# Anomalous Quartic Gauge Couplings at OPAL

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# Synopsis

- **Introduction**
  - Motivation for studying Anomalous Quartic Gauge Couplings (AQGCs)
  - AQGCs and the $\nu\nu\gamma\gamma$ final state
  - Formalism
  - The $WW\gamma$ and $qq\gamma\gamma$ final states at OPAL
- **Method of Analysis**
  - Event selection and MC modelling
  - Assigning limits using a binned maximum likelihood method
- **Results**
  - Bias and ensemble tests
  - One- and two-dimensional fit results to the AQGC parameters
- **Combination with other channels at OPAL**

- **Summary**

# Introduction to QGCs at OPAL

# Motivation for Studying QGCs

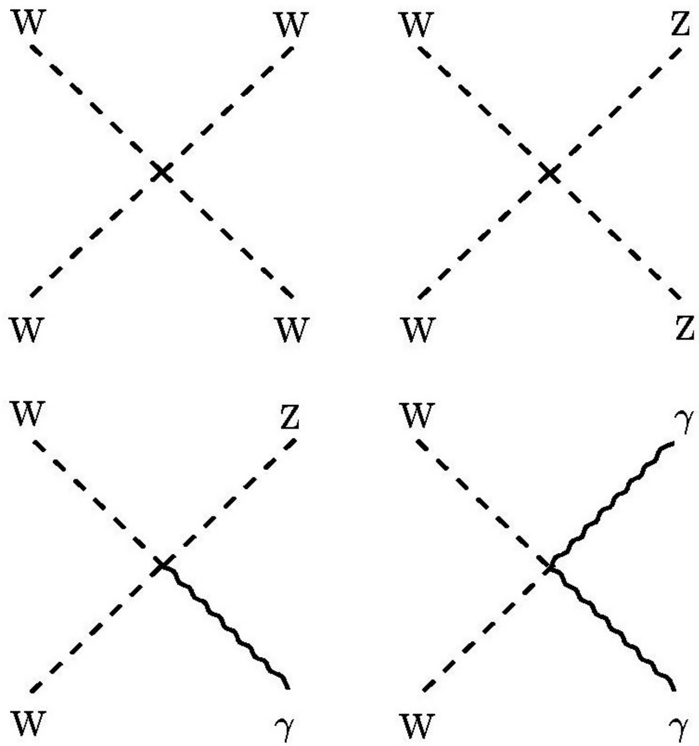
The *non-Abelian* structure of the Standard Model predicts *four-point* gauge boson interactions

- The couplings at the vertices are specified by the SM gauge symmetry

⇒ probing the QGCs provides a check on non-Abelian gauge structure of the SM

- Could not measure the QGCs precisely at LEP

*But*, New Physics at an unprobed energy scale may have low energy effects equivalent to *anomalous* QGCs - supplementary to those present in the SM



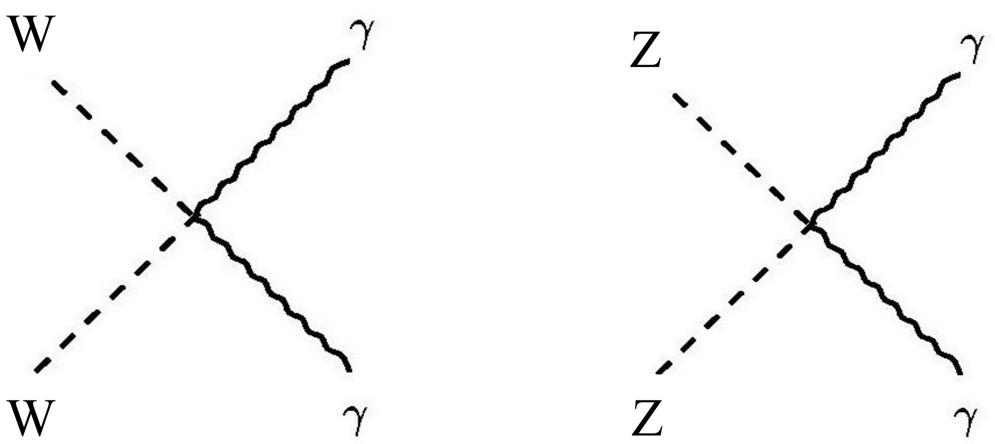

*Also,* anomalous couplings of *four massive vector bosons* occur in alternative (without Higgs) symmetry breaking theories

⇒ the study of AQGCs may "*provide a window on the electroweak symmetry breaking sector*"

# QGCs at LEP 2

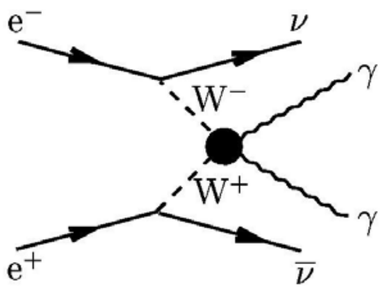
Self-couplings of four massive vector bosons connected to Higgs sector, but $\sqrt{s}$ at LEP never high enough to produce either three massive vector bosons or two through a fusion process } can only probe AQGCs *involving one or more photons…*

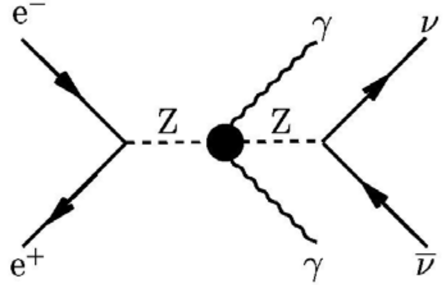
**WWγγ** and **ZZγγ**



# QGCs in the $\nu\bar{\nu}\gamma\gamma$ Final State at OPAL

Contribution from possible anomalous **WW$\gamma\gamma$** and **ZZ$\gamma\gamma$** vertices to $\nu\nu\gamma\gamma$ enter via:

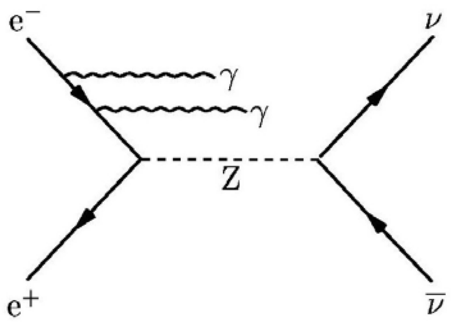


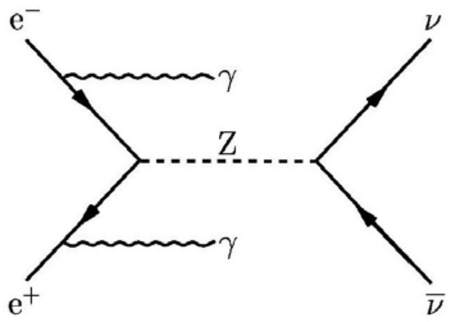



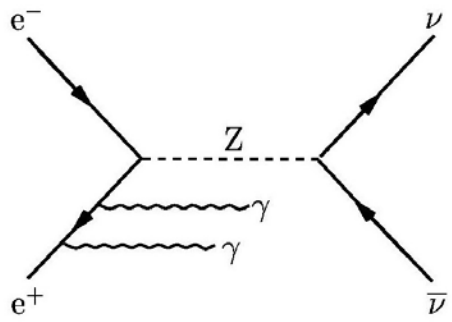

**WW$\gamma\gamma$ vertex:** couplings $a_0^W$, $a_c^W$

**ZZ$\gamma\gamma$ vertex:** couplings $a_0^Z$, $a_c^Z$

Dominant SM contribution to the $\nu\nu\gamma\gamma$ final state comes from radiative return diagrams:



# Parameterisation of AQGCs

AQGCs parameterised by effective terms added to EW Lagrangian:

$$\mathcal{L}_0 = -\frac{e^2}{8}\frac{a_0^{\mathrm{W}}}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-_\alpha - \frac{e^2}{16\cos^2\theta_W}\frac{a_0^{\mathrm{Z}}}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}Z^\alpha Z_\alpha,$$

$$\mathcal{L}_{\mathrm{c}} = -\frac{e^2}{16}\frac{a_{\mathrm{c}}^{\mathrm{W}}}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W^-_\beta + W^{-\alpha}W^+_\beta) - \frac{e^2}{16\cos^2\theta_W}\frac{a_{\mathrm{c}}^{\mathrm{Z}}}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}Z^\alpha Z_\beta$$

Contribution from anomalous diagrams controlled by the four parameters

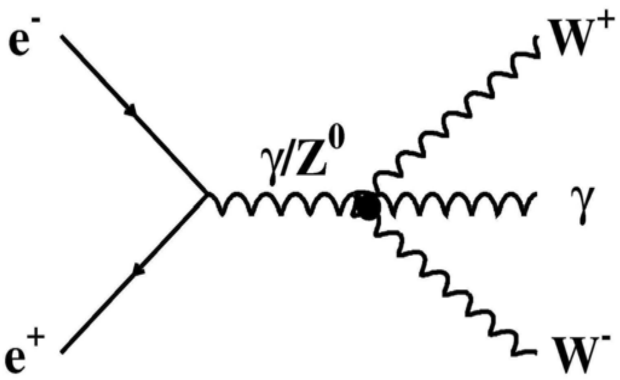
$$\frac{a_0^{W}}{\Lambda^2} \qquad \frac{a_c^{W}}{\Lambda^2} \qquad \frac{a_0^{Z}}{\Lambda^2} \qquad \frac{a_c^{Z}}{\Lambda^2}$$

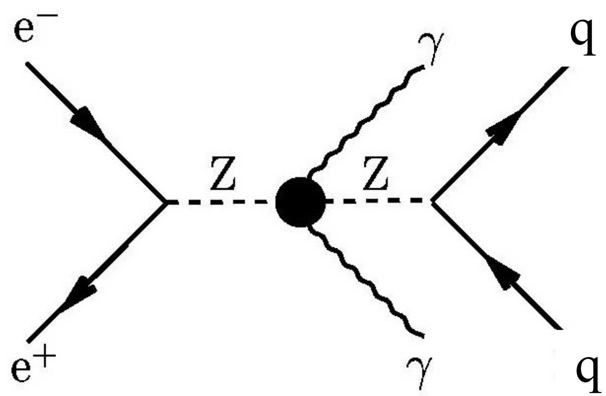
where Λ is interpreted as the energy scale of the new physics.

Using the ννγγ final state, seek constraints on these four parameters

# The WWγ and $q\bar{q}\gamma\gamma$ Final States at OPAL

OPAL has also used the **WWγ** and **qqγγ** final states to study the AQGCs:




Sensitive to WWγγ AQGC: $a_0^W, a_c^W$

SM contribution mainly from ISR, FSR from charged fermions and radiation from the W

Sensitive to WWγγ AQGC: $a_0^Z, a_c^Z$

SM contribution comes from ISR and FSR photons

# Method of Analysis for $\nu\bar{\nu}\gamma\gamma$

# Event Selection for $\nu\bar{\nu}\gamma\gamma$

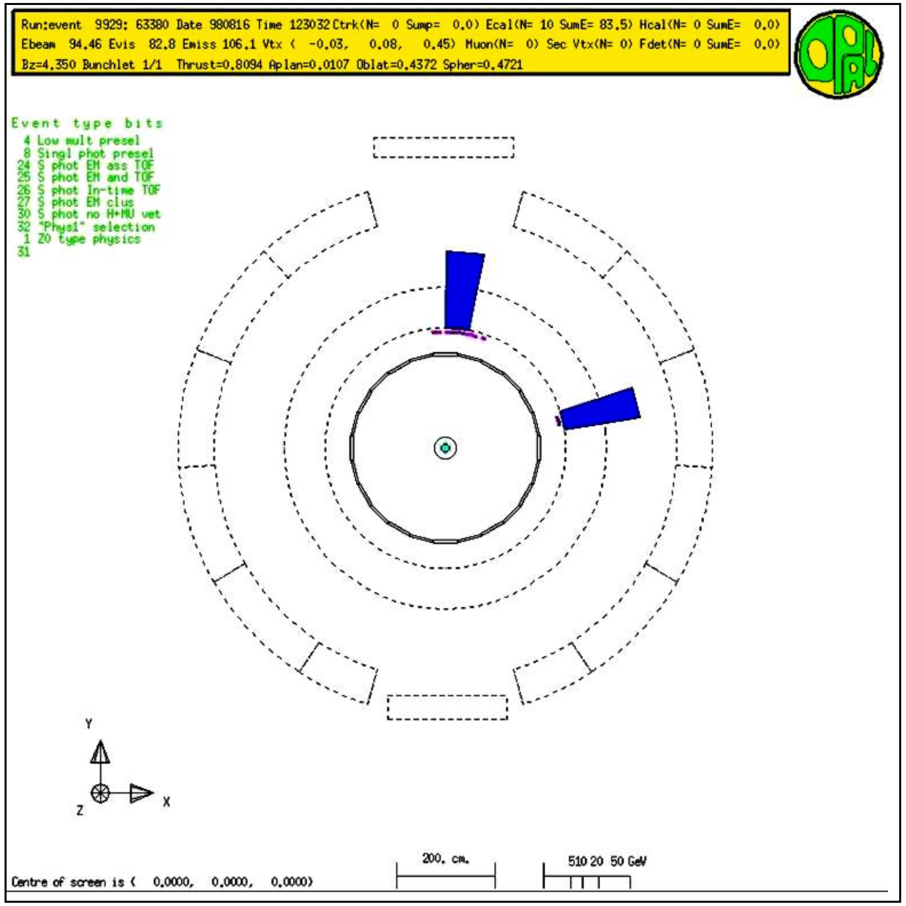
Signature: *two photons and missing energy*

$\Rightarrow$ use established acoplanar photon pair selection, which takes two-photon candidate events then cuts on:

- photon acoplanarity and total energy deposition in ECAL (to veto $\gamma\gamma$ events)
- charged track activity (to veto $ll\gamma\gamma$ events)
- $p_T$ of two photon system (to veto low angle Bhabha with two-photon ISR events)

$\Rightarrow$ Efficiency ~ 65% , Purity > 99%

- Additional cuts to suppress SM radiative return contribution and enhance any AQGC:
  - $E_{\gamma 1}, E_{\gamma 2} > 10$ GeV
  - $|\cos(\theta_{1,2})| < 0.9$

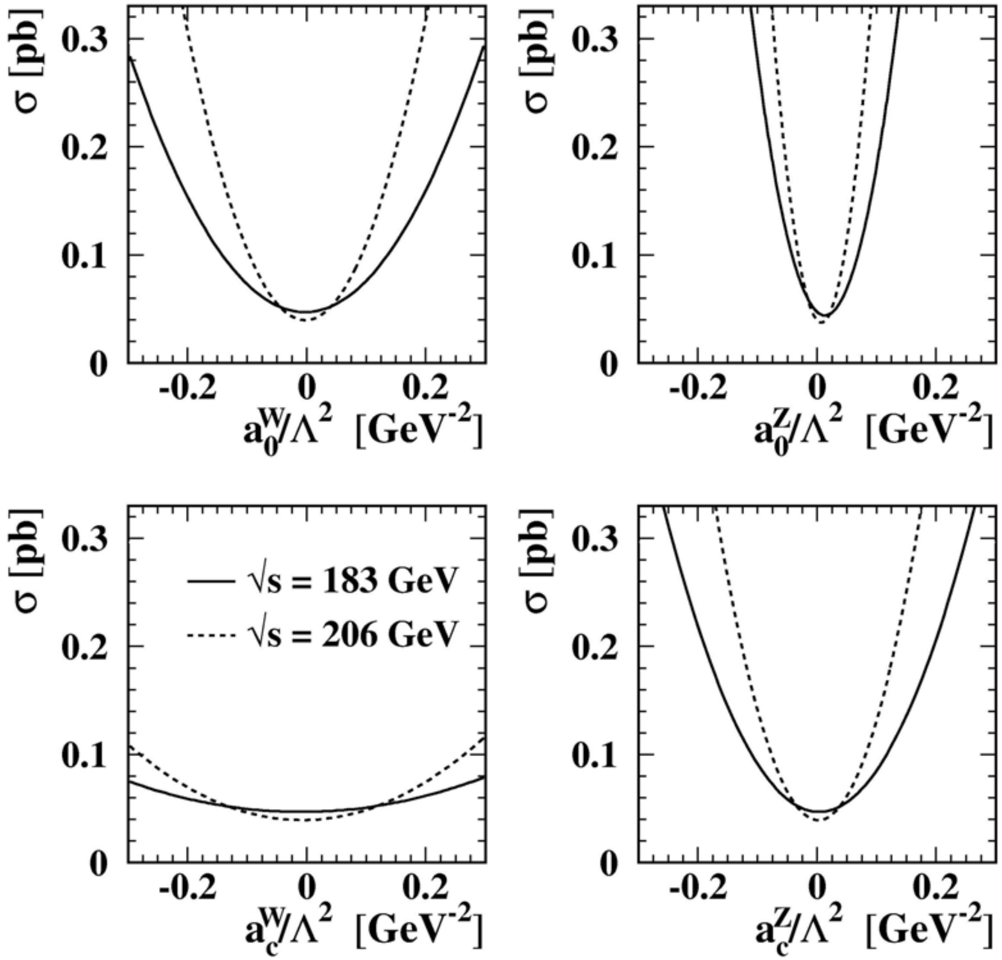



OPAL data (180–209 GeV): **20 events**

# Monte Carlo Modelling

- Used NUNUGPV Monte Carlo program with generated events fully simulated in OPAL
- AQGC vertices implemented as function of the four anomalous couplings
- Total cross-section varies quadratically with each coupling
- Generated samples reweighted to obtain $\sigma(a_0^W, a_c^W, a_0^Z, a_c^Z)$

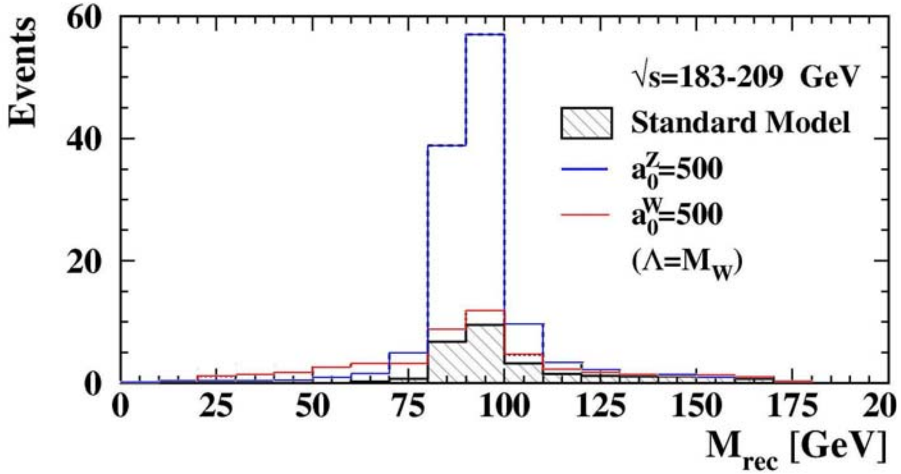
SM MC (180–209GeV): **27.6 events**



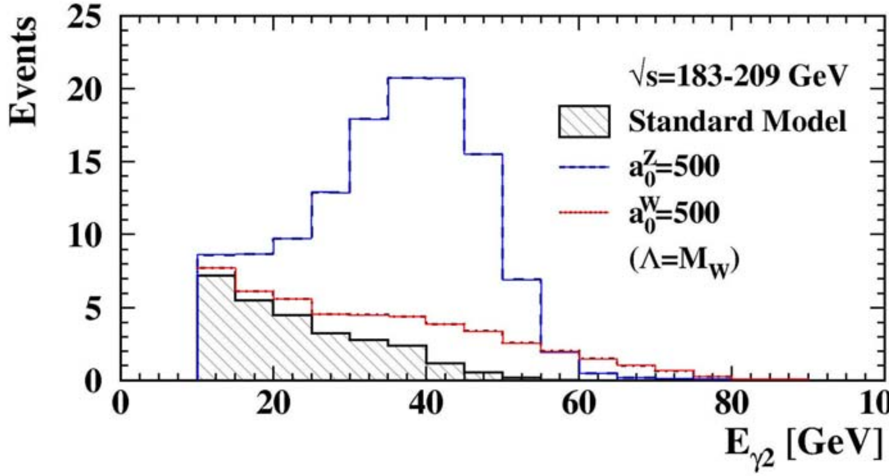
# Effects of Anomalous Couplings

Distributions most sensitive to the AQGCs:

*$M_{rec}$*




*$E_{\gamma 2}$*




Want to use shape information in these distributions as well as information from the total cross-section dependence shown previously:

⇒ Employ a *binned maximum likelihood analysis* with bins in the two dimensional distribution of $M_{rec}$ vs $E_{\gamma 2}$

# Method of Maximum Likelihood

*Without systematics*, the likelihood function for one parameter *a* is given by:

$$-\ln L(a) = -\sum_{i=1}^{bins} n_i \ln P_i(a) + \left(N_{ex}(a) - N_{obs} \ln N_{ex}(a)\right)$$

Shape information based on the number of events in each bin *i*

Poisson term making use of information in total cross section

A transformation is then made to fold in the systematic uncertainties:

*expect these to make a small contribution with only 20 data events*

Seek the optimal binning for maximum sensitivity to the anomalous couplings

⇒Optimise binning using SM MC as input to the fit

# Systematics

- Energy scale of ECAL
- Energy resolution of ECAL

} main experimental uncertainties

- Uncertainty on luminosity
- ISR uncertainty in the MC modelling
- SM theory uncertainty
  – comparison of NUNUGPV with KK2F
- AQGC theory uncertainty
  – comparison with Belanger *et al*.

# Results for $\nu\bar{\nu}\gamma\gamma$ channel

# Bias and Ensemble Tests

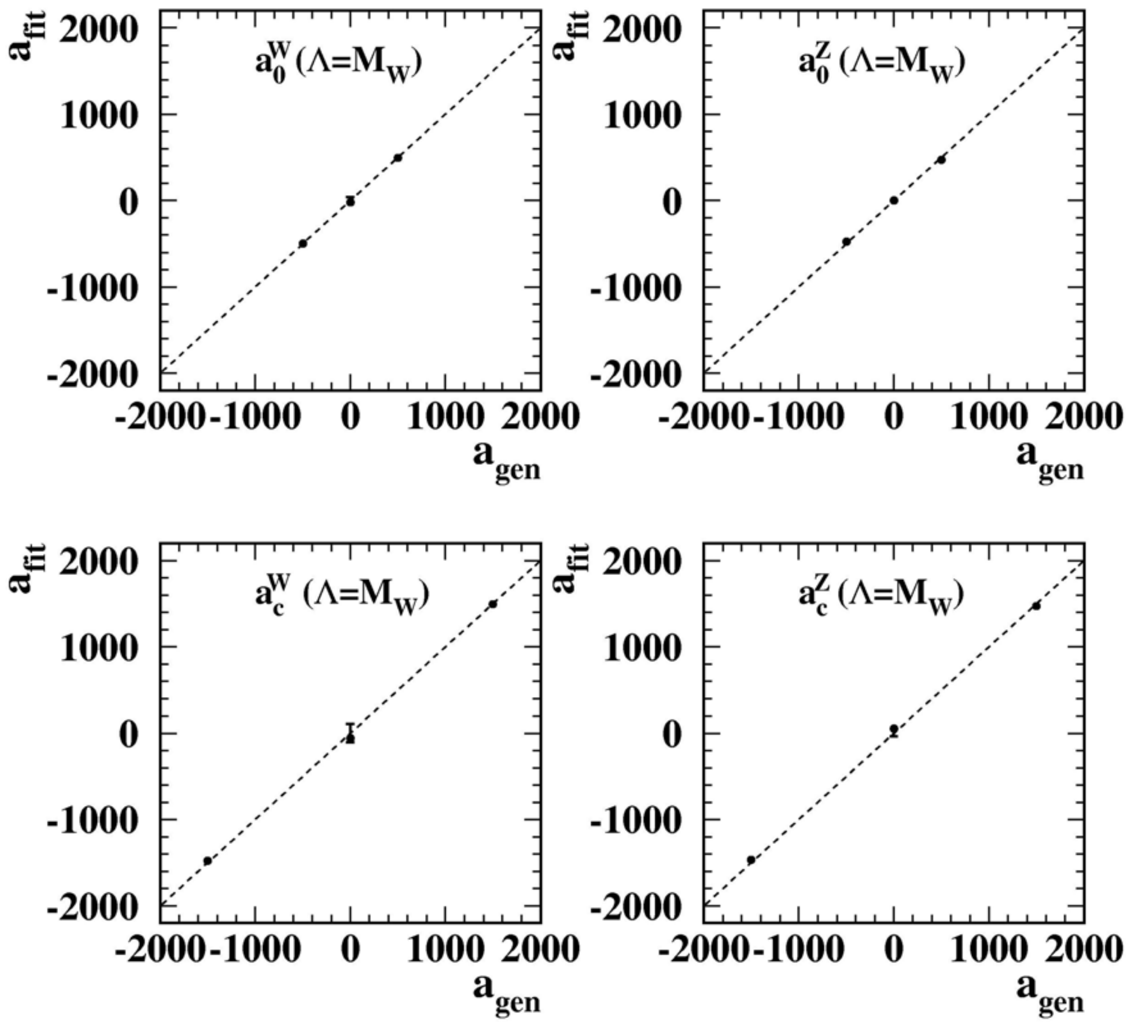
## Bias Tests

• Minimise $-\ln L(a)$ using different MC samples as data-like input

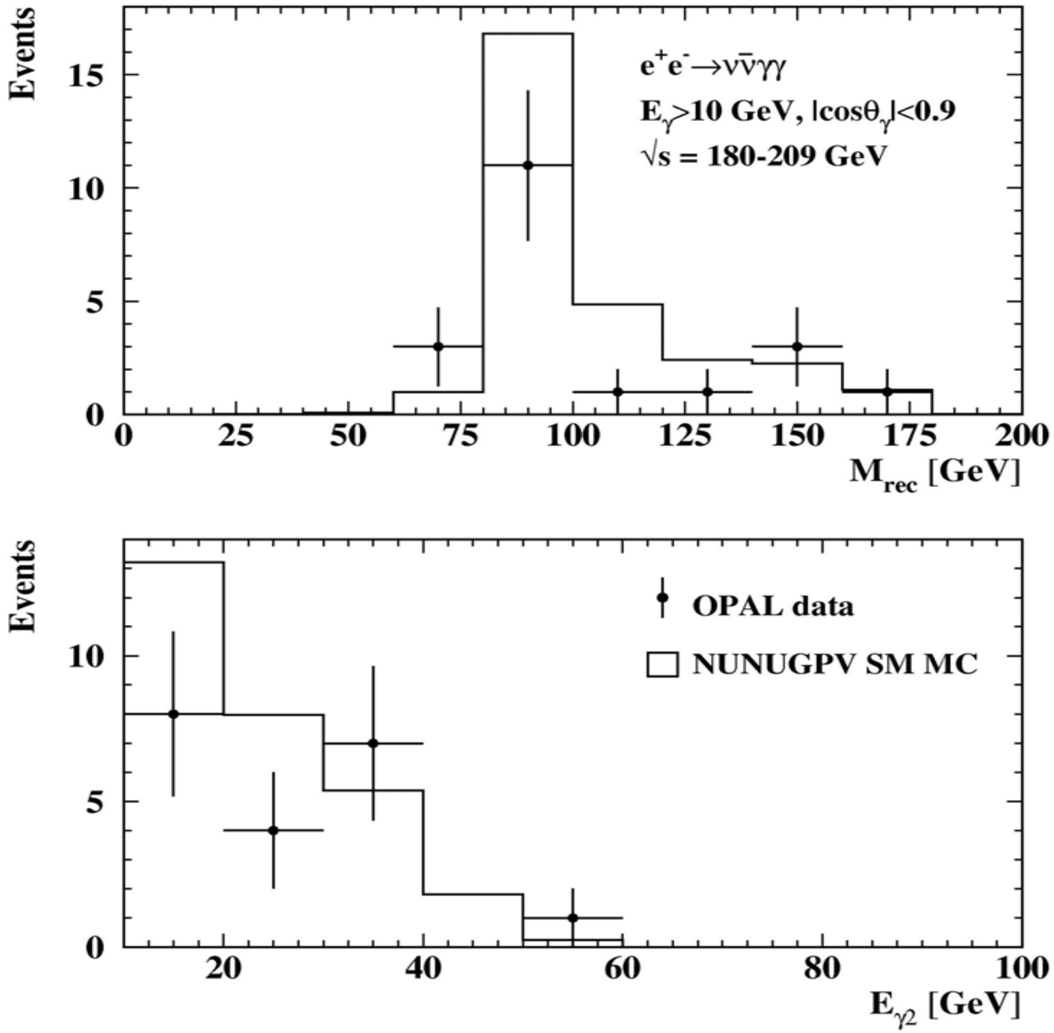
## Ensemble Tests

• Study a large number of SM MC samples with same statistics as the data

• For each coupling, 3% of the samples return $\Delta \ln L(a) > 1.92$

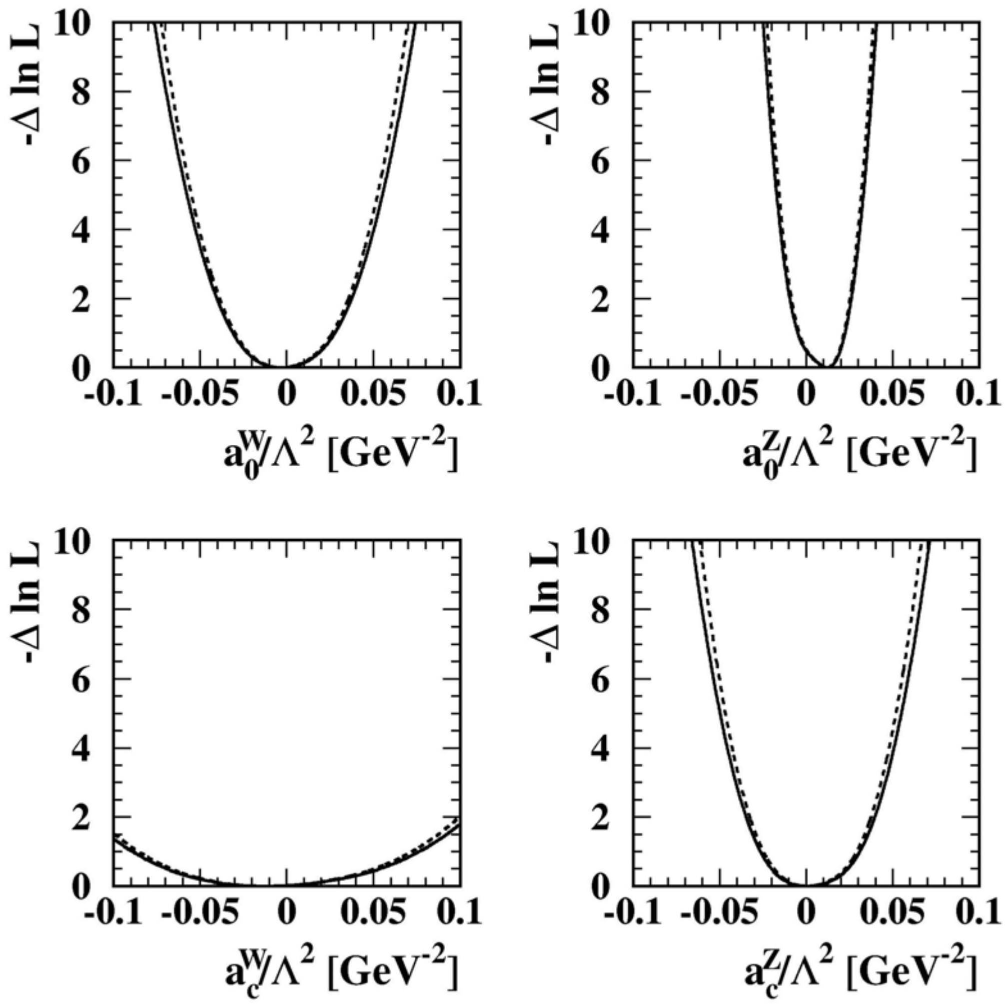


# Data vs SM Monte Carlo




SM distributions of $M_{rec}$ and $E_{\gamma 2}$ describe the data well

# One-Dimensional Fits




- Fits performed by varying parameter of interest, other three fixed at SM value (0)

- Systematic uncertainties negligible compared to statistical precision

- Gaussian 95% CL limits are:

  $-0.040 < a_0^W/\Lambda^2 < 0.037$ GeV$^{-2}$

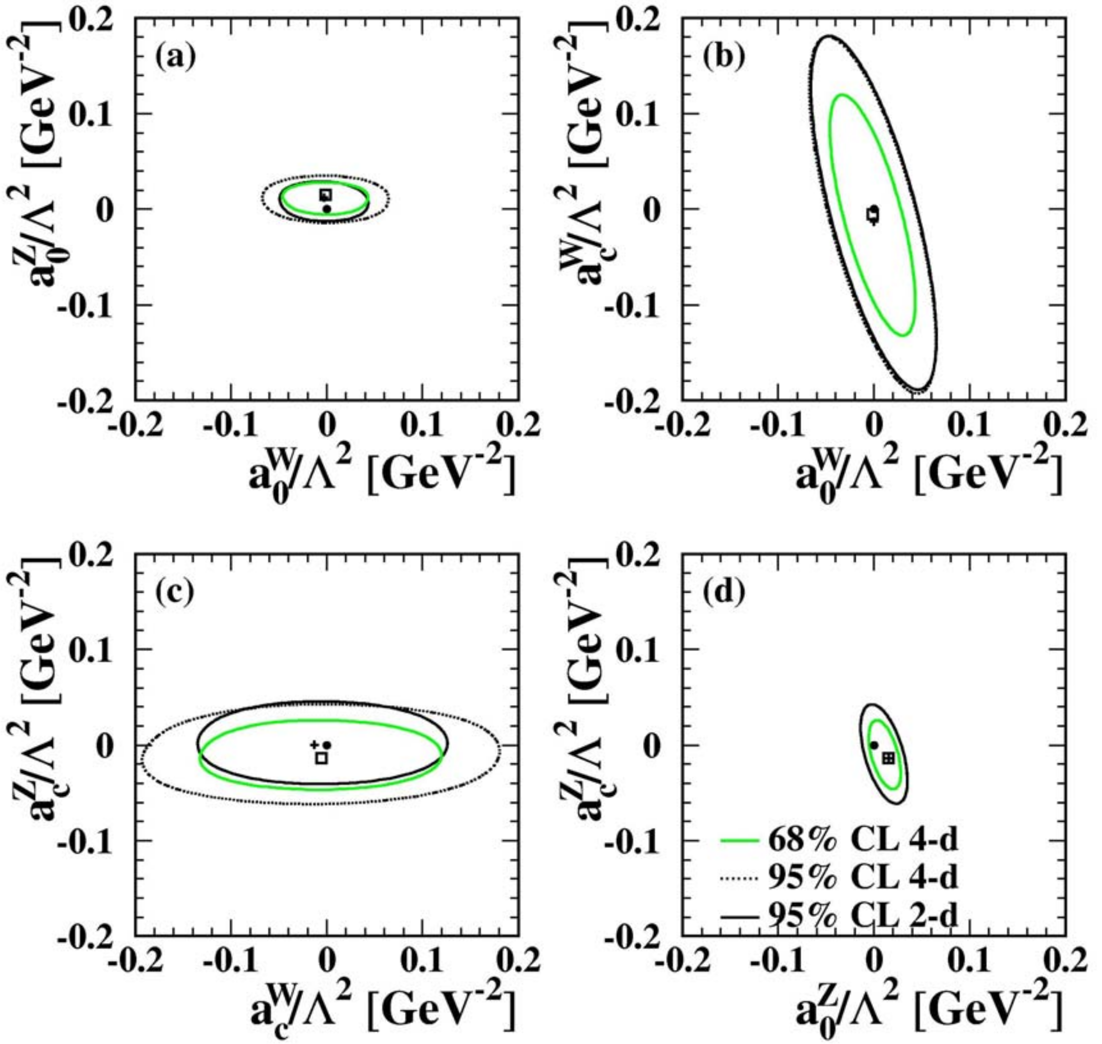
  $-0.114 < a_c^W/\Lambda^2 < 0.103$ GeV$^{-2}$

  $-0.090 < a_0^Z/\Lambda^2 < 0.026$ GeV$^{-2}$

  $-0.034 < a_c^Z/\Lambda^2 < 0.039$ GeV$^{-2}$

⇒ All compatible with zero and consistent with SM limits from ensemble test

# Two- and Four- Dimensional Fits




- Two-dimensional fits performed by varying two parameters of interest, other two fixed at SM value (0)
- Two-dimensional projections of full four-dimensional fits superimposed
- Systematic uncertainties included

**Note**

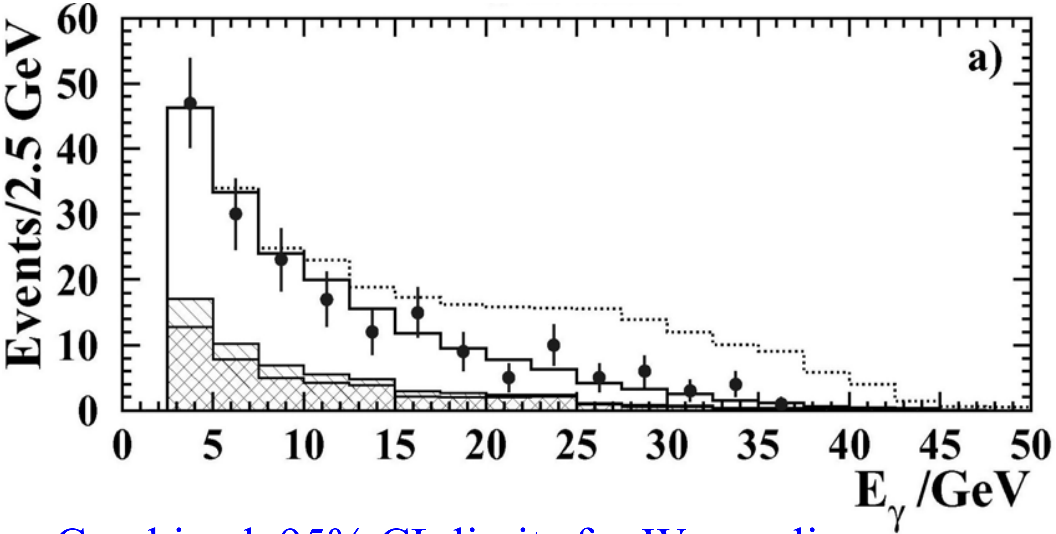
- Relatively tighter constraints on Z couplings evident
- Limits on Z and W couplings uncorrelated

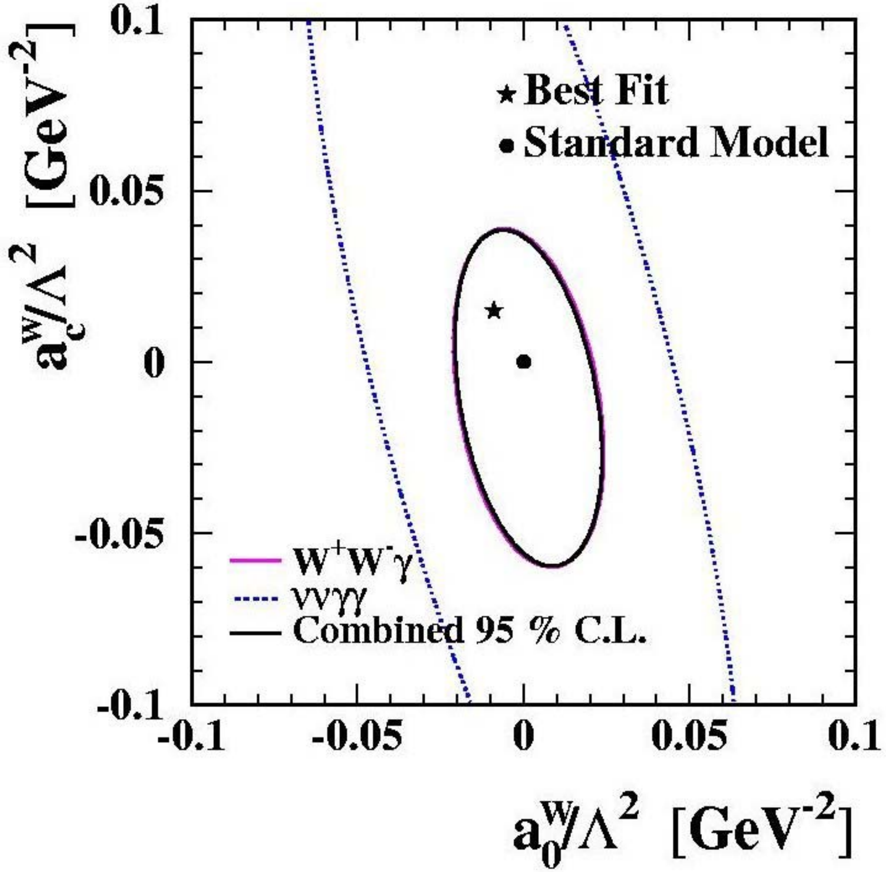
**Again, SM compatibility is illustrated**

# Combination

# Limits on WWγγ from $\nu\bar{\nu}\gamma\gamma$ and $W^+W^-\gamma$

WWγ analysis employed photon energy spectrum and angular distribution for the likelihood function, *using 187 selected events at* $\sqrt{s} > 180$ GeV




Combined 95% CL limits for W couplings are:

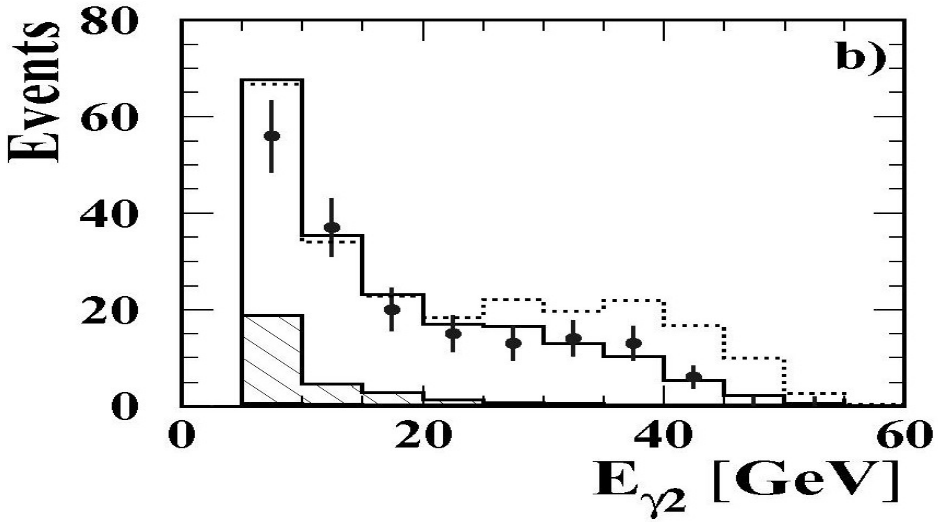
$-0.020 < a_0^W/\Lambda^2 < 0.020$ GeV$^{-2}$

$-0.052 < a_c^W/\Lambda^2 < 0.037$ GeV$^{-2}$

⇒ no deviations from SM seen

# Limits on ZZγγ from $\nu\bar{\nu}\gamma\gamma$ and $q\bar{q}\gamma\gamma$

qqγγ analysis employed energy spectrum of second highest energy photon for the likelihood function, *using 176 selected events at* $\sqrt{s} > 130$ GeV

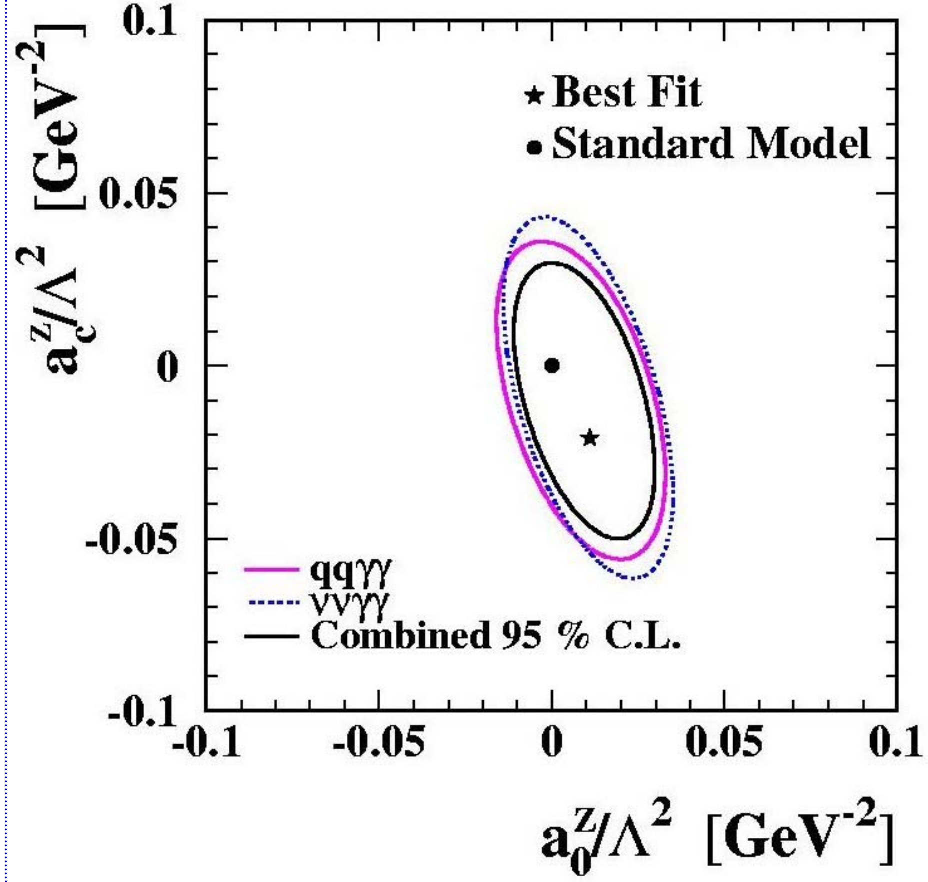



Combined 95% CL limits for Z couplings are:

$-0.007 < a_0^Z/\Lambda^2 < 0.023\ \mathrm{GeV}^{-2}$

$-0.029 < a_c^Z/\Lambda^2 < 0.029\ \mathrm{GeV}^{-2}$

⇒ no deviations from SM seen



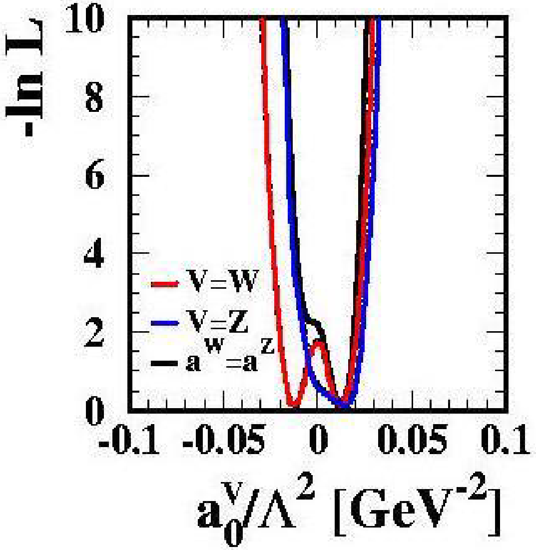
# Overall Combination

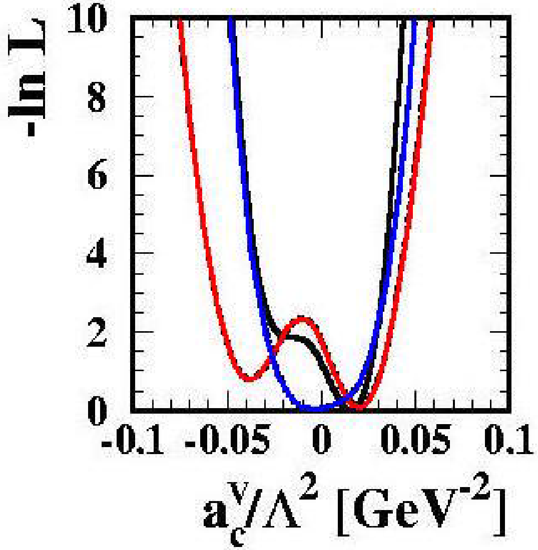
- Assume $a_0^W = a_0^Z = a_0$ and $a_c^W = a_c^Z = a_c$

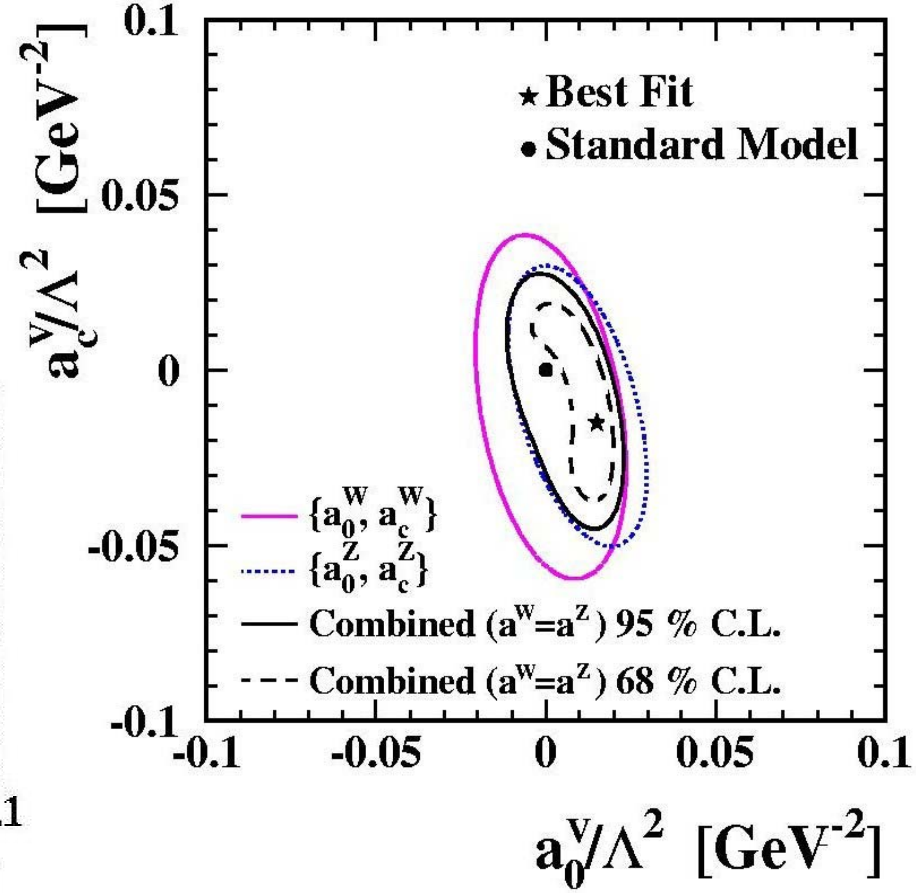
⇒ combine likelihoods from ννγγ, qqγγ and WWγ:

$$+0.002 < a_0/\Lambda^2 < 0.019 \quad GeV^{-2}$$
$$-0.022 < a_c/\Lambda^2 < 0.029 \quad GeV^{-2}$$

⇒ due to double minima in the $a_0$ couplings from WWγ and qqγγ, SM agreement is at the 2σ level



# Summary

# Summary

- *Observe* 20 $\nu\nu\gamma\gamma$ events in OPAL data passing acoplanar photon selection with additional cuts on energies and angles at $\sqrt{s}$ = 183-209 GeV

- $M_{rec}$ and $E_{\gamma 2}$ distributions are sensitive to different anomalous couplings:

$\Rightarrow$ optimised the use of this shape information in a binned $\Delta\ln L$ function of the four coupling parameters $a_0^W$, $a_c^W$, $a_0^Z$, $a_c^Z$.

- Observed distributions of $M_{rec}$ and $E_{\gamma 2}$ are in good agreement with SM MC prediction

- Combining with $qq\gamma\gamma$ and $WW\gamma$ final states at OPAL, 95% CL limits at $\Delta\ln L(a) = 1.92$ are:

$$-0.020 < a_0^W/\Lambda^2 < 0.020 \text{ GeV}^{-2}$$
$$-0.052 < a_0^Z/\Lambda^2 < 0.037 \text{ GeV}^{-2}$$
$$-0.007 < a_c^W/\Lambda^2 < 0.023 \text{ GeV}^{-2}$$
$$-0.029 < a_c^Z/\Lambda^2 < 0.029 \text{ GeV}^{-2}$$

- Limits have also been reported allowing two parameters to vary

**Results are consistent with the SM**