# W,Z couplings at L3

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**Lake Louise Winter Institute**
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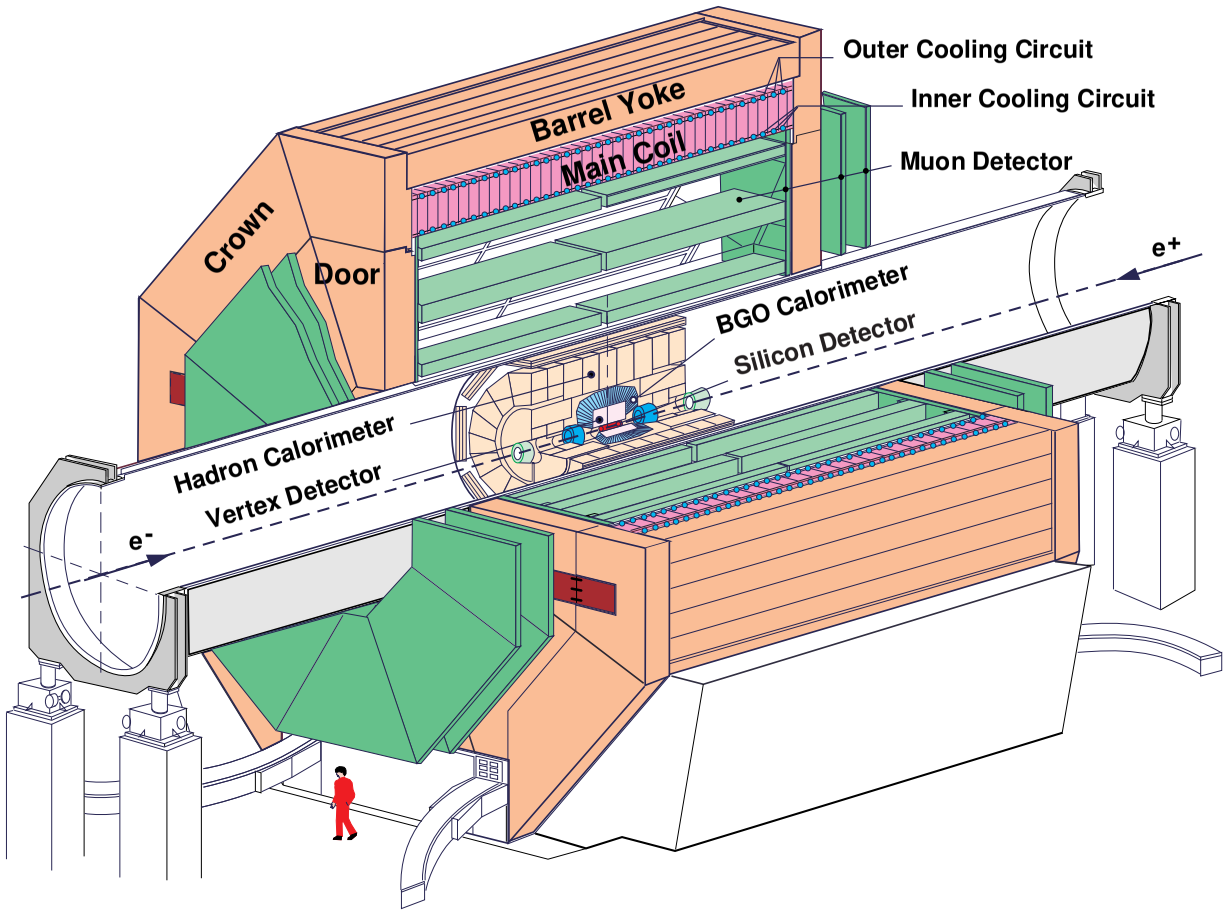
- L3 Data
- WWV couplings from W pairs
- Couplings from single W and single $\gamma$
- Neutral couplings from ZZ and Z$\gamma$
- Quartic couplings from Z$\gamma\gamma$
- Conclusion

# L3 detector at LEP $e^+e^-$ collider




- L3 is one of the four LEP experiments.
- High resolution for Photons/Electrons and Muons.
- Hermeticity for jet reconstruction.

Focus on 1998 Data:

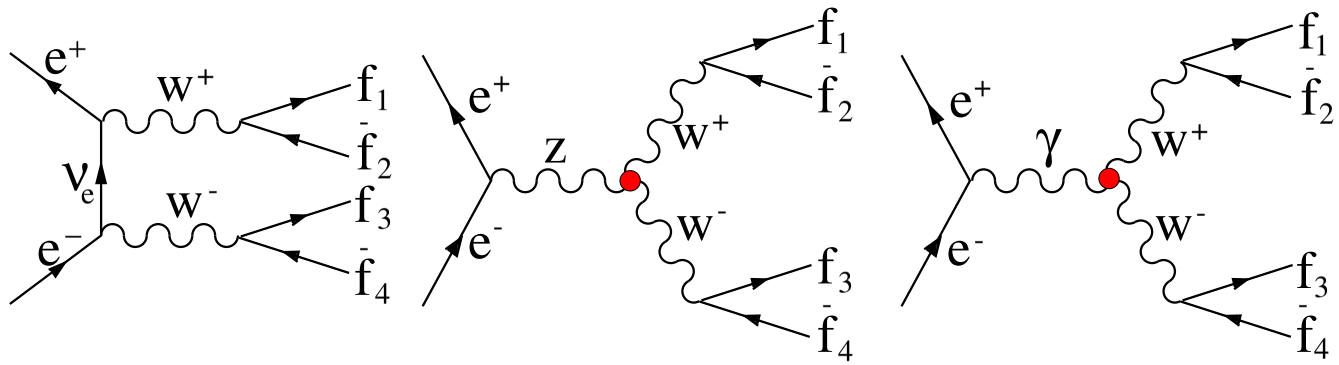
- 1998 data: 176.4 $\mathrm{pb}^{-1}$ at $\sqrt{s} = 189$ GeV.
- 1999 data: 232 $\mathrm{pb}^{-1}$ at $\sqrt{s} = 192$-$202$ GeV.

Analysis of 1999 data is being finished.

# Measurement of $WW\gamma$ TGC

Non-Abelian gauge structure of the electroweak theory $\Rightarrow$ existence of Triple Gauge Couplings (TGC)

For W-pair production :




Extend the Standard Model $\longrightarrow$ write the most general Lorentz invariant Lagrangian of the type WWV (V either Z or $\gamma$):

$$
\begin{aligned}
i\mathcal{L}^{\mathrm{WWV}}_{eff} = \\
& g_{\mathrm{WWV}} \Big[ g_1^V V^\mu \left( W^-_{\mu\nu} W^{+\nu} - W^+_{\mu\nu} W^{-\nu} \right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \\
& \frac{\lambda_V}{m_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu} + i g_4^V W^+_\mu W^-_\nu \left( \partial^\mu V^\nu + \partial^\nu V^\mu \right) + \\
& i g_5^V \varepsilon_{\mu\nu\rho\sigma} \left( (\partial^\rho W^{-\mu}) W^{+\nu} - W^{-\mu} (\partial^\rho W^{+\nu}) \right) V^\sigma \\
& - \frac{\tilde{\kappa}_V}{2} W^-_\mu W^+_\nu \varepsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \frac{\tilde{\lambda}_V}{2 m_W^2} W^-_{\rho\mu} W^{+\mu}_\nu \varepsilon^{\nu\rho\alpha\beta} V_{\alpha\beta} \Big]
\end{aligned}
$$

## In the Standard Model:

$$
\begin{aligned}
g_{WW\gamma} &= e \\
g_{WWZ} &= e \cot\theta_W \\
g_1^Z = g_1^\gamma &= 1 \\
\kappa_Z = \kappa_\gamma &= 1 \\
\text{all others} &= 0
\end{aligned}
$$

- EM gauge invariance $\Rightarrow$ $g_1^\gamma = 1$ and $g_5^\gamma = 0$
- $g_1^V$, $\kappa_V$, $\lambda_V$ conserve C and P separately
- $g_5^V$ conserves CP but not C and P separately
- $g_4^V$, $\tilde{\kappa}_V$, $\tilde{\lambda}_V$ are CP violating

# Measurement of $WW\gamma$ TGC

Define deviations from SM:

$$\begin{aligned} \Delta g_1^Z &\equiv g_1^Z - 1 \\ \Delta\kappa_\gamma &\equiv \kappa_\gamma - 1 \\ \Delta\kappa_Z &\equiv \kappa_Z - 1 \end{aligned}$$

Consider only the couplings which conserve both C and P: only 5 (of 14) are left

$$\Delta g_1^Z, \Delta\kappa_\gamma, \Delta\kappa_Z, \lambda_\gamma, \lambda_Z$$

For a further reduction, require SU(2) symmetry:

$$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W \text{ and } \lambda_Z = \lambda_\gamma$$

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

Possible channels:

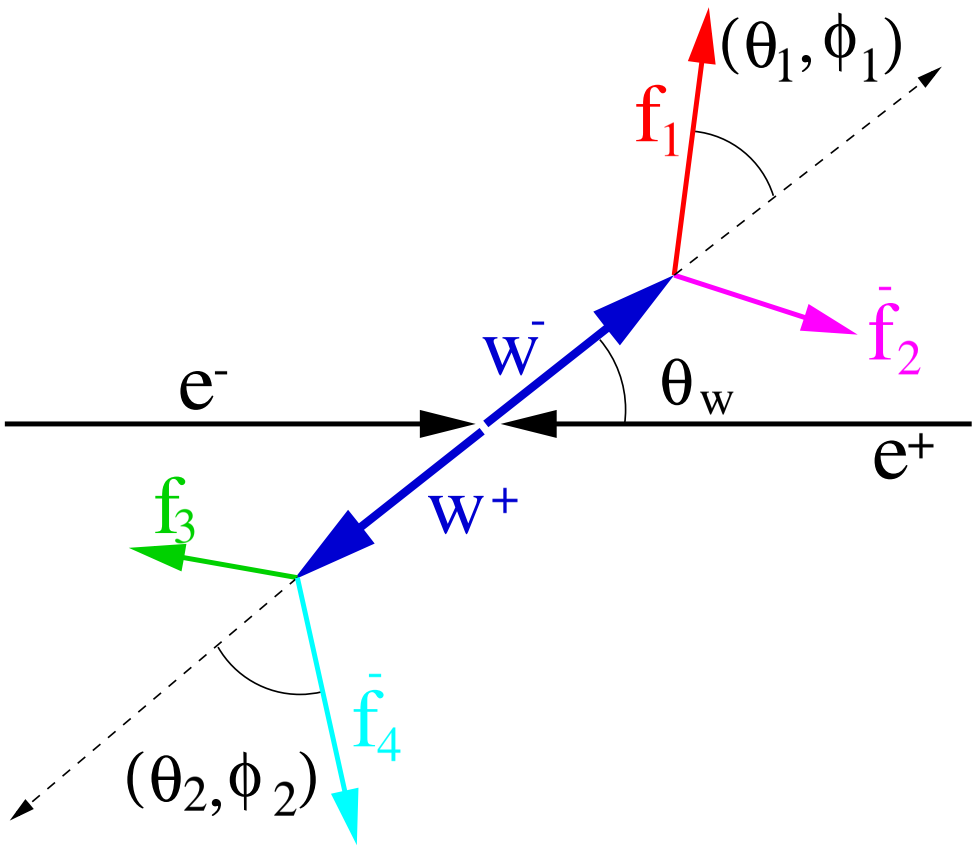
- WW pairs: $Q^2 = s$
- Single W: $Q^2 = M_W^2$
- Single $\gamma$: $Q^2 = 0$

# WW pairs

Anomalous Couplings would affect polarization, angular distributions and total cross section of WW.

A given W pair event can be described in terms of 5 variables (neglect $\gamma$ radiation):

- $\cos\theta_{W-}$ polar angle of the $W^-$
- $\cos\theta_1$, $\phi_1$ polar and azimuthal angles of the fermion in the $W^-$ rest frame
- $\cos\theta_2$, $\phi_2$ polar and azimuthal angles of the antifermion in the $W^+$ rest frame

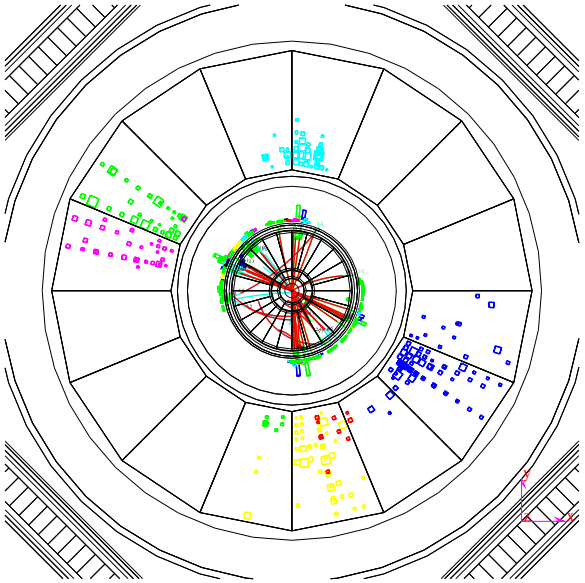



## Information used in the different channels:

- qqqq $\rightarrow \cos\theta_{W-}$
- qqe$\nu$, qq$\mu\nu$ and qq$\tau\nu$ $\rightarrow \cos\theta_{W-}$, $\cos\theta_{lepton}$ and $\phi_{lepton}$
- $\ell\nu\ell\nu$ $\rightarrow$ only total cross section, will use $\cos\theta_{W-}$

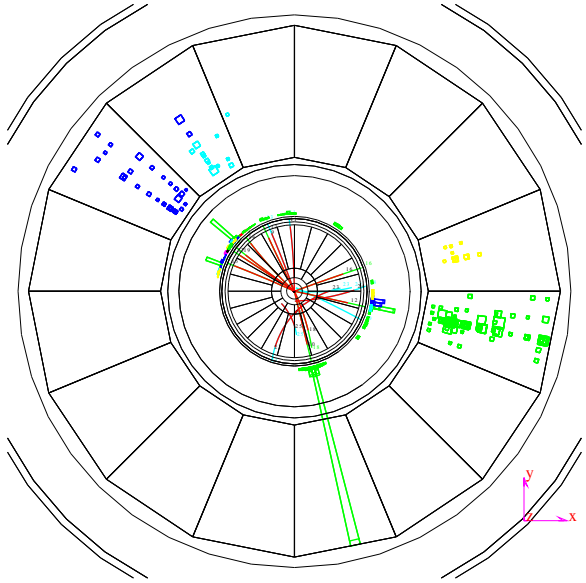
# WW selection

qqqq



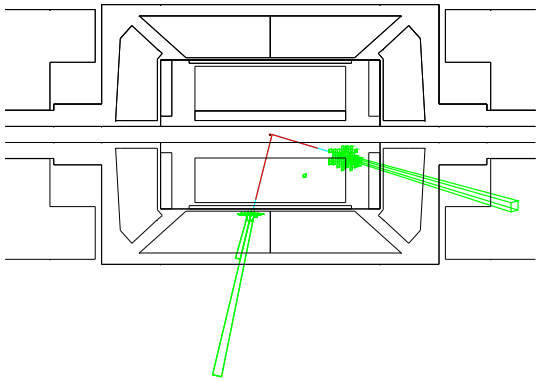
No missing energy, high multiplicity. Neural Net based selection

$qq\ell\nu$



2 jets and an isolated lepton. Missing energy.

$\ell\nu\ell\nu$



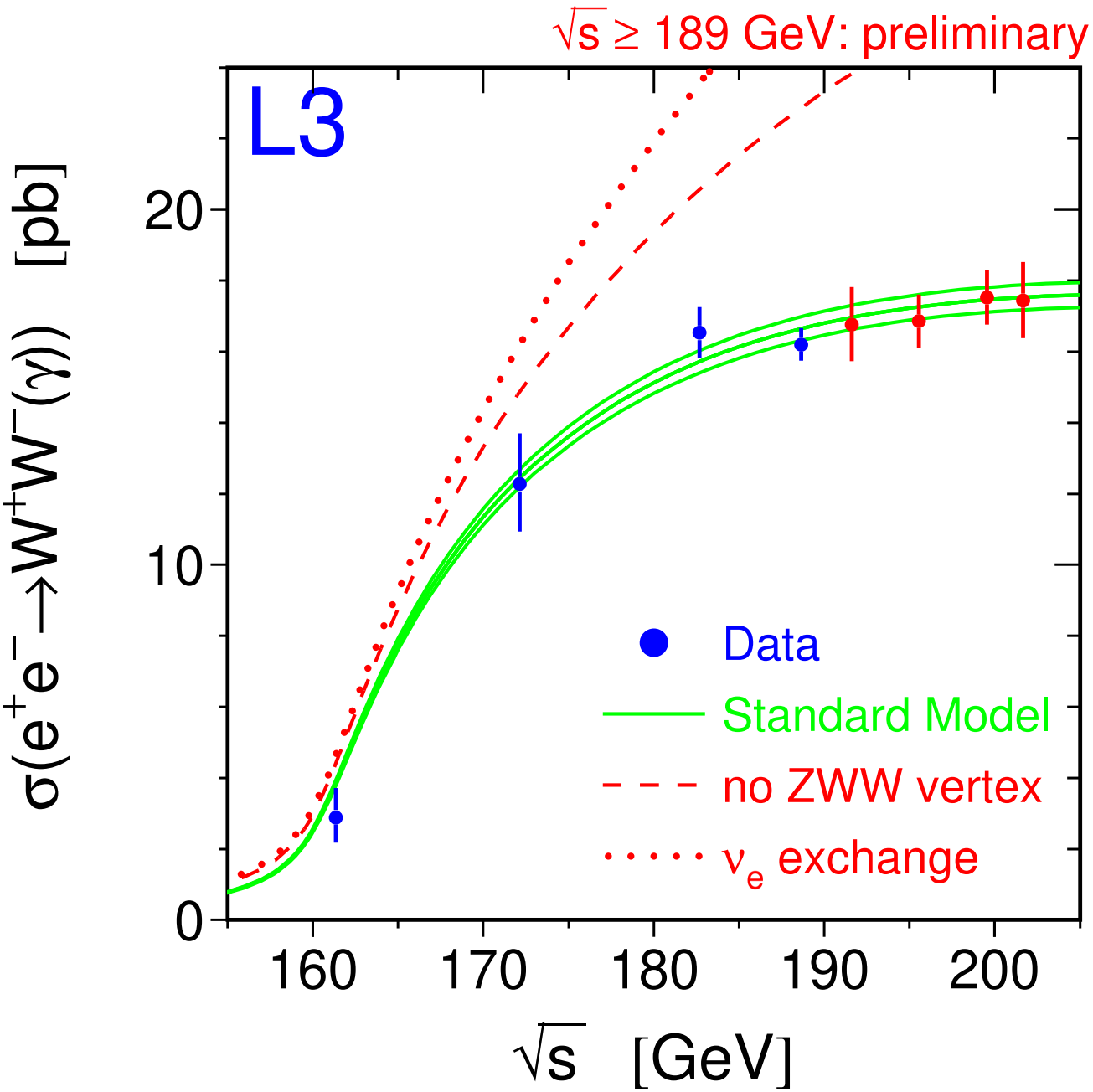
2 acoplanar leptons, large missing energy.

WW events collected by L3:

| Year | Energy | Luminosity | WW events |
|---|---|---|---|
| 1996 | 161 GeV | 10.8 $\mathrm{pb}^{-1}$ | 21 |
| 1996 | 172 GeV | 10.2 $\mathrm{pb}^{-1}$ | 113 |
| 1997 | 183 GeV | 55.5 $\mathrm{pb}^{-1}$ | 844 |
| 1998 | 189 GeV | 176.4 $\mathrm{pb}^{-1}$ | 2663 |
| 1999 | 192-202 GeV | 232 $\mathrm{pb}^{-1}$ | 3414 |

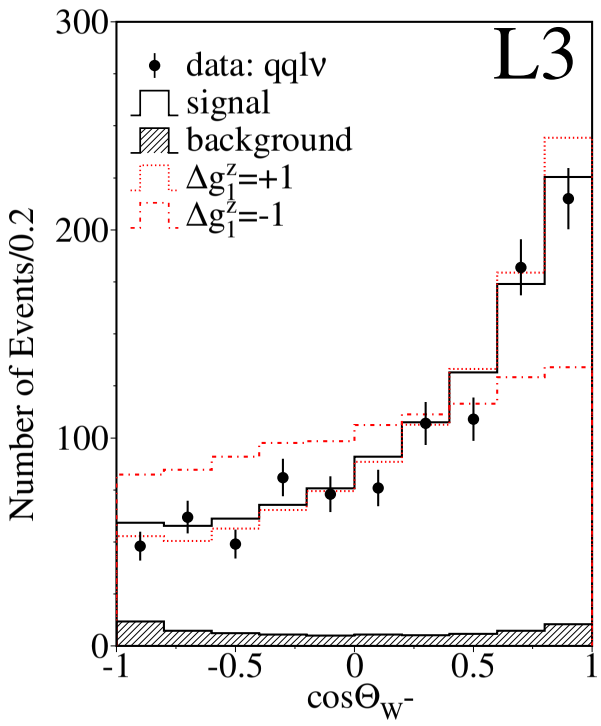
# W pair cross section

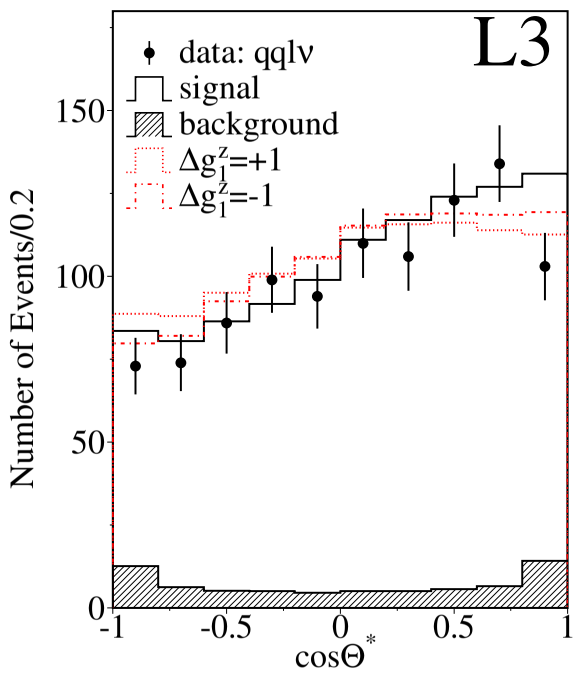
W pair cross section already excludes models with no ZWW or $\gamma$WW vertex.

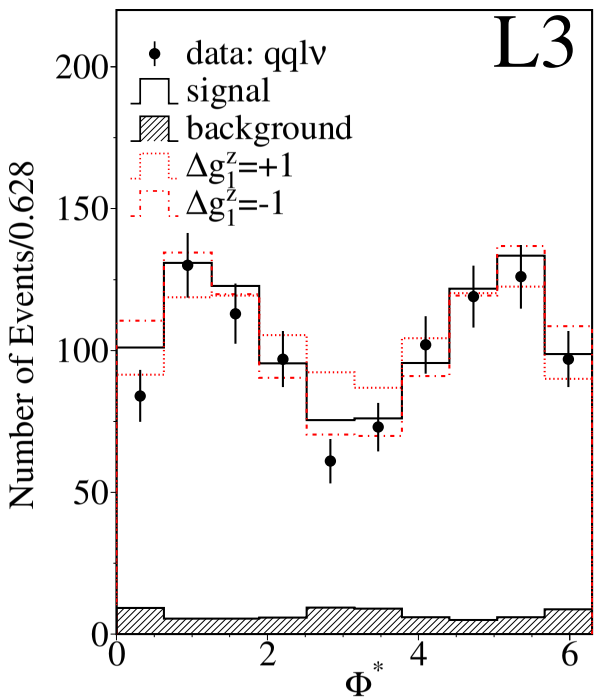


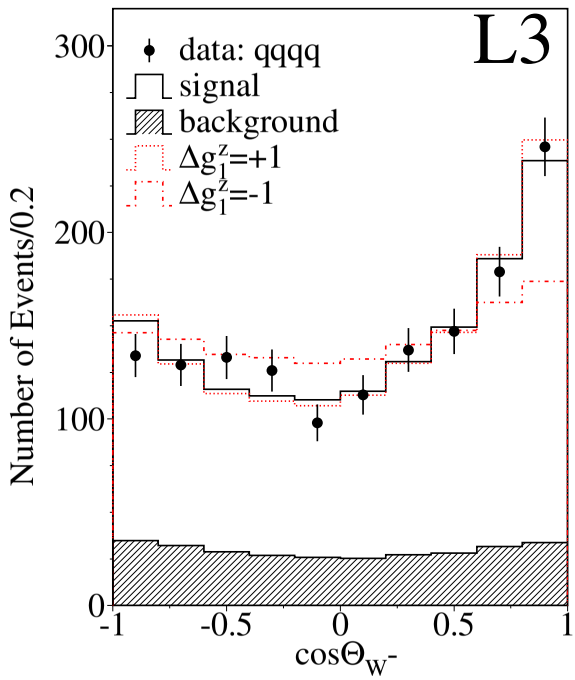
# Phase space variables

## Distributions with non-zero values of $\Delta g_1^Z$



# Results of 1-D and 2-D fits

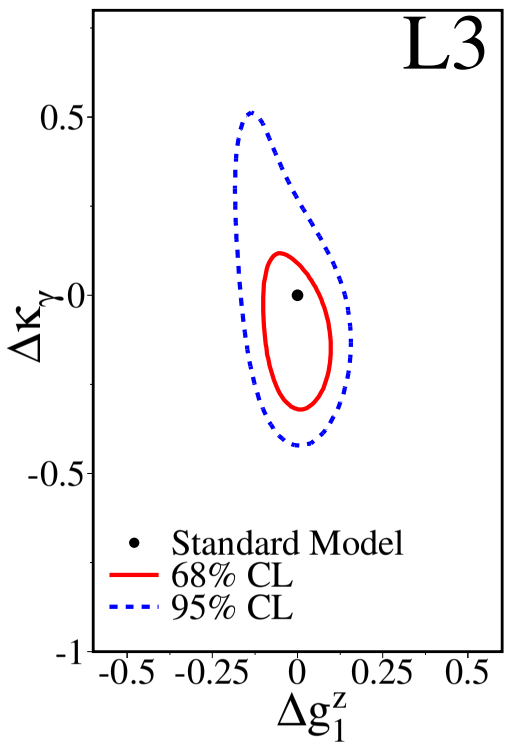
172 GeV, 183 GeV final and 189 GeV preliminary

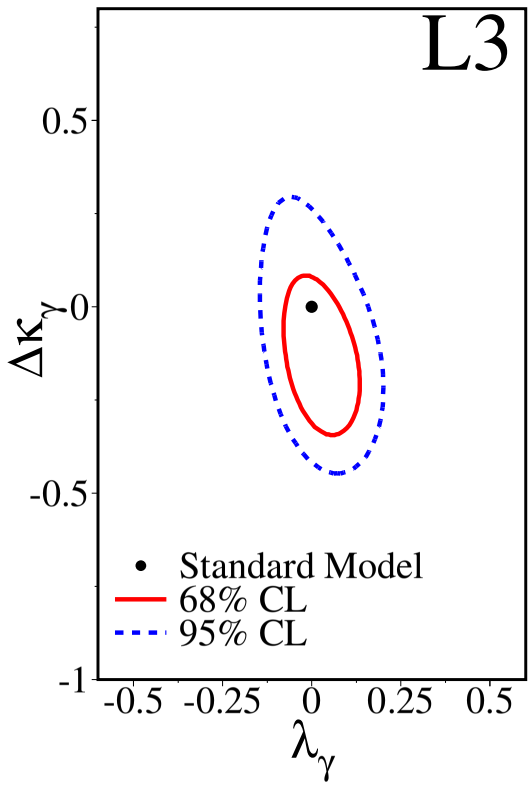
1-D fit: All other couplings set to SM value.

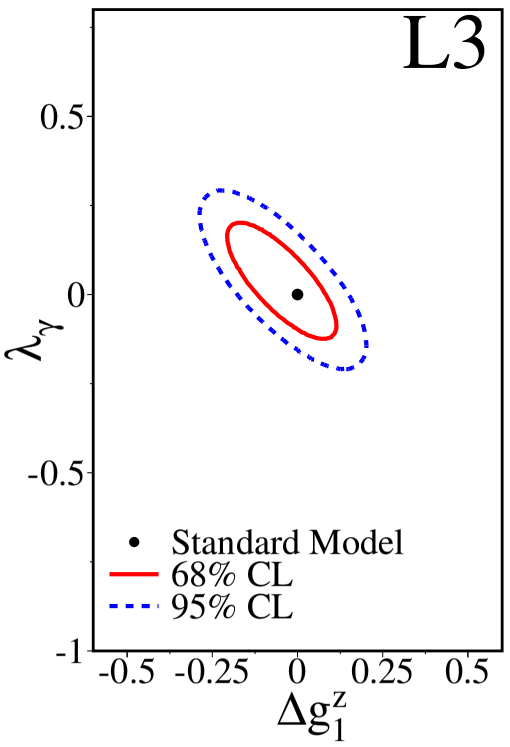
With *preliminary* estimate of systematic errors

| | |
|---|---|
| $\Delta g_1^z$ | $-0.02^{+0.07}_{-0.07} \pm 0.03$ |
| $\Delta\kappa_\gamma$ | $-0.12^{+0.14}_{-0.12} \pm 0.08$ |
| $\lambda_\gamma$ | $0.00^{+0.07}_{-0.07} \pm 0.03$ |

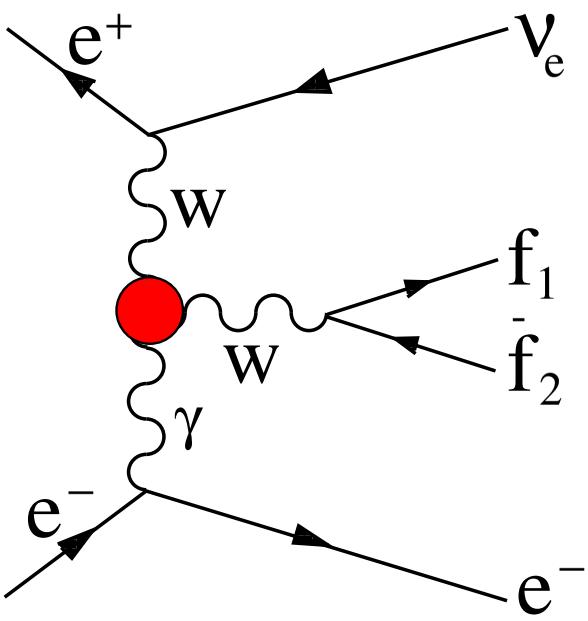
Third coupling set to SM value.



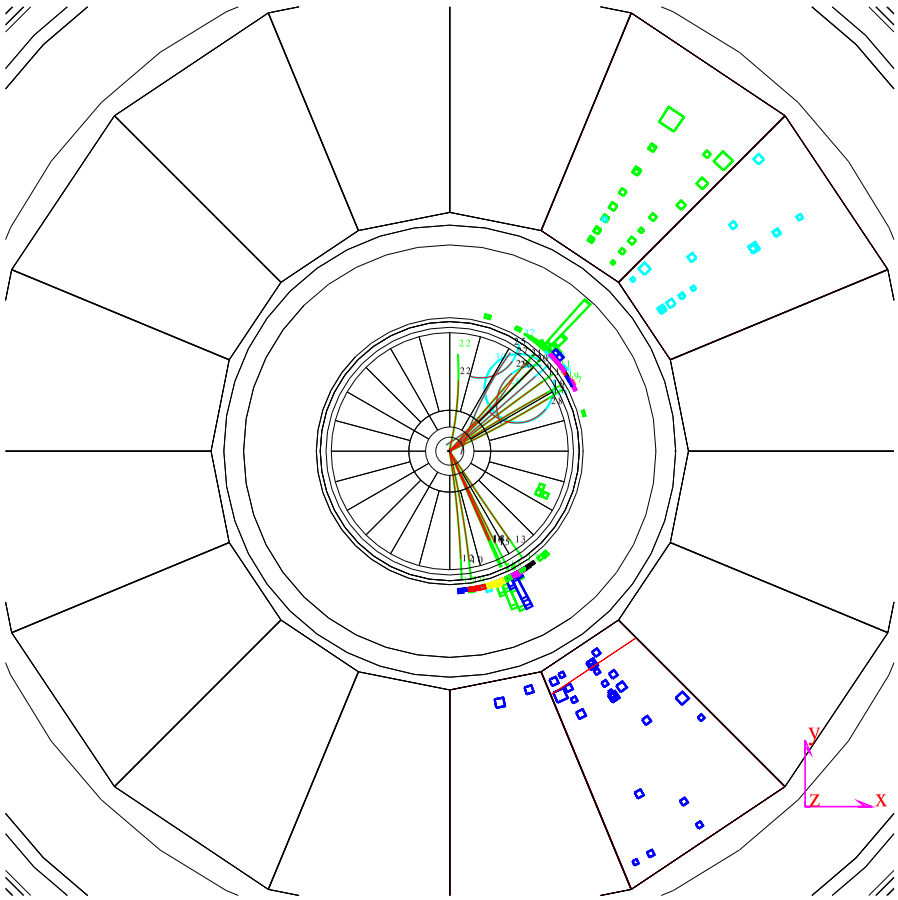



# Single W

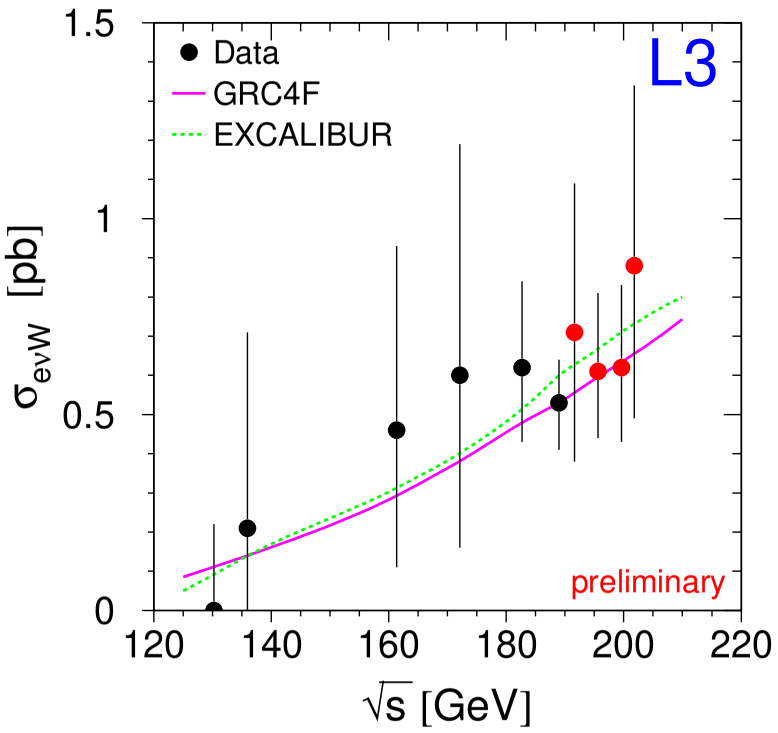



← is one of the dominant diagrams in single W production: allows to disentangle WW$\gamma$ from WWZ couplings.

- Final state electron (positron) produced at very low polar angle $\Longrightarrow$ not detected
- All W decay modes analysed.

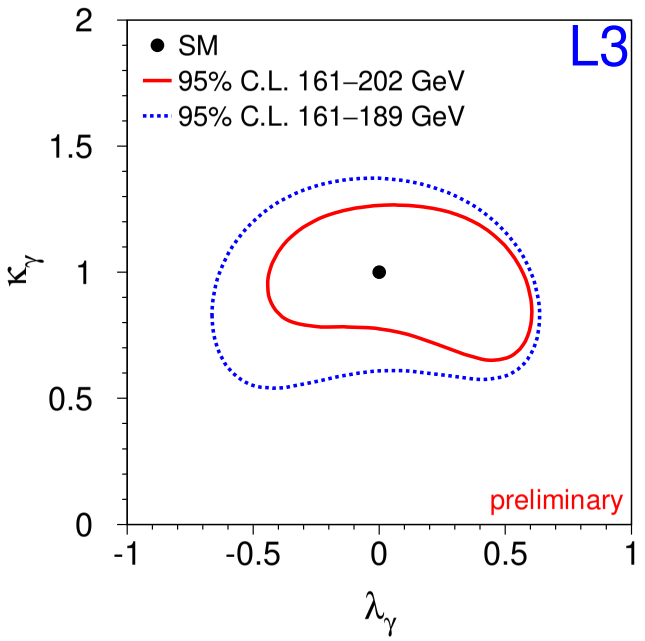


# Single W



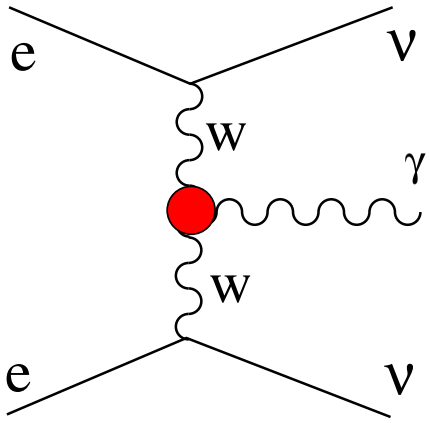

Preliminary 2-D fit results from 189 GeV ( 95% C.L.)

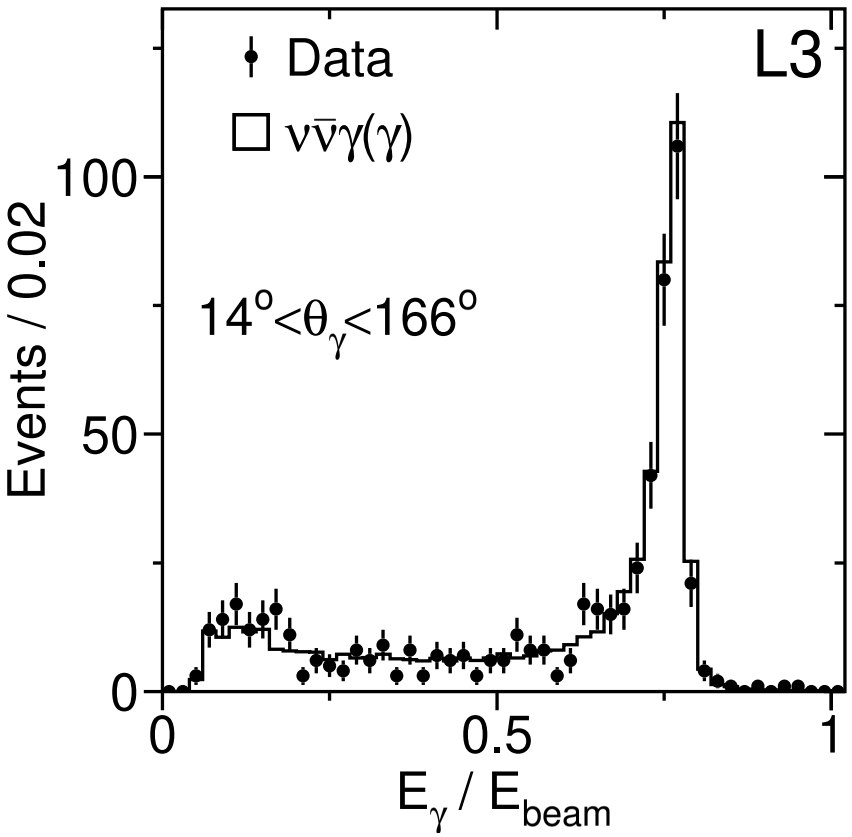
$$-0.42 < \Delta\kappa_\gamma < 0.22 \quad -0.64 < \lambda_\gamma < 0.61$$



# Single $\gamma$

Single photon production is sensitive to $\Delta\kappa_\gamma, \lambda_\gamma$

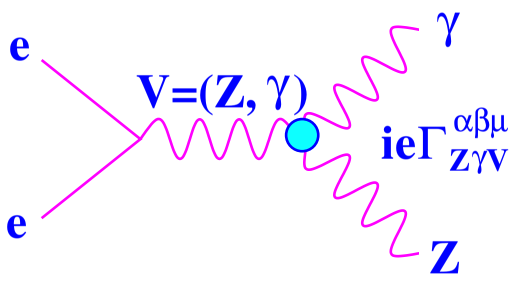



**Preliminary** result from 1998 data:

$$\Delta\kappa_\gamma = 1.1^{+0.9}_{-1.0}(stat.) \pm 0.4(syst.)$$
$$\lambda_\gamma = 0.4^{+1.4}_{-1.4}(stat.) \pm 0.5(syst.)$$

# Searches for $Z\gamma\gamma$ and $Z\gamma Z$ couplings




Set of 8 couplings describes $Z\gamma V$ vertex ($Z\gamma$ on shell):

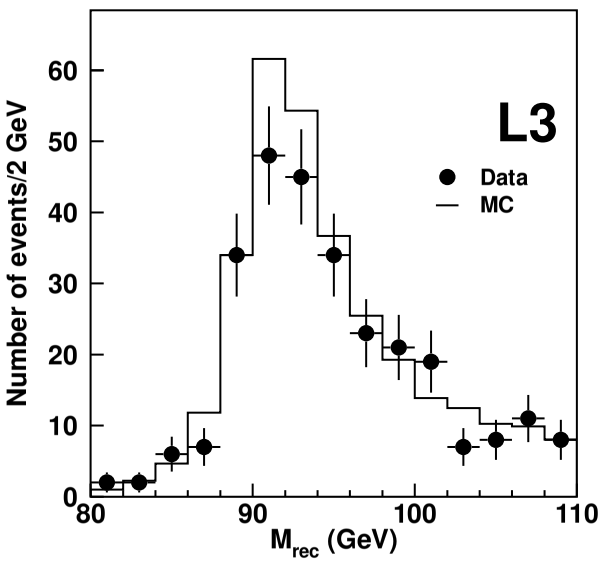
$$\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1,q_2,P) = i\frac{s-m_V^2}{m_Z^2}\left[h_1^V\left(q_2^\mu g^{\alpha\beta}-q_2^\alpha g^{\mu\beta}\right)\right.$$
$$\left.+\frac{h_2^V}{m_Z^2}P^\alpha\left(P\cdot q_2 g^{\mu\beta}-q_2^\mu P^\beta\right)+h_3^V\epsilon^{\mu\alpha\beta\rho}q_{2\rho}-\frac{h_4^V}{m_Z^2}P^\alpha\epsilon^{\mu\beta\rho\sigma}P_\rho q_{2\sigma}\right]$$

ZZV couplings are zero in SM (at tree level).

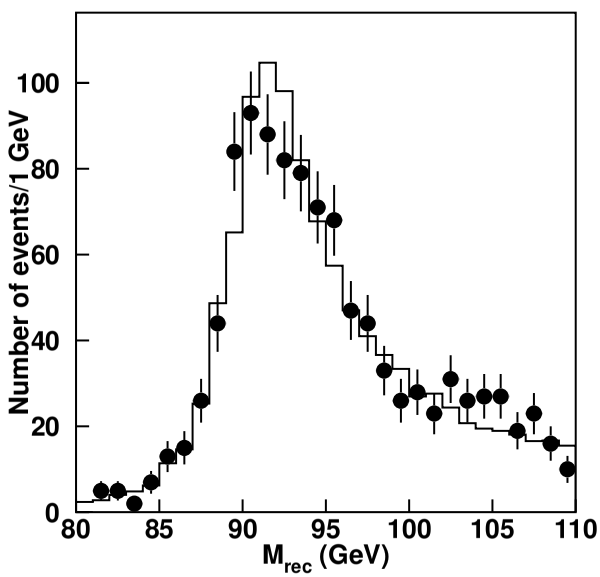
$h_{3,4}^V$ CP conserving, $h_{1,2}^V$ CP violating.

2 subchannels studied, at 189 GeV:

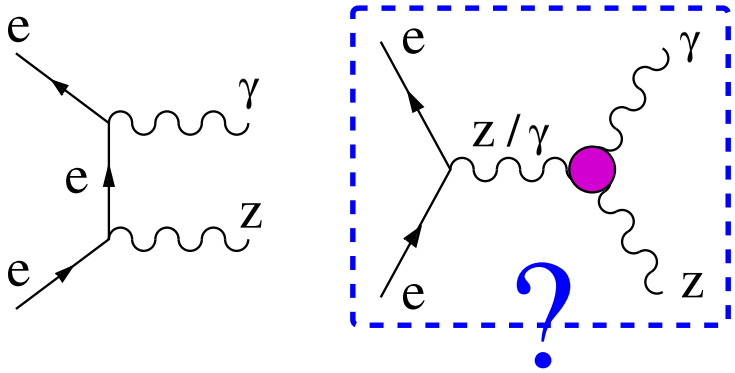
$e^+e^- \to \nu\bar{\nu}\gamma(\gamma)$

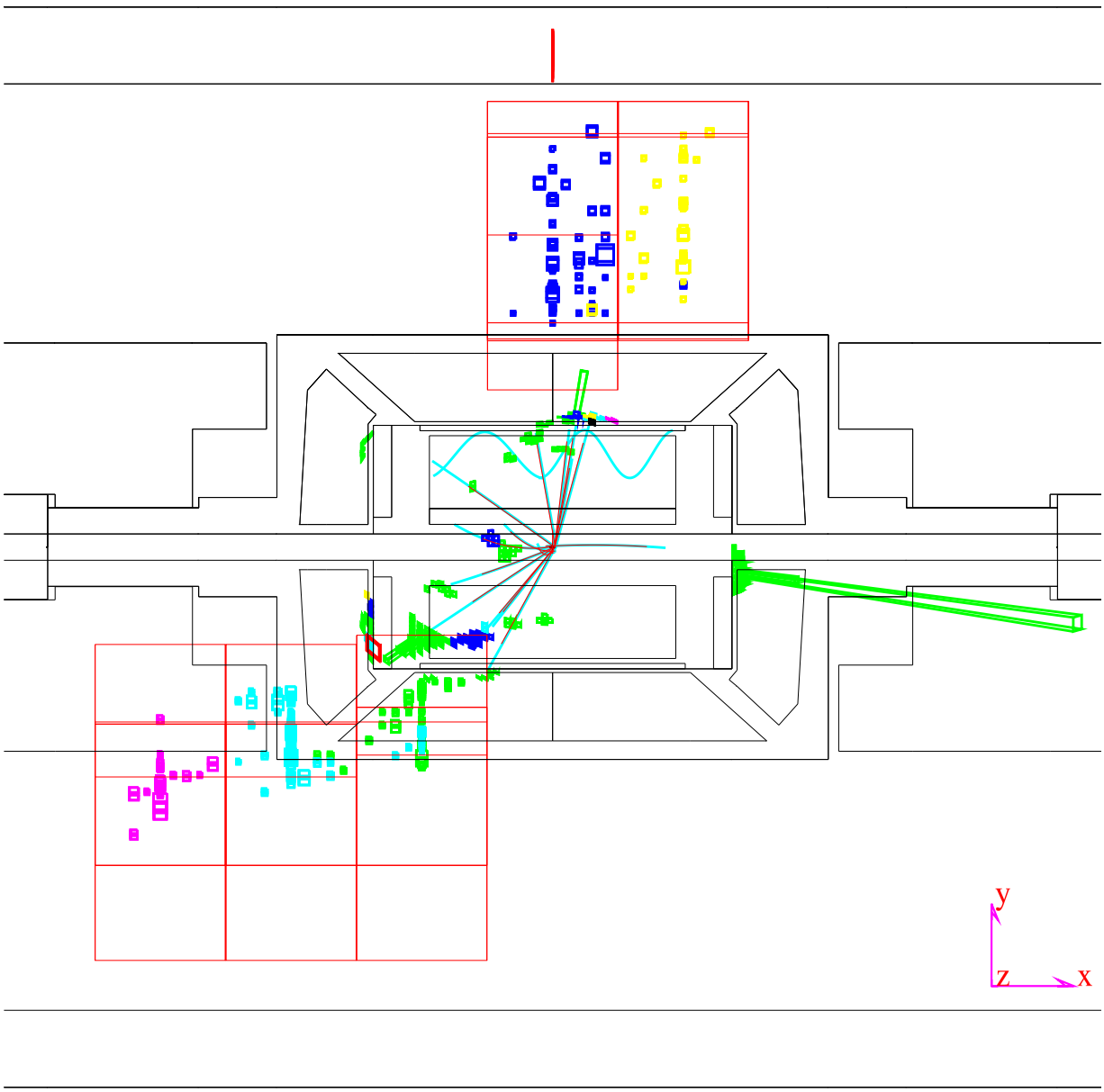



$e^+e^- \to q\bar{q}\gamma(\gamma)$



# Searches for $Z\gamma\gamma$ and $Z\gamma Z$ couplings



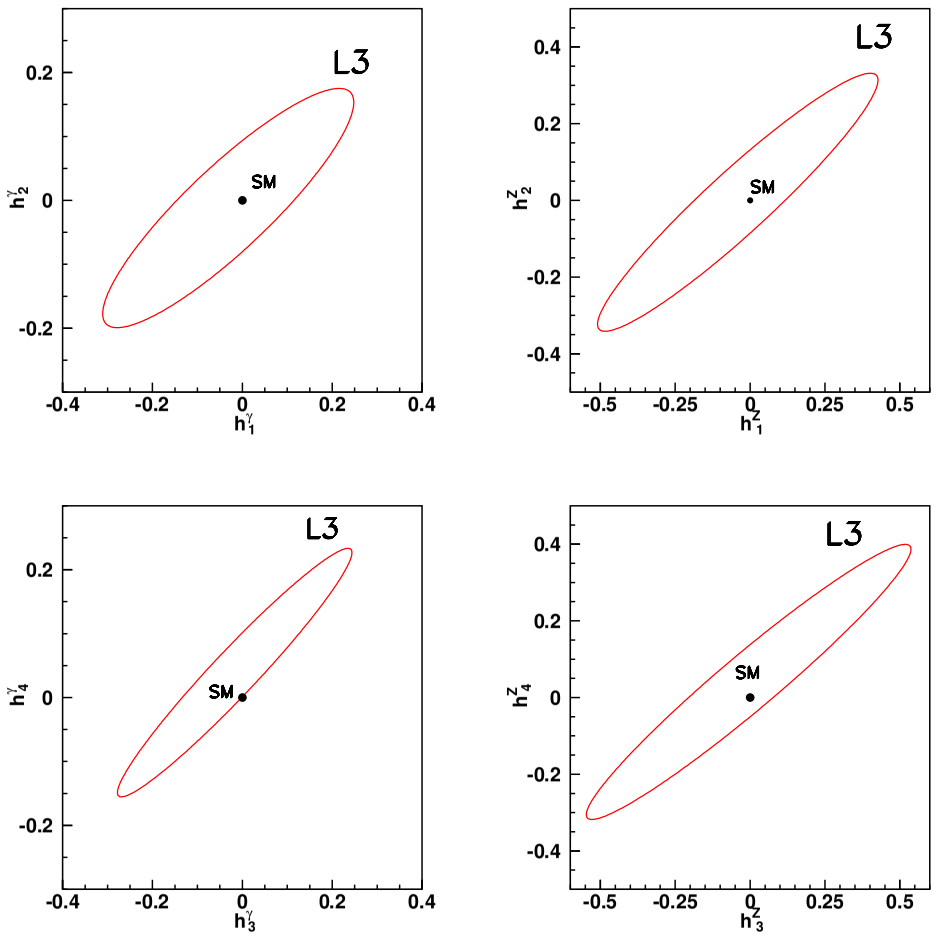



# Searches for $Z\gamma\gamma$ and $Z\gamma Z$ couplings

## At 95% Confidence Level (1-D fits)

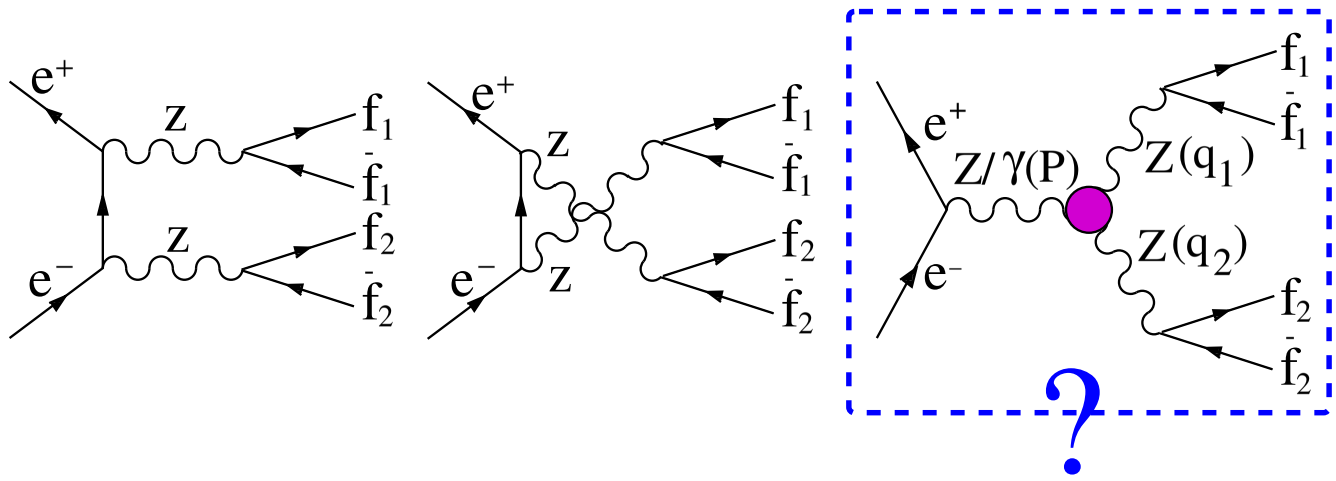
$$-0.16 < h_1^Z < 0.09 \qquad -0.12 < h_1^\gamma < 0.09$$
$$-0.07 < h_2^Z < 0.11 \qquad -0.06 < h_2^\gamma < 0.07$$
$$-0.22 < h_3^Z < 0.10 \qquad -0.12 < h_3^\gamma < 0.01$$
$$-0.06 < h_4^Z < 0.14 \qquad -0.01 < h_4^\gamma < 0.09$$

## Two-parameter fits to couplings with the same CP-parity and exchanged boson:



# Searches for ZZ$\gamma$ and ZZZ couplings

Anomalous Couplings from Z-pair production:
Production through ZZV vertex (impossible in SM).




$$\Gamma^{\alpha\beta\mu}_{\mathrm{ZZV}}\left(q_1,q_2,P\right)=\frac{s-m^2_{\mathrm{V}}}{m^2_{\mathrm{Z}}}\times$$

$$\left(if^{\mathrm{V}}_4\left(P^\alpha g^{\mu\beta}+P^\beta g^{\mu\alpha}\right)+if^{\mathrm{V}}_5\epsilon^{\mu\alpha\beta\rho}\left(q_1-q_2\right)_\rho\right)$$

$f^{\mathrm{V}}_4$ CP violating, $f^{\mathrm{V}}_5$ CP conserving.

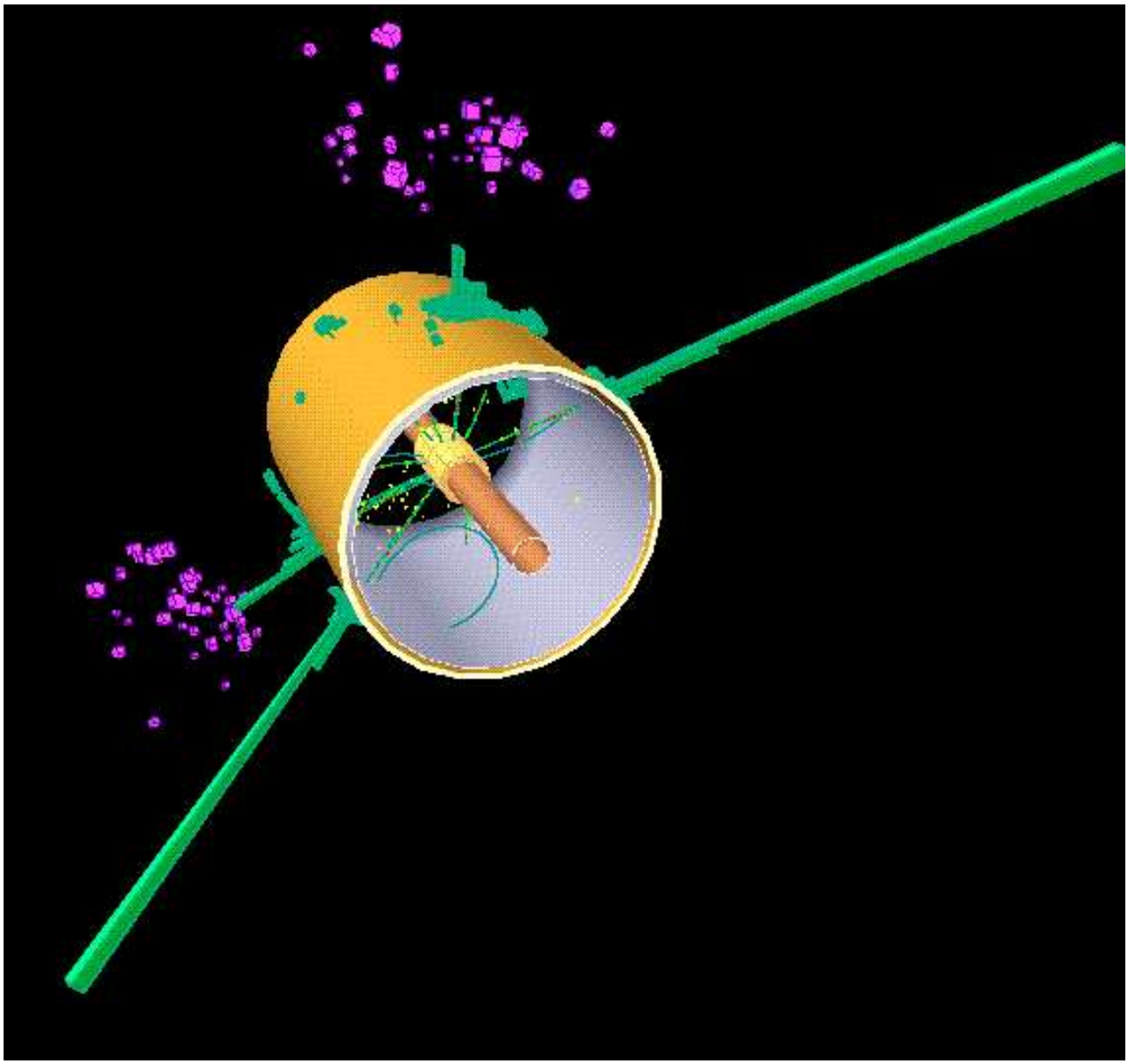
Deviations from SM zero values affects:

- Total ZZ cross section
- Angular distribution of the Z's

# Searches for ZZ$\gamma$ and ZZZ couplings

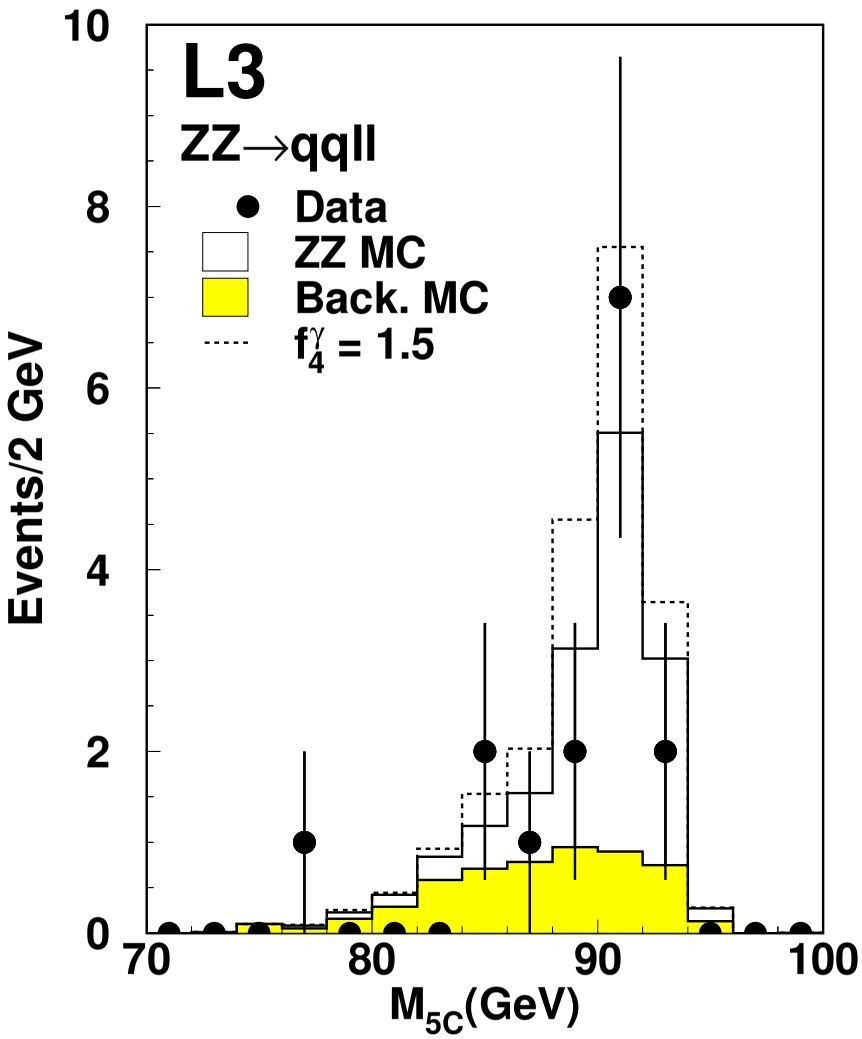
## Experimental Signature of the ZZ channels:

| | |
|---|---|
| $q\bar{q}q'\bar{q}'$ | 4 hadronic jets |
| $q\bar{q}\nu\bar{\nu}$ | 2 hadronic jets + missing energy |
| $q\bar{q}\ell^+\ell^-$ | 2 hadronic jets + 2 leptons |
| $\ell^+\ell^-\nu\bar{\nu}$ | 2 leptons + missing energy |
| $\ell^+\ell^-\ell'^+\ell'^-$ | 4 leptons |



# Searches for ZZ$\gamma$ and ZZZ couplings

Reconstructed 5C fit mass from $q\bar{q}\ell^+\ell^-$ channel:

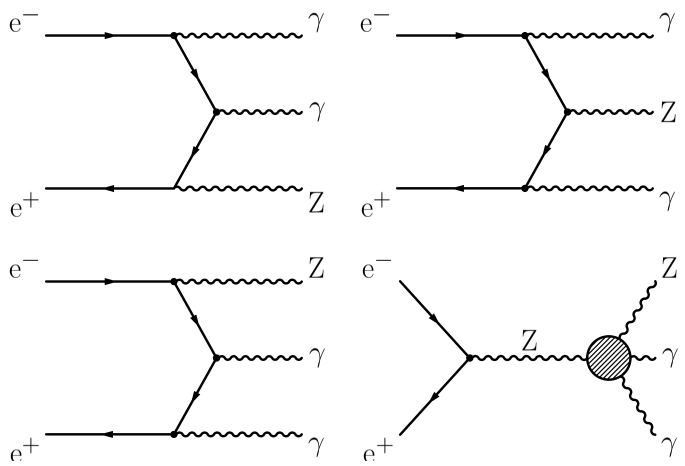



Fit results (95% CL limits):

$$-1.9 \leq f_4^Z \leq 1.9 \quad -5.0 \leq f_5^Z \leq 4.5$$
$$-1.1 \leq f_4^\gamma \leq 1.2 \quad -3.0 \leq f_5^\gamma \leq 2.9$$

Inclusion of 192-202 GeV data
improves limits by a factor of two.

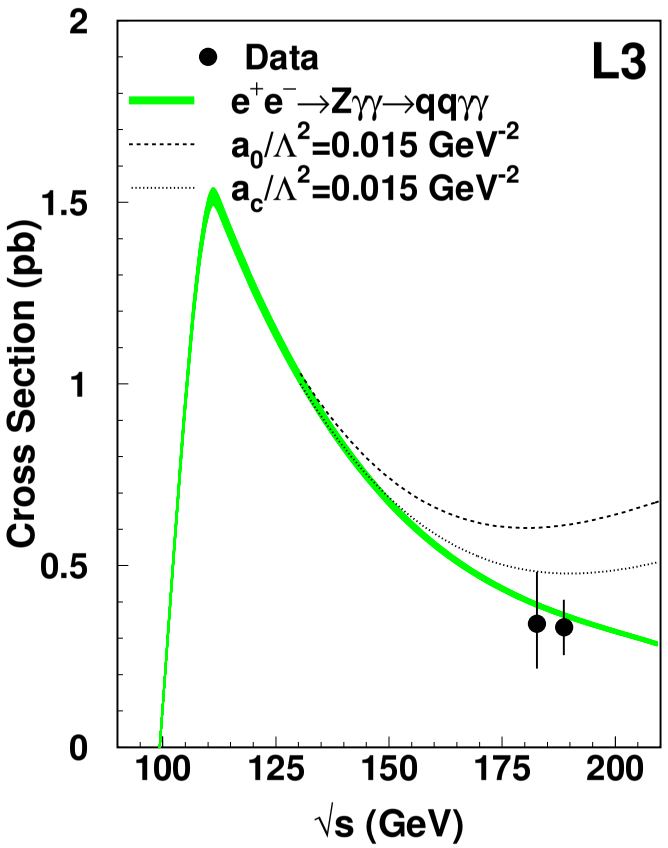
# Searches for anomalous quartic couplings




$ZZ\gamma\gamma$ vertex can be studied in $e^+e^- \to Z\gamma\gamma$ channel.
Anomalous QGC contributions to the Lagrangian:

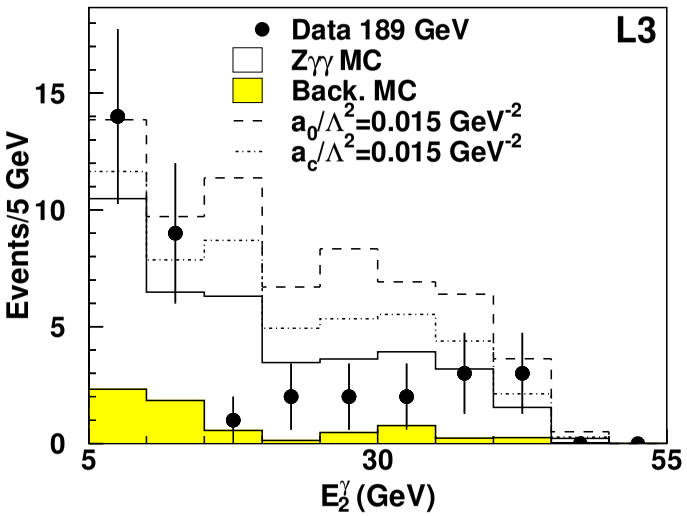
$$\mathcal{L}_6^0 = -\frac{\pi\alpha}{4\Lambda^2} a_0 F_{\mu\nu} F^{\mu\nu} \vec{W}_\rho \cdot \vec{W}^\rho$$

$$\mathcal{L}_6^c = -\frac{\pi\alpha}{4\Lambda^2} a_c F_{\mu\rho} F^{\mu\sigma} \vec{W}^\rho \cdot \vec{W}_\sigma,$$



# Searches for anomalous quartic couplings

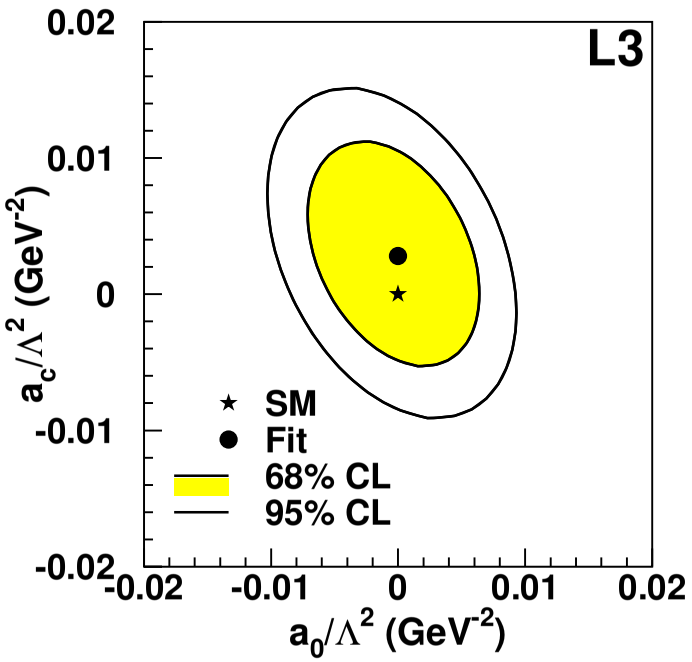
AQC would significantly change photon energy spectrum:




Using photon energy spectrum information 95% CL limits:

$$-0.009 \ \ \mathrm{GeV}^{-2} < a_0/\Lambda^2 < 0.008 \ \ \mathrm{GeV}^{-2}$$
$$-0.007 \ \ \mathrm{GeV}^{-2} < a_c/\Lambda^2 < 0.013 \ \ \mathrm{GeV}^{-2}$$

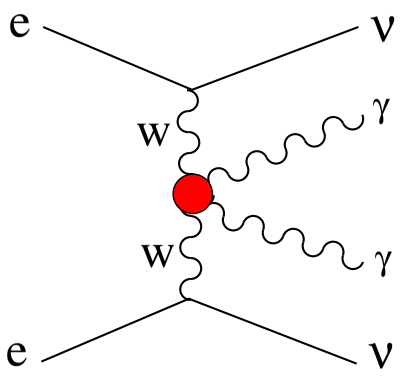
(189 GeV data final result).



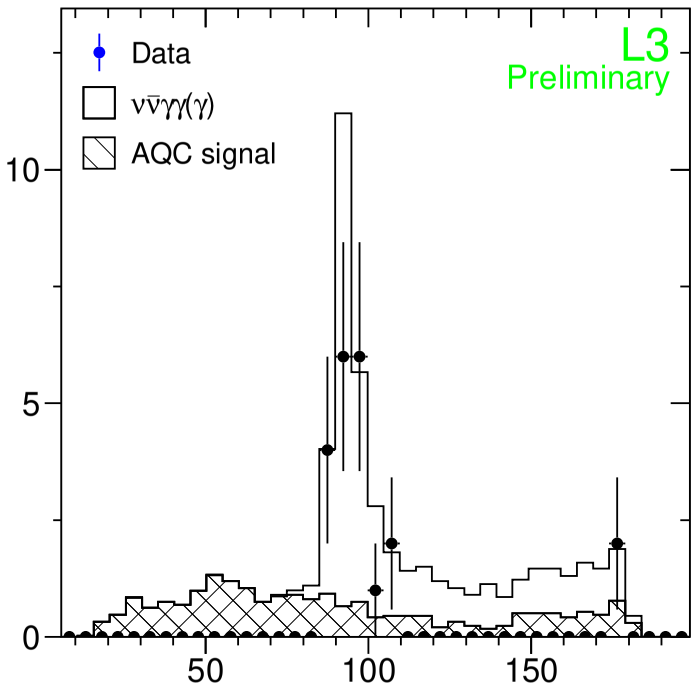

(At present: best direct limits).

# Searches for anomalous quartic couplings

WW$\gamma\gamma$ vertex can be studied in $e^+e^- \to \nu\nu\gamma\gamma$ channel:




SM model cross section is very small: O(1 fb).
Main SM background is radiative return to Z.
Recoil mass spectrum of the two-photon system would be modified:




189 GeV preliminary result:

$$-0.075 \ \ \mathrm{GeV}^{-2} < a_0/\Lambda^2 < 0.075 \ \ \mathrm{GeV}^{-2}$$
$$-0.21 \ \ \mathrm{GeV}^{-2} < a_c/\Lambda^2 < 0.21 \ \ \mathrm{GeV}^{-2}$$

# Conclusion

- No evidence for New Physics in 1998 data, Standard Model is still invincible
- Analysis of 1999 data is being finished.
- New energy frontier will be crossed in 2000