Gauge couplings meaurements at LEP2

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8 March 2001
Frontiers in Contemporary Physics II

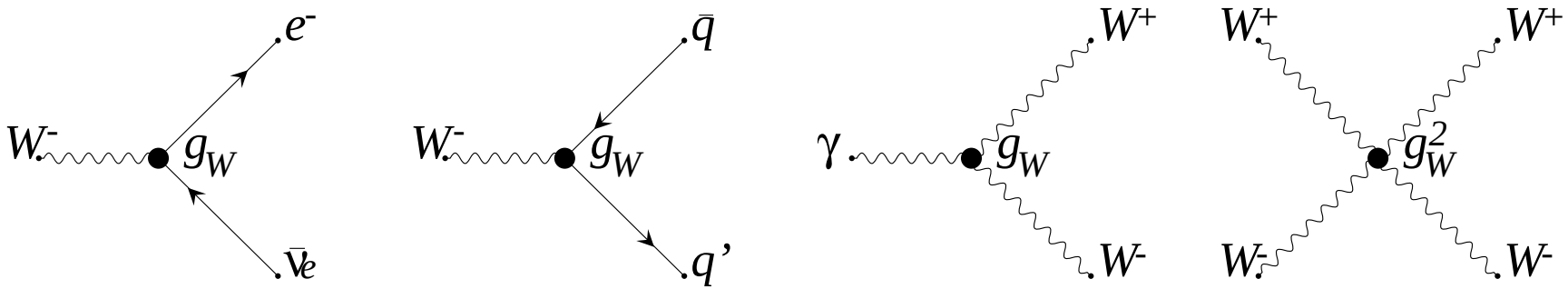
- Testing couplings between bosons
  - ☛ different channels
- Direct observables
- Extracting the triple gauge couplings
  - ☛ methods
  - ☛ uncertainties
- .... and the quartic ones
- Neutral vertices ?
- Future prospects

Visit http://www.cern.ch/LEPEWWG/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

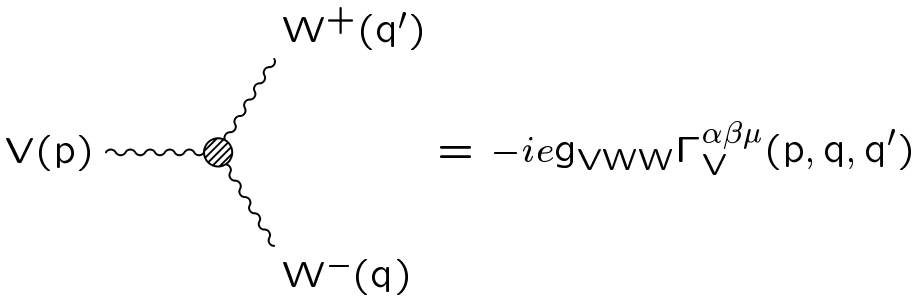
$$\mathcal{L}_{int} = -ig_W[W^{\mu\nu-}W^+_\mu - W^{\mu\nu+}W^-_\mu](\cos\theta_W Z_\nu + \sin\theta_W A_\nu)$$
$$-ig_W(\cos\theta_W Z^{\mu\nu} + \sin\theta_W A^{\mu\nu})[W^-_\mu W^+_\nu - W^+_\mu W^-_\nu] + ...$$

- 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



- 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

Too many parameters

- 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

$$\Delta g_Z^1,\ \Delta\kappa_\gamma \text{ and } \lambda = \lambda_\gamma$$

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 ?

e^+e^- colliders

- Non polarised beams ➠ cannot separate γWW and ZWW contributions to $e^+e^- \to W^+W^-$
- Fixed centre of mass energy

Hadron colliders

- Some final states (e.g. $W\gamma$) 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 ($\Lambda = 2$ TeV)

Keep in mind these differences !!!

LEP constraints justified by

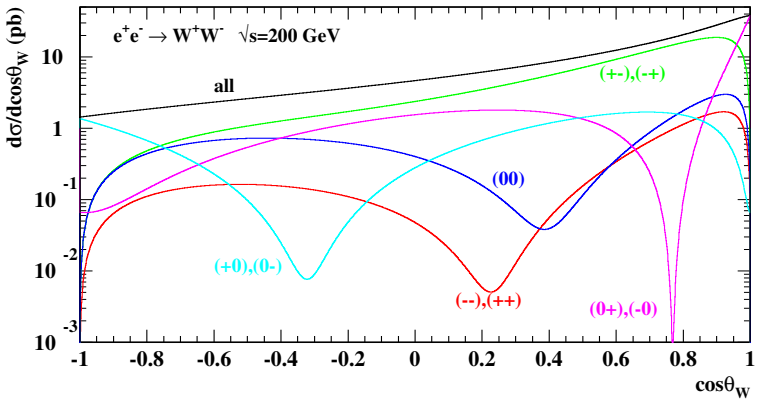
- Low energy constraints and $SU(2)_L \otimes U(1)_Y$ gauge invariance
- Light Higgs boson
- Same constraints used to calculate TGC contribution to $b \to s\gamma$ and $(g-2)_\mu$

Sensitivity to anomalous couplings

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

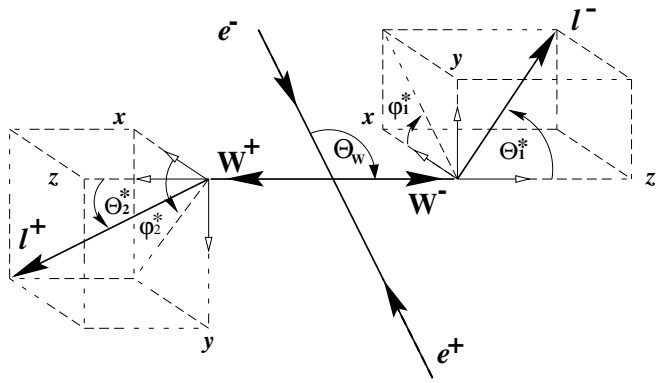
- TGC change contribution of each W helicity
- Affect total cross section and $d\sigma/d\cos\theta_{W^-}$
- Sensitivity increases with $\sqrt{s}$

$\mathcal{L}$ 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 $\Gamma_W \to 0$ 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**

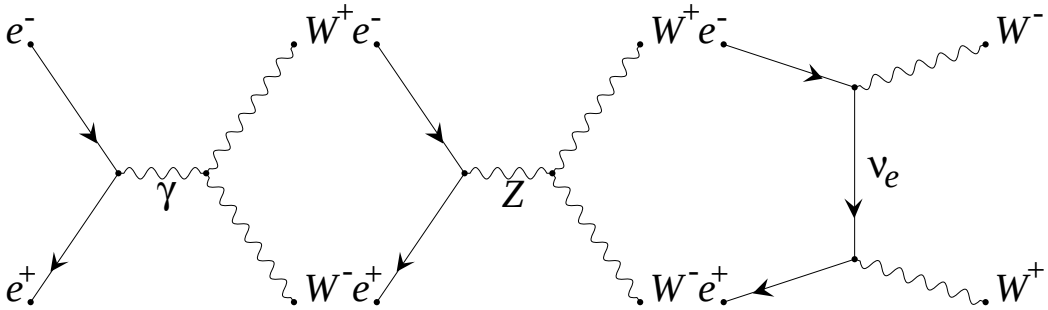
General approach in the analyses:

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

Available data sets

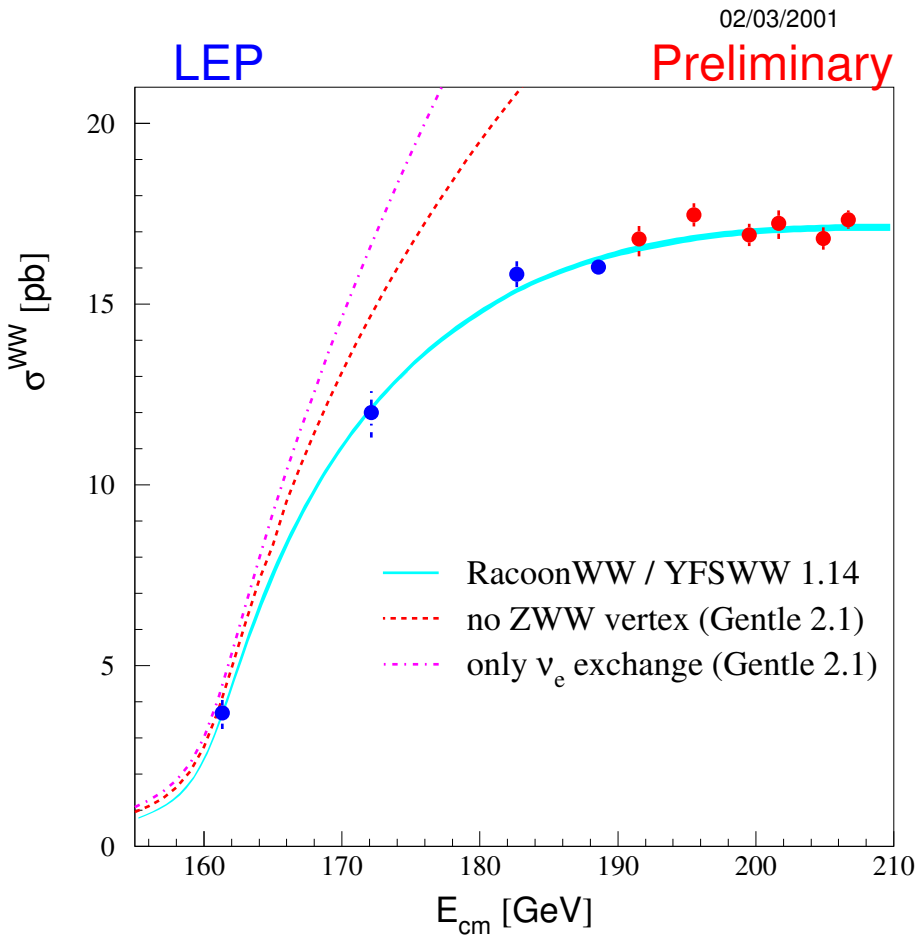
- $680\ \mathrm{pb}^{-1}$ **collected at 183–208 GeV**
  - ➥ **9K W pairs per experiment**
- **Only data collected in 1997–1999 are analysed**
- **Most results are still preliminary**

The total CC03 cross section



W pair production cross section

➥ **Strong constraints on** TGC

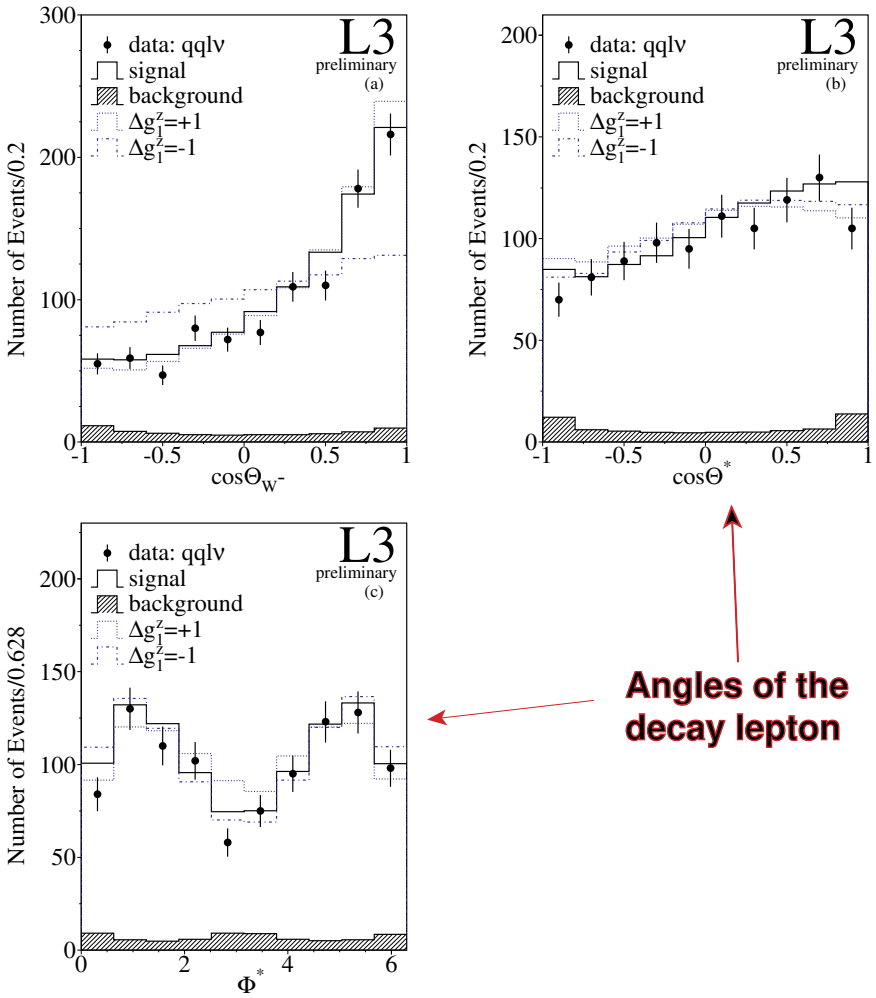


Gauge cancellation at work !!!

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

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

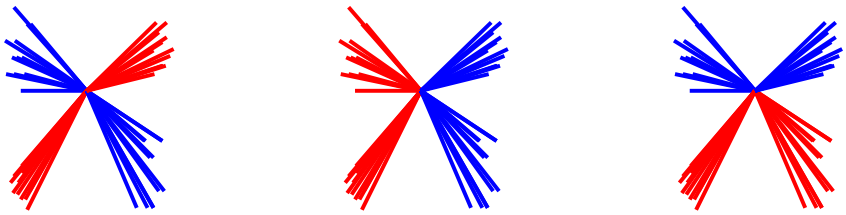
189 GeV



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

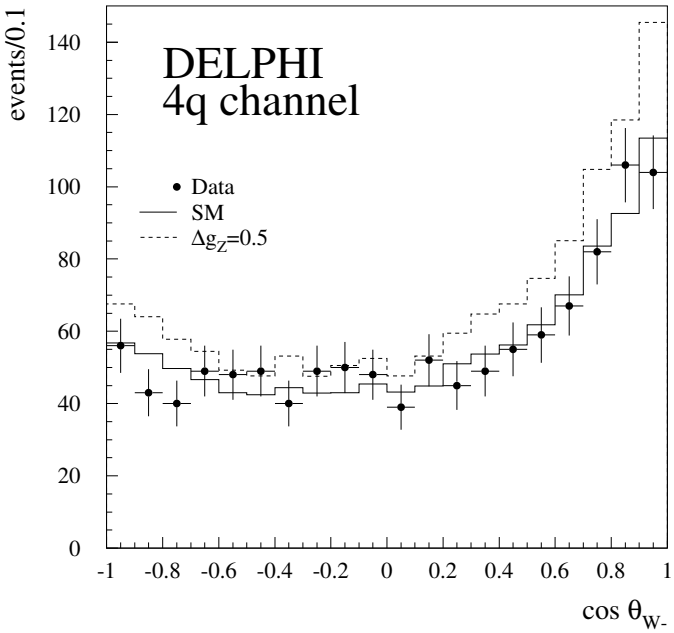
The $W^+W^- \to q\bar{q}'q\bar{q}'$ channel

- **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** $\cos\theta_{W^-}$

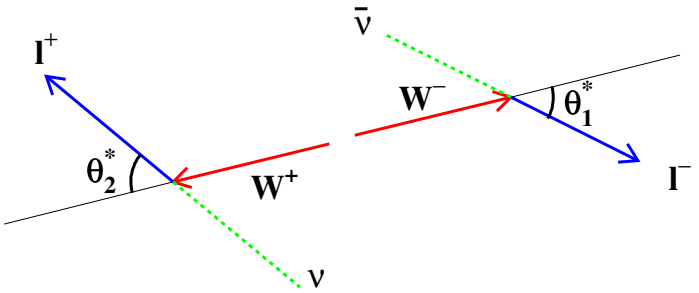


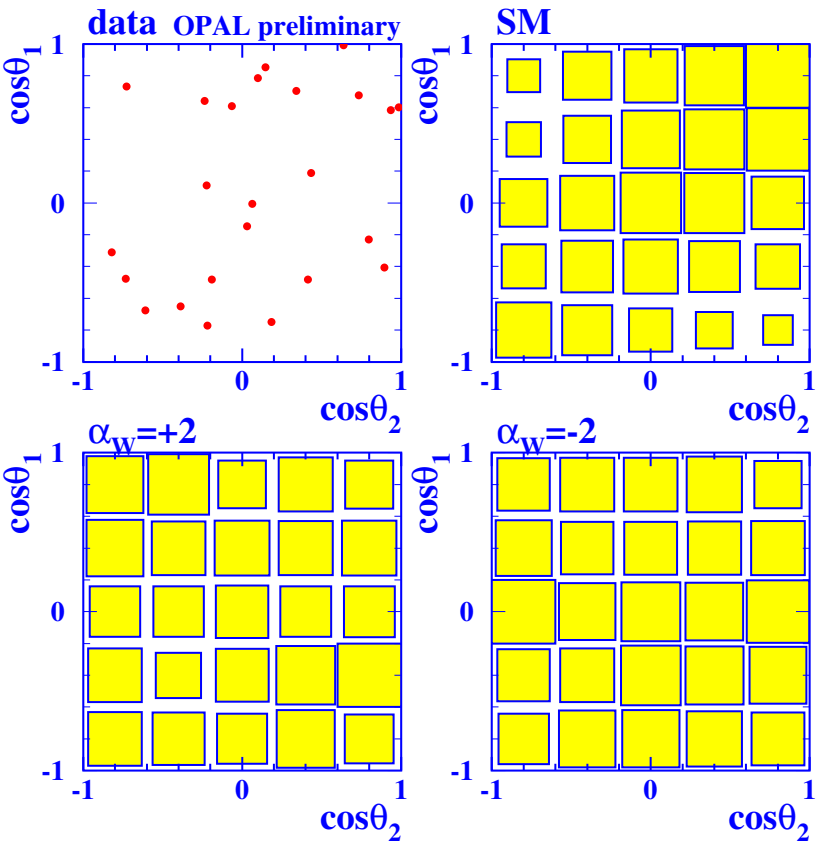
⊕ **high statistics**

⊖ **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

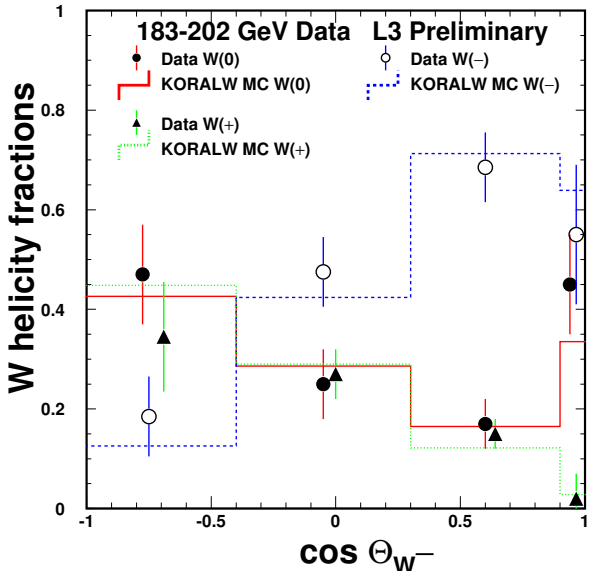
$$\frac{1}{N}\frac{dN}{dx} = f_-\frac{3}{8}(1+x)^2 + f_+\frac{3}{8}(1-x)^2 + f_L\frac{3}{4}(1-x^2) \quad \text{with} \quad x = \cos\theta^*$$

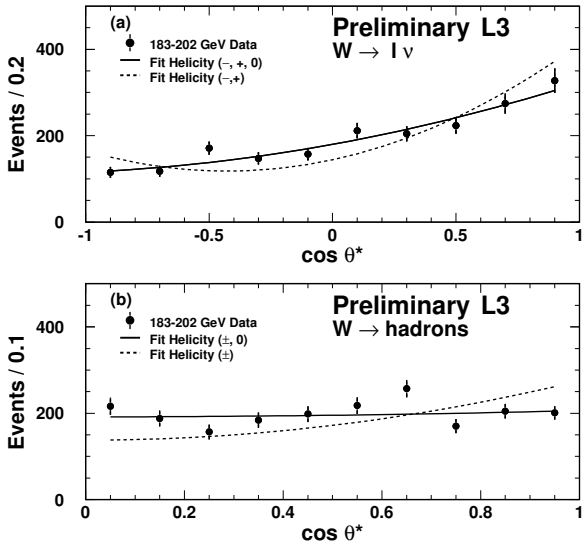
★ L3: fit to $\cos\theta^*$ distribution (183–204 GeV)

➥ $f(\mathrm{W}^{\pm}_L) = (0.259 \pm 0.035)$

★ $\mathcal{SM}$: $f(\mathrm{W}^{\pm}_L) = 0.248$

➥ $> 7\sigma$ 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 $W^\pm$

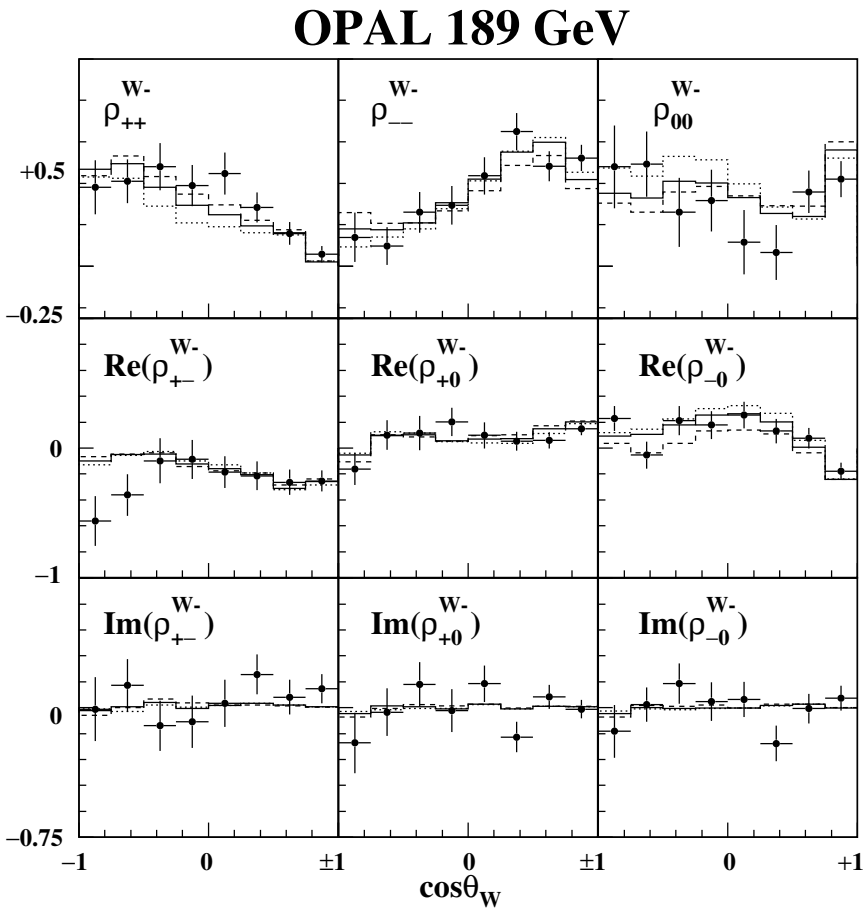
$\Rightarrow$ $\tau = 1$

$\Uparrow$ $\tau = 0$

$\Leftarrow$ $\tau = -1$

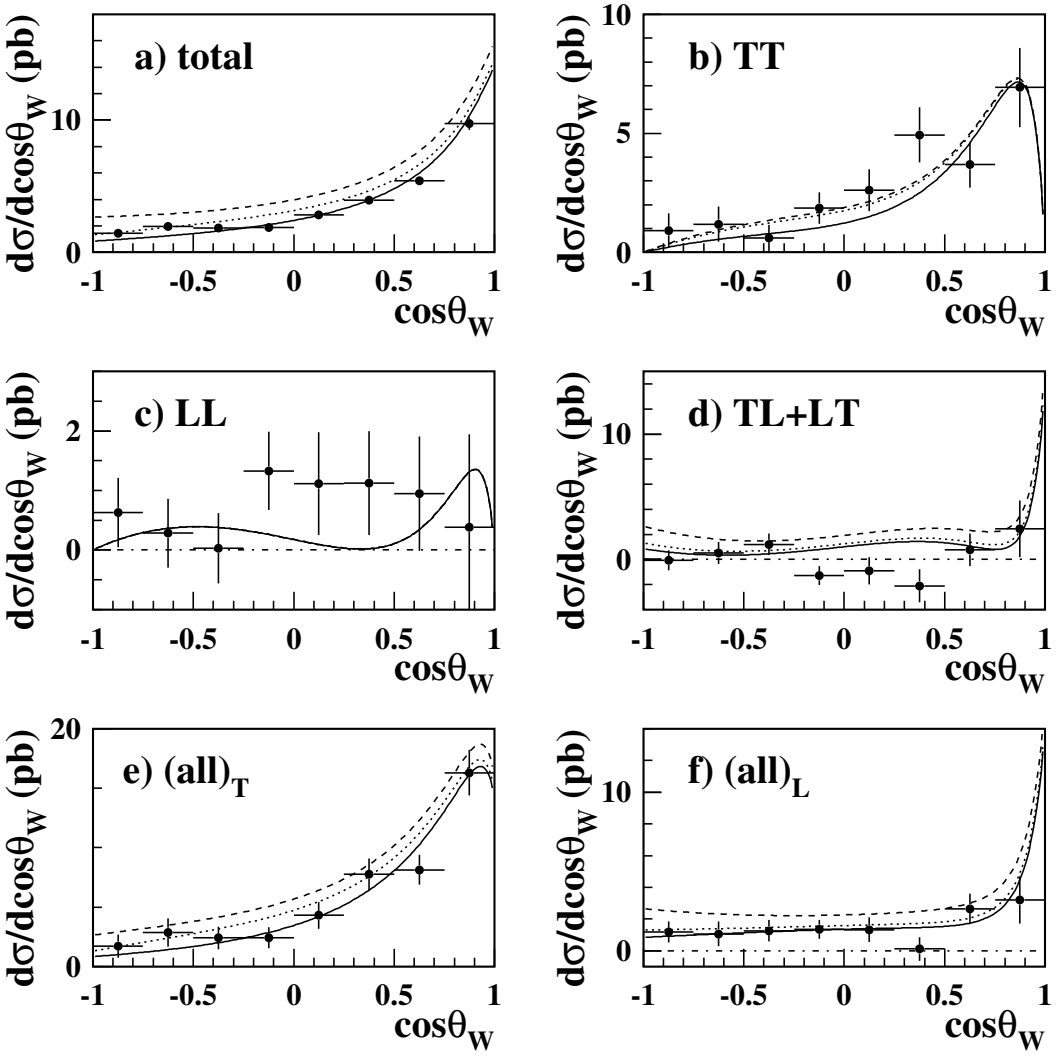
λ: e^- spin

- $\rho_{\tau\tau'}$ 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



W Polarisation

OPAL 189 GeV



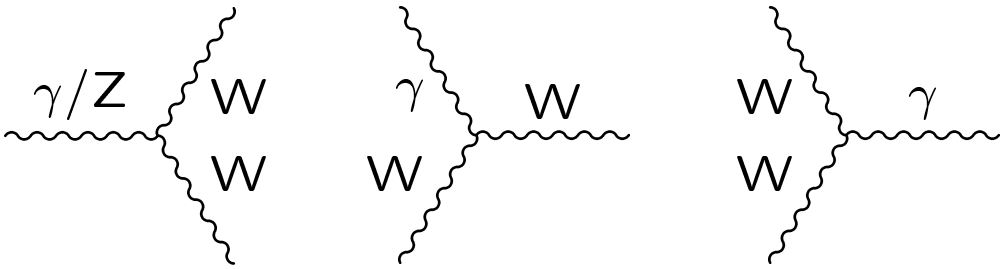
σ_T/σ_{total}	$0.790 \pm 0.033 \pm 0.016$	0.74
σ_L/σ_{total}	$0.210 \pm 0.033 \pm 0.016$	0.26
$\sigma_{TT}/\sigma_{total}$	$0.781 \pm 0.090 \pm 0.033$	0.57
$\sigma_{LL}/\sigma_{total}$	$0.201 \pm 0.072 \pm 0.018$	0.09
$\sigma_{TL}/\sigma_{total}$	$0.018 \pm 0.147 \pm 0.038$	0.34

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

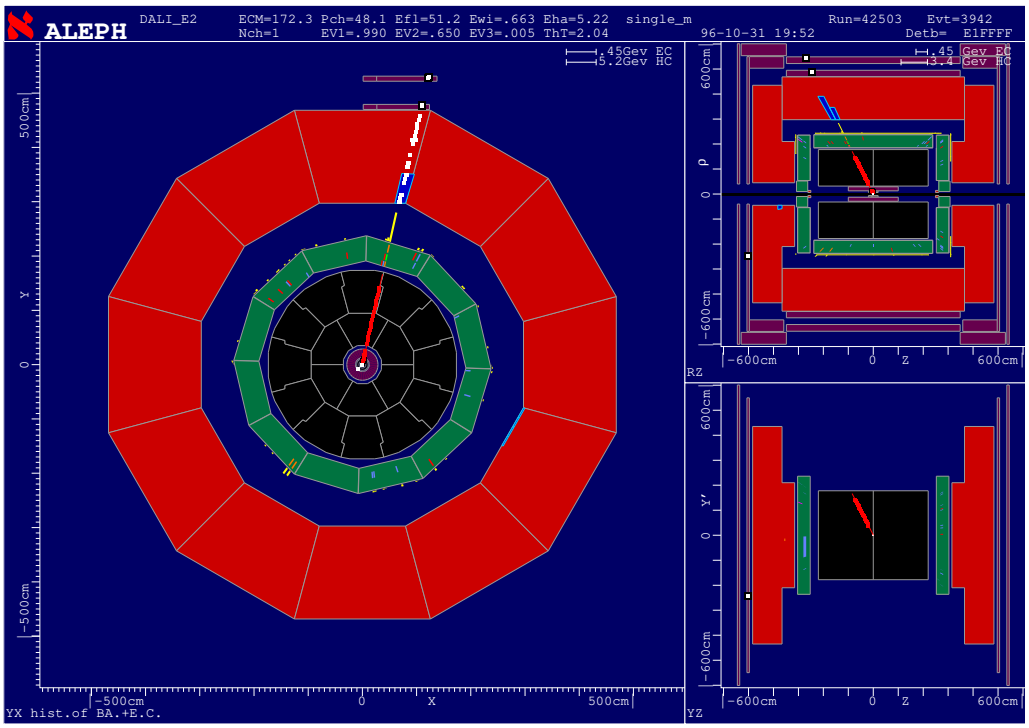
Other ways of measuring the TGC

γWW couplings measurable also in the "single W" process and in the $\nu\overline{\nu}\gamma$ 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 ...



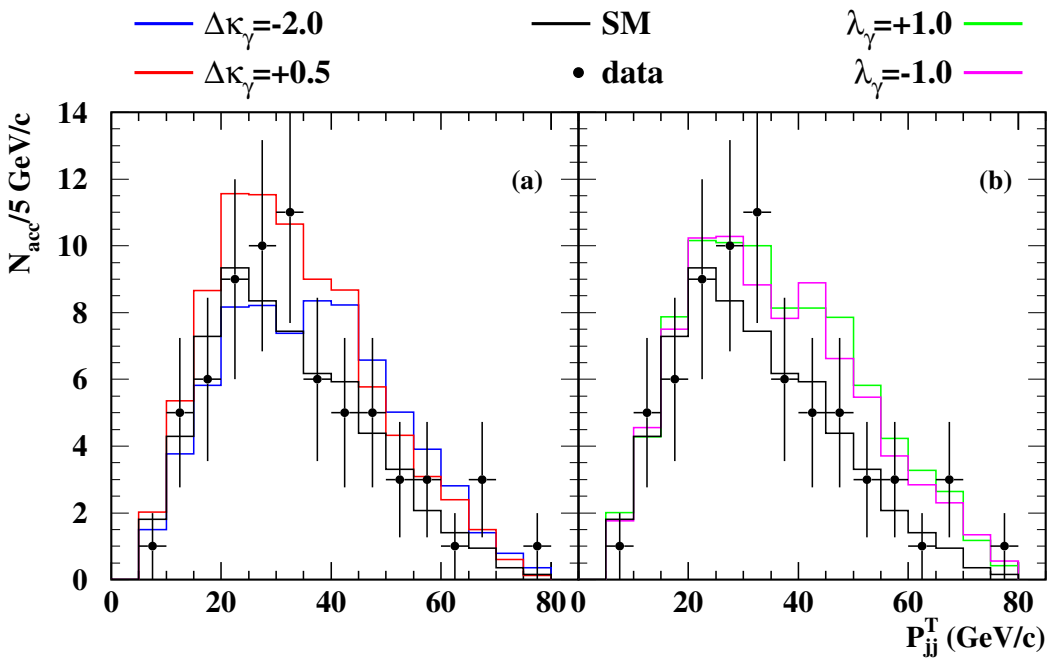
- ... acoplanar jet pair with $M_{jj} \sim M_W$

Caveats:

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

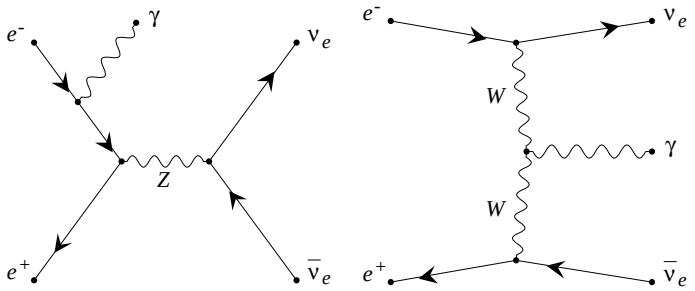
Extracting the TGC:

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

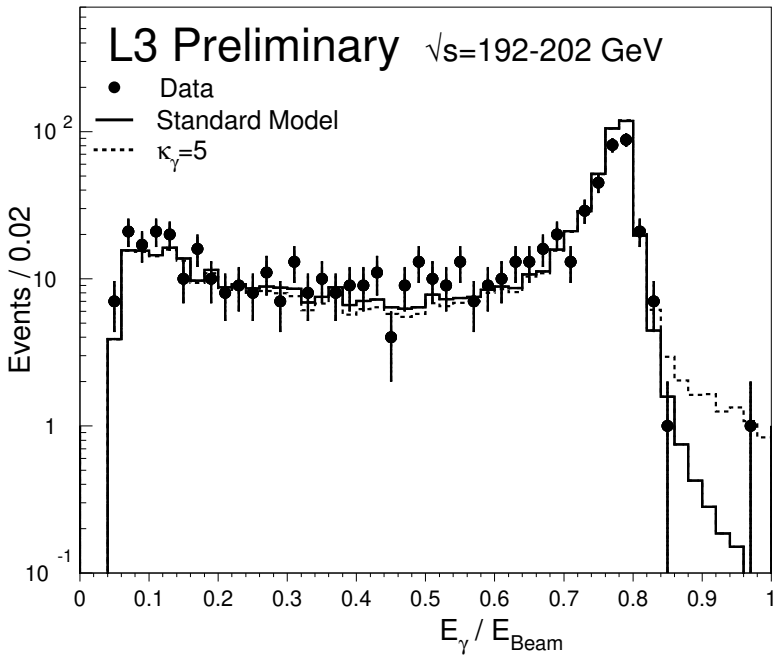


Distributions used by OPAL and ALEPH

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

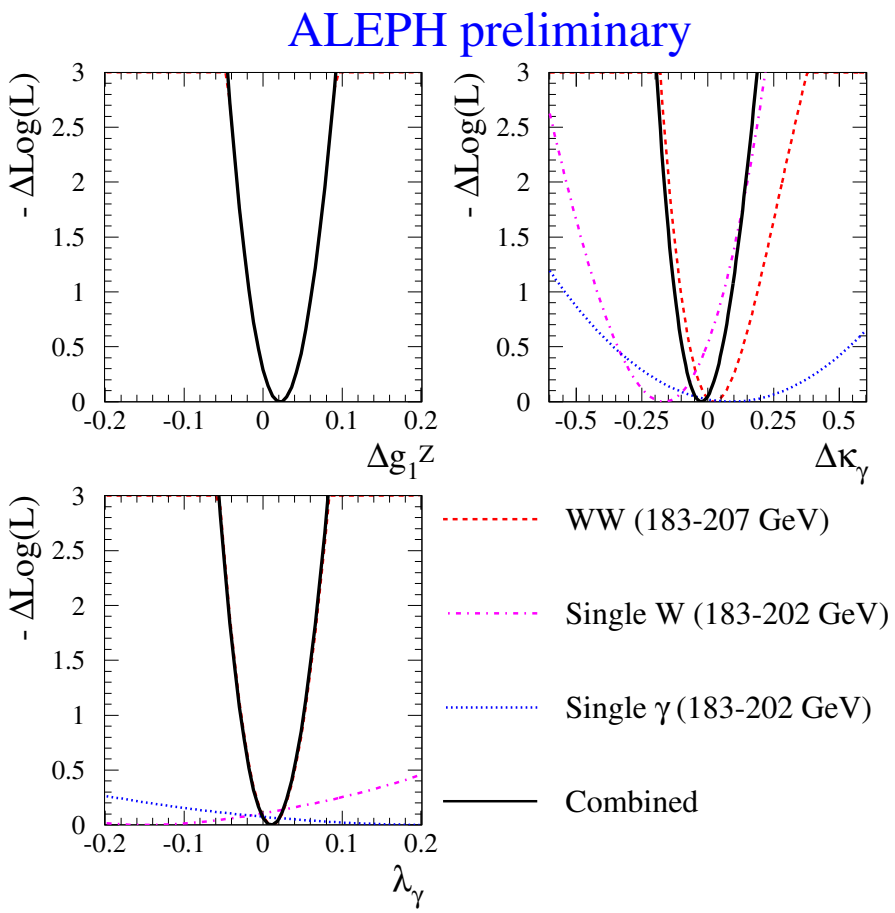
Example: combining results from various channels

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

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

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

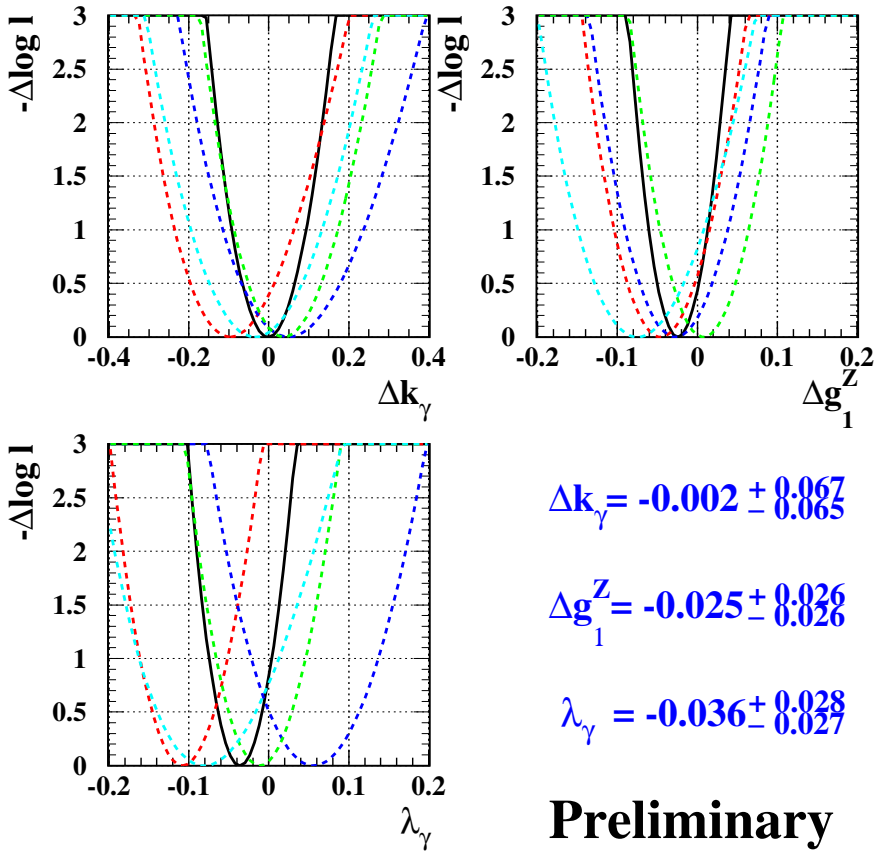
  - **First error experimental (stat. + syst.)**
  - **Second error: theoretical contribution to systematics. See later ....**



LEP combination (ICHEP 2000)

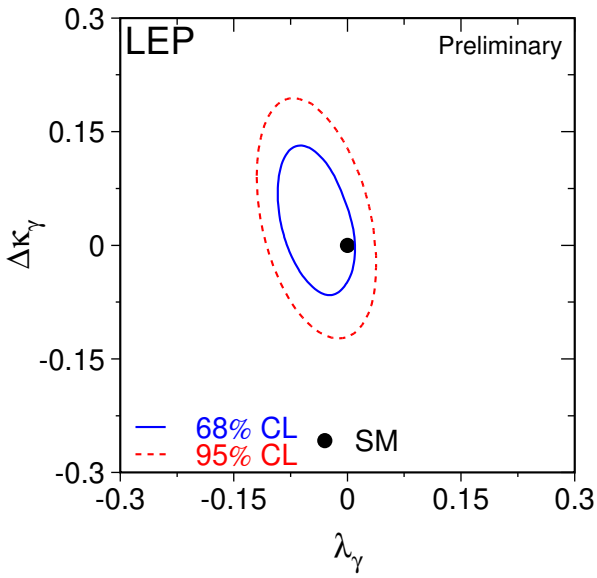
- Add log–$\mathcal{L}$ curves from different experiments
- Consider correlations of systematic uncertainties
  - ★ $W^+W^- \to q\bar{q}'\ell^-\bar{\nu}_\ell$: fragmentation
  - ★ $W^+W^- \to q\bar{q}'q\bar{q}'$: fragmentation, FSI
  - ★ single W: theoretical prediction for σ_{tot}

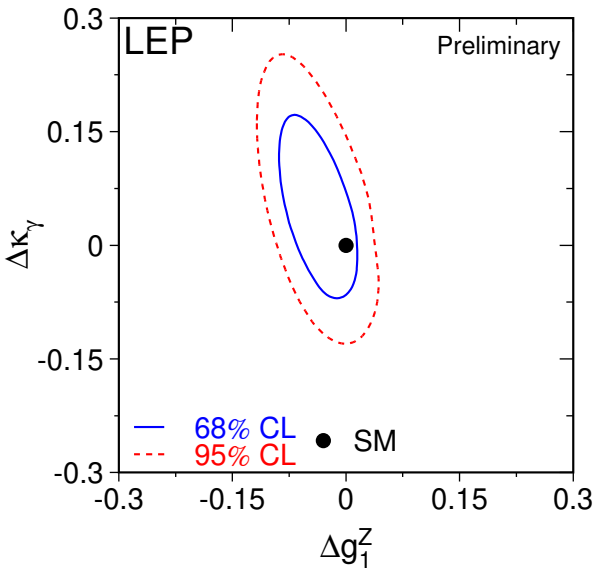
ALEPH + DELPHI +L3 + OPAL

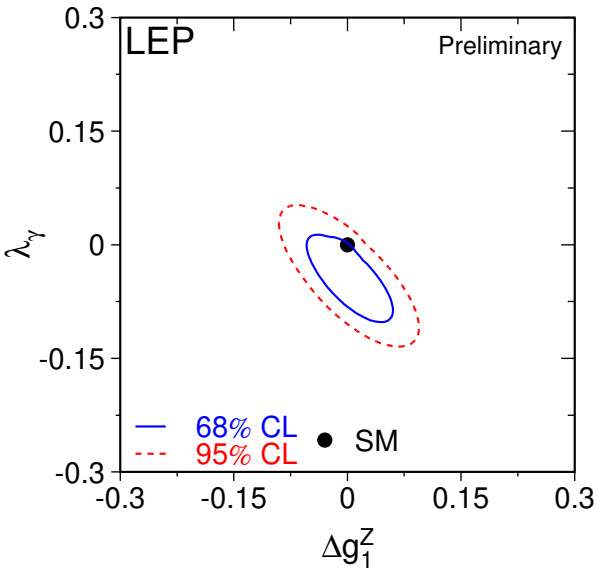


No deviation from $\mathcal{SM}$ observed

.... also 2d and 3d fits



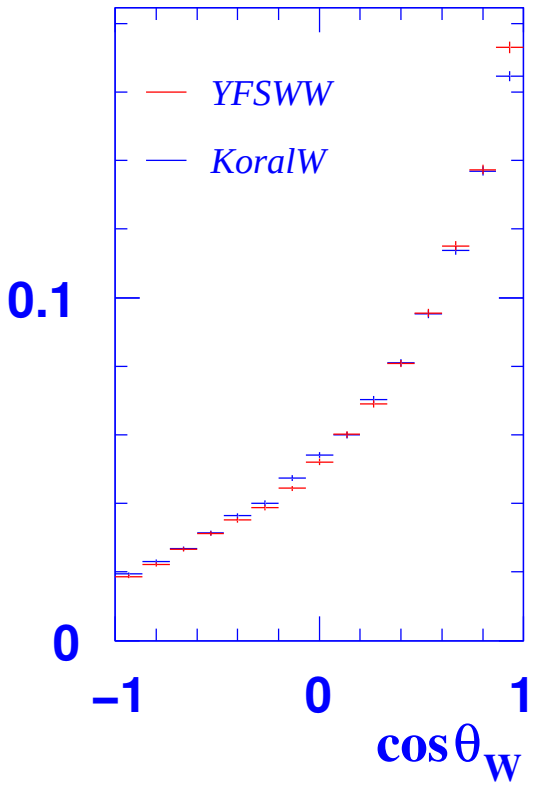




- **Systematic errors relevant for LEP combination**
- **End of LEP 2:**
  - Δg_Z^1 and λ_γ measured with 2% accuracy
  - $\Delta\kappa_\gamma$ with 5% accuracy

... and if the model was wrong ?

- New theoretical calculations of $e^+e^- \to W^+W^-$ 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 $d\sigma/d\cos\theta_{W^-}$



- MC codes now available
- Shift in 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 $\mathrm{W^+W^- \to q\overline{q}'\ell^-\overline{\nu}_\ell}$, 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)

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

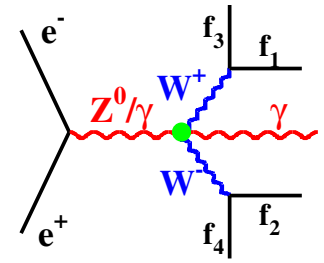
$$\mathcal{L}_6^c = -\frac{e^2}{16}\frac{a_c}{\Lambda^2}\mathrm{F}^{\mu\alpha}\mathrm{F}_{\mu\beta}\vec{\mathrm{W}}^{\beta}\cdot\vec{\mathrm{W}}_{\alpha}$$

- Λ scale of new physics

➥ Results on $a_{0,6}$ expressed in GeV^{-2}
(TeV^{-2} is the natural scale for QGC)

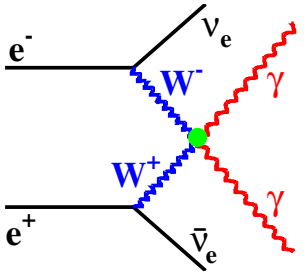
- Some controversy on an additional $\mathcal{CP}$ violating term
- Some disagreement on theory predictions and models

Analyses at LEP



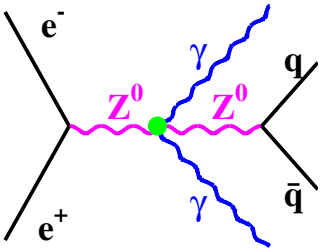
$$e^+e^- \to W^+W^-\gamma$$

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



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

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



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

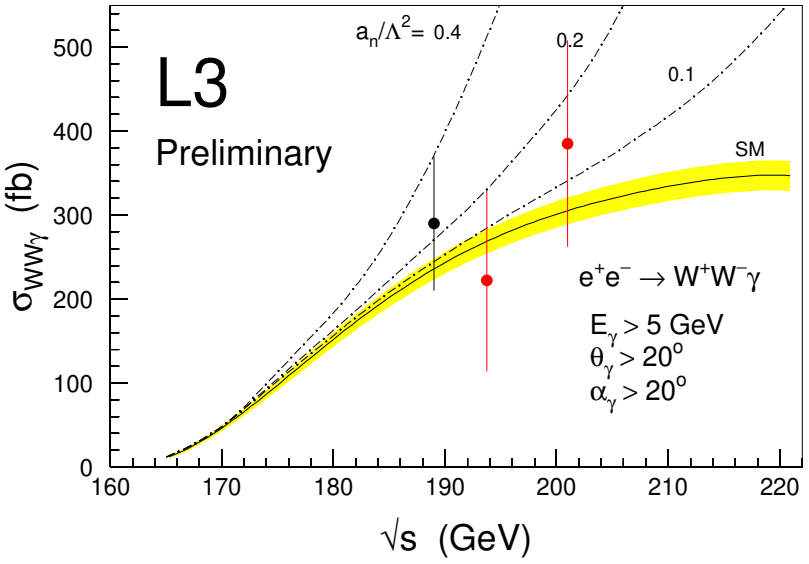
L3	$\sqrt{s} = 130 - 202$ GeV	$\mathcal{L}_{int} \approx 500$ pb^{-1}
OPAL	$\sqrt{s} = 130 - 208$ GeV	$\mathcal{L}_{int} \approx 580$ pb^{-1}

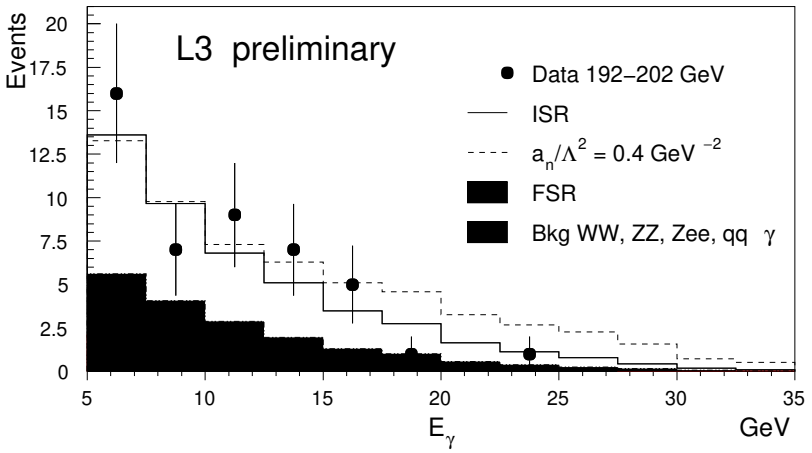
Setting limits on QGC is for a high energy collider not for LEP2 !

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

γ sources in W^+W events:

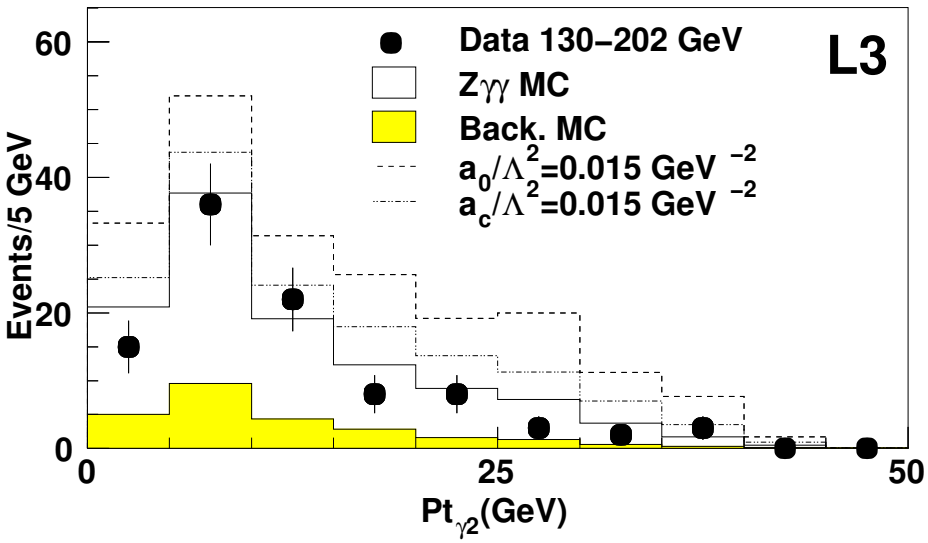
- **ISR: large $|\cos\theta|$**
- **FSR: close to jets, leptons, $M_{f\bar{f}/\gamma} \approx M_W$**
- **Radiation from W bosons: small**
- **QGC: excess of photons in central region, large E_γ, increase of total cross section**



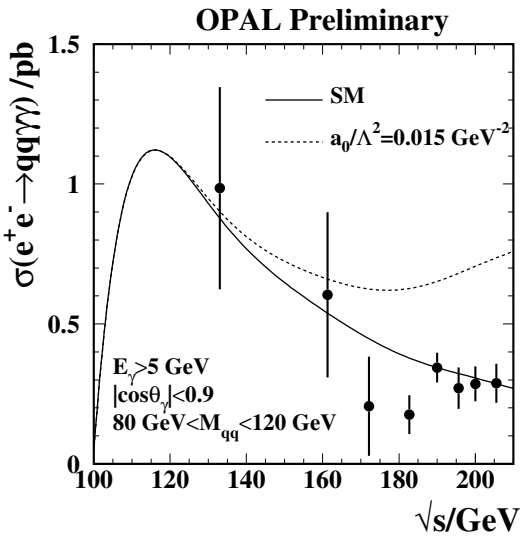


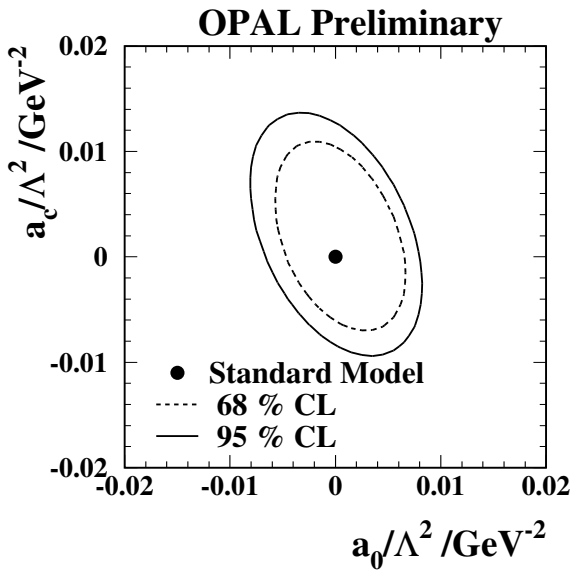
The $Z\gamma\gamma$ channel

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



Use cross section and p_{T_γ} to constrain QGC

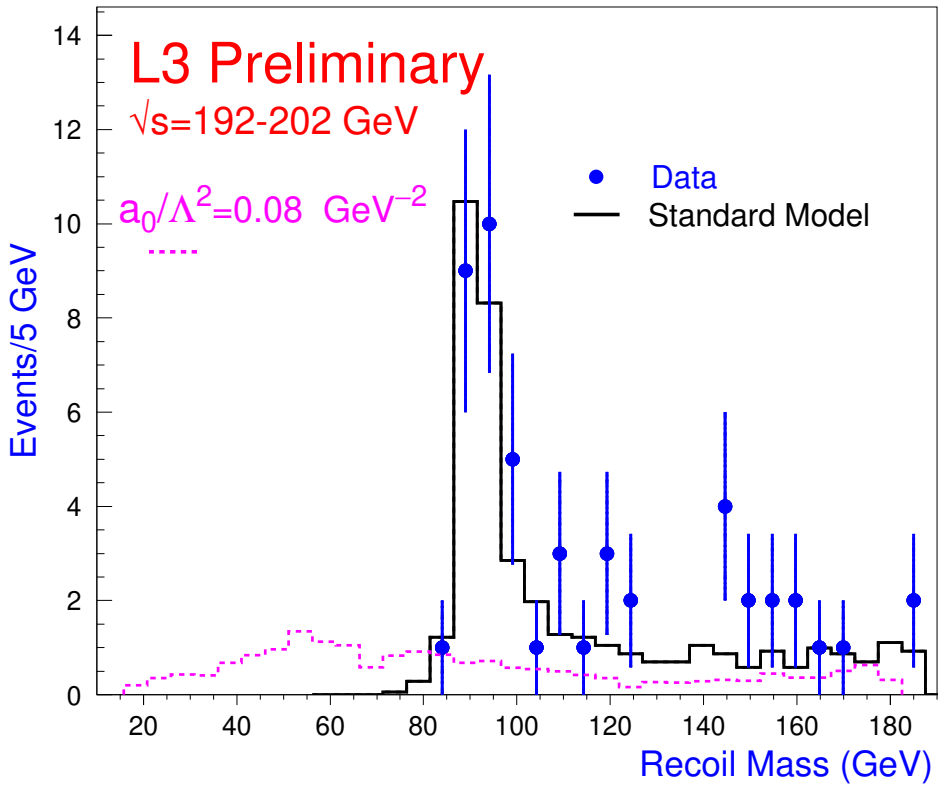




Most stringent limits on QGC

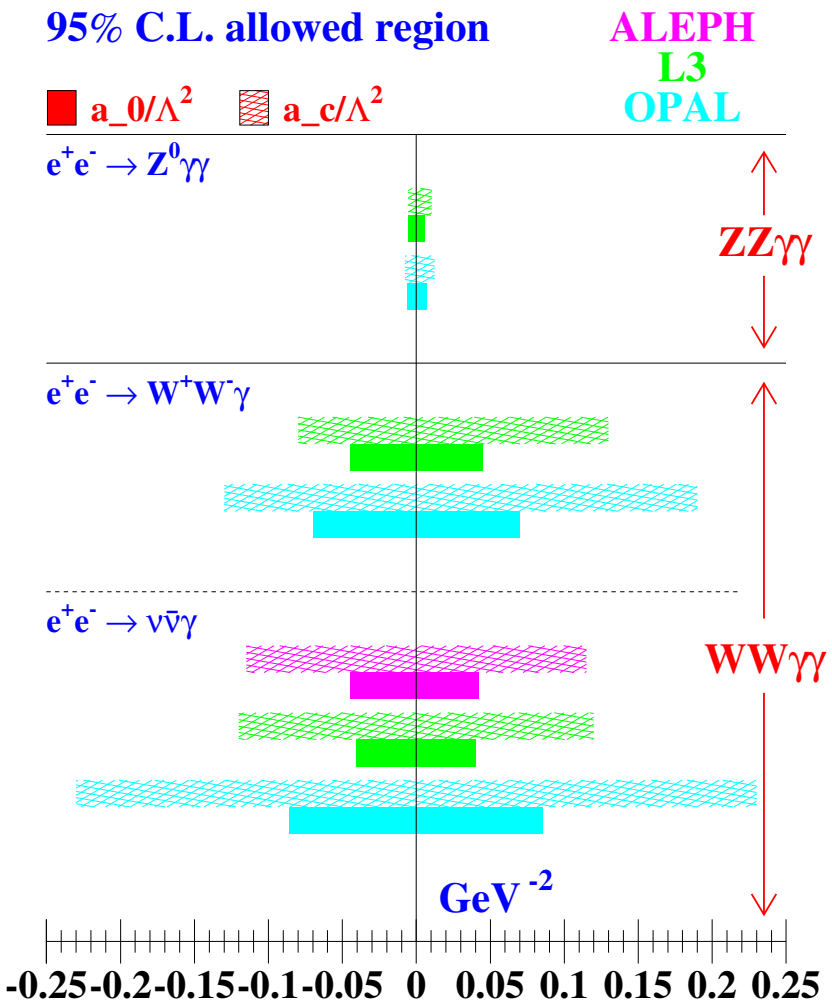
The $\nu\bar{\nu}\gamma\gamma$ channel

- $\mathcal{SM}$: double radiative returns to Z^0
- Receive contribution from $ZZ\gamma\gamma$ and $WW\gamma\gamma$ 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 $\mathcal{SM}$ $\mathrm{Z}\gamma\gamma$, $\mathrm{ZZ}\gamma$ and ZZZ vertices: zero at tree level
- Radiative corrections not observable
- Observation of non zero couplings $\longrightarrow$ new physics
- Investigate these couplings with the $\mathrm{Z}\gamma$ and ZZ final states

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

- 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

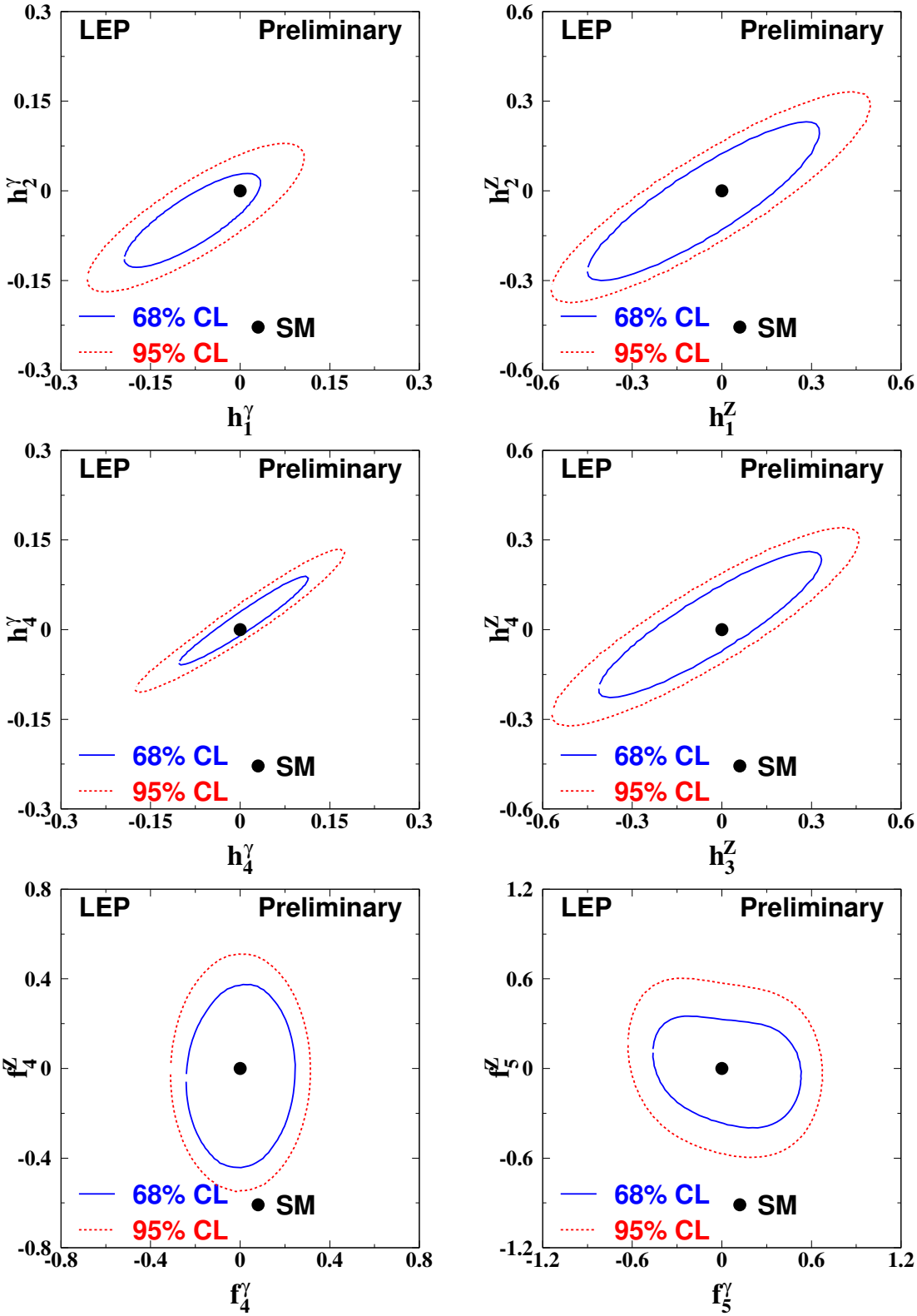
- h_V^i couplings: new analysis from L3, no new data
- f_V^i couplings: new data from DELPHI, new results from ALEPH

1–dimensional fits

h_γ^1	$[-0.09\ ,0.05\ ]$
h_Z^1	$[-0.15\ ,0.14\ ]$
h_γ^2	$[-0.05\ ,0.05\ ]$
h_Z^2	$[-0.10\ ,0.10\ ]$
h_γ^3	$[-0.07\ ,0.002]$
h_Z^3	$[-0.22\ ,0.07\ ]$
h_γ^4	$[\ 0.002,0.05\ ]$
h_Z^4	$[-0.05\ ,0.15\ ]$
f_γ^4	$[-0.21\ ,0.23\ ]$
f_Z^4	$[-0.40\ ,0.33\ ]$
f_γ^5	$[-0.37\ ,0.49\ ]$
f_Z^5	$[-0.27\ ,0.29\ ]$

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