0.53$
- Photon(s) in Endcap : $M_{\gamma\gamma} < 75 \text{ GeV}$



L3 preliminary results at $\sqrt{s} = 189 \text{ GeV}$

$$-0.075 \text{ GeV}^{-2} < a_0 / \Lambda^2 < 0.075 \text{ GeV}^{-2}$$

$$-0.021 \text{ GeV}^{-2} < a_c / \Lambda^2 < 0.021 \text{ GeV}^{-2}$$

Sensitivity limited by small cross section: $O(1 \text{ fb})$,
 and by the need of killing SM background
 (interference effects are not taken into account).

- ◇ First measurement of $Z\gamma\gamma$ and $WW\gamma$ cross sections
- ◇ L3 $Z\gamma\gamma$ analysis already gives the tightest limits on $a_0, a_c/\Lambda^2$, but no constrain on a_n/Λ^2
- ◇ Measurement of a_n/Λ^2 will benefit from higher centre-of-mass energies
- ◇ still room for theoretical improvement in the acoplanar $\nu\bar{\nu}\gamma\gamma$ channel
- ◇ Combination of all LEP results !!!

