Four-Fermions Processes and Gauge Couplings at LEP

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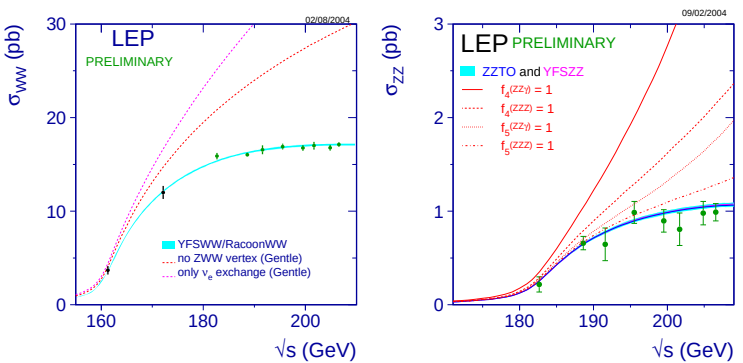
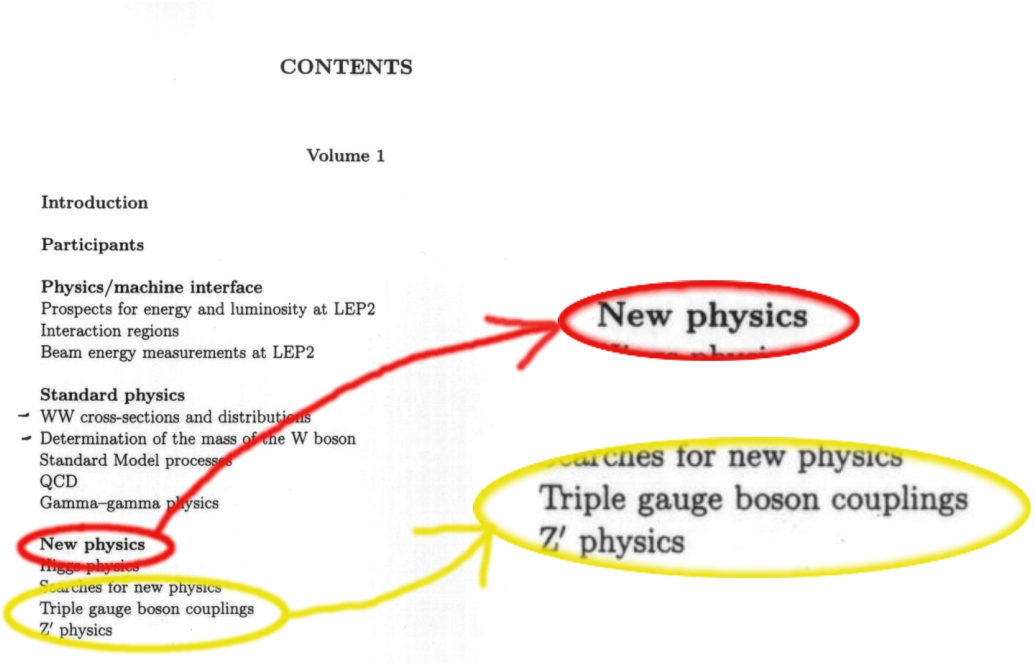
On behalf of the LEP collaborations

August 17^{th}, 2004 - ICHEP 2004, Beijing



A little of history

Once upon a time, eight years ago.....(LEP2 Physics - Yellow Report)



Limits on κ_γ in 1996: $-0.6 < \kappa_\gamma < 2.8$ (SM $= 1$)

Topics

- Four-fermion final states
- Signal definitions

results

combinations

- Charged gauge couplings
- Neutral gauge couplings
- Conclusions

Four-fermion final states

Processes:

- **W-pair production** *
- **W-pair + γ production** *
- **Weν production** *
- **Z-pair production** *
- **Zee production** *
- **qq$\ell\ell$ production**
- **qq$\nu\nu$ production**

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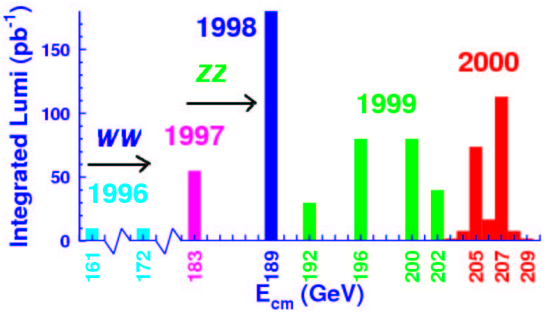
* **LEP combinations are performed**

Data sample

The complete statistics collected by the four LEP experiments from year 1996 to 2000:

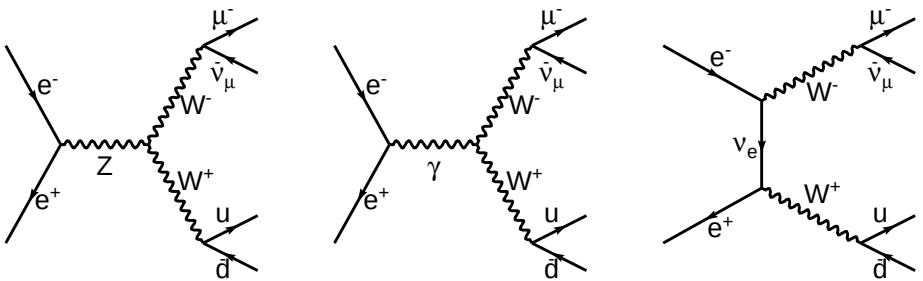


Total integrated luminosity: $\int \mathcal{L} dt \simeq 700 \text{ pb}^{-1}$/ exp. at centre-of-mass energies in the range $\sqrt{s} = 161 - 209$ GeV

Unless differently stated, all following results have been obtained using the full statistics

W-pair production- signal definition

The measured cross sections are combined at "Charged Current 03" level:



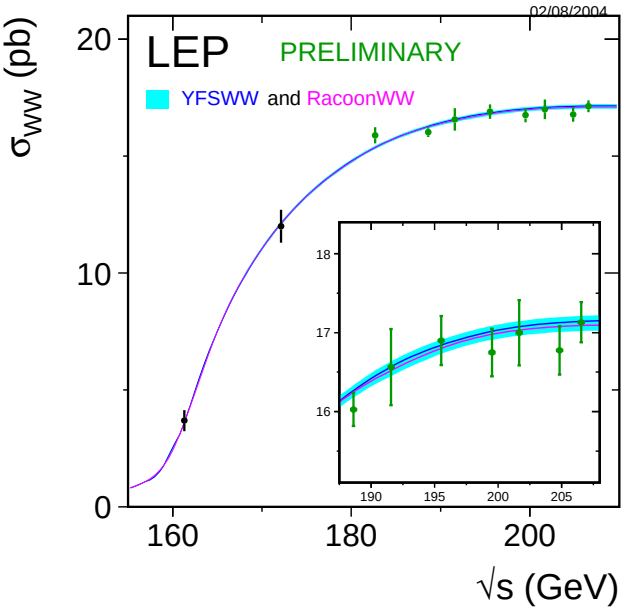
(→ "corrected" by the theoretical factor: $|M(\mathrm{CC03})|^2/|M(\mathrm{full})|^2$)

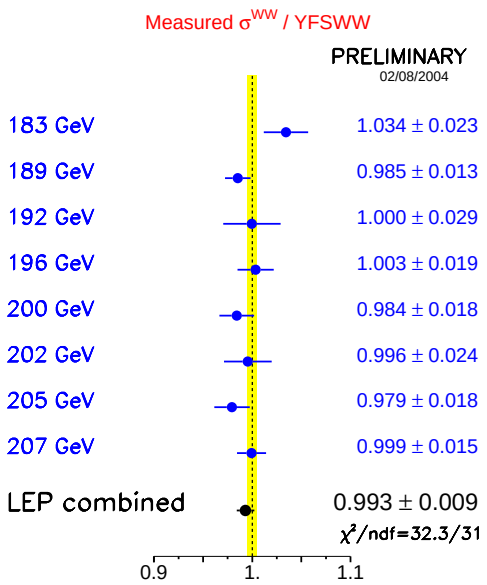
All W-boson decay modes have been analysed

# channels	process	BR
1	$\mathrm{WW} \to \mathrm{qqqq}$	45.6 %
3	$\mathrm{WW} \to \mathrm{qq}\ell\nu$	43.8 %
6	$\mathrm{WW} \to \ell\nu\ell\nu$	10.6 %

W-pair production - cross section

Step n. 1: counting the events





Theoretical accuracy: $\sim 0.5\%$

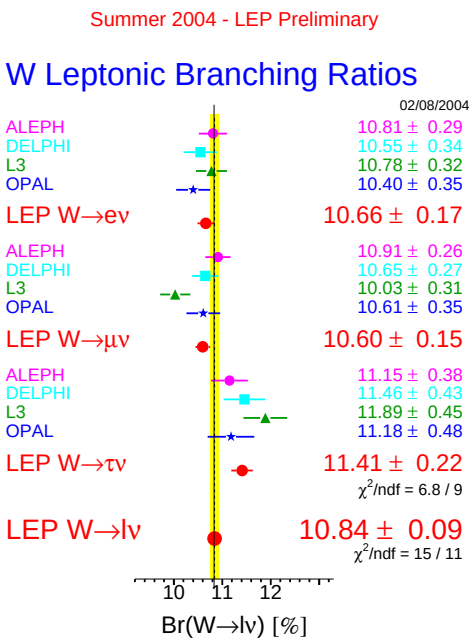
The common systematic uncertainty, dominated by the uncertainty on the hadronization modeling, is 0.6%.

W-pair production - cross section

Step n. 2: single channel analysis

From cross sections to branching ratios:

$$\sigma_{\mathrm{qq}\ell\nu} = 2Br(\mathrm{W} \to \mathrm{qq})Br(\mathrm{W} \to \ell\nu)\sigma_{\mathrm{WW}}$$



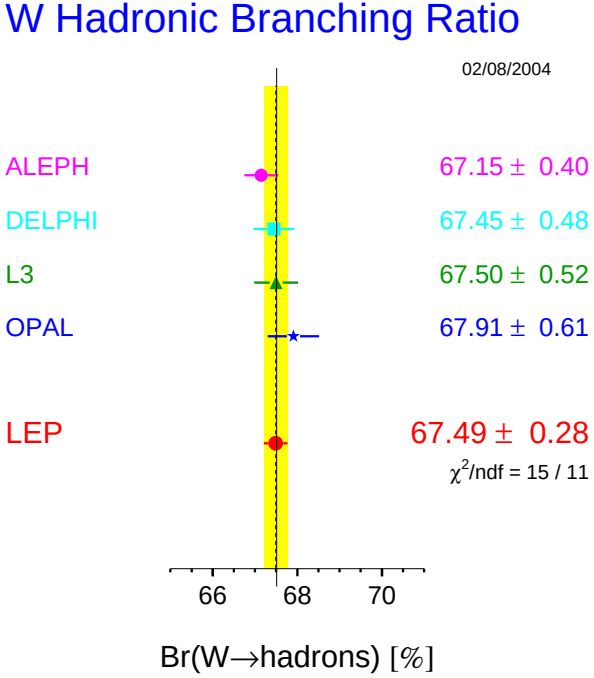
Few remarks:

1) **Aleph, Delphi and L3 results are FINAL**
2) **Lepton universality test (compatibility with averaged BR(W$\to \ell\nu$)): 2.4 equivalent sigmas**
3) **Compatibility BR(W$\to \tau\nu$) with averaged BR(W$\to$ eν)–BR(W$\to \mu\nu$): 3.0 equivalent sigmas (biased estimator...)**

W-pair production - cross section

Derived quantities:

Summer 2004 - LEP Preliminary



$$\frac{\mathbf{BR}(W \to qq)}{1 - \mathbf{BR}(W \to qq)} = \left(1 + \frac{\alpha_s(M_W^2)}{\pi}\right) \sum |\mathrm{V}_{ij}^{CKM}|^2$$

$$\Longrightarrow |V_{cs}| = 0.976 \pm 0.014$$

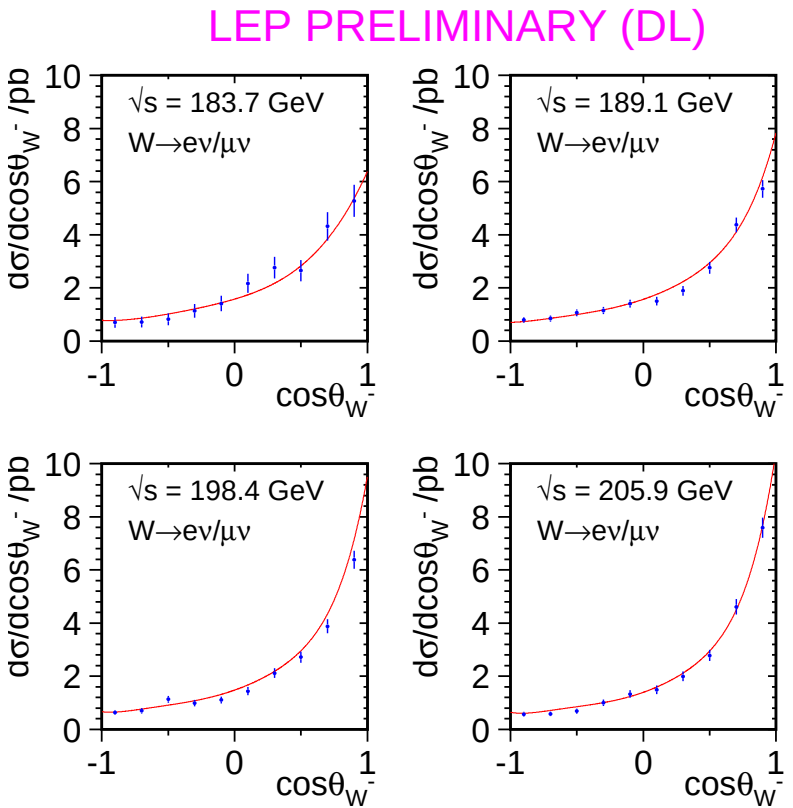
W-pair production - cross section

Step n. 3: differential cross section

The most recent legacy

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_{\mathrm{W}^-}}$$

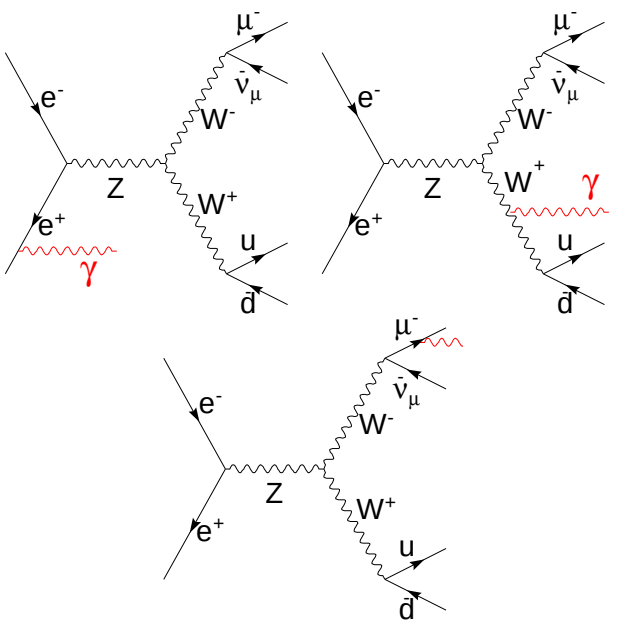
First informal combination
(only DELPHI and L3)

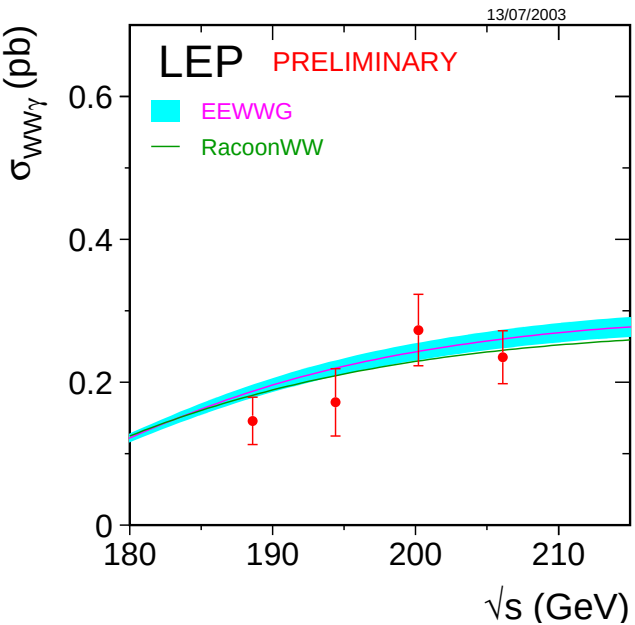


W-pair + photon production - cross section

Step n. 4: an additional photon is required in the final state

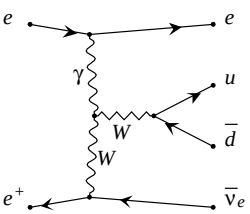
- **As a test for initial, intermediate and final state radiation**
- **Search for quartic anomalous couplings: WWZγ, WW$\gamma\gamma$**

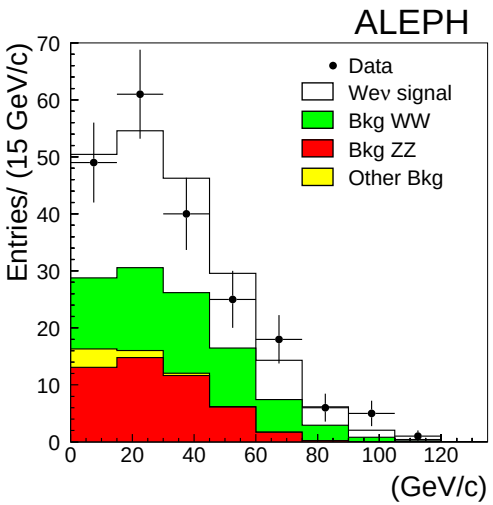


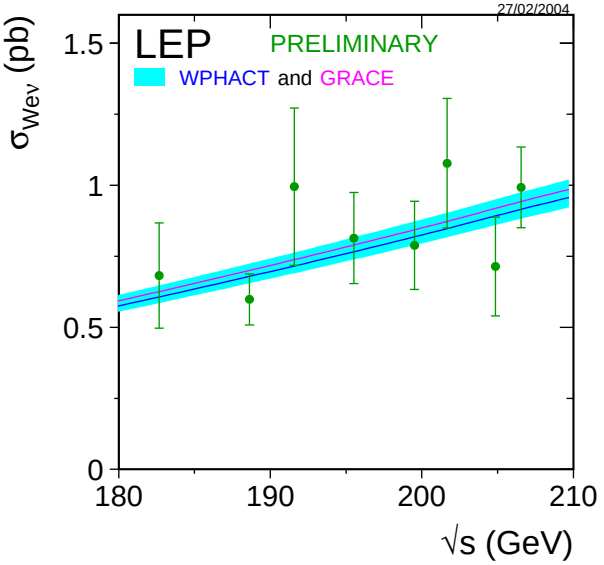


Single W production ($We\nu$) - cross section

- **Overlapping (and interfering) with $e^+e^- \rightarrow WW \rightarrow qqe\nu \Longrightarrow$ signal definition based on the t-channel diagrams**
- **Tool to study the WWγ coupling**

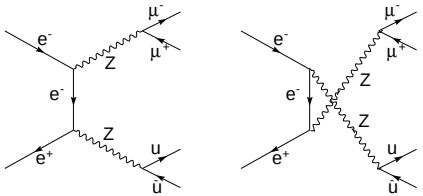


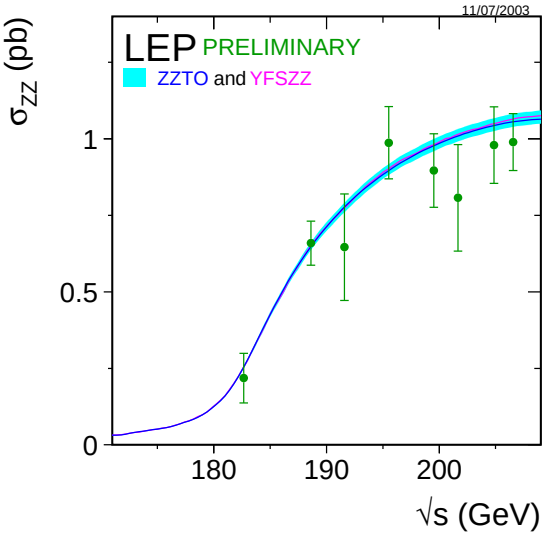




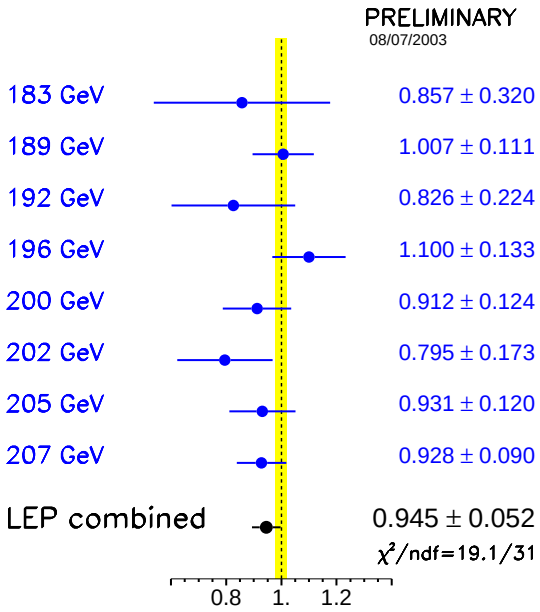
Z-pair production - cross section

- **(NC02) diagrams similar to W-pair production**
- **4-jet discriminants: b-tag and invariant mass**





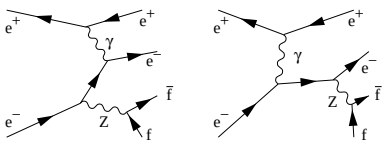
Measured σ^{ZZ} / YFSZZ

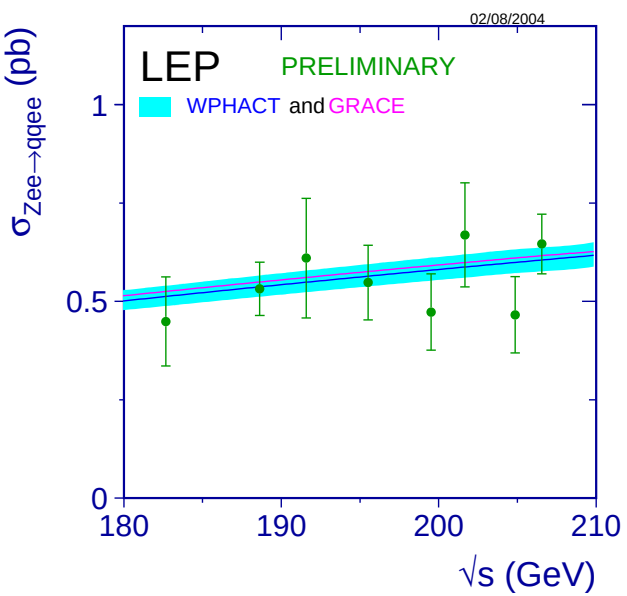


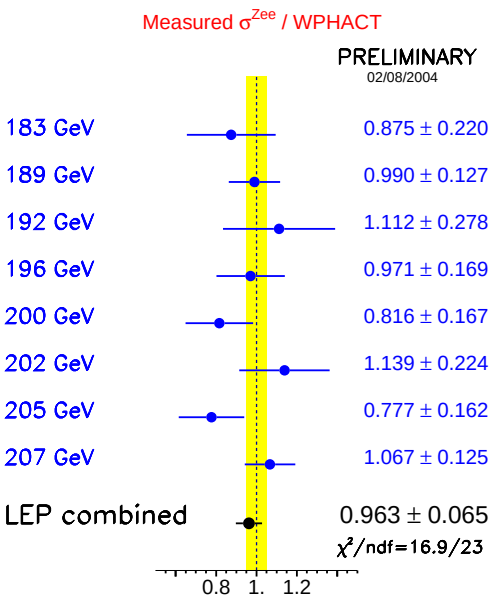
Zee production - cross section

- **Latest arrival in LEP combinations: Zee : ZZ = Weν : WW**

- **The signal definition is based on phase-space slices such to maximize:**







Charged gauge couplings

Since 1978 a general formalization of couplings in W-pair production has been adopted.
The most general Lagrangian, where only Lorentz invariance is assumed:

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

foresees 7×2 complex couplings for a total of 28 parameters.

"More or less" physical assumption, as $U(1)$, $SU(2)$ and CP conservation, help to reduce the number of free parameters.

Standard Model: $g_1^Z = g_1^\gamma = k_Z = k_\gamma = 1$
all other couplings are vanishing

Charged gauge couplings

From math to physics: observables and couplings.

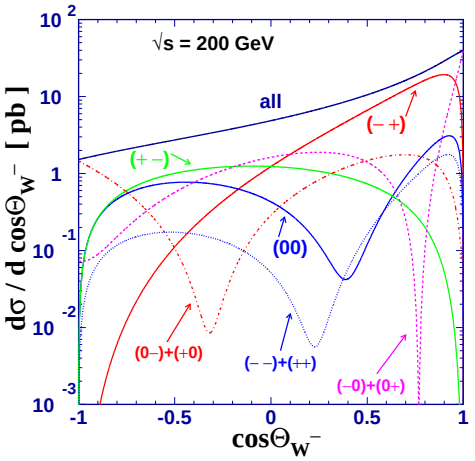
W-boson structure:

W-boson charge	Magnetic dipole moment	Electric quadrupole moment
$Q_W = e g_1^\gamma$	$\mu_W = \frac{e}{2m_W}(g_1^\gamma + \kappa_\gamma + \lambda_\gamma)$	$q_W = -\frac{e}{m_W^2}(\kappa_\gamma - \lambda_\gamma)$

(Polarized) Differential cross sections:

Production amplitudes vs W-pair polarization:

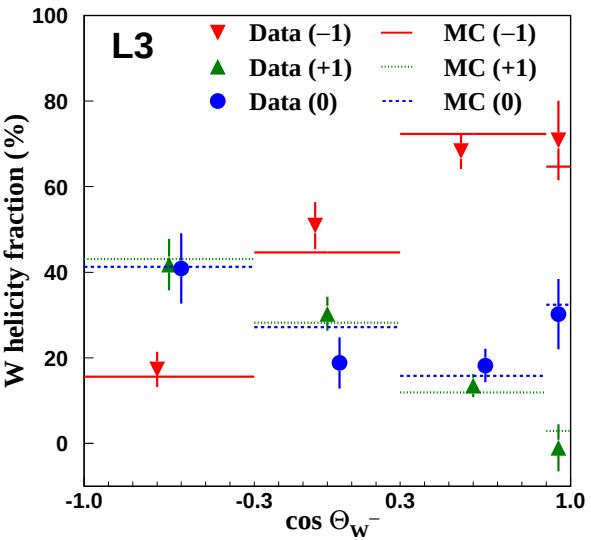
$\lambda\bar{\lambda}$	$A^V_{\lambda\bar{\lambda}}$
$++$	$g_1^V + 2\gamma^2\lambda_V + \frac{i}{\beta}(\tilde{\kappa}_V + \tilde{\lambda}_V - 2\gamma^2\tilde{\lambda}_V)$
$--$	$g_1^V + 2\gamma^2\lambda_V - \frac{i}{\beta}(\tilde{\kappa}_V + \tilde{\lambda}_V - 2\gamma^2\tilde{\lambda}_V)$
$+0$	$\gamma(f_3^V - ig_4^V + \beta g_5^V + \frac{i}{\beta}(\tilde{\kappa}_V - \tilde{\lambda}_V))$
$0-$	$\gamma(f_3^V + ig_4^V + \beta g_5^V - \frac{i}{\beta}(\tilde{\kappa}_V - \tilde{\lambda}_V))$
$0+$	$\gamma(f_3^V + ig_4^V - \beta g_5^V + \frac{i}{\beta}(\tilde{\kappa}_V - \tilde{\lambda}_V))$
-0	$\gamma(f_3^V - ig_4^V - \beta g_5^V - \frac{i}{\beta}(\tilde{\kappa}_V - \tilde{\lambda}_V))$
00	$g_1^V + 2\gamma^2\kappa_V$



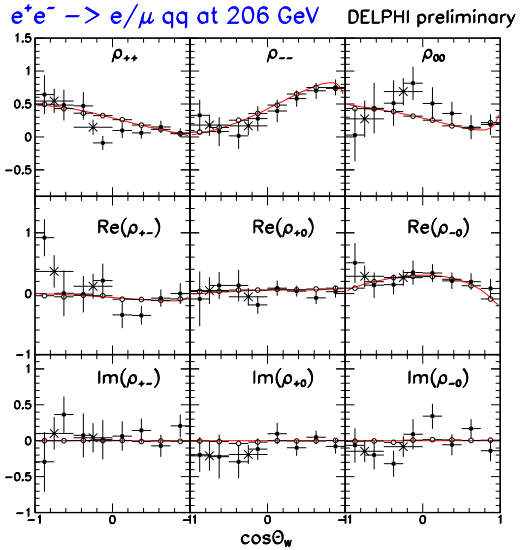
Charged gauge couplings

Step n.1: verify the Standard Model in the most general way.
Only assumption: two bosons in the final state.

Polarization studies



Spin density matrix

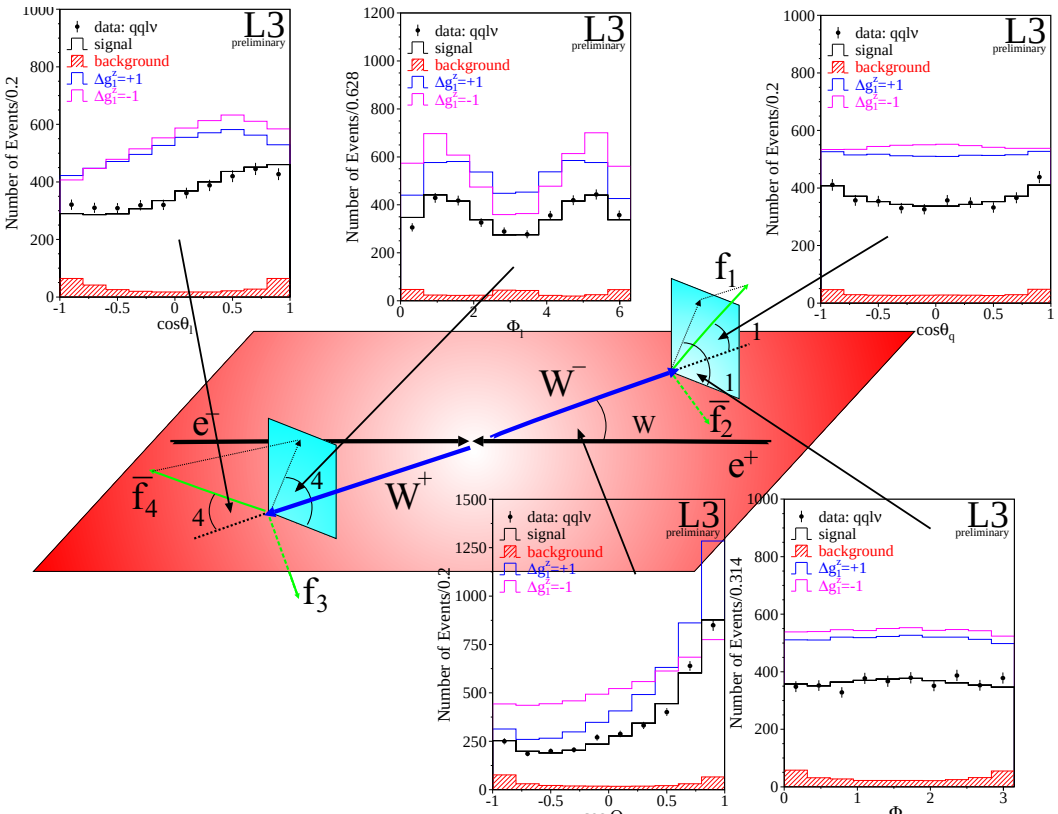


$$\rho^{W^-}_{\tau_1\tau_1'} = \sum_{\tau_2} \rho_{\tau_1\tau_1'\tau_2\tau_2} \;\; ; \;\; \rho_{\tau_1\tau_1'\tau_2\tau_2'} = \frac{\sum_\lambda F^\lambda_{\tau_1\tau_2}(F^\lambda_{\tau_1'\tau_2'})^\star}{\sum_{\lambda,\tau_1,\tau_2}|F^\lambda_{\tau_1\tau_2}|^2}$$

$\lambda =$ electrons helicities; $\tau =$ W helicities; $F =$ amplitudes

Charged gauge couplings: measurement

Maximal precision ⟶ must use the full phase-space

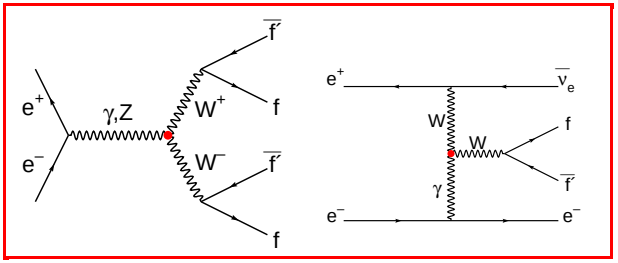


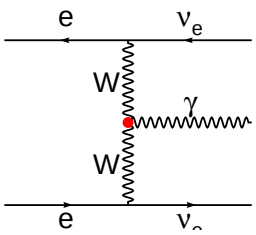
Charged gauge couplings: measurement

Common (agreed) assumptions ($U(1)$ + custodial $SU(2)$):

$$g_1^\gamma = 1$$
$$k_Z = g_1^Z - (\kappa_\gamma - 1)\tan^2\theta_W$$
$$\lambda_\gamma = \lambda_Z$$

Used channels



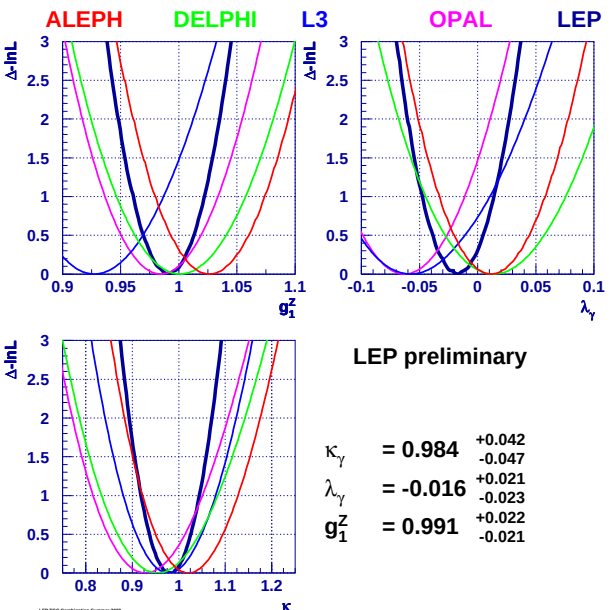


Dictionary jargon:

n–D fit: fit to n couplings fixing all others to the SM value

Charged gauge couplings: results

Lep combined 1–D fit



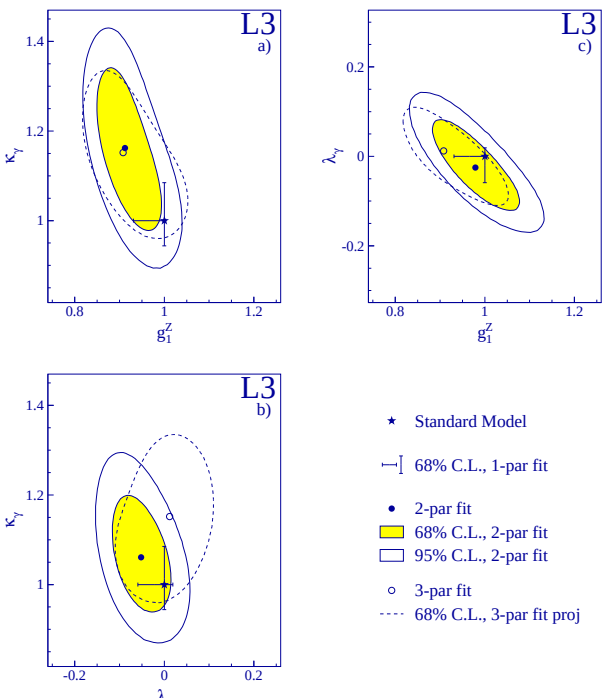
LEP preliminary

κ_γ = 0.984 $^{+0.042}_{-0.047}$

λ_γ = -0.016 $^{+0.021}_{-0.023}$

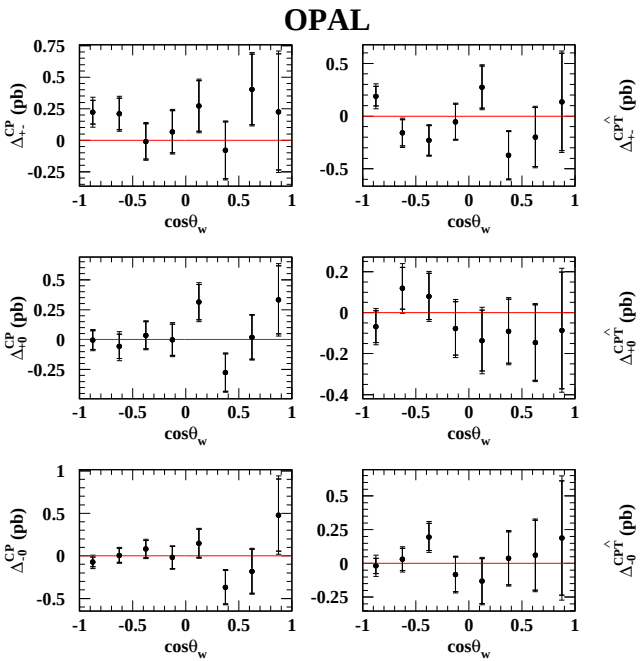
g_1^Z = 0.991 $^{+0.022}_{-0.021}$

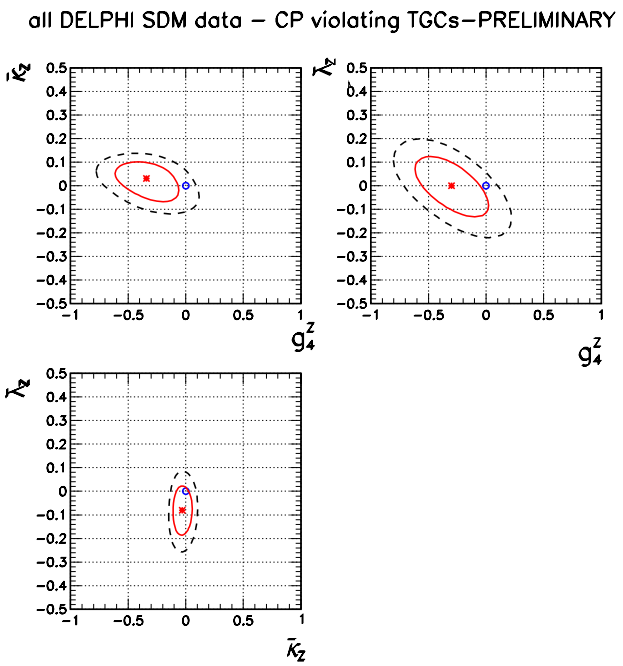
2–D e 3–D fits (L3 taken as example)



Charged gauge couplings: results

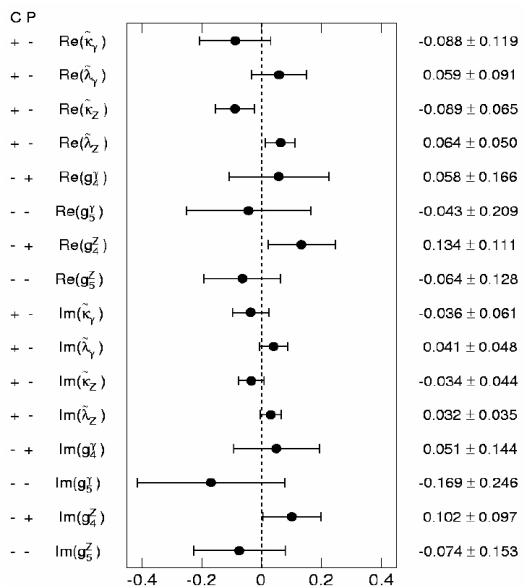
More..... CP tests, CPT tests and CP-violating couplings from SDM analyses.

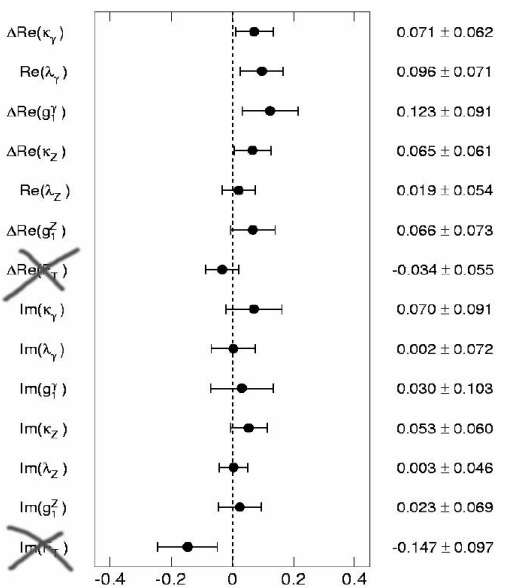




Charged gauge couplings: results

Even more..... 1–D fit (Aleph) to all 28 parameters.





F_T describes the hypothetical technirho form factor - - not discussed here

Charged gauge couplings: few comments

- All measurements are interpreted also as 95% CL limits for anomalous contributions.

$\longrightarrow$ LEPEWWG/TGC/2003-01

- The biggest systematic source comes from the uncertainties in the $\mathcal{O}(\alpha)$ (DPA) corrections.

Correlated systematics	g_1^Z	λ_γ	κ_γ
$\mathcal{O}(\alpha)$ correction	0.010	0.010	0.020
σ_{WW}	0.003	0.005	0.014
Hadronization	0.004	0.002	0.004
Bose-Einstein correlations	0.005	0.004	0.009
Colour Reconnection	0.005	0.004	0.010
$\sigma_{We\nu}$	–	–	0.011

- The total uncertainty is anyway dominated by the statistical component ($\sim 2/3$)

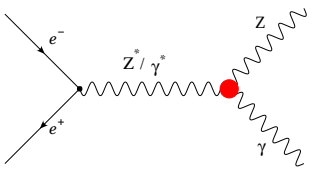
Neutral gauge couplings

Not present in the Standard Model

Formalization similar to the charged couplings (s-channel)

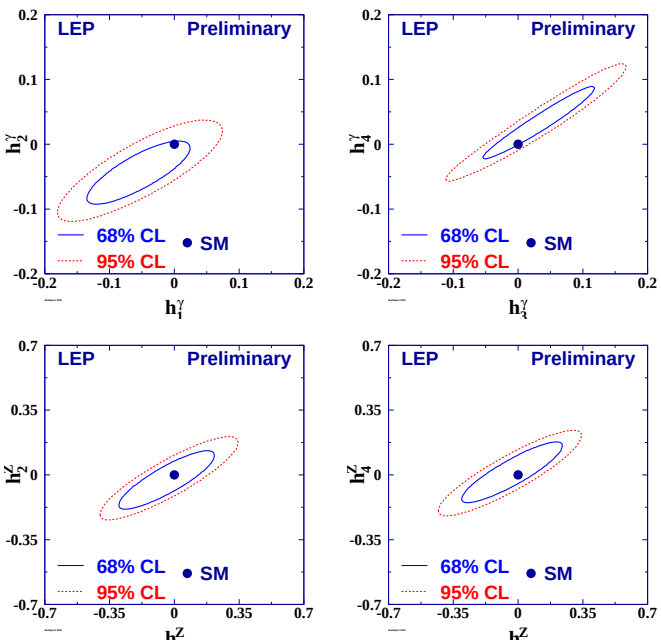
Class n. 1

(for completeness even if not four-fermion)



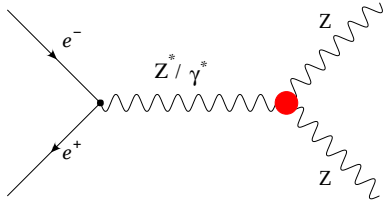
final state:
two fermions + photon

h-couplings
(8 in total)



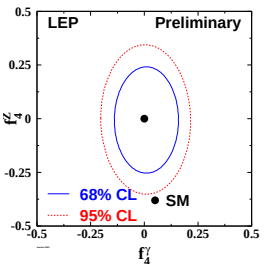
Neutral gauge couplings

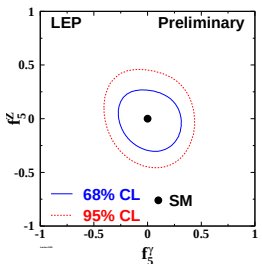
Class n. 2

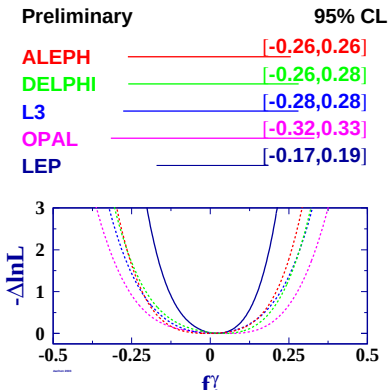


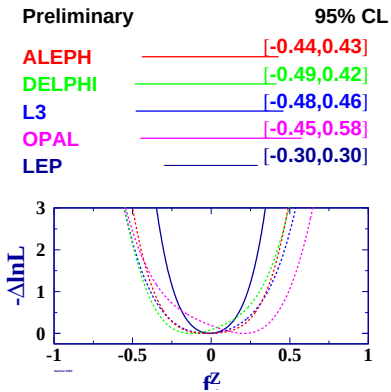
final state : four fermions

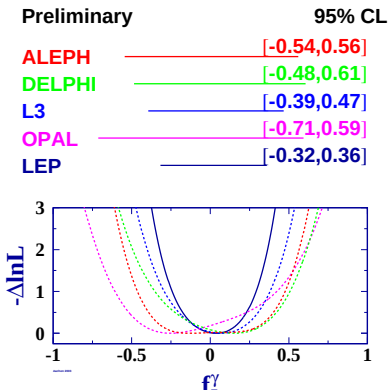
***f*-couplings**
(4 in total)

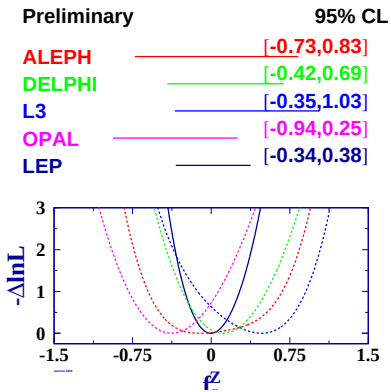








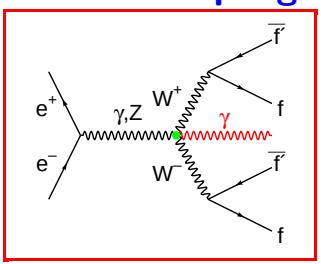


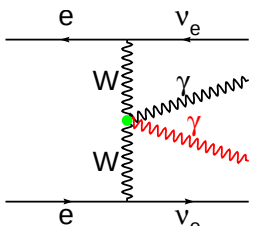


Quartic gauge couplings: W-pair final states

Present in the Standard Model but statistically inaccessible at LEP

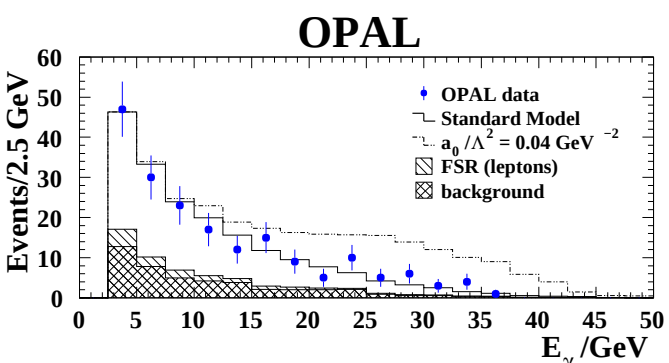
$\Longrightarrow$ search for anomalous couplings:





Parametrized in function of the couplings: a_0^W, a_c^W e a_n^W

Fit based on total and differential cross sections



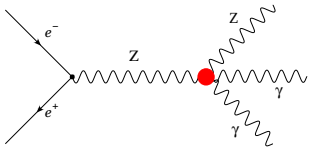
Latest LEP combination
(2001 – ALEPH, L3, OPAL)

$$-0.02 \leq a_0^W/\Lambda^2 \leq 0.02 \text{ GeV}^{-2}$$
$$-0.03 \leq a_c^W/\Lambda^2 \leq 0.05 \text{ GeV}^{-2}$$
$$-0.17 \leq a_n^W/\Lambda^2 \leq 0.15 \text{ GeV}^{-2}$$

(95% CL)

Quartic gauge couplings: $Z\gamma\gamma$ final states

Not present in the Standard Model $\Longrightarrow$ search for anomalous contributions

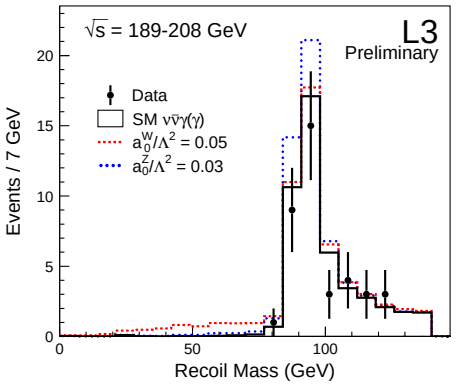


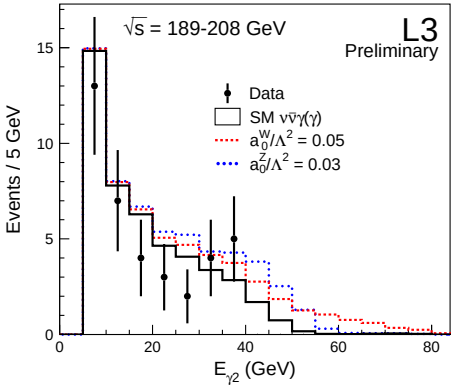
Couplings: a_0^Z e a_c^Z

Latest LEP combination
(2003 – ALEPH, L3, OPAL)

$$-0.008 \leq a_0^Z/\Lambda^2 \leq 0.021 \text{ GeV}^{-2}$$
$$-0.029 \leq a_c^Z/\Lambda^2 \leq 0.039 \text{ GeV}^{-2}$$

(95% CL)





Summary table

Towards final results.....

	Aleph	L3	Delphi	Opal
W-pair	✓	✓	✓	✗
Single W	✓	✓	✗	✗
Z-pair	✗	✓	✓	✓
Zee	✓	✓	✗	✗
Charged TGC	✗	✓	✗	✓

Most of the ✗ are in their final stage

Conclusions

- Four-fermion cross sections measured at the level of the theoretical accuracy
- Gauge couplings measured at the percent level
- All data analyzed
- Marginal changes expected from final combinations (winter 2004/2005?)

- In eight years, from "new physics" to precision measurements
- The Standard Model is still frustrately healthy

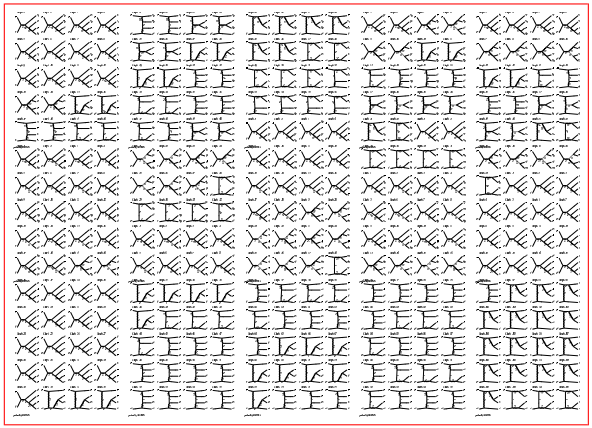
Backup Slides

Four-fermion final states

Conceptually simple:

$$e^+e^- \to f\,f\,f\,f$$

In practice:



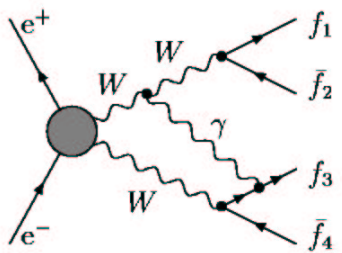
$\times$ 10 = 3000 diagrams

Theoretical calculations

The theoretical uncertainty on the four-fermion production cross section varies from 2% to 5% depending on the final state.

In the case of $\mathbf{e^+e^- \rightarrow W^+W^-}$ the uncertainty has been reduced under the push of the experimental precision.

The "Double Pole Approximation" used to calculate $\mathcal{O}(\alpha)$ virtual corrections of the type:



DPA - A. Aeppli, G.J. van Oldenborgh, D. Wyler
Nucl. Phys. **B428** (1994) 126

YFSWW3 - S. Jadach, W. Płaczek, M. Skrzypek, B.F.L. Ward, Z. Wąs,
Phys. Rev. **D61**, 113010 (2000)

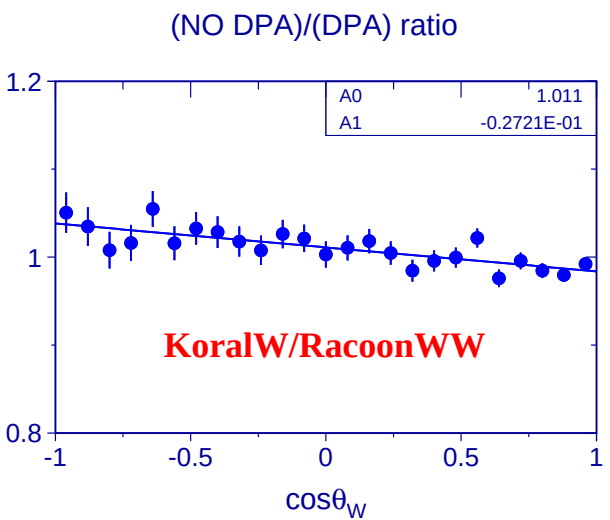
RacoonWW - A.Denner, S.Dittmaier, M.Roth, D.Wackeroth,
Nucl. Phys. **B587** (2000) 67-117

allowed to reduce the theoretical uncertainty to the 0.5% level..

Theoretical calculations

The biggest effect of the DPA approach is visible in the angular distributions:

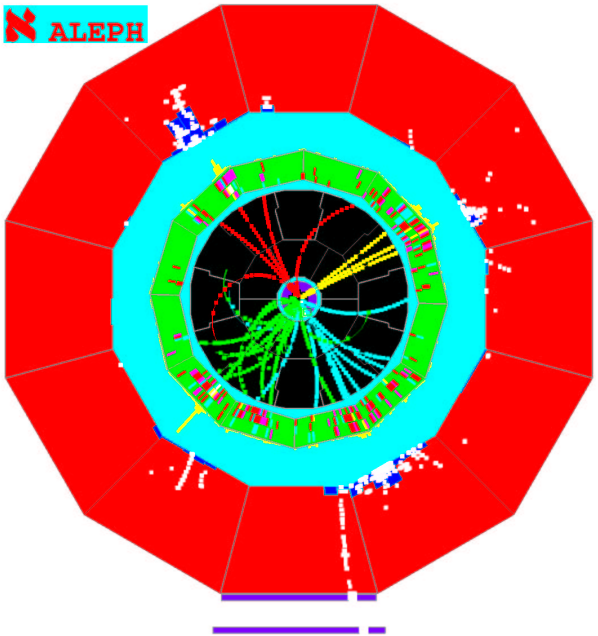
$\frac{d\sigma}{d\cos\theta_W}$, θ_W: W-boson polar angle in the lab frame



Up to 2 % of relative difference
Potentially dangerous for the derivation of gauge couplings.

W-pair production - selections

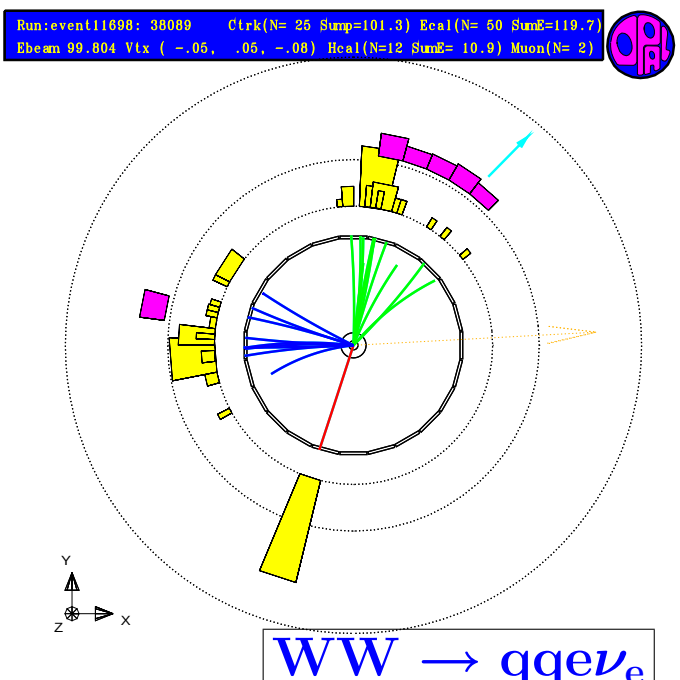
Hadronic channel: $\mathrm{WW} \rightarrow \mathrm{qqqq}$



- Four hadronic jets
- Low missing energy
- 6000 events/experiment

W-pair production - selections

Semileptonic channels: $\mathrm{WW} \to \mathrm{qq}\ell\nu$

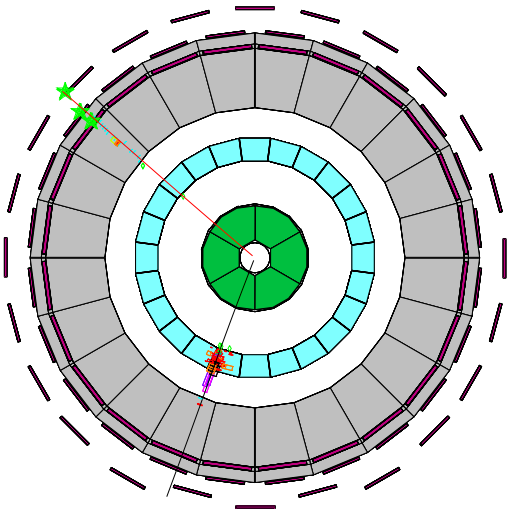


$\mathrm{WW} \to \mathrm{qqe}\nu_\mathrm{e}$

- Two hadronic jets + isolated lepton
- Missing energy due to the neutrino
- 4500 events/experiment

W-pair production - selections

Leptonic channels: $\mathrm{WW} \to \ell\nu\ell\nu$



$\mathrm{WW} \to \mu\nu_\mu \mathrm{e}\nu_\mathrm{e}$

- Two acoplanar high-energy leptons
- Missing energy due to the neutrinos
- 800 events/experiment

Contents