Gauge couplings meaurements at LEP2

Marco Verzocchi
University of Maryland / OPAL–DØ

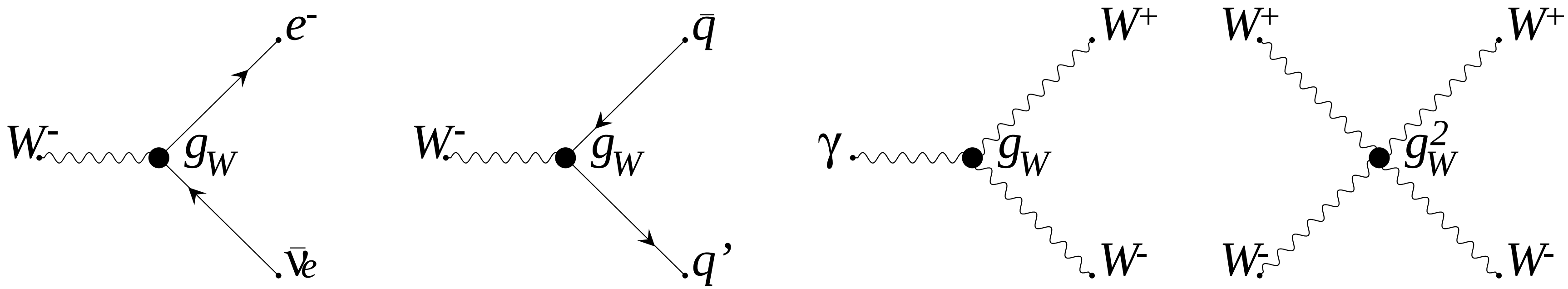
8 March 2001
Frontiers in Contemporary Physics II

- Testing couplings between bosons
  - different channels
- Direct observables
- Extracting the triple gauge couplings
  - methods
  - uncertainties
- .... and the quartic ones
- Neutral vertices ?
- Future prospects

Visit http://www.cern.ch/LEPWEWWG/tgc
for more infos and results

Gauge invariance and boson couplings

$\mathcal{SM}$: non abelian gauge theory ($\mathrm{SU(2)_L \otimes U(1)_Y}$)
➠ vertices with 3 and 4 gauge bosons



Gauge invariance specifies form and strength of couplings

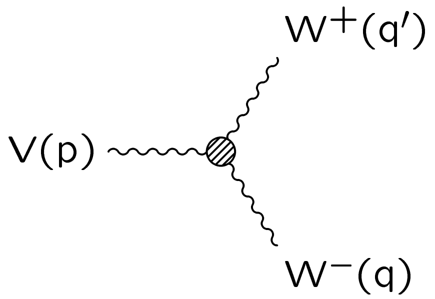
$$\mathcal{L}_{int} = -ig_W[W^{\mu\nu -}W^+_\mu - W^{\mu\nu +}W^-_\mu](\cos\theta_W Z_\nu + \sin\theta_W A_\nu)$$
$$-ig_W(\cos\theta_W Z^{\mu\nu} + \sin\theta_W A^{\mu\nu})[W^-_\mu W^+_\nu - W^+_\mu W^-_\nu] + \ldots.$$

- On the scale of g_W the coupling at the VWW vertex is 1
- 1–Loop radiative corrections change it by 10^{-3}

Can this be tested ?

Triple gauge boson vertices

- Extend the $\mathcal{SM}$ lagrangian, introduce new couplings, ➠ measure them



$$= -ieg_{VWW}\Gamma_V^{\alpha\beta\mu}(p,q,q')$$

- TGC: anomalous couplings of the triple gauge boson vertex: parameters of the triple–gauge boson part of the electroweak Lagrangian
- For each VWW vertex ($V = \gamma, Z$) introduce general Lorentz invariant form
- Consider only operators with dimension ≤ 6
  $\Longrightarrow$ 7 independent terms for γ and Z

<u>Too many parameters</u>

- Require C,P and CP conservation
- Require $U(1)_{em}$ gauge invariance ($q_W = \pm 1$)

Only 5 parameters to describe the vertices:

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

In the $\mathcal{SM}$: $g_1^Z, \kappa_\gamma, \kappa_Z = 1$ and $\lambda_\gamma, \lambda_Z = 0$

Relation with physical quantities

$$
\begin{aligned}
q_W &= e \cdot g_1^\gamma &\overset{\mathcal{SM}}{=}\; & e \\
\mu_W &= \frac{e}{2M_W}(g_1^\gamma + \kappa_\gamma + \lambda_\gamma) &\overset{\mathcal{SM}}{=}\; & \frac{e}{2M_W} \\
Q_W &= -\frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma) &\overset{\mathcal{SM}}{=}\; & -\frac{e}{M_W^2}
\end{aligned}
$$

- Still too many parameters (5) to measure
- Impose $SU(2)_L \otimes U(1)_Y$ gauge invariance
- Consider only operators not constrained from lower energy measurements
- Only 3 anomalous couplings remain

Δg_Z^1, $\Delta\kappa_\gamma$ and $\lambda = \lambda_\gamma$

Δ is the deviation from the $\mathcal{SM}$ value 1

- All are zero in the $\mathcal{SM}$
- The remaining parameters are obtained through gauge invariance:

$$
\begin{aligned}
\Delta\kappa_Z &= \Delta g_Z^1 - \Delta\kappa_\gamma \tan^2\theta_w \\
\lambda_Z &= \lambda_\gamma
\end{aligned}
$$

Relations used in most LEP TGC analyses !!!

- Necessary to reduce parameters
- Theoretically justified

Differences with collider experiments

Are these assumptions really needed ?

$\mathrm{e^+e^-}$ colliders

- Non polarised beams ➠ cannot separate $\gamma\mathrm{WW}$ and ZWW contributions to $\mathrm{e^+e^-} \to \mathrm{W^+W^-}$
- Fixed centre of mass energy

Hadron colliders

- Some final states (e.g. $\mathrm{W}\gamma$) are only sensitive to 1 type of couplings ➠ relations between couplings only for combinations
- Effective center of mass energy varies ➠ introduce form factors
- Different relations ($\Delta\kappa_\gamma = \Delta\kappa_Z$ and $\lambda_\gamma = \lambda_Z$)
- Use dipole form factors ($\Lambda = 2\ \mathrm{TeV}$)

Keep in mind these differences !!!

LEP constraints justified by

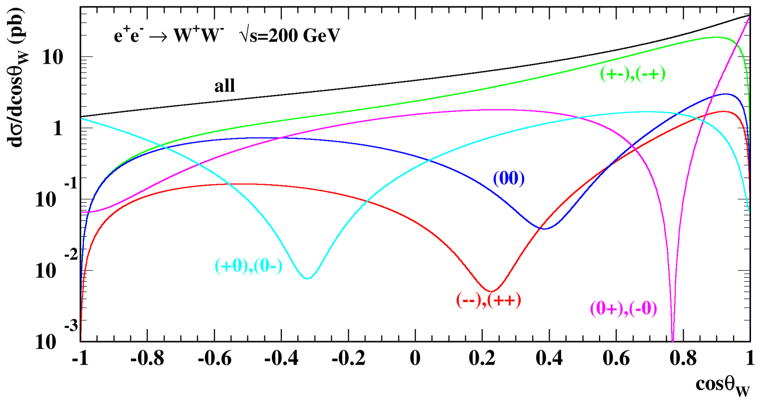
- Low energy constraints and $\mathrm{SU(2)_L \otimes U(1)_Y}$ gauge invariance
- Light Higgs boson
- Same constraints used to calculate TGC contribution to $b \to s\gamma$ and $(g-2)_\mu$

Sensitivity to anomalous couplings

$e^+e^- \rightarrow W^+W^-$ **main channel for** TGC **measurement**

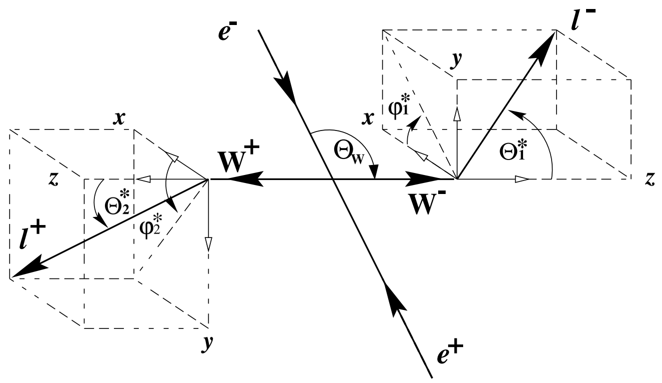
- TGC change contribution of each W helicity
- Affect total cross section and $d\sigma/d\cos\theta_{W^-}$
- Sensitivity increases with $\sqrt{s}$

$\mathcal{L}$ linear in TGC ➠ $\sigma, d\sigma$ quadratic



Measure the W^- scattering angle and the helicities of the two W bosons

- Use the W decay as a polarimeter



For $\Gamma_W \rightarrow 0$ and no ISR

➥ Measurement of 5 angles determines **completely** the final state

Some experimental considerations ....

In the real life

Accessibility of $\Omega = (\theta_W, \theta^*_f, \phi^*_f, \theta^*_{\bar{f}}, \phi^*_{\bar{f}})$ depends on W decay channels

- Cannot neglect the W width
- ISR photons are mostly unmeasured
- Neutrinos are unmeasured (≥ 2 in τ events)
- Quark charges cannot be measured (efficiently ?)
- Detector resolution, selection biases
- Backgrounds

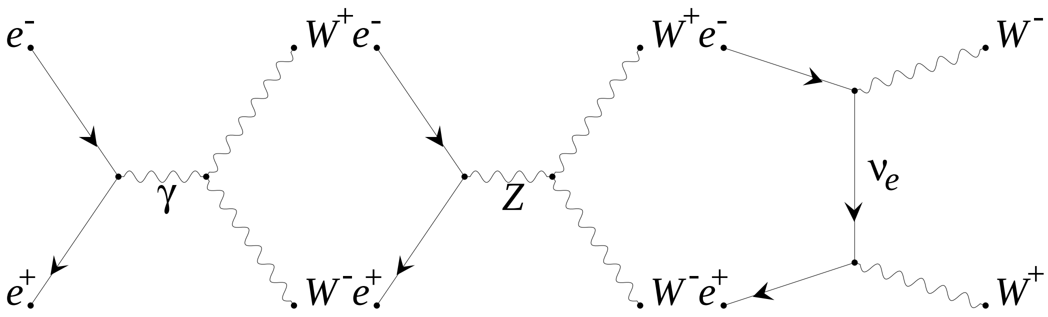
General approach in the analyses:

- Refine the event selections
  - ➥ Events are properly measured
- Kinematic fits,
  - ➥ Improve resolution

Available data sets

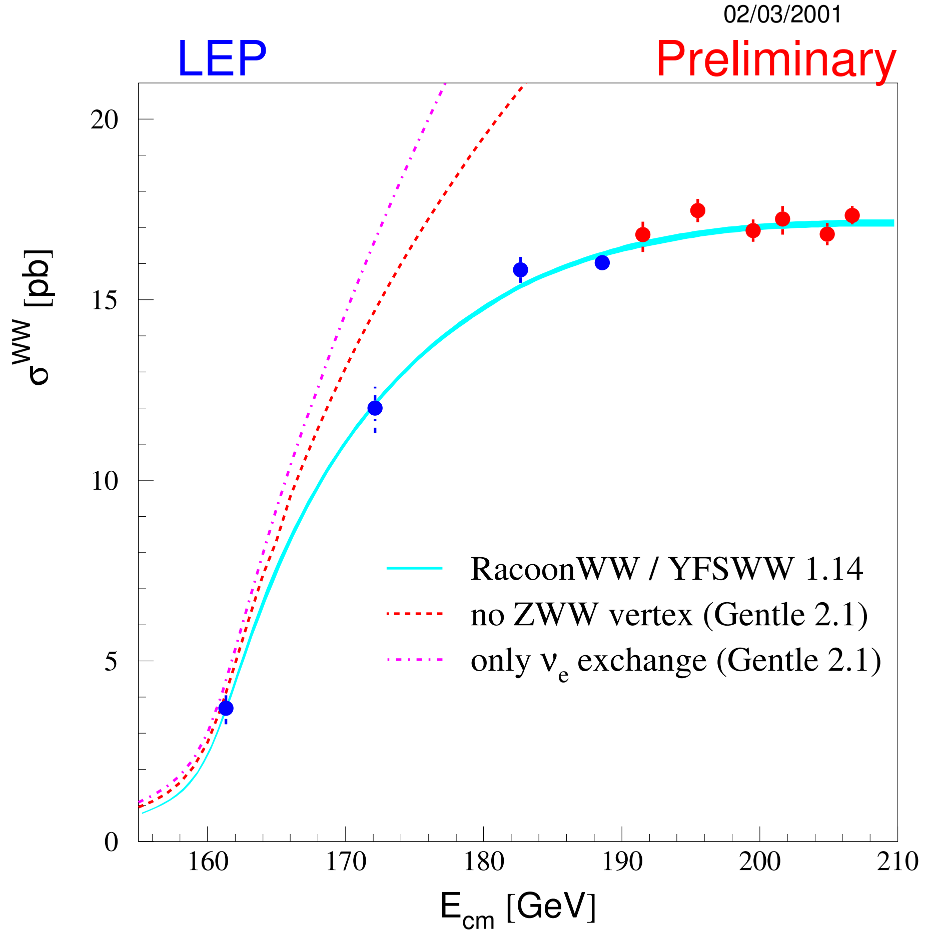
- $680\ \mathrm{pb}^{-1}$ collected at 183–208 GeV
  - ➥ 9K W pairs per experiment
- Only data collected in 1997–1999 are analysed
- Most results are still preliminary

The total CC03 cross section



W pair production cross section

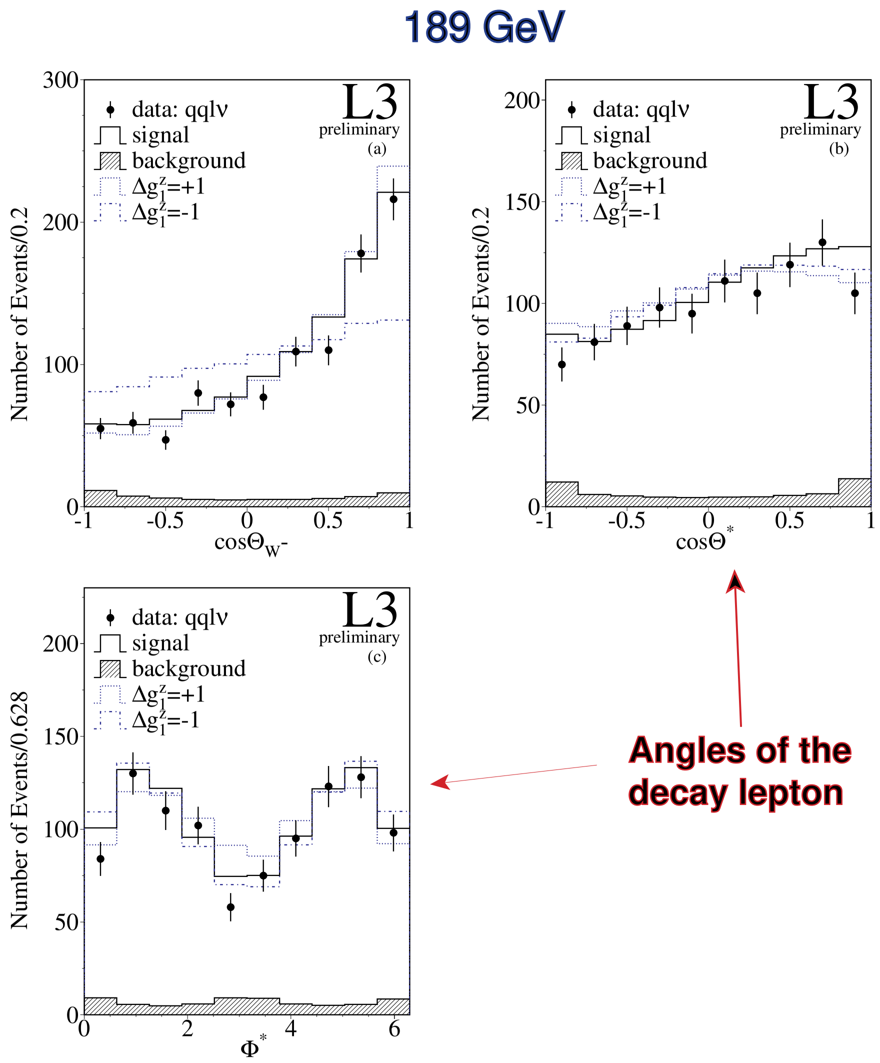
➥ **Strong constraints on** TGC



Gauge cancellation at work !!!

The $W^+W^- \rightarrow q\bar{q}'\ell^-\bar{\nu}_\ell$ channel

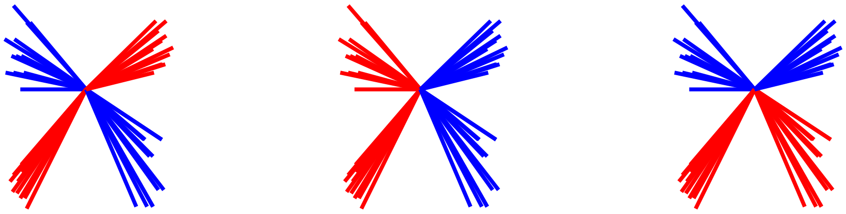
- Large branching ratio, W charge from the lepton
- Integrate over quark variables (twofold ambiguity)



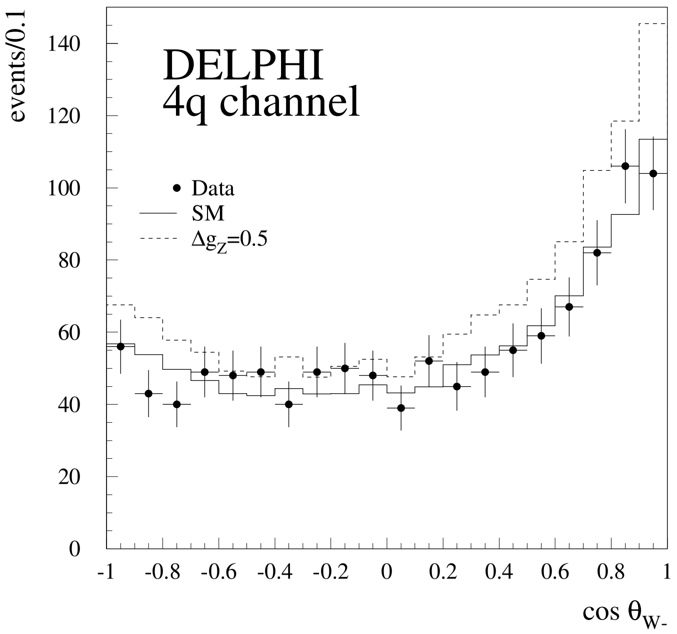
- Measure 3 out of 5 angles
- Highest sensitivity to TGC: $\cos\theta_{W^-}$

The $W^+W^- \to q\bar{q}'q\bar{q}'$ channel

- Jet pairing: 3 possibilities
  $\Longrightarrow$ correct combination $\varepsilon = 74 - 84\%$



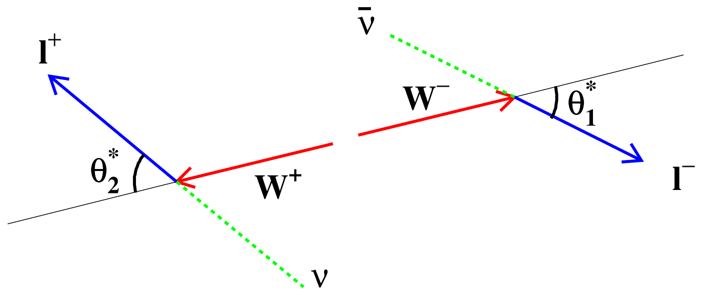
- W charge assignment $\Longrightarrow$ jet charge
  ($\Delta Q = 2$ between $W^\pm$, $\varepsilon = 71 - 79\%$)
  ➠ Distortion of the angular distribution
- Complete folding over decay angles
- ➥ Measure only $\cos\theta_{W^-}$

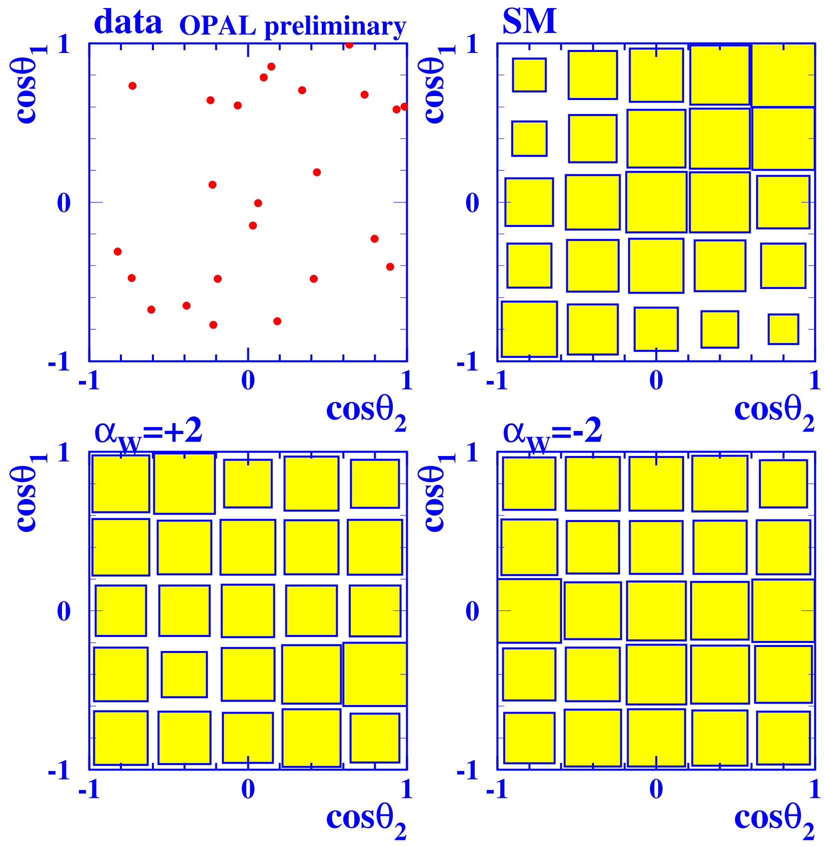


$\oplus$ high statistics
$\ominus$ only $\approx$ 60 % ε of correct reconstruction

The $W^+W^- \to \ell^-\overline{\nu}_\ell \ell'^+\nu_{\ell'}$ channel

- Small useful branching ratio ($\approx 5\%$)
- All 5 angles can be determined (up to a twofold ambiguity)
- Correlation of the W helicities





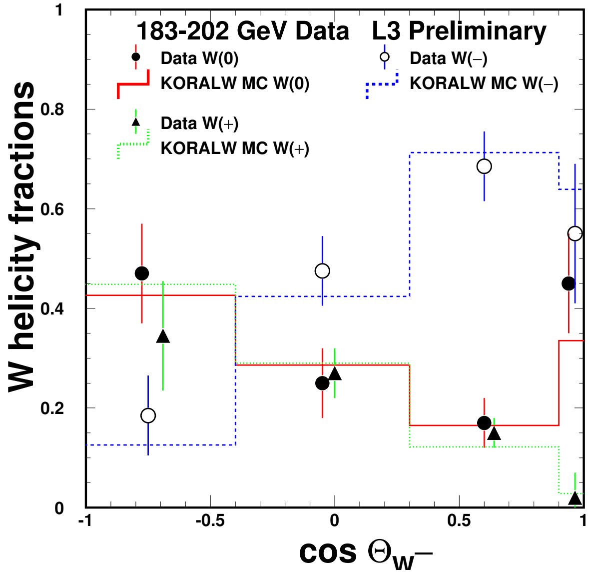
Only OPAL + ALEPH

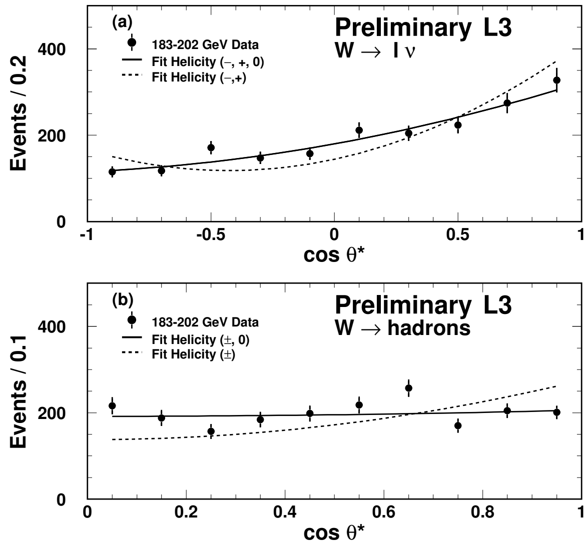
Model independent measurement of W helicity structure

Helicity analysis: W decay angles only

$$\frac{1}{N}\frac{dN}{dx} = f_-\frac{3}{8}(1+x)^2 + f_+\frac{3}{8}(1-x)^2 + f_L\frac{3}{4}(1-x^2) \quad \text{with} \quad x = \cos\theta^*$$

- ★ L3: fit to $\cos\theta^*$ distribution (183–204 GeV)
- ➥ $f(\mathrm{W}_L^{\pm}) = (0.259 \pm 0.035)$
- ★ $\mathcal{SM}$: $f(\mathrm{W}_L^{\pm}) = 0.248$
- ➥ $> 7\sigma$ observation





- ★ Measurement of W helicity vs $\cos\theta_W$ agrees with SM
- ★ Results updated with Y2K data

Spin Density Matrix elements

Summing over all possible helicities of the second W....

$$\rho_{\tau\tau'}(\cos\theta_W) = \frac{\sum_\lambda \mathcal{F}_\tau^{(\lambda)} (\mathcal{F}_{\tau'}^{(\lambda)})^*}{\sum_{\lambda\tau} |\mathcal{F}_\tau^{(\lambda)}|^2}$$

helicity of $W^\pm$

$\Rightarrow$ $\tau = 1$

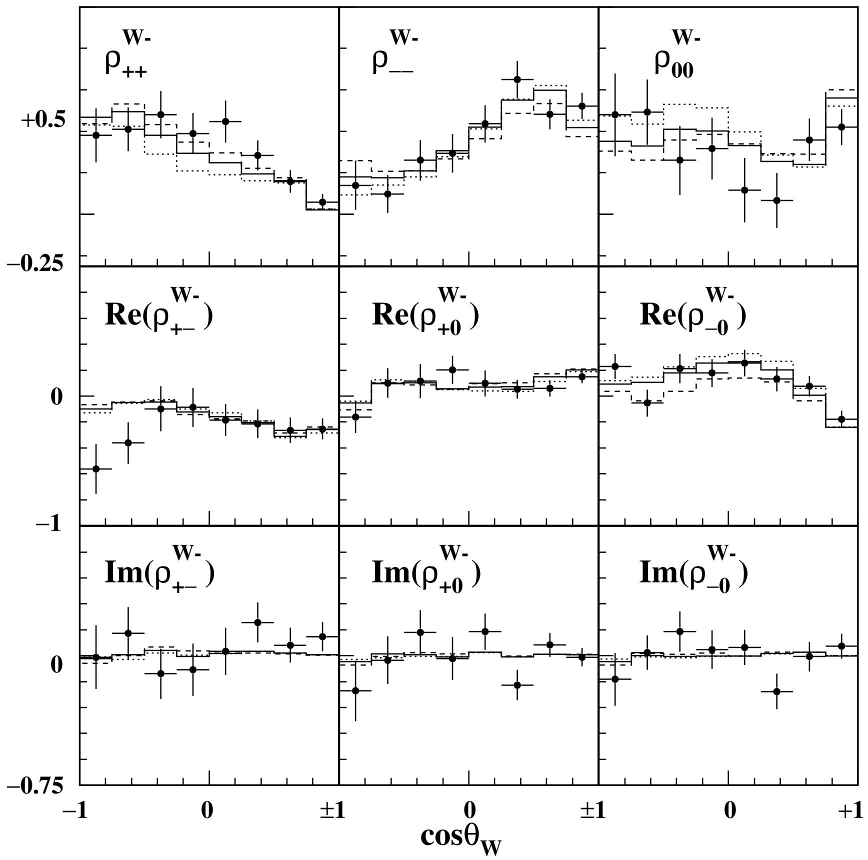
$\Uparrow$ $\tau = 0$

$\Leftarrow$ $\tau = -1$

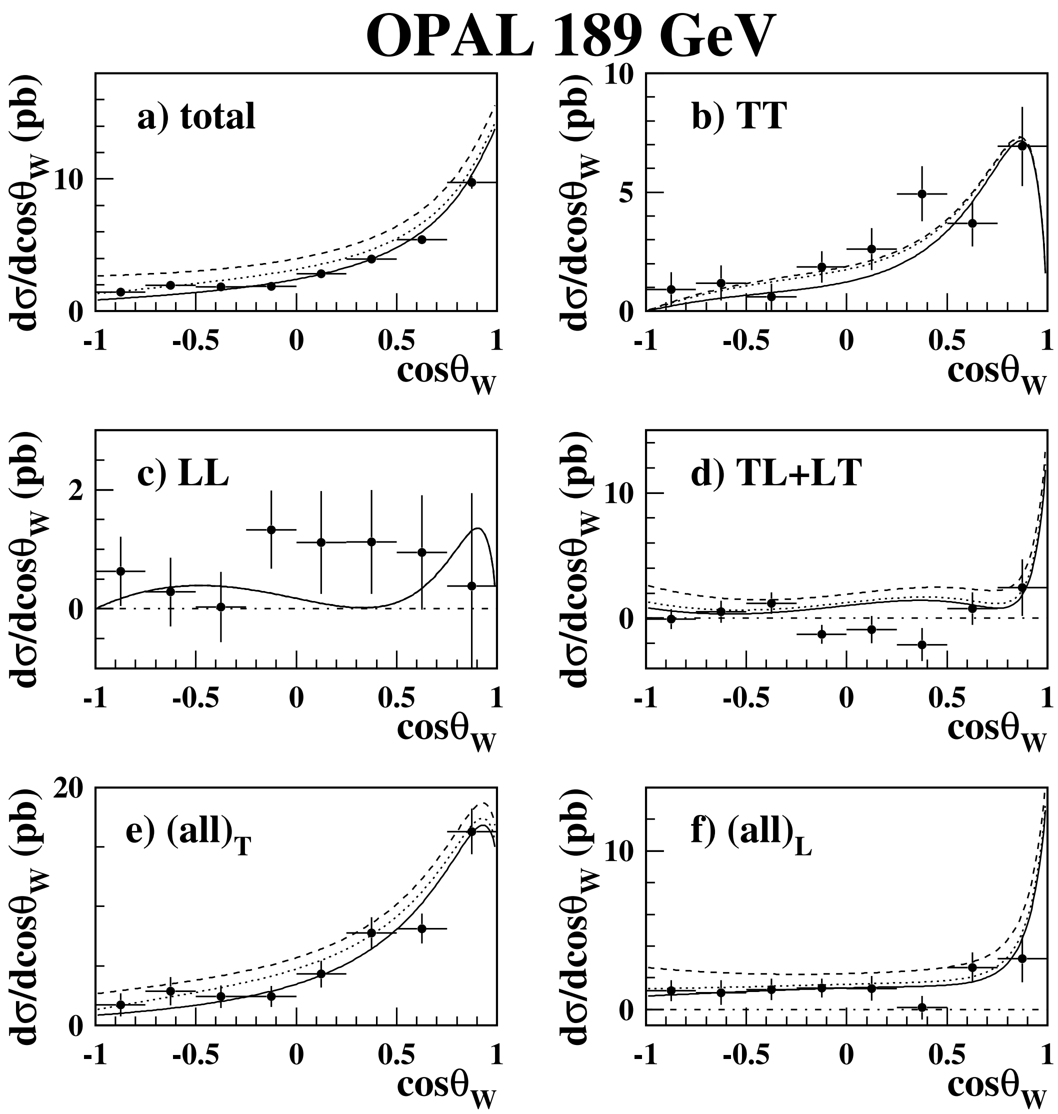
λ: e^- spin

- $\rho_{\tau\tau'}$ is a 3×3 hermitian matrix
- Practically the SDM elements are extracted in bins of $\cos\theta_W$ with projection operators that are functions of θ^* and ϕ^*
- $\rho_{\tau\tau}$ (diagonal elements)= probability to produce a boson with helicity τ
- imaginary part of off-diagonal elements: vanish in CP-conserving theories

OPAL 189 GeV



W Polarisation



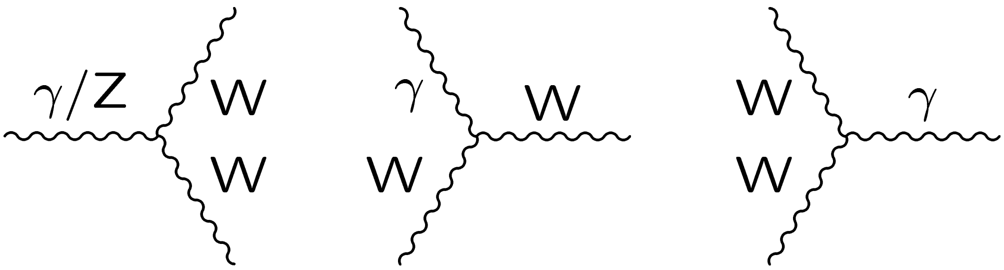
σ_T/σ_{total}	$0.790 \pm 0.033 \pm 0.016$	0.74
σ_L/σ_{total}	$0.210 \pm 0.033 \pm 0.016$	0.26
$\sigma_{TT}/\sigma_{total}$	$0.781 \pm 0.090 \pm 0.033$	0.57
$\sigma_{LL}/\sigma_{total}$	$0.201 \pm 0.072 \pm 0.018$	0.09
$\sigma_{TL}/\sigma_{total}$	$0.018 \pm 0.147 \pm 0.038$	0.34

Methods to extract the TGC

- Event counting: fit to the total cross section
- Differential distributions:
  - ★ unbinned ML fit to theoretical distribution
    - ISR, Γ_{W}, backgrounds not considered
    - requires folding with detector resolution
  - ★ binned ML fit to MC
    - all physical and detector effects
    - requires large MC samples
    - some loss of statistical precision
  - ★ "optimal" observables method
    - retain sensitivity of unbinned ML fit
    - all informations in a single variable
    - value of TGC obtained from the mean value of the distribution or from a fit
- Checks for biases in the procedure using MC events generated with $\mathrm{TGC} \neq 0$
- Small event samples, non gaussian detector resolution $\Longrightarrow$ error calibration required
- Multidimensional fits performed
- Present results as 1–dim or 2–dim likelihood curves combining the different channels/experiments
- Include also single W and single γ results

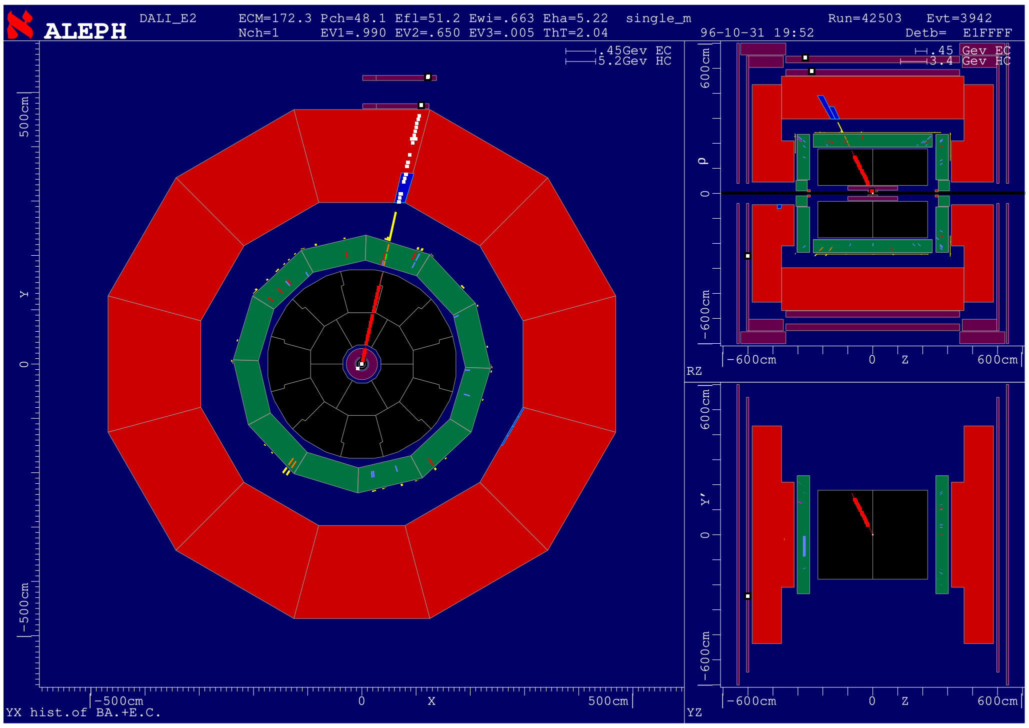
Other ways of measuring the TGC

γWW couplings measurable also in the **"single W"** process and in the $\nu\bar{\nu}\gamma$ final state



The "single W" process

- 1 electron lost in the beam pipe
- missing transverse momentum from the ν_e
- 1 isolated energetic lepton or ...



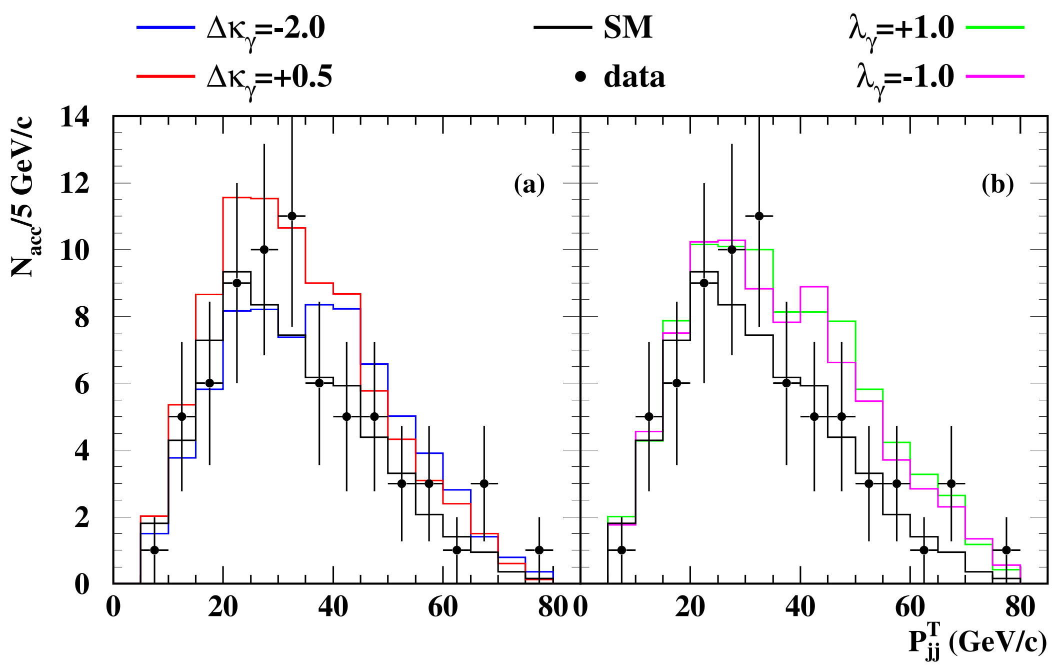
- ... acoplanar jet pair with $M_{jj} \sim M_W$

Caveats:

- Some sensitivity to the ZWW couplings
- Background (mostly $W^+W^- \rightarrow q\bar{q}'\tau^-\bar{\nu}_\tau$, $S/N \sim 1$) also depends on the TGC

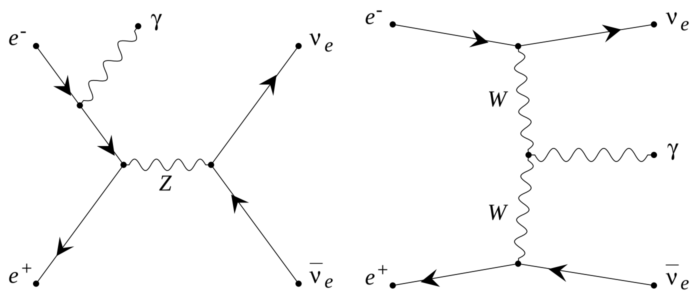
Extracting the TGC:

- Event counting
- Rate 1/10th of $e^+e^- \rightarrow W^+W^-$ .....
- .....but same sensitivity to $\Delta\kappa_\gamma$
- Twofold ambiguity: $\kappa_\gamma = \pm 1$
- Use also differential distributions

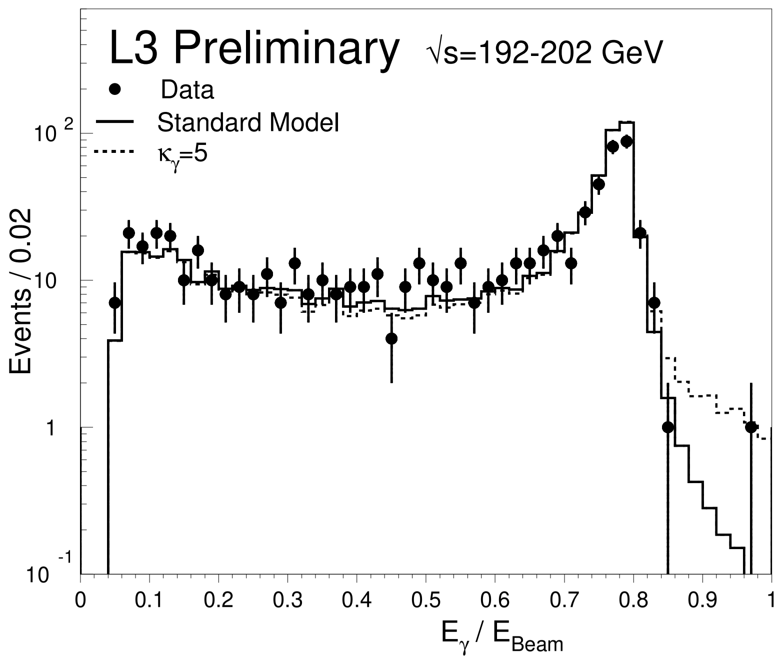


Distributions used by OPAL and ALEPH

The $\nu\overline{\nu}\gamma$ final state



- $\nu_e\overline{\nu}_e\gamma$ final state sensitive **ONLY** to the γWW vertex
- Signature: high energy isolated γ in the detector
- Anomalous couplings change energy and angular distributions
- ML fit to the differential distributions



Much worse sensitivity to TGC

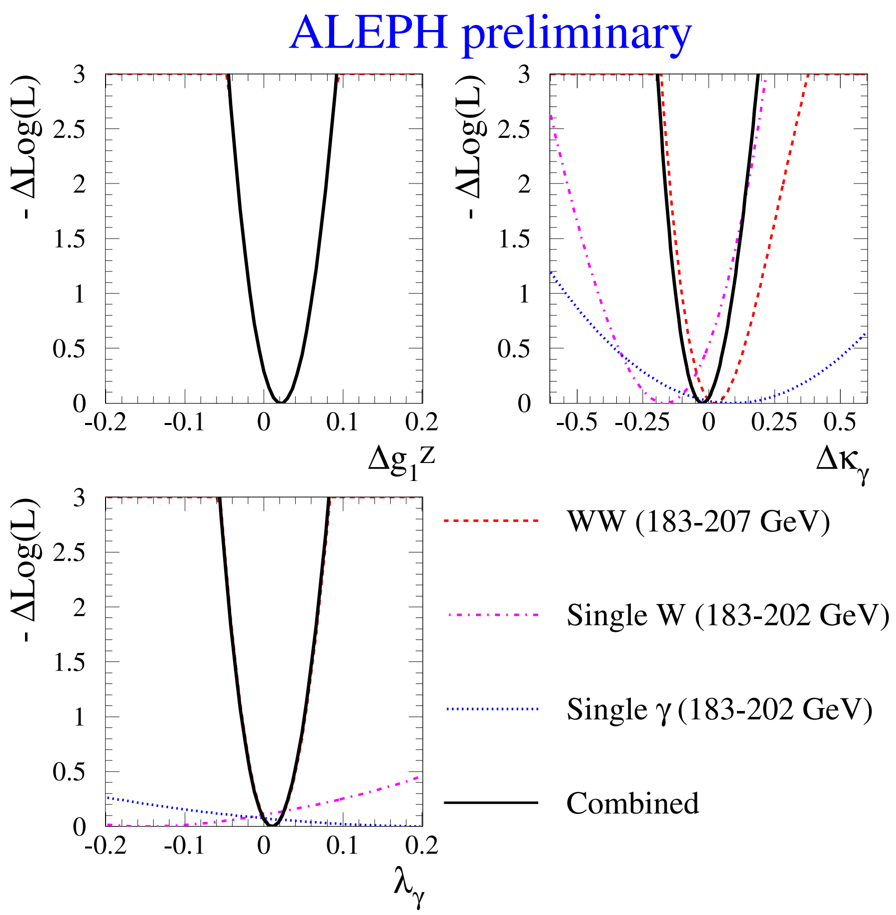
Example: combining results from various channels

Add log–$\mathcal{L}$ curves from three different channels

- Results dominated by $e^+e^- \longrightarrow W^+W^-$
- Except for $\Delta\kappa_\gamma > 0$
- Only experiment to include Y2K data

$$\Delta\kappa_\gamma = \quad 0.015 \pm 0.034\ (\pm 0.013)$$
$$\lambda_\gamma = -0.021 \pm 0.077\ (\pm 0.037)$$
$$\Delta g_Z^1 = -0.001 \pm 0.033\ (\pm 0.015)$$

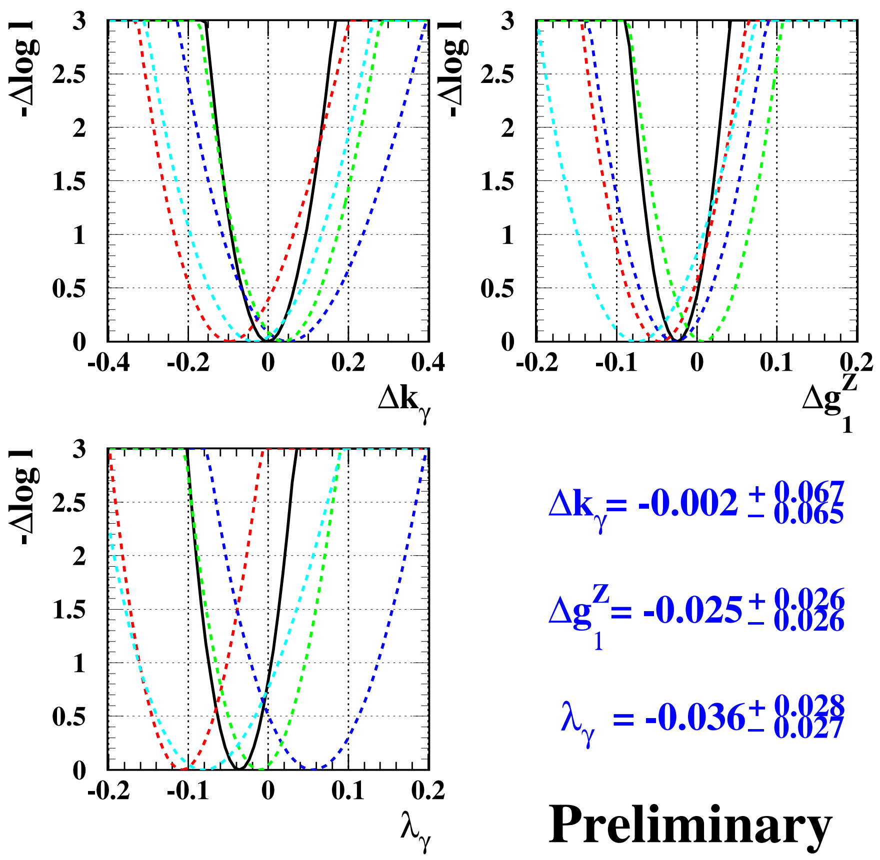
- First error experimental (stat. + syst.)
- Second error: theoretical contribution to systematics. See later ....



LEP combination (ICHEP 2000)

- Add log–$\mathcal{L}$ curves from different experiments
- Consider correlations of systematic uncertainties
  - $W^+W^- \longrightarrow q\overline{q}'\ell^-\overline{\nu}_\ell$: fragmentation
  - $W^+W^- \longrightarrow q\overline{q}'q\overline{q}'$: fragmentation, FSI
  - single W: theoretical prediction for σ_{tot}

ALEPH + DELPHI +L3 + OPAL



$\Delta k_\gamma = -0.002^{+0.067}_{-0.065}$

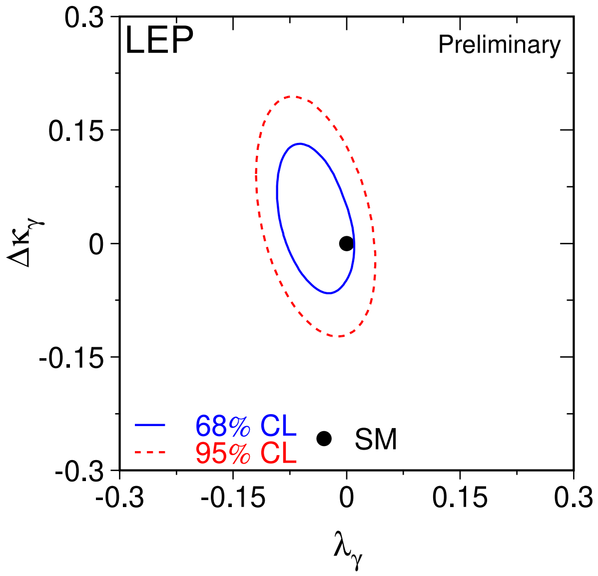
$\Delta g_1^Z = -0.025^{+0.026}_{-0.026}$

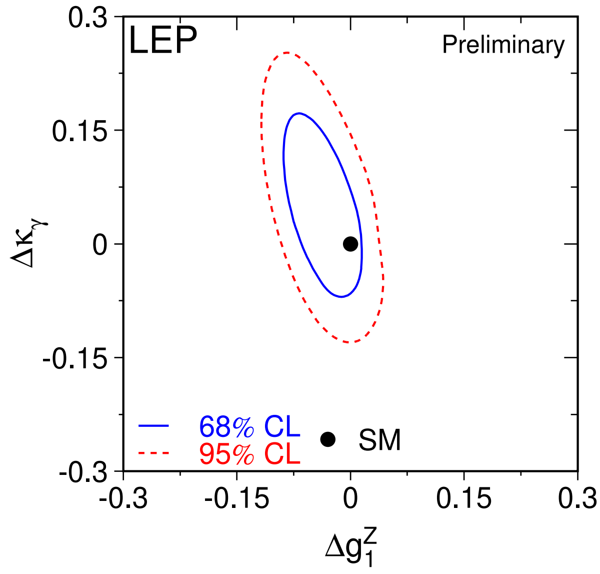
$\lambda_\gamma = -0.036^{+0.028}_{-0.027}$

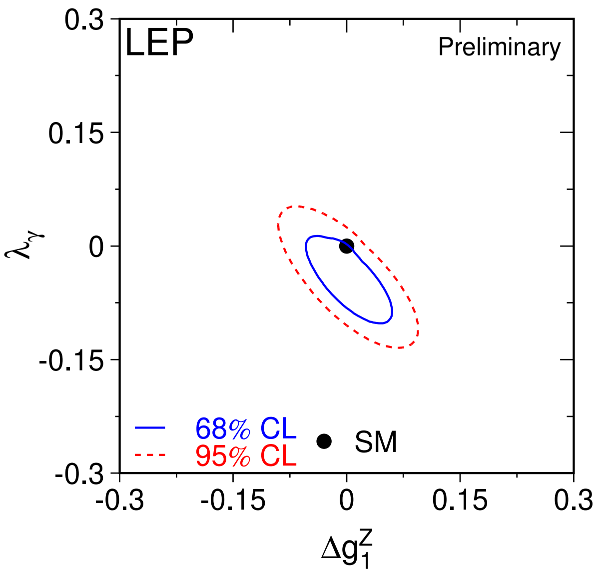
Preliminary

No deviation from $\mathcal{SM}$ observed

.... also 2d and 3d fits



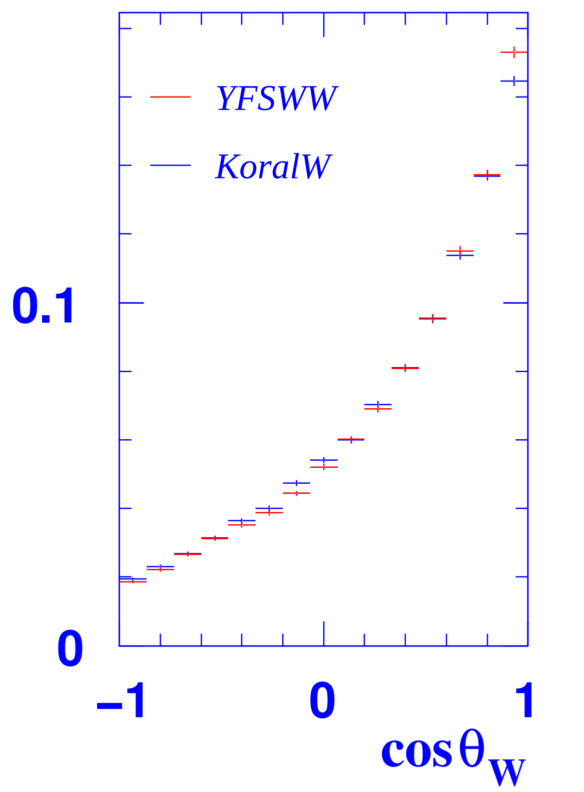




- Systematic errors relevant for LEP combination
- End of LEP 2:
  - Δg_Z^1 and λ_γ measured with 2% accuracy
  - $\Delta\kappa_\gamma$ with 5% accuracy

… and if the model was wrong ?

- New theoretical calculations of $e^+e^- \longrightarrow W^+W^-$ available since may 2000
- Implement $\mathcal{O}(\alpha)$ radiative corrections (pure weak loops, radiation off W's)
- Cause decrease (2%) of σ_{tot} …..
- …. and change of $\mathrm{d}\sigma/\mathrm{d}\cos\theta_{W^-}$



- MC codes now available
- Shift in $\mathrm{TGC} \approx$ error of LEP combination
- Must use new MC codes for new results
- Theoretical uncertainty ????

General parameters scan

Why consider only the $\mathrm{SU(2)_L \otimes U(1)_Y}$ inspired model ?

- ALEPH only $\mathrm{W^+W^-} \rightarrow \mathrm{q\overline{q}'}\ell^-\overline{\nu}_\ell$, 183–202 GeV:
  - ★ General scan of all 14 couplings (1 at a time)
- ALEPH, 189 GeV:
  - ★ Investigate $\mathcal{CP}$ violating couplings $\tilde{\kappa}, \tilde{\lambda}, \mathrm{g}^4$
- L3, 183–202 GeV:
  - ★ 1 parameter fit to $\kappa_\mathrm{Z}, \lambda_\mathrm{Z}, \mathrm{g}^5_\mathrm{Z}$
- OPAL, 189 GeV:
  - ★ Investigate $\mathcal{CP}$ violating couplings $\tilde{\kappa}, \tilde{\lambda}, \mathrm{g}^4$ using the SDM method

Statistics now allows scan of all parameters
Foresee increased activity in this area

Quartic gauge couplings

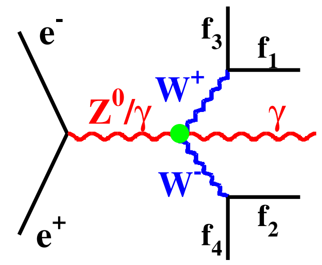
$\mathcal{SM}$ Lagrangian ☛ 4 vertices with 4 bosons:
$\gamma\gamma\mathrm{WW}$, $\gamma\mathrm{ZWW}$, ZZWW, WWWW
Investigate also this sector ?
Are the results interesting ????

- Repeat same procedure as for TGC
- Consider only dimension 6 operators which do not contribute to TGC
- Impose $\mathcal{C}$ and $\mathcal{P}$
- Require $\mathrm{SU(2)_L} \otimes \mathrm{U(1)_Y}$ gauge invariance
- ➥ Only two operators are left ($\gamma\gamma\mathrm{WW}$ and $\gamma\gamma\mathrm{ZZ}$ vertices)

$$\mathcal{L}_6^0 = -\frac{e^2}{16}\frac{a_0}{\Lambda^2}\mathrm{F}^{\mu\nu}\mathrm{F}_{\mu\nu}\vec{\mathrm{W}}^{\alpha}\cdot\vec{\mathrm{W}}_{\alpha}$$
$$\mathcal{L}_6^c = -\frac{e^2}{16}\frac{a_c}{\Lambda^2}\mathrm{F}^{\mu\alpha}\mathrm{F}_{\mu\beta}\vec{\mathrm{W}}^{\beta}\cdot\vec{\mathrm{W}}_{\alpha}$$

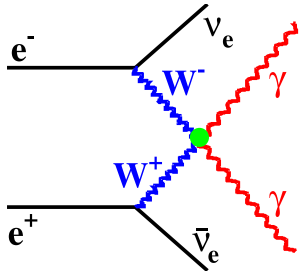
- Λ scale of new physics
- ➥ Results on $a_{0,6}$ expressed in GeV^{-2} (TeV^{-2} is the natural scale for QGC)
- Some controversy on an additional $\mathcal{CP}$ violating term
- Some disagreement on theory predictions and models

Analyses at LEP



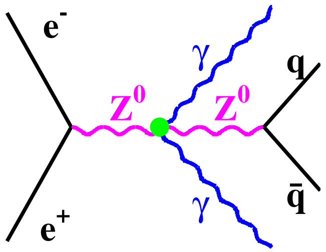
$$e^+e^- \to W^+W^-\gamma$$

L3	$\sqrt{s} = 189 - 202$ GeV	$\mathcal{L}_{int} \approx 180\ \mathrm{pb}^{-1}$
OPAL	$\sqrt{s} = 189$ GeV	$\mathcal{L}_{int} \approx 180\ \mathrm{pb}^{-1}$



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

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



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

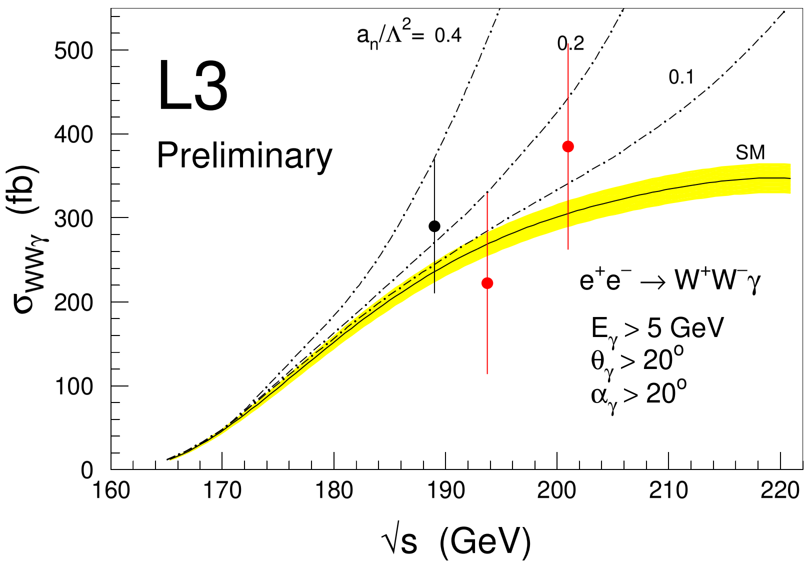
L3	$\sqrt{s} = 130 - 202$ GeV	$\mathcal{L}_{int} \approx 500\ \mathrm{pb}^{-1}$
OPAL	$\sqrt{s} = 130 - 208$ GeV	$\mathcal{L}_{int} \approx 580\ \mathrm{pb}^{-1}$

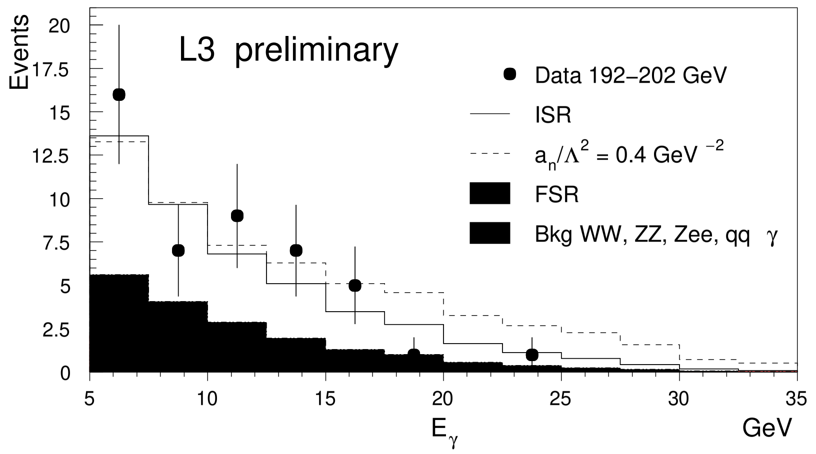
Setting limits on QGC is for a high energy collider not for LEP2 !

The $W^+W^-\gamma$ channel

γ sources in W^+W events:

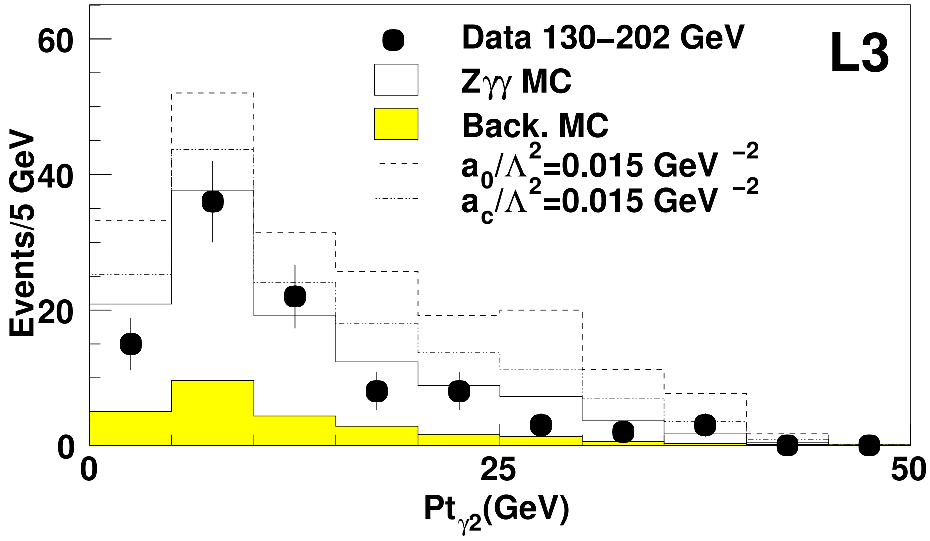
- ISR: large $|\cos\theta|$
- FSR: close to jets, leptons, $M_{f\bar{f}'\gamma} \approx M_W$
- Radiation from W bosons: small
- QGC: excess of photons in central region, large E_γ, increase of total cross section



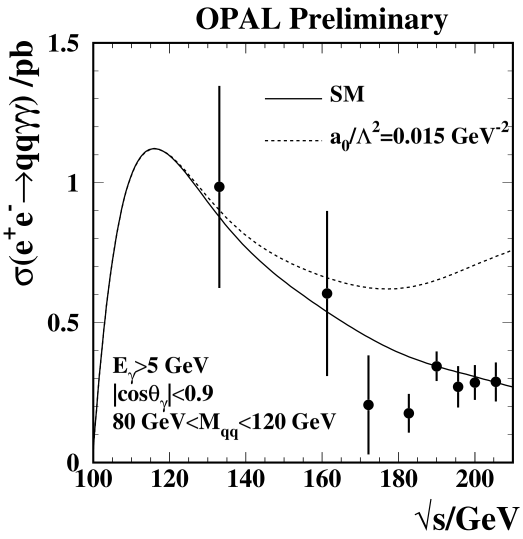


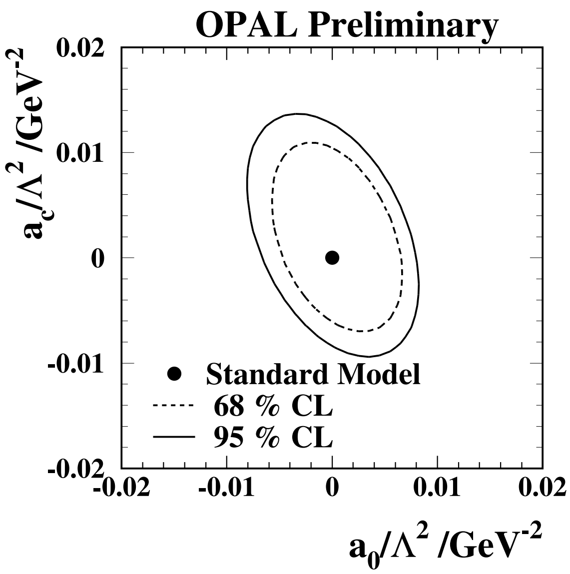
The $Z\gamma\gamma$ channel

- $\mathcal{SM}$: double radiative returns to Z^0
- Small background from photons from jets



Use cross section and p_{T_γ} to constrain QGC

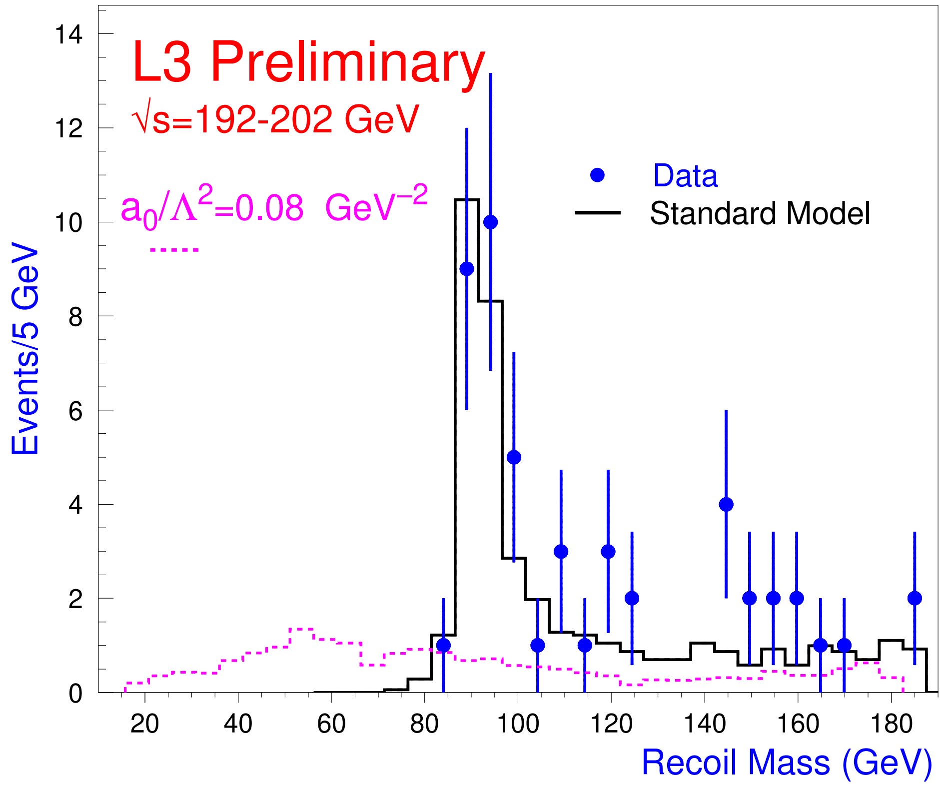




Most stringent limits on QGC

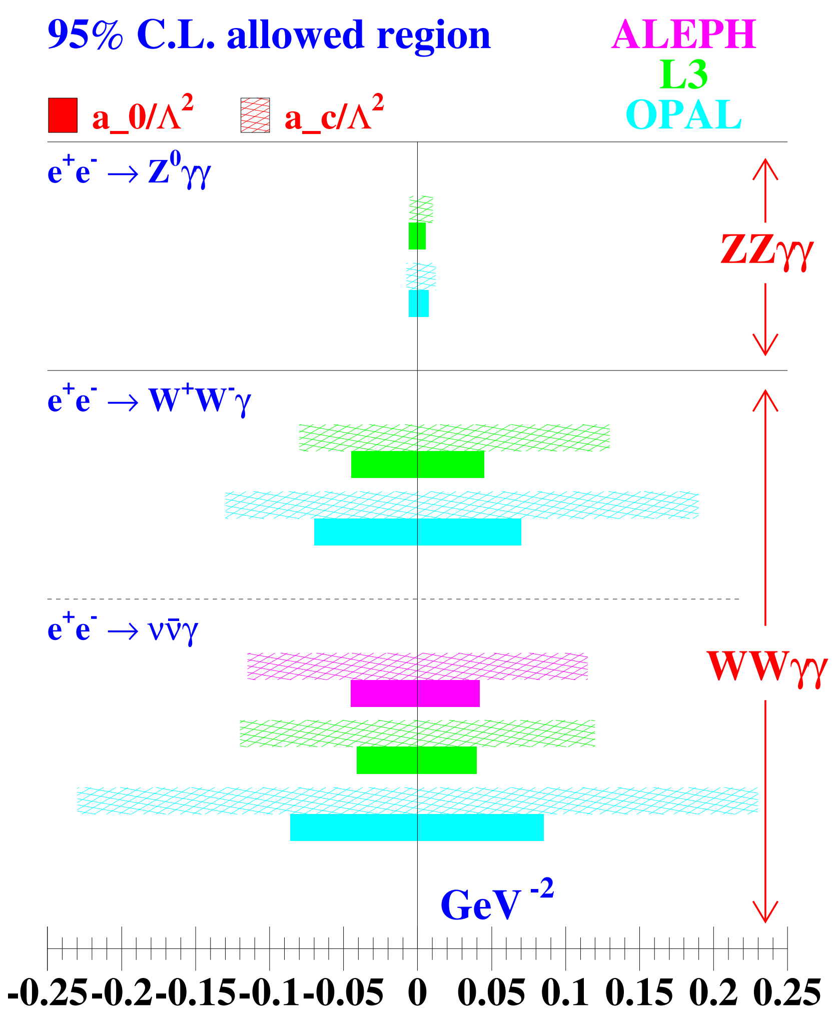
The $\nu\bar{\nu}\gamma\gamma$ channel

- $\mathcal{SM}$: double radiative returns to Z^0
- Receive contribution from $\mathrm{ZZ}\gamma\gamma$ and $\mathrm{WW}\gamma\gamma$ vertices – No MC for this
- Avoid Z peak – Cannot make full use of the data



- Background free region below the Z^0 peak
- Two different theoretical calculations give different QGC limits ...... Currently not reliable

Combined results on QGC



Combine result assuming same new physics effects in $ZZ\gamma\gamma$ and $WW\gamma\gamma$

- First direct limits on QGC
- As meaningful (or meaningless) as TGC limits
- Same order of magnitude of indirect constraints

Neutral vertices

- In the $\mathcal{SM}$ $Z\gamma\gamma$, $ZZ\gamma$ and ZZZ vertices: zero at tree level
- Radiative corrections not observable
- Observation of non zero couplings $\longrightarrow$ new physics
- Investigate these couplings with the $Z\gamma$ and ZZ final states

$Z\gamma$ final state ($V \rightarrow Z\gamma$, $V = \gamma, Z$)

- Parametrised with 8 anomalous couplings
  - h_1^V and $h_2^V \Longrightarrow$ CP violating (angular asimmetries), no interference with $\mathcal{SM}$
  - h_3^V and $h_4^V \Longrightarrow$ CP conserving
  - h_1^V and h_3^V dimension 6
  - h_2^V and h_4^V dimension 8
- Use form factors not to violate unitarity:

$$h_i^V = h_{i0}^V/(1+s/\Lambda^2)^3 \quad \text{for } i = 1, 3$$
$$h_i^V = h_{i0}^V/(1+s/\Lambda^2)^4 \quad \text{for } i = 2, 4$$

- Not the same h_i^V used at Tevatron (factor i in the $\mathcal{L}$)

ZZ final state ($V \to ZZ$, $V = \gamma, Z$)

- Parametrised with 4 anomalous couplings
  - $f_4^V \Longrightarrow$ CP violating (angular asimmetries), no interference with $\mathcal{SM}$
  - $f_5^V \Longrightarrow$ CP conserving
  - f_4^V and f_5^V dimension 6
- Use form factors not to violate unitarity

$$f_i^V = f_{i0}^V/(1 + s/\Lambda^2)^3 \quad \text{for } i = 4, 5$$

- Just above threshold – Very strong $\sqrt{s}$ dependence of sensitivity

Both final states

- Anomalous nTGC ➠ production of highly energetic and central bosons
- Fit to total cross section, angular distributions and (only for $Z\gamma$) energy spectra
- Use $\Lambda = \infty$ for limits
- LEP combined results updated march 2001

95% CL limits

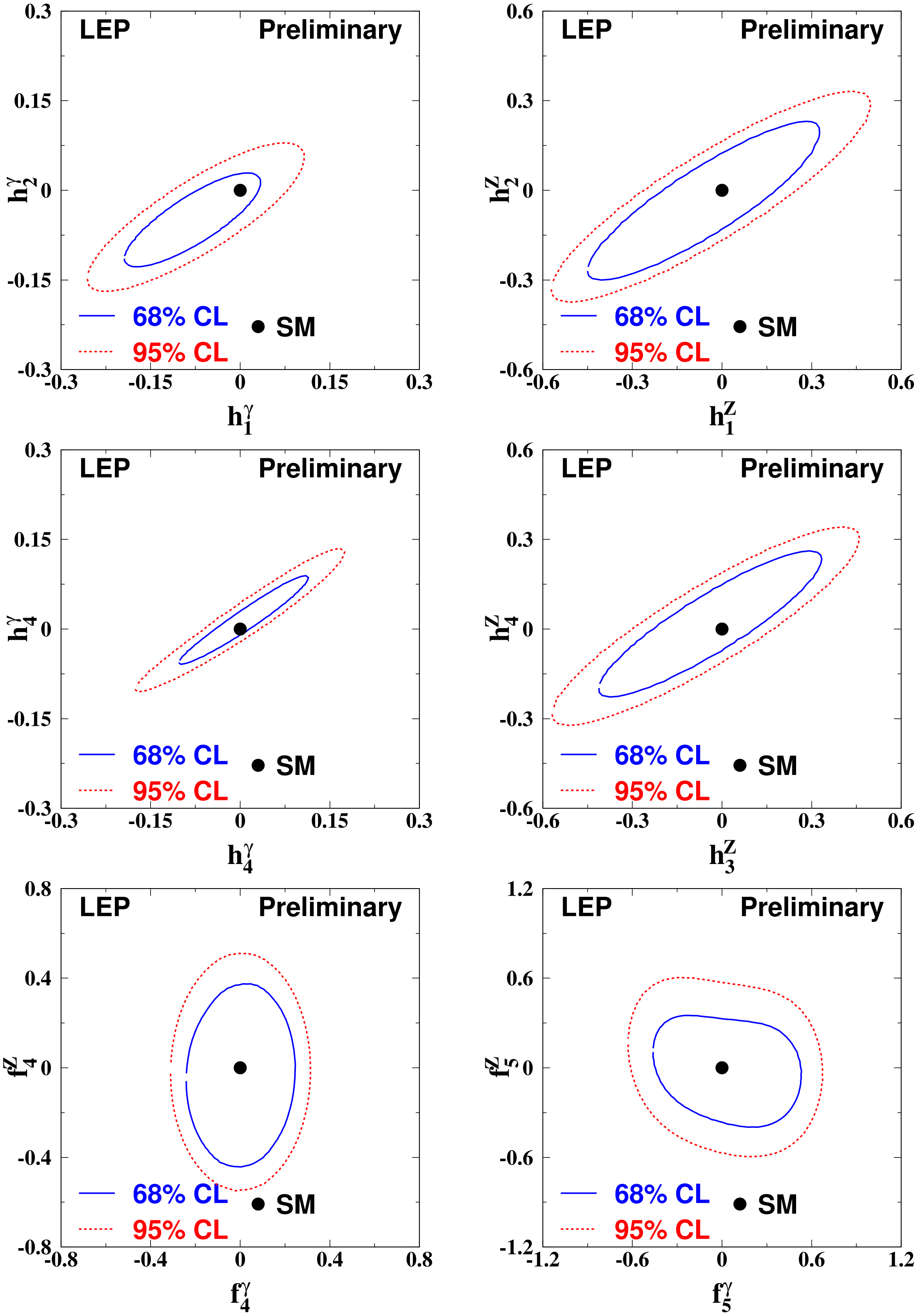
- h_V^i couplings: new analysis from L3, no new data
- f_V^i couplings: new data from DELPHI, new results from ALEPH

1–dimensional fits

$$
\begin{array}{ll}
h_\gamma^1 & [-0.09\ , 0.05\ ] \\
h_Z^1 & [-0.15\ , 0.14\ ] \\
h_\gamma^2 & [-0.05\ , 0.05\ ] \\
h_Z^2 & [-0.10\ , 0.10\ ] \\
h_\gamma^3 & [-0.07\ , 0.002] \\
h_Z^3 & [-0.22\ , 0.07\ ] \\
h_\gamma^4 & [\ \ 0.002, 0.05\ ] \\
h_Z^4 & [-0.05\ , 0.15\ ] \\
\hline\hline
f_\gamma^4 & [-0.21\ , 0.23\ ] \\
f_Z^4 & [-0.40\ , 0.33\ ] \\
f_\gamma^5 & [-0.37\ , 0.49\ ] \\
f_Z^5 & [-0.27\ , 0.29\ ]
\end{array}
$$

Everything compatible with $\mathcal{SM}$

2–dimensional fits



Future prospects and conclusions

- Expect final LEP result during next year
- Δg_Z^1 and λ_γ measured with 2% accuracy
- $\Delta\kappa_\gamma$ with 5% accuracy
- Improve understanding of systematics
- and the combination procedure
- Need help from theorists: assess theoretical uncertainty on (what we call) $\mathcal{SM}$

On a longer time scale

- CDF and DØ will not improve LEP results
- ATLAS and CMS might improve slightly on $\Delta\kappa_\gamma$ and Δg_Z^1 (more on λ_γ)
- Radiative corrections and $\mathcal{SUSY}$ are at the 10^{-3} level
- Need a e^+e^- linear collider to study this kind of physics
- ECFA/DESY studies indicate that a precision of $\mathcal{O}(5 \cdot 10^{-4})$ might be achieved
- Big challenge for theorists !!!!
- Direct investigation of the Higgs potential might be much more rewarding