W physics at LEP

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On behalf of the L3 collaboration

- WW Cross section
- W mass
- Trilinear Gauge Boson Couplings
- Interconnection effects
- Charm production in W decays
- Conclusions

Introduction

In summer 1996 LEP crossed for the first time the WW production threshold.

Data-taking periods can be grouped around four energies:

Period	$\int \mathcal{L}$ (pb^{-1})	Energy (GeV)
1996 a	12.1	161
1996 b	11.3	172
1997	63.8	183
1998	150 ?	189

Most of the results presented here are dominated by the results from the 183 GeV run.

Signal definition

W pair decays can be classified into 5 channels:

Channel	SM B.R.(%)
$l\nu l\nu$	10.6
$qq\mu\nu$	14.6
$qqe\nu$	14.6
$qq\tau\nu$	14.6
$qqqq$	45.6

For each different final state, there is a different set of diagrams contributing to the process:

	$\bar{d}u$	$\bar{s}c$	$\bar{e}\nu_e$	$\bar{\mu}\nu_\mu$	$\bar{\tau}\nu_\tau$
$d\bar{u}$	*43*	**11**	20	**10**	**10**
$e\bar{\nu}_e$	20	20	*56*	18	18
$\mu\bar{\nu}_\mu$	**10**	**10**	18	*19*	**9**

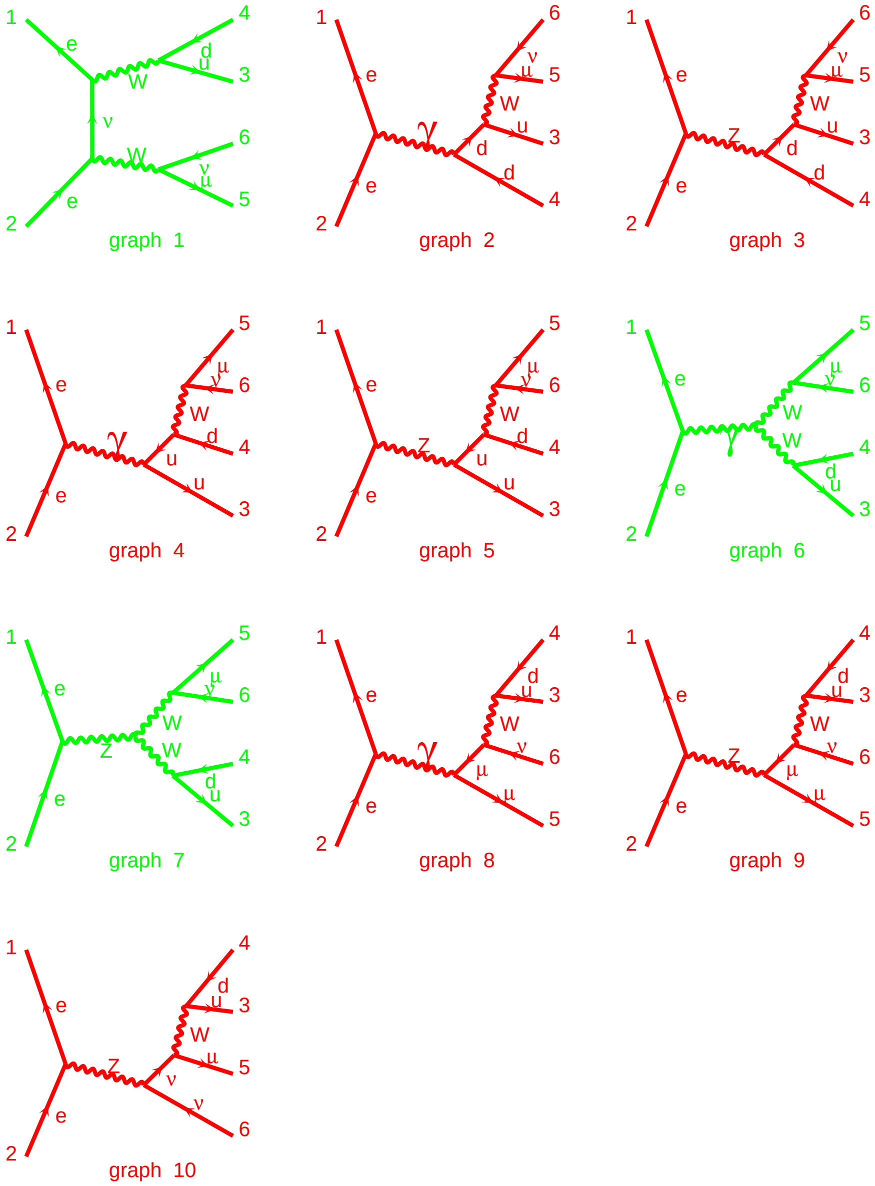
different fermion pairs

e, ν_e in the final state

neutral current diagrams present

Signal definition

As an example, the following diagrams contribute to $e^+e^- \to u\bar{d}\mu\bar{\nu}_\mu$ processes:



Signal definition

Only three diagrams (in green) are "genuine" W-pair production.

Contributions from single- and non-resonant processes are particularly important in $l\nu l\nu$ and $qqe\nu$ final states.

Treatment of the other diagrams is different for the LEP experiments, leading to different signal definitions:

- DELPHI, L3: consider efficiencies inside generator level cuts, and apply multiplicative factors for CC03-equivalent cross section
- ALEPH, OPAL: consider additional diagrams as a background, neglecting interference

These procedures give the same results within a 1% accuracy.

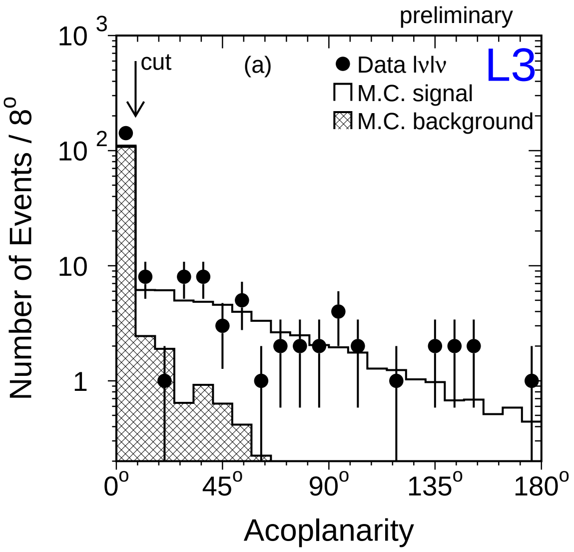
Event topology:

- two high-energy acoplanar leptons
- missing momentum not pointing to the beam-pipe.

main backgrounds:

- Two-fermion events from Z/γ decays (especially τ), Bhabha
- $\gamma - \gamma$ interactions

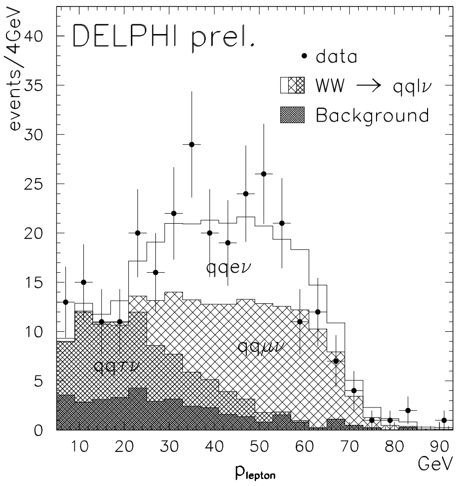
The selections for this channel require two identified leptons (or narrow jets to account for τ decays)



Selection of Semileptonic Events

The three semileptonic channels have similar topology but different background. Analysis is similar, requiring a lepton (or jet for τ), two hadronic jets and a neutrino (large $\not{P}$).
Background:

- $q\bar{q}\gamma$ (photon detected for $qqe\nu$, $b\bar{b}$ for $qq\mu\nu$, photon undetected for $qq\tau\nu$)
- 4-fermion, $\gamma - \gamma$ processes



Selection:

- ALEPH, OPAL build event probability function
- L3, DELPHI use cuts on lepton isolation, invariant masses etc.

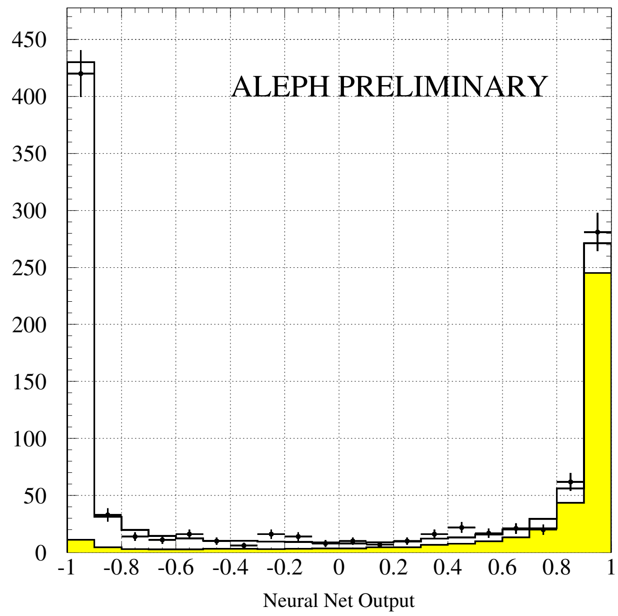
Signal and the main background ($q\bar{q}$ with hard gluon radiation) are quite similar.

Gluon jets are on average softer and closer to the emitting quark. This is exploited by DELPHI, where the variable

$$D = \frac{E_{min}}{E_{max}} \frac{\theta_{min}}{E_{max} - E_{min}}$$

is used.

All other experiments use a likelihood discriminator (OPAL) or a neural network (ALEPH, L3).



Cross Section and Branching Ratios

Measurements of total WW cross sections and W branching fractions are obtained via a likelihood fit to observed and expected number of events in all channels (N_i and μ_i).

$$\mathcal{L} = \Pi_i P(N_i, \mu_i)$$

The expected number is computed accounting for background (σ_i^{bg}) and cross-efficiencies (ϵ_{ij}):

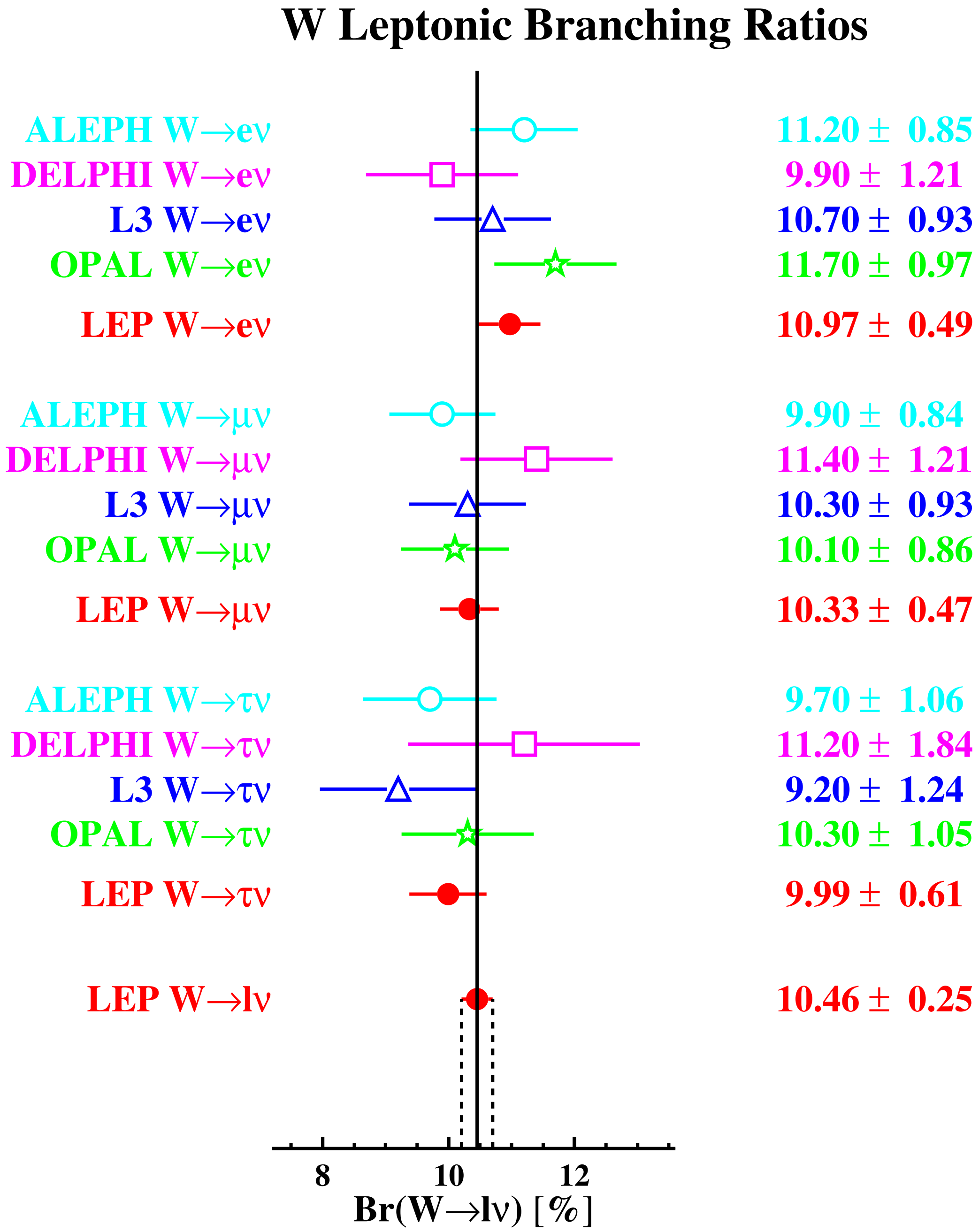
$$\mu_i = \mathcal{L}(\epsilon_{ij}\sigma^j + \sigma_i^{bg})$$

When a cross section is extracted via a likelihood function, the likelihood itself is used.

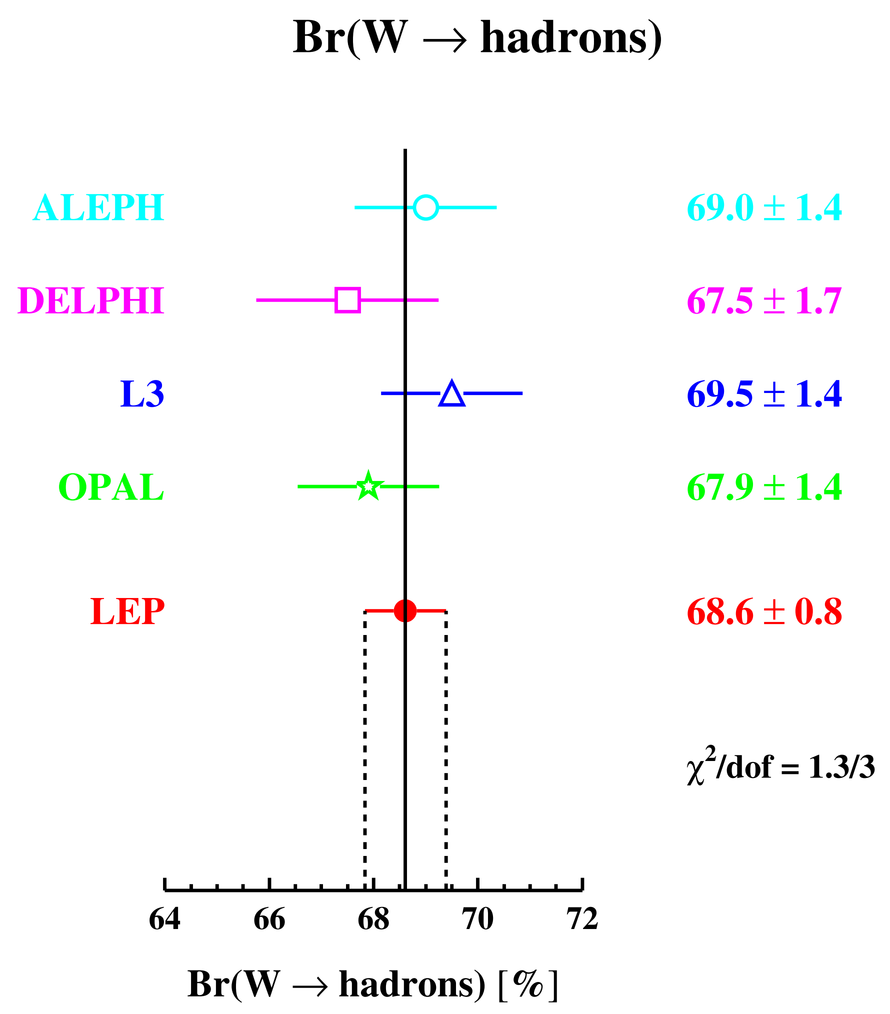
The individual cross sections σ^j are obtained as parameters from the fit.

It is possible to express them as a function of the total cross section imposing SM branching fraction, or as a function of the latter, assuming or not lepton universality.

W Branching Fractions



SM prediction: 10.8%

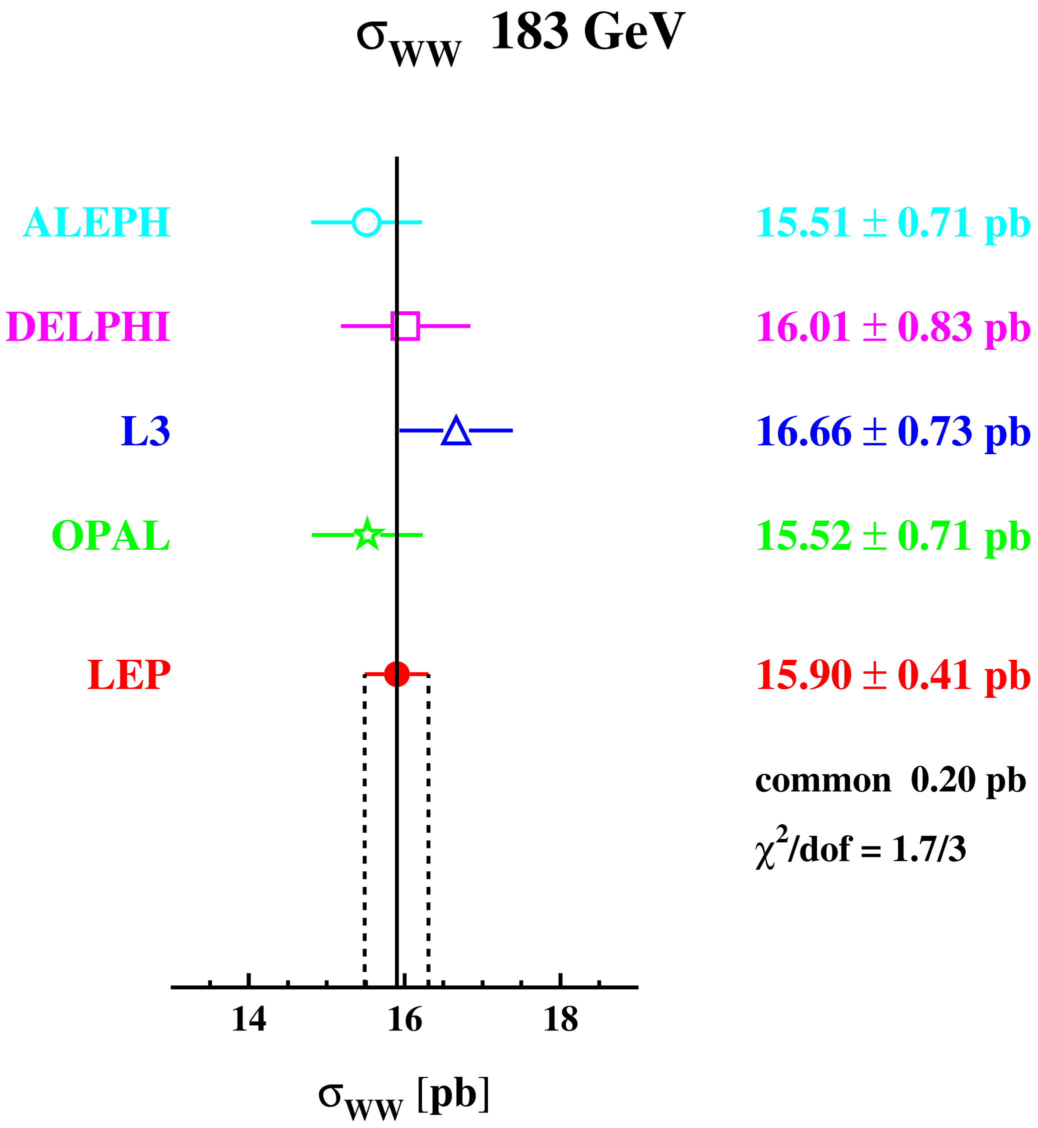


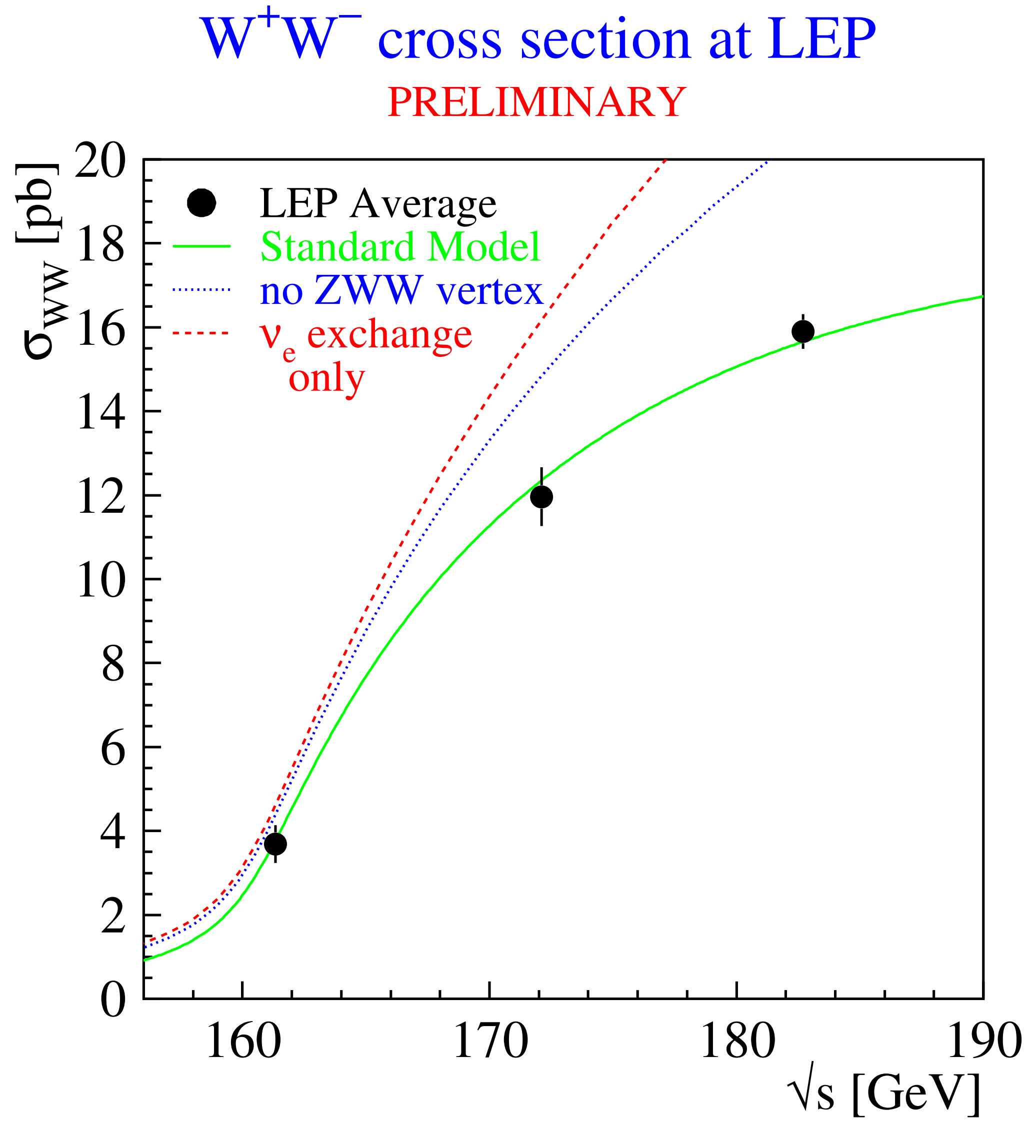
SM prediction: 67.5%

$$\frac{Br(W \to q\bar{q})}{1 - Br(W \to q\bar{q})} = (1 + \frac{\alpha}{\pi})\Sigma|V_{ij}|^2$$

$$\Sigma|V_{ij}|^2 = 2.10 \pm 0.08$$

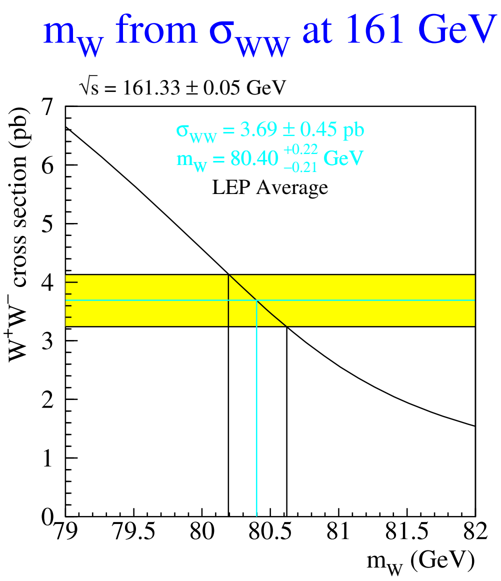
$$|V_{cs}| = 1.03 \pm 0.04$$


σ_{WW} 183 GeV
ALEPH
DELPHI
L3
OPAL
LEP
15.51 ± 0.71 pb
16.01 ± 0.83 pb
16.66 ± 0.73 pb
15.52 ± 0.71 pb
15.90 ± 0.41 pb
common 0.20 pb
χ^2/dof = 1.7/3
14
16
18
σ_{WW} [pb]



Non-Abelian structure of the electroweak interactions confirmed.

Assuming validity on the SM, the W mass can be extracted from the cross section. The sensitivity of this approach is maximal close to threshold:



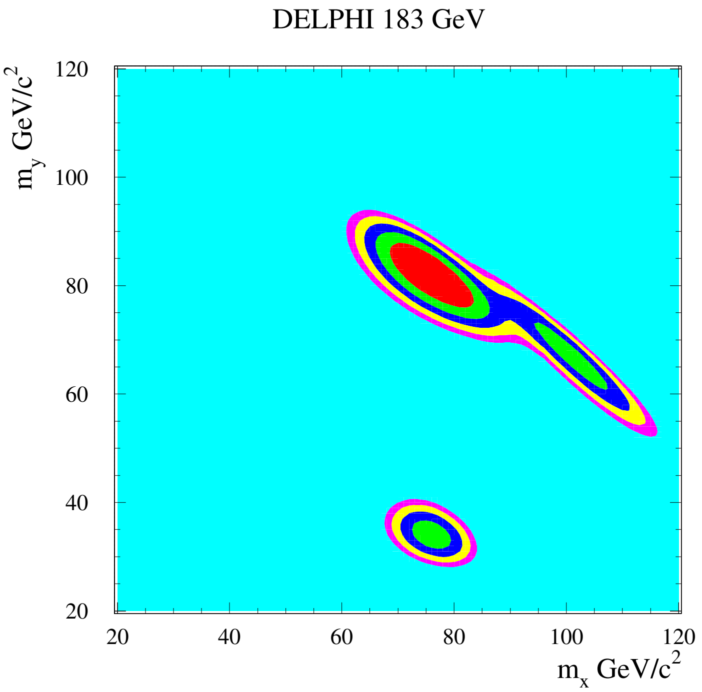
At higher energies, the W mass is extracted fitting the invariant mass distribution of W decay products.
Two main approaches are used:

- convolution
- MC reweighting

All collaborations use both, one for the final results and the other as a crosscheck.

Convolution

In the convolution method (Delphi), the theoretical W line-shape curve is convoluted with an analytical function describing detector effects. All data events are then compared with the theoretical+convolution curve, obtaining a likelihood dependent on the W mass.

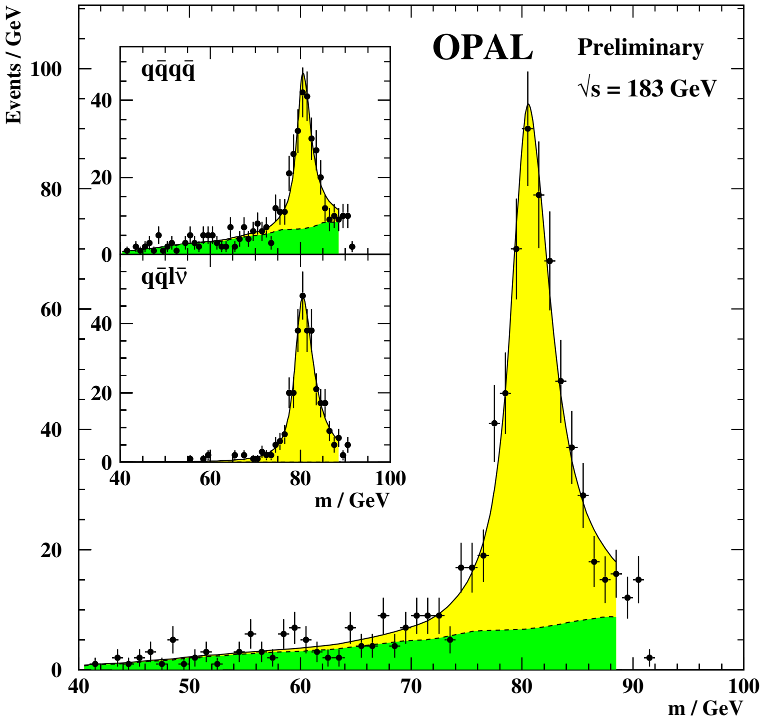


This allows use of different event weight depending on the resolution (see above) thus improving the precision.
In particular, Delphi fits the masses in the M_W^1, M_W^2 plane, using all three combinations for the qqqq channel.

MC Reweighting

This method, used by the other collaborations, uses a large number of Monte Carlo events to establish the correspondence between generated and reconstructed masses.

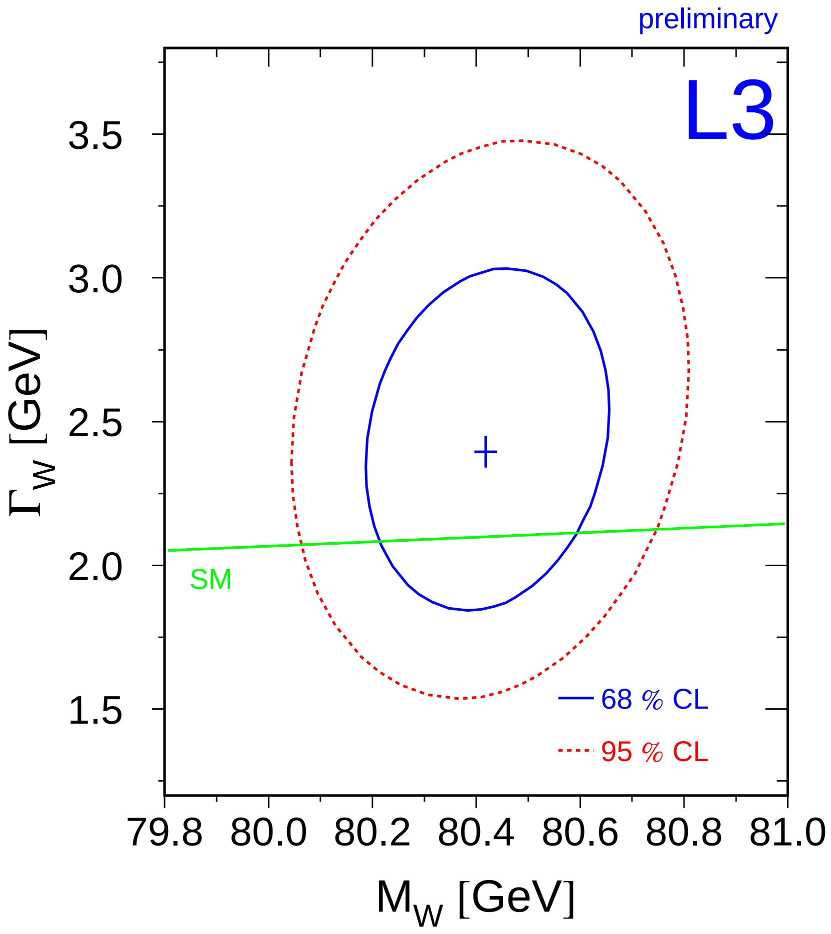
These events are generated with a value of the W mass; an analytical code is used to reweight them according to the mass that best fits the data.



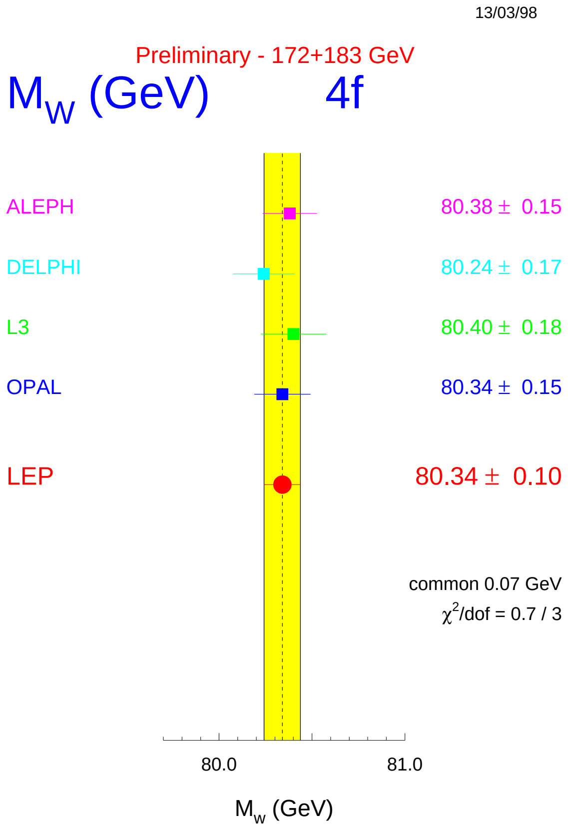
The curve shown is obtained via the reweighting procedure, in the fitted range.

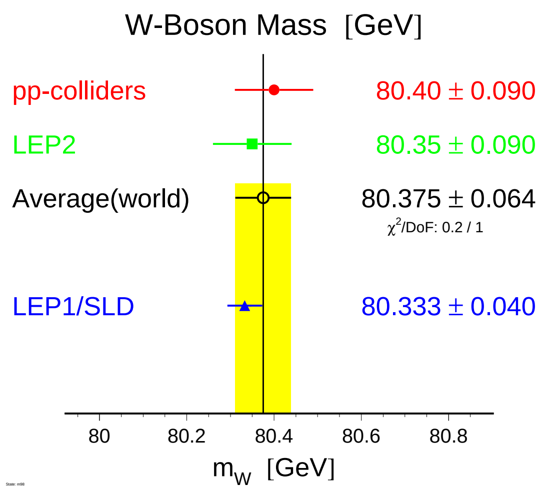
With both reweighting and convolution methods it is possible to perform two-parameter fits to extract both W mass and width.

The correlation between the two measurements is usually small.



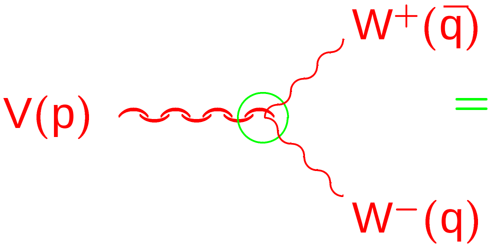
W Mass Results





Trilinear Gauge Coupling

New physics can show up in the couplings of gauge bosons:



$$= -ieg_{VWW}\Gamma_{V}^{\alpha\beta\mu}(q,\bar{q},p)$$
$$g_{\gamma WW} = 1$$
$$g_{ZWW} = \cot\theta_W$$
$$\delta_Z = g_{ZWW} - \cot\theta_W$$

Assuming real couplings, C-, P- and CP invariance, 5 couplings remain:

$$\delta_z, \kappa_\gamma, \kappa_Z, \lambda_\gamma, \lambda_Z$$

Related to magnetic and electric W quadrupole moments:

$$\mu_W = \frac{e}{2m_W}(1+\kappa_\gamma+\lambda_\gamma), Q_W = -\frac{e}{m_W}(\kappa_\gamma-\lambda_\gamma)$$

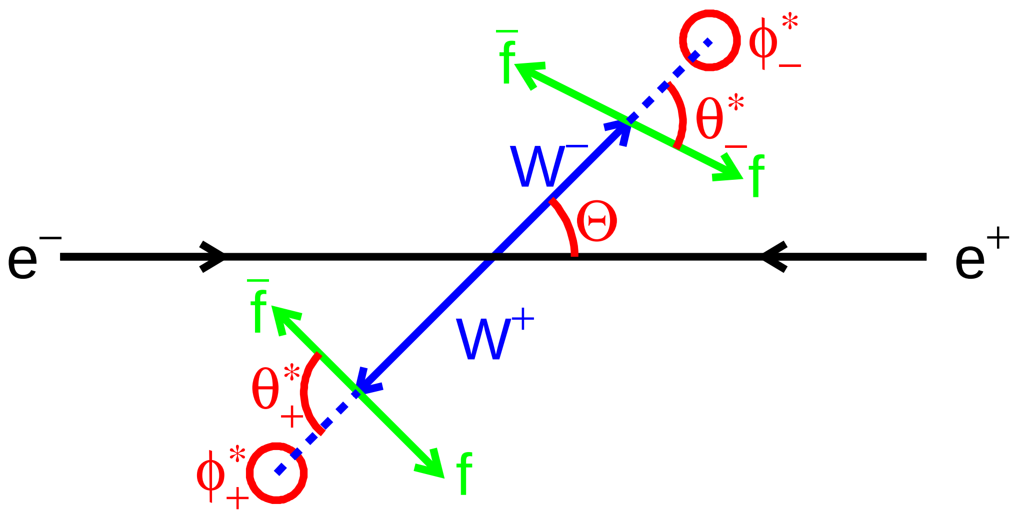
Results are given in terms of linear combinations of the above:

$$\alpha_{W\Phi} = \Delta g_{ZWW}\cos^2\Theta_W$$
$$\alpha_W = \lambda_\gamma$$
$$\alpha_{B\Phi} = \Delta\kappa_\gamma - g_{ZWW}\cos^2\Theta_W$$

Trilinear Gauge Coupling

Anomalous couplings modify the WW production cross section and to a distortion of the event kinematics.

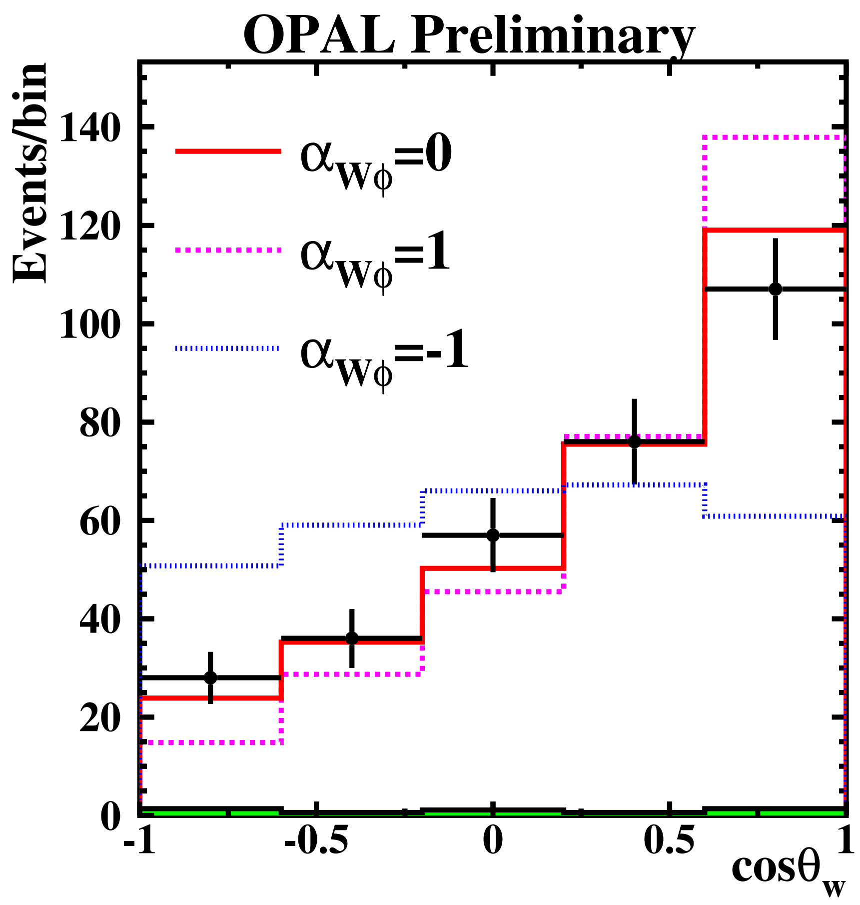
Experimentally, the study of these couplings is performed fitting both cross section and the distribution of the W production and decay angles.



Θ — W^- polar production angle

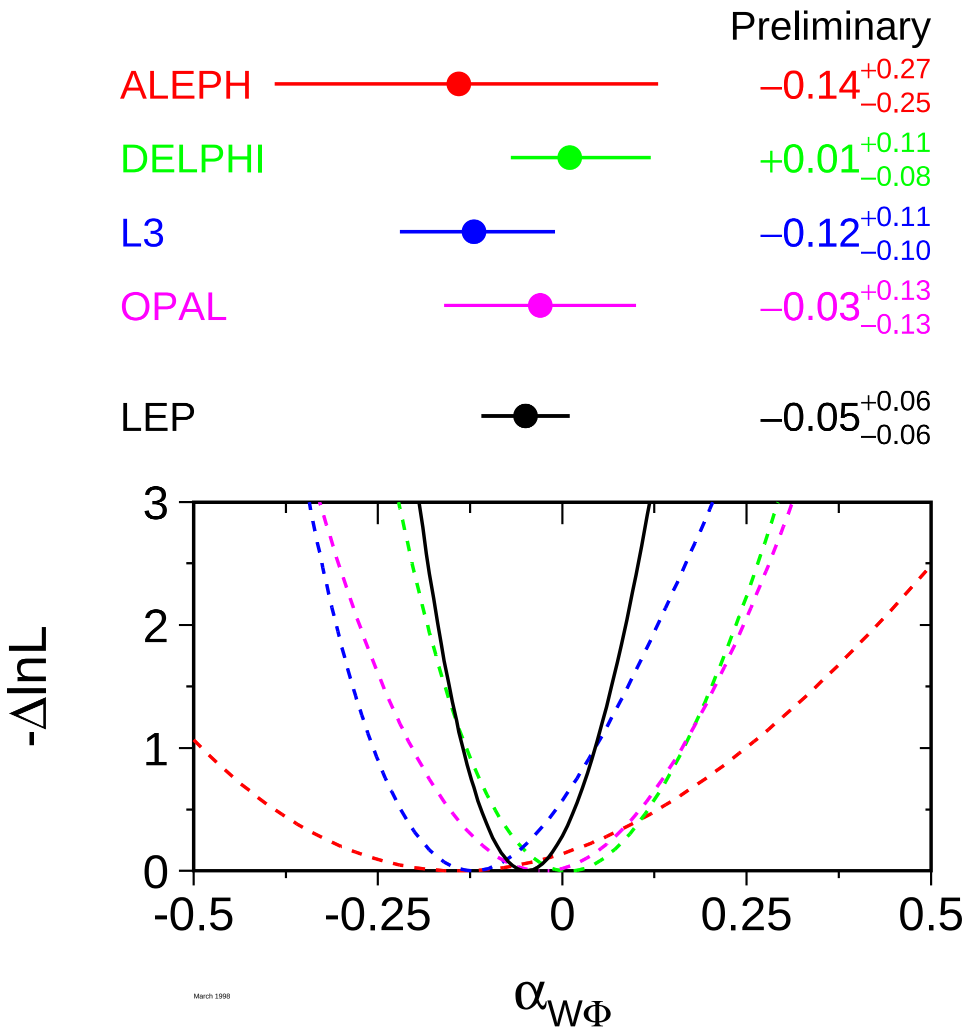
$\left.\begin{array}{l}\theta^*_+, \phi^*_+ \\ \theta^*_-, \phi^*_-\end{array}\right\}$ $W^\pm$ decay angles in respective W rest system

Detector effects for the angular distribution are accounted for using reweighting algorithms similar to those used for the mass.



Reconstructed W^- production angle for semileptonic events in OPAL at $\sqrt{s} = 183$ GeV.

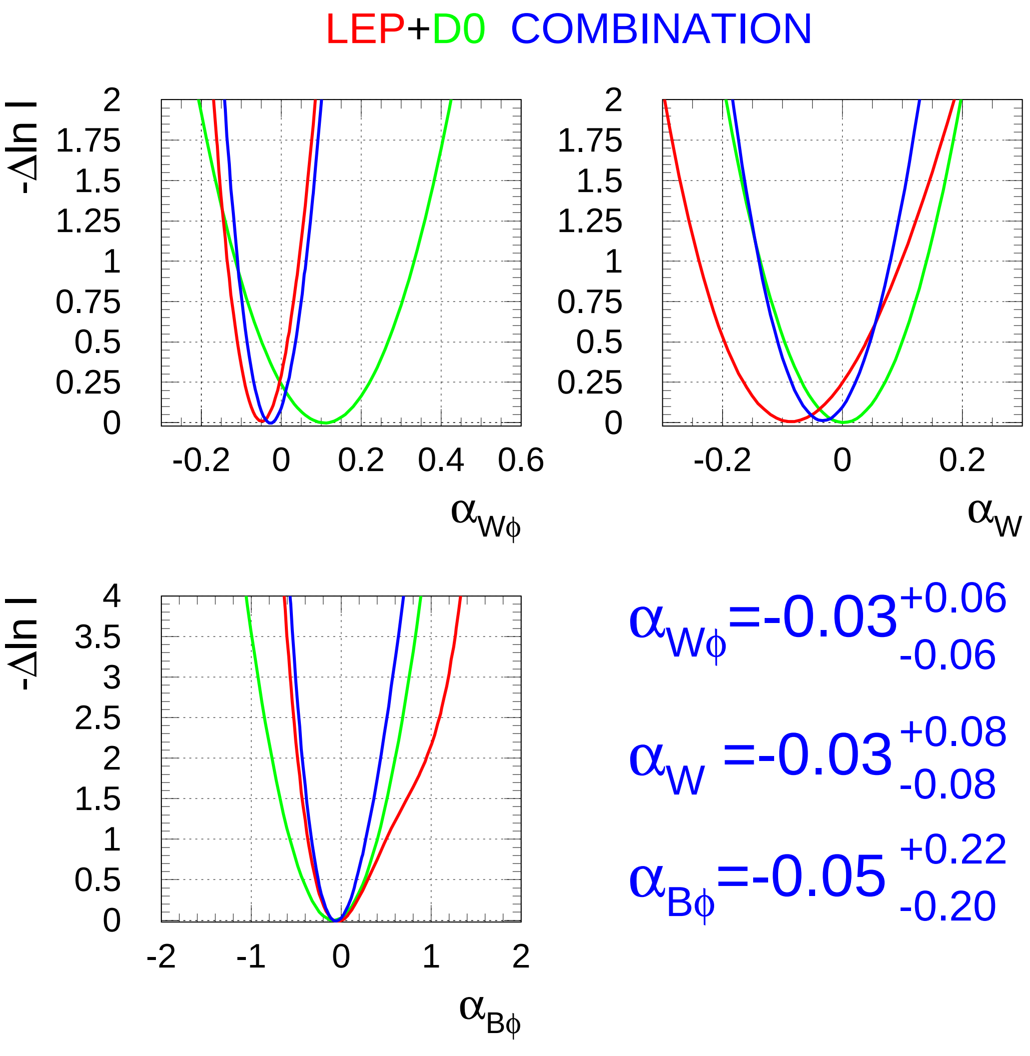
TGC Results



Preliminary
ALEPH
$-0.14^{+0.27}_{-0.25}$
DELPHI
$+0.01^{+0.11}_{-0.08}$
L3
$-0.12^{+0.11}_{-0.10}$
OPAL
$-0.03^{+0.13}_{-0.13}$
LEP
$-0.05^{+0.06}_{-0.06}$
-ΔlnL
3
2
1
0
-0.5
-0.25
0
0.25
0.5
March 1998
$\alpha_{W\Phi}$

TGC results

The sensitivity to the gauge couplings is similar to that obtained in hadronic machines with many more events:



Bose-Einstein Correlation and Colour Reconnection lead to distortions to the W mass distribution that may induce important systematics.

BEC enhance production of identical bosons close in phase-space.
Already seen in nucleus-nucleus, hadron-hadron and $e^+e^- \to Z$ processes.

They can occur:

- between bosons within same jet
- between bosons from same W
- between bosons from different Ws

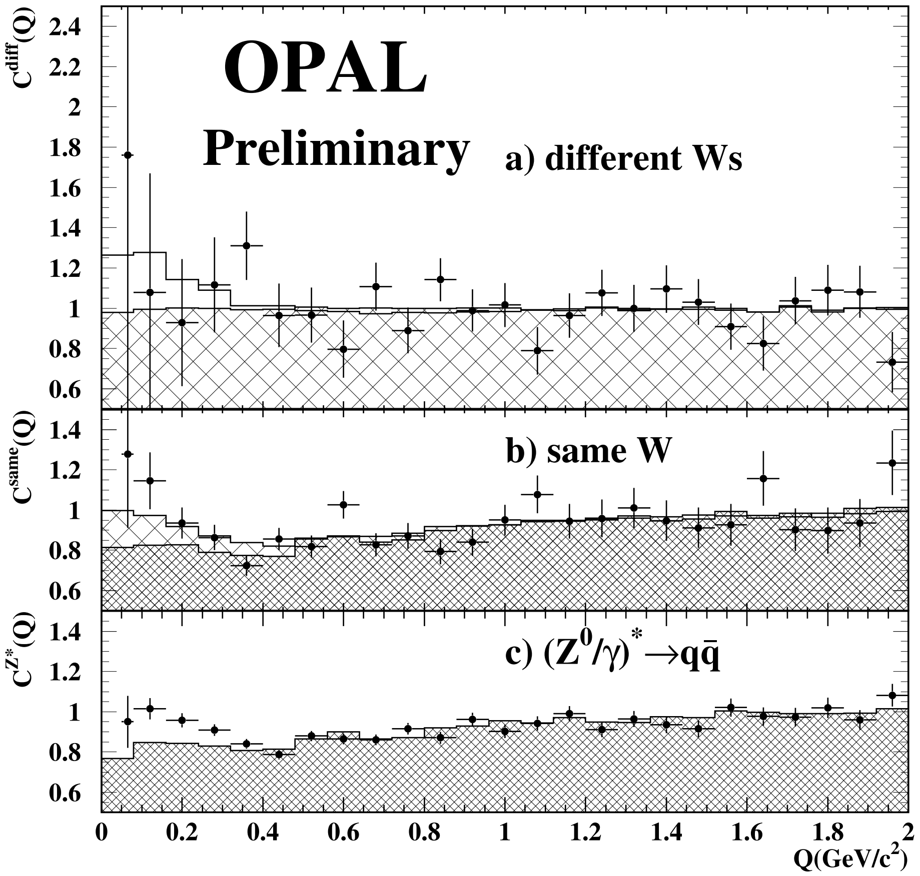
The last case generates distortions in the W mass spectrum.

The correlation function between two equal bosons is assumed to be Gaussian:

$$C(Q) = (1 + \lambda e^{-Q^2 R^2})(1 + \delta(Q))$$

Where λ and R are the amplitude and the radius of the effect.

Experimentally the Q distribution of the ratio of same sign and different sign charged pions is studied.



The BE correlations between pions from same W is visible, but statistics is not sufficient to draw any conclusion for correlations between different Ws. (Very few pion pairs have small Q^2)

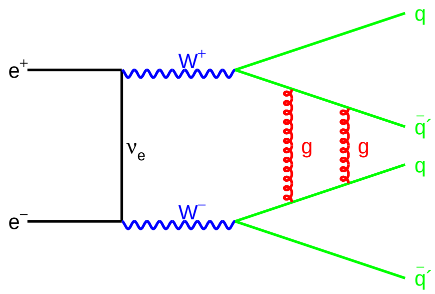
Fitting for the amount of correlation λ in the Gaussian approximation:

Experiment	λ
ALEPH	-0.64 ± 1.14
DELPHI	-0.20 ± 0.23
L3	0.75 ± 1.80
OPAL	0.40 ± 0.63

Aleph and Delphi data use 172 GeV sample only; L3 and OPAL combine 172 and 183 GeV.

Colour Reconnection

String effects between jets coming from different Ws (but from partons with equal colour) is another source of distortion of the mass distribution.



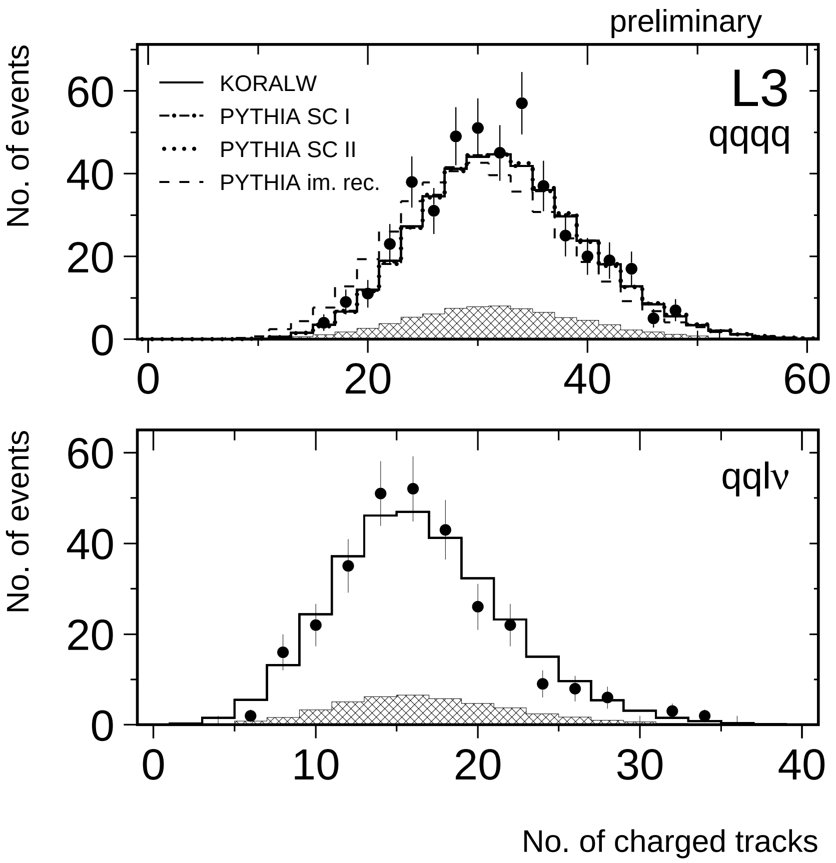
Perturbative effects are expected to be small, but non perturbative ones can be up to some hundreds of MeV, depending on the model.

In addition to W mass shifts, colour reconnections produce modifications in event topology.

Discrimination among models is done comparing charged particle production in $qqqq$ and $2 \times qql\nu$ events (removing the lepton):

- Extreme models: $\Delta N_{ch} \approx 4$
- Intermediate models: $\Delta N_{ch} \approx 1$

Colour Reconnection



Experiment	N_{ch}^{qqqq}	$N_{ch}^{qql\nu}$	ΔN_{ch}
DELPHI	$37.4 \pm 0.5 \pm 0.9$	$19.5 \pm 0.4 \pm 0.6$	-1.6 ± 1.5
L3	$36.3 \pm 0.4 \pm 0.8$	$18.6 \pm 0.3 \pm 0.4$	-1.0 ± 0.9
OPAL	$39.4 \pm 0.5 \pm 0.7$	$19.3 \pm 0.3 \pm 0.3$	0.7 ± 0.9

Extreme models seem disfavoured by present data.

Charm production in W decays

For real Ws:

- $W \to tb$ forbidden for energy conservation
- $W \to cb$ extremely rare due to $|V_{cb}|^2$ suppression

Charm is the heaviest quark produced in W decays.

Using its heavy-quark characteristics it is possible to measure charm production branching ratio in W decays.

In the standard model:

$$R_c^W = \frac{|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2}{|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 + |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2} = \frac{1}{2}$$

So this measurement is a test of unitarity of the CKM matrix.

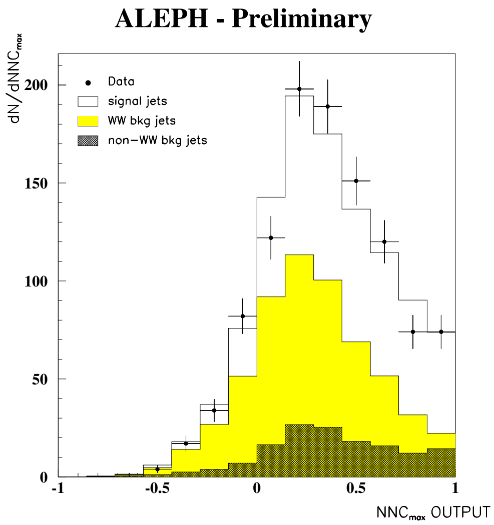
Furthermore, using the precise determinations of the other elements, it is possible to convert this measurement into a determination of $|V_{cs}|$.

Less precise then the measurement from the hadronic branching ratio, but more direct.

Charm Tagging

Different experimental techniques:

- ALEPH (172+183 GeV data) use of both a neural network with 12 input variables,or a Fisher discriminator. Variables used come from b-tagging, event shapes, exclusive decays etc. NN used for final result.
- L3 (183 GeV data) splits jets into four categories, depending whether an inclusive lepton (e, μ), a $D^* \rightarrow D^0\pi^\pm$ or none of the above is found. Each category is analysed by a separate network.
- DELPHI (172 GeV data) exploits its RICH detector for kaon identification, thus directly measuring V_{cs} through an s-tag.



Results for Charm BR

Summary of the results:

	R_c^W	$\lvert V_{cs}\rvert$
$D \to Kl\nu$(PDG)		1.04 ± 0.16
ALEPH L3 DELPHI	$0.51 \pm 0.05 \pm 0.03$ $0.50 \pm 0.11 \pm 0.04$ $0.42 \pm 0.13 \pm 0.06$	$1.00 \pm 0.10 \pm 0.06$ $0.98 \pm 0.22 \pm 0.08$ $0.87 \pm 0.24 \pm 0.11$
LEP direct		0.98 ± 0.11
LEP BR(W→qq)		1.03 ± 0.04
CKM unitarity		0.9745 ± 0.0005

This measurement from WW production at LEP is the best determination of $\lvert V_{cs}\rvert$ without assuming CKM matrix unitarity.

Conclusions

- W pairs have been produced at LEP for the first time in e^+e^- collisions
- data collected at CM energies of 161, 172, 183 GeV
- total WW cross section and branching ratios measured
- W mass derived from direct reconstruction and cross section: $M_W = 80.35 \pm 0.09$ GeV
- gauge couplings measured from cross section and W production and decay angles
- QCD effects in W decays studied to better understand systematics on the mass; more data needed to draw definite conclusions
- Charm production in W decays provides the best determinations of V_{cs} not assuming unitarity: $|V_{cs}| = 0.98 \pm 0.11$ (direct); $|V_{cs}| = 1.03 \pm 0.04$ (indirect)
- up to now about 85 pb^{-1} delivered above WW threshold
- LEP run in year 2000 approved; statistics expected to improve by about a factor 4