WW Production at LEP

Cross Sections and W Properties

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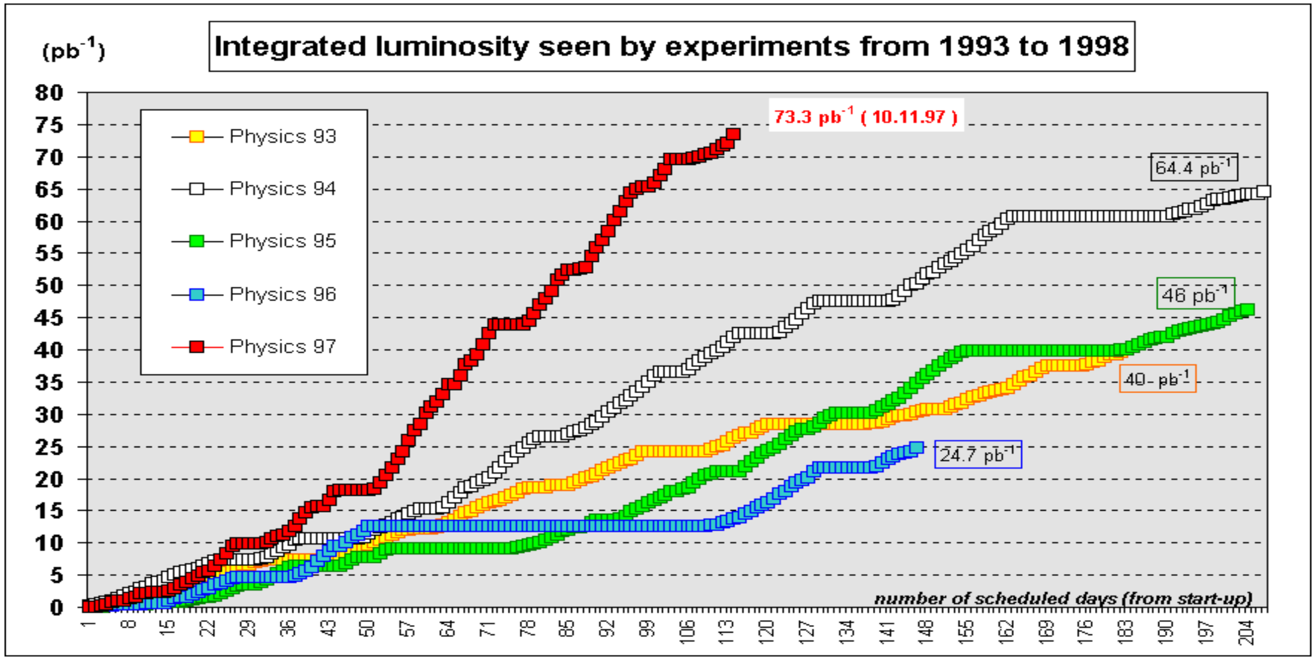
- WW selections and cross sections
- W branching fractions
- Measurements of $|\mathrm{V_{cs}}|$
- Properties of WW events: charged tracks, Bose-Einstein correlations

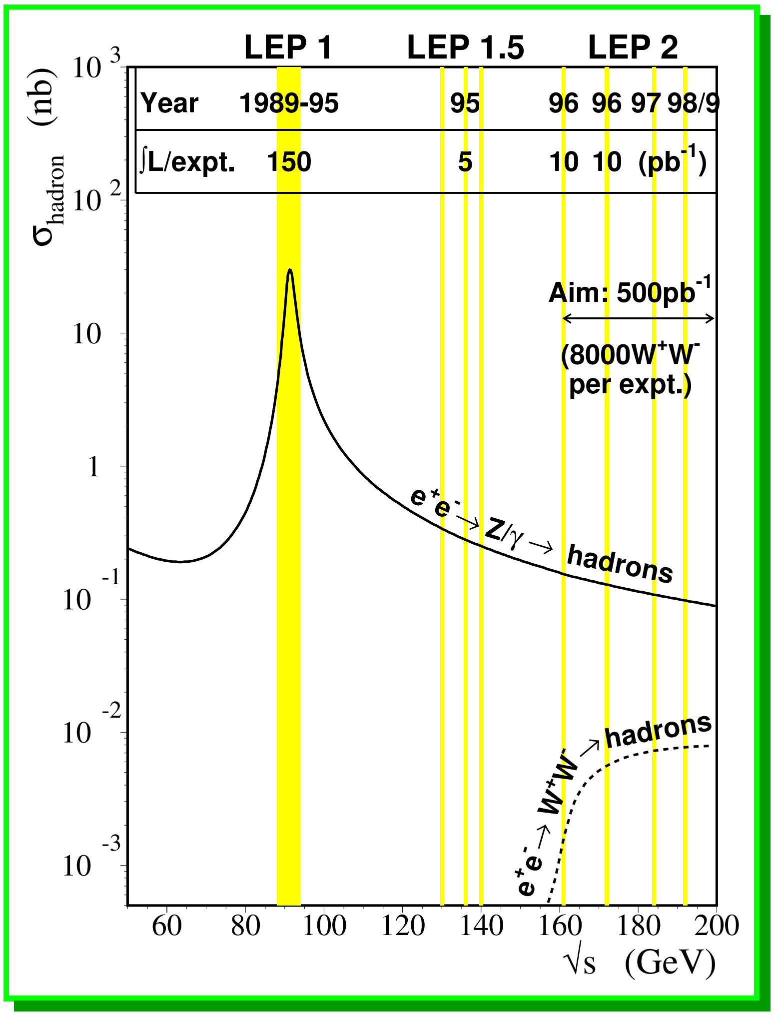
LEP Performance



LEP above the Z-pole:

- $\sim$ 12 pb^{-1}/exp at $\sqrt{s}$ = 130-136 GeV (1995 and 1997)
- $\sim$ 11 pb^{-1}/exp at $\sqrt{s}$ = 161 GeV (1996)
- $\sim$ 10 pb^{-1}/exp at $\sqrt{s}$ = 172 GeV (1996)
- $\sim$ 54-57 pb^{-1}/exp at $\sqrt{s}$ = 183 GeV (1997) : all results preliminary !

Typical hadronic cross sections at LEP



From 161 $\rightarrow$ 172 $\rightarrow$ 183 GeV: WW signal has increased, 2-fermion production cross section has decreased.

$$\frac{\sigma(WW \rightarrow qqqq)}{\sigma(Z/\gamma \rightarrow qq)} \approx \frac{1}{90} @ 161\,\mathrm{GeV}, \qquad \frac{1}{15} @ 183\,\mathrm{GeV}$$

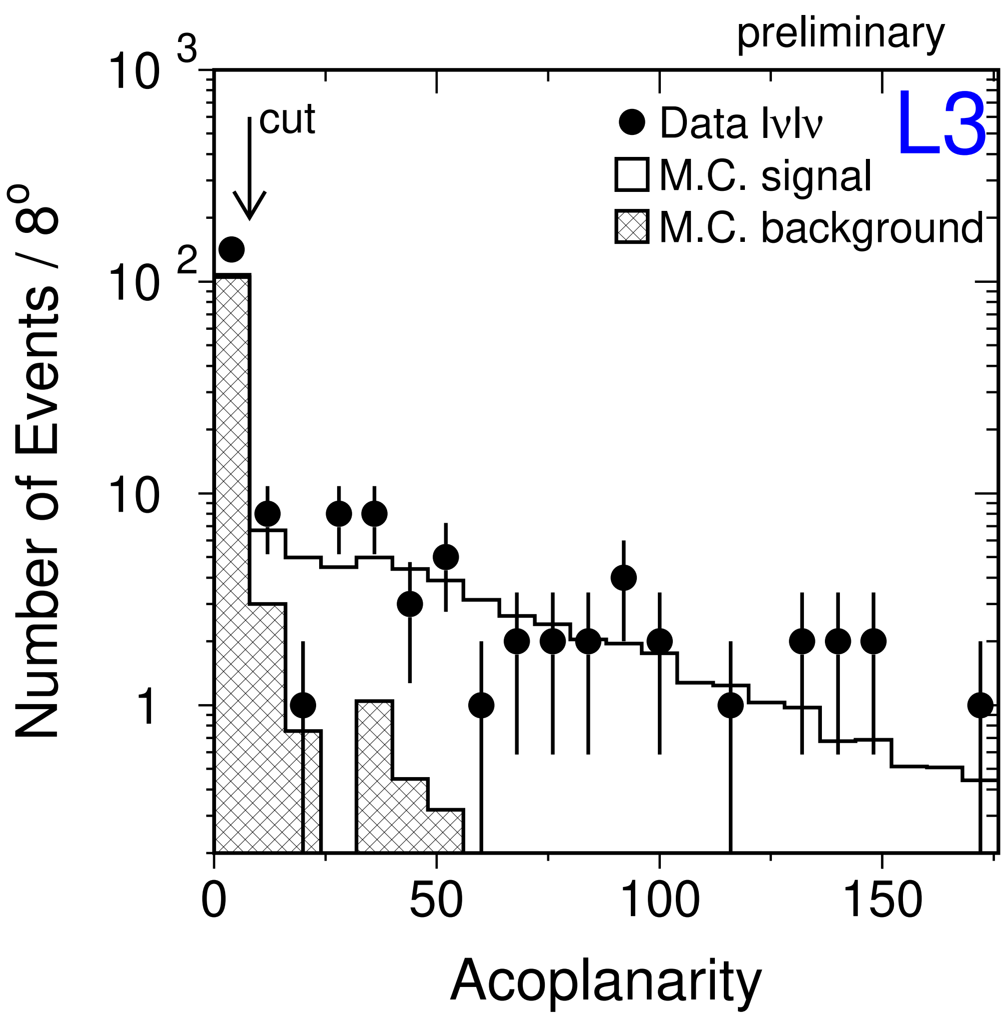
$\rightarrow$ Reoptimize analyses.

$WW \to \ell\nu\ell\nu$ (~11%)

Signature: 2 acoplanar energetic leptons (or tau jets) plus missing momentum not along the beam pipe.

Backgrounds: $e^+e^- \to Z + \gamma \to \ell^+\ell^-\gamma$, Bhabha's, Two-Photon processes.

Typical analysis: OR of topological 2 lepton search and dedicated final states selections.



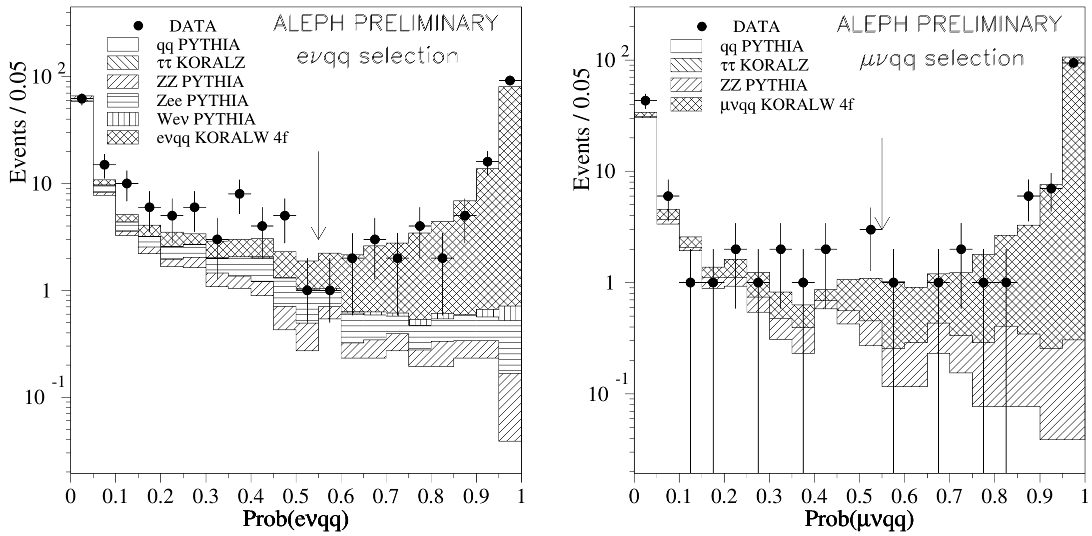
Selected: 54–78 events per experiment at 183 GeV.

$WW \to q\bar{q}\ell\nu$ (~44%)

Signature: 2 separated jets, 1 energetic isolated lepton (or tau jet), plus missing momentum not along the beam pipe. The neutrino is identified with the missing momentum vector.

Backgrounds: $e^+e^- \to q\bar{q}(\gamma)$, 4-fermion processes $e^+e^- \to q\bar{q}\ell^+\ell^-$.

Analyses: ALEPH, OPAL build probability/likelihood of event to be $qq\ell\nu$ from lepton energy and isolation, and missing momentum. DELPHI, L3 select events by cutting on these variables.



Selected: 288–362 events per experiment at 183 GeV. Typical efficiencies: 75-90% for e and μ, 50-65% for τ.

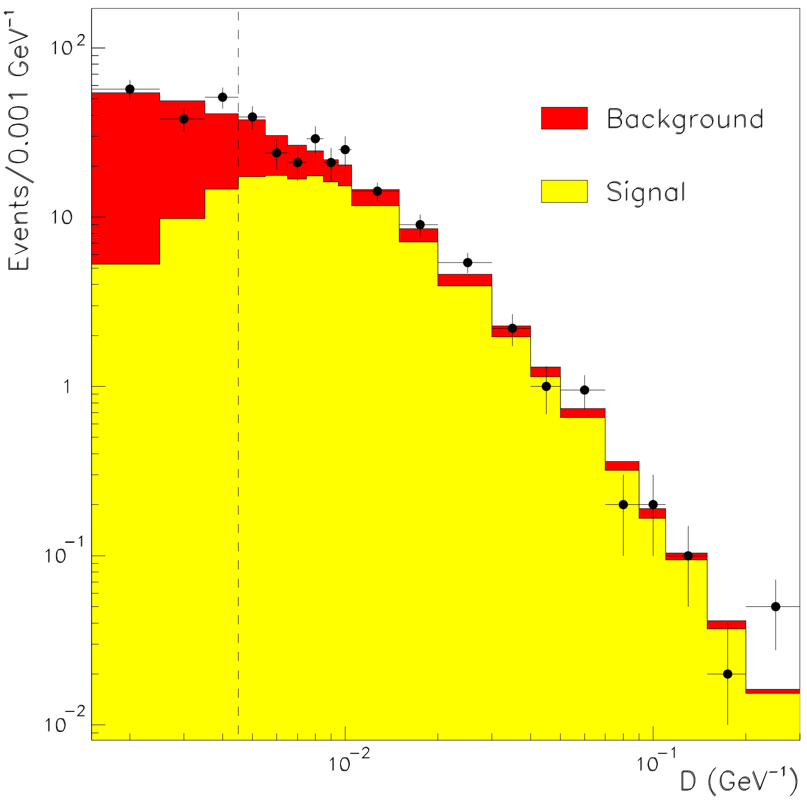
$WW \to q\bar{q}q\bar{q}$ (~46%) and DELPHI 4q analysis

Signature: 4 jets of similar energies, little missing energy.

Backgrounds: $e^+e^- \to q\bar{q}(\gamma) + n$ gluons ($\sim$ 100 pb), ZZ production.

Exploit difference in jet energies and jet-jet angles between signal and QCD background. DELPHI uses:

$$D = \frac{E_{min}}{E_{max}} \cdot \frac{\Theta_{min}}{(E_{max} - E_{min})}$$

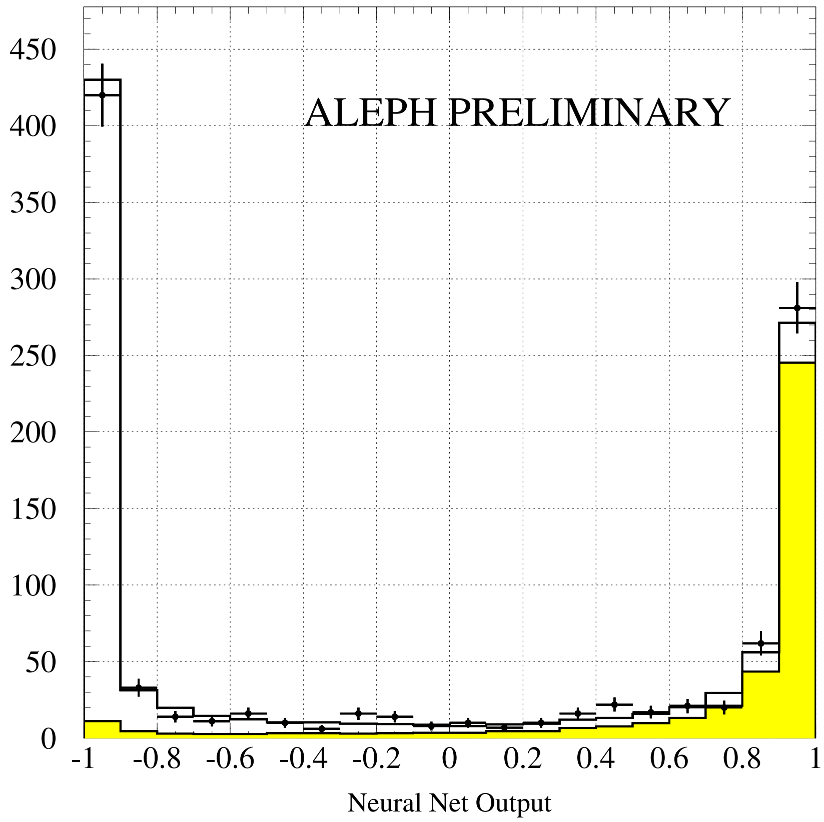


ALEPH 4q analysis

ALEPH: Preselection, followed by:

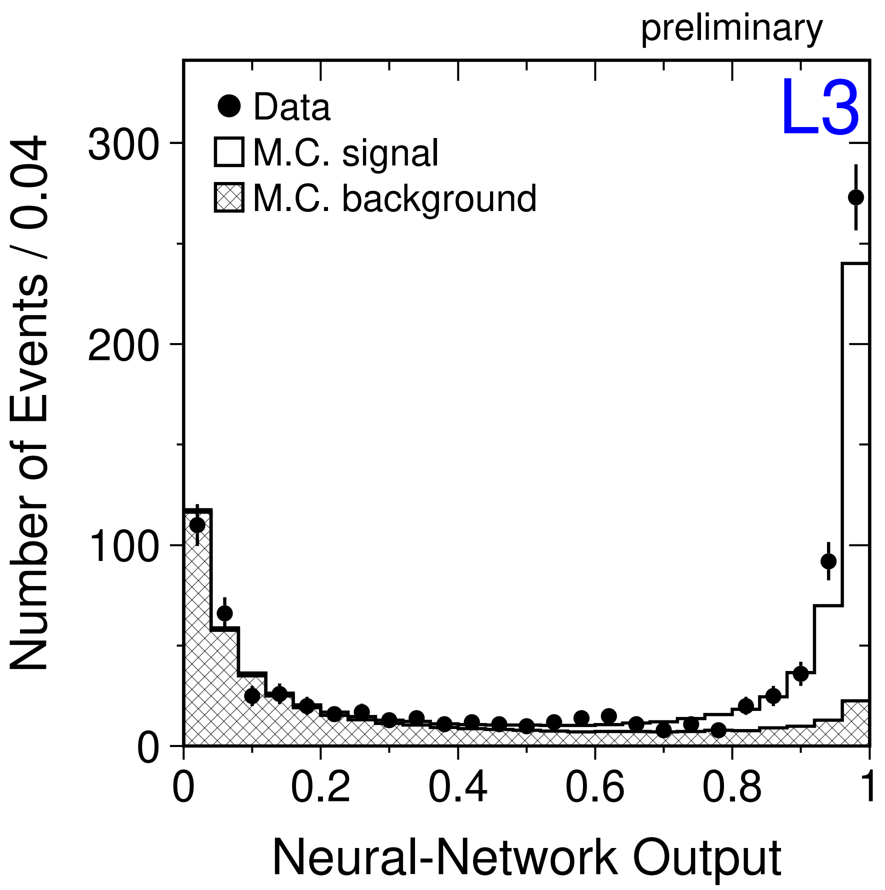
@ 172 GeV: assignment of weight to event based on location in 5-dimensional space of observables, get cross section from fit to weight distribution.

@ 183 GeV: neural network analysis, with 21 input variables related to event and jet properties and WW kinematics. Most discriminating: angles between jets, Fox-Wolfram moments, minimum and maximum invariant masses. Get cross section from fit to neural network output distribution.



L3 4q analysis

L3: Preselection, followed by neural network to distinguish WW signal and QCD background. The network has 10 input variables related to event shapes, jet properties and WW kinematics. Most discriminating: Y_{34}, minimum jet-jet angle, minimum and maximum jet energies. Get cross section from fit to neural network output distribution.



Resulting $WW \to q\bar{q}q\bar{q}$ cross section shows excess above prediction corresponding to 2.4 standard deviations.

Results confirmed by alternative cut-based and weights analyses.

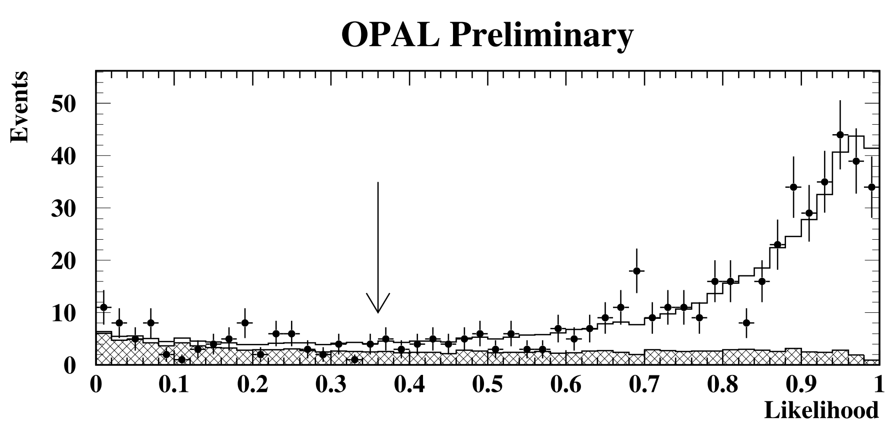
OPAL 4q analysis

OPAL: Preselection, followed by likelihood analysis:

@ 172 GeV: 7 input variables, using 4-jet-like signature, momentum balance and angular structure of signal events.

@ 183 GeV: 4 input variables: $\log(y_{45})$, QCD matrix element, modified Nachtmann-Reiter angle, sphericity.

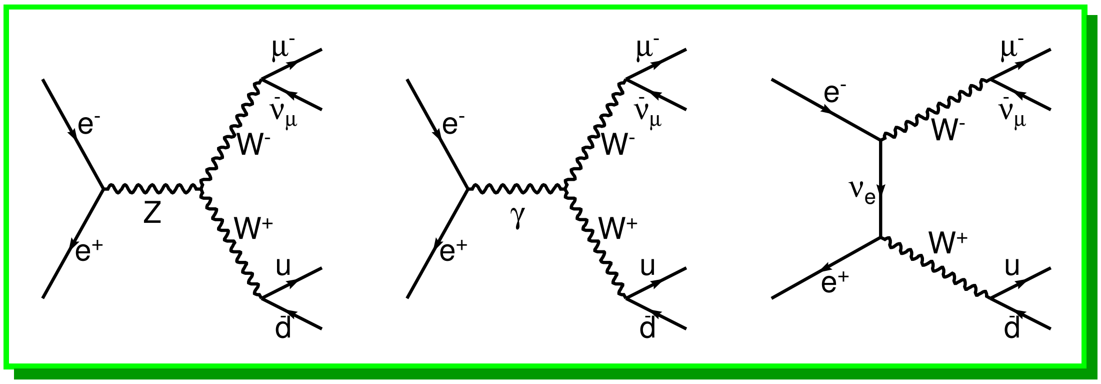
Variables are used to construct likelihood discriminator, transformed into event weights. Get cross section by weighting events (172 GeV), or cutting on likelihood discriminator (183 GeV).



All 4 experiments reach selection efficiency $\sim 85\%$ while reducing background to 1.0-1.8 pb. Selected: 391–475 events per experiment at 183 GeV.

CC 4-fermion Production

WW production is a special case of CC 4-fermion production. Three (CC03) diagrams contribute at Born level:



Many more diagrams contribute to 4-fermion production. Those with the same final states as WW production interfere with the CC03 processes.

In order to obtain CC03 cross sections, the measurements have to be corrected for 4-fermion effects, in particular for events with an electron/positron in the final state.

- ALEPH, OPAL: treat 4-fermion effects as additional background to CC03, to be subtracted (or added!).
- DELPHI, L3: apply multiplicative correction factor to go from measured 4-fermion cross section to CC03 cross section.

Both procedures give the same results to within $< 1\%$.

Cross Section Derivation and Results

To obtain the cross section σ_{WW} from the selected events N^i_{obs}:

$$\begin{pmatrix} N^{qqe\nu}_{exp} \\ N^{qq\mu\nu}_{exp} \\ \vdots \\ N^{qqqq}_{exp} \end{pmatrix} = \begin{pmatrix} N^{qqe\nu}_{bkg} \\ N^{qq\mu\nu}_{bkg} \\ \vdots \\ N^{qqqq}_{bkg} \end{pmatrix} + \mathcal{L}\sigma_{WW} \begin{pmatrix} \varepsilon^{qqe\nu}_{qqe\nu} & \varepsilon^{qqe\nu}_{qq\mu\nu} & \cdots & \varepsilon^{qqe\nu}_{qqqq} \\ \varepsilon^{qq\mu\nu}_{qqe\nu} & \varepsilon^{qq\mu\nu}_{qq\mu\nu} & \cdots & \varepsilon^{qq\mu\nu}_{qqqq} \\ \vdots & \vdots & \ddots & \vdots \\ \varepsilon^{qqqq}_{qqe\nu} & \varepsilon^{qqqq}_{qq\mu\nu} & \cdots & \varepsilon^{qqqq}_{qqqq} \end{pmatrix} \begin{pmatrix} 2Br(qq)Br(e\nu) \\ 2Br(qq)Br(\mu\nu) \\ \vdots \\ Br(qq)^2 \end{pmatrix}$$

and maximize likelihood of observing N^i_{obs} events when N^i_{exp} are expected.

Fit results for the leptonic branching fractions of the W, without assuming lepton-universality, combining the 161 GeV, 172 GeV and 183 GeV data for the 4 LEP experiments:

$$Br(e\nu) = 10.97 \pm 0.49\%, \qquad Br(\mu\nu) = 10.33 \pm 0.47\%, \qquad Br(\tau\nu) = 9.99 \pm 0.61\%$$

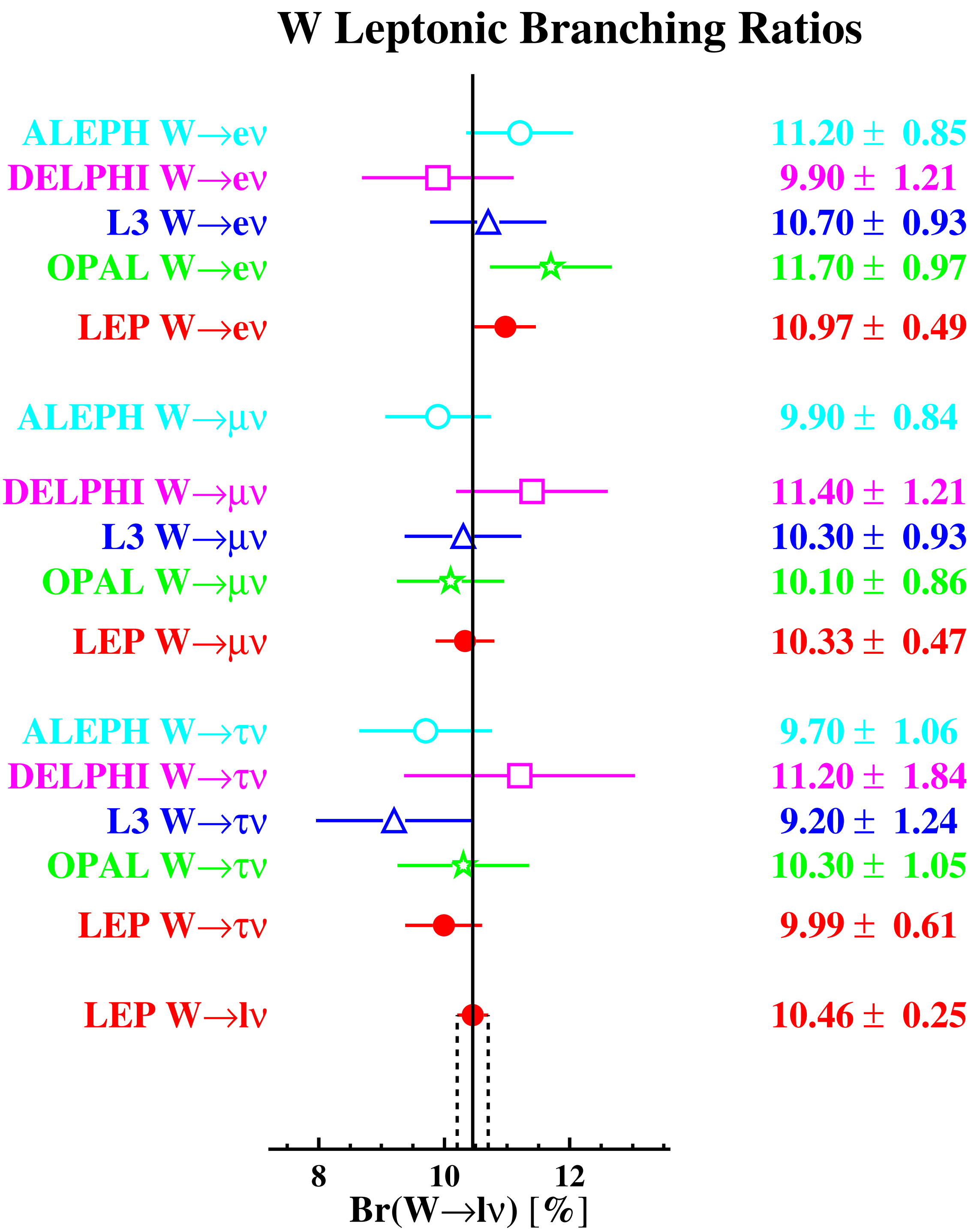
Assuming lepton-universality:

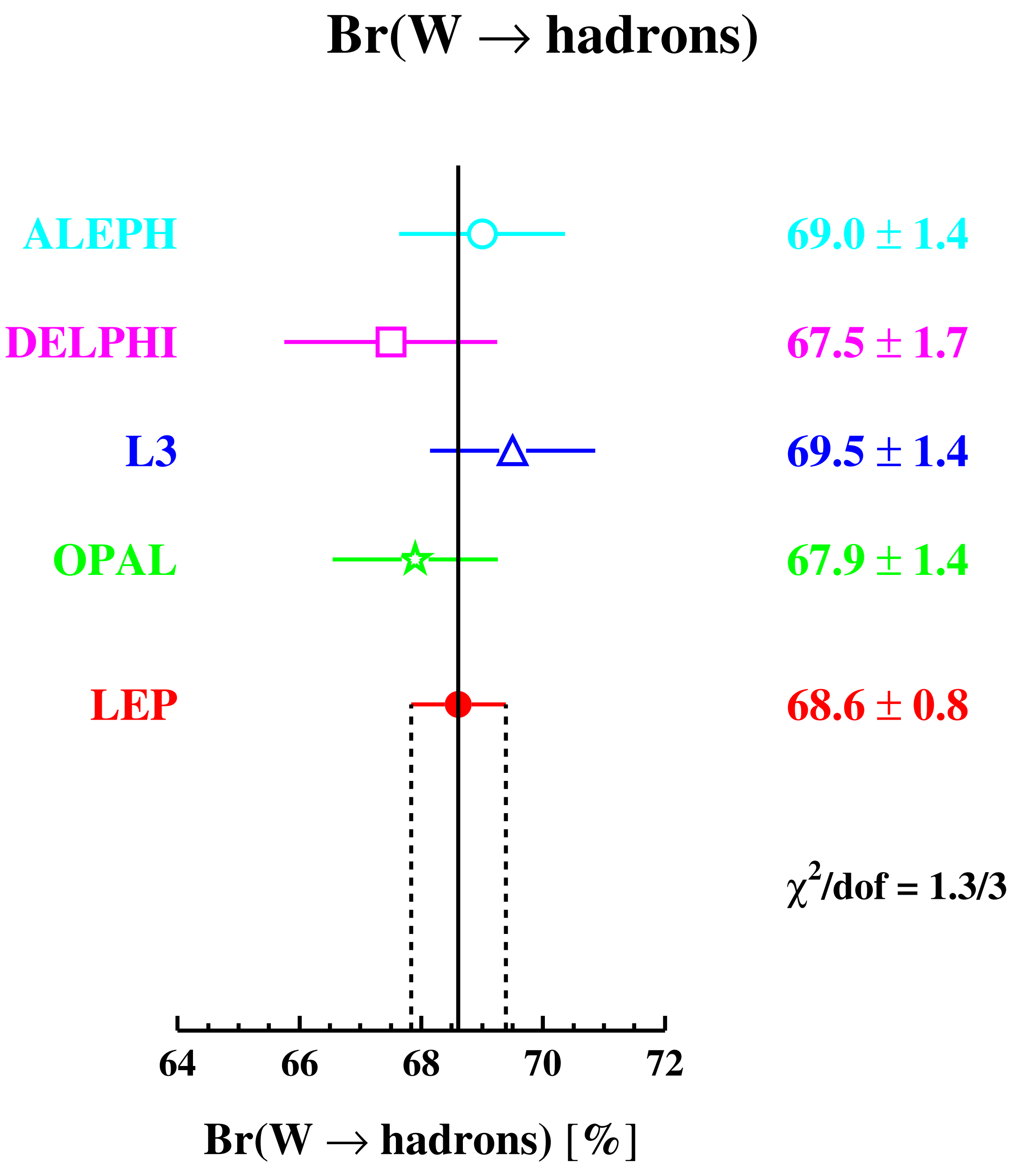
$$Br(\ell\nu) = 10.46 \pm 0.26\%$$

$$Br(qq) = 68.61 \pm 0.78\%$$

(SM expectation: $Br(\ell\nu) = 10.8\%$, $Br(qq) = 67.5\%$, PDG values: $Br(e\nu) = 10.8 \pm 0.4\%$, $Br(\mu\nu) = 10.4 \pm 0.6\%$)

W Leptonic Branching Ratios




Br(W → hadrons)
ALEPH
DELPHI
L3
OPAL
LEP
69.0 ± 1.4
67.5 ± 1.7
69.5 ± 1.4
67.9 ± 1.4
68.6 ± 0.8
χ2/dof = 1.3/3
64
66
68
70
72
Br(W → hadrons) [%]

Cross Sections Fits

Fitting instead for individual CC03 signal cross sections at 183 GeV, one obtains (in pb):

	$WW \to \ell\nu\ell\nu$	$WW \to qq\ell\nu$	$WW \to qqqq$
ALEPH	$1.34 \pm 0.20 \pm 0.05$	$6.79 \pm 0.40 \pm 0.14$	$7.33 \pm 0.41 \pm 0.30$
DELPHI	$1.64 \pm 0.26 \pm 0.09$	$7.04 \pm 0.47 \pm 0.28$	$7.33 \pm 0.48 \pm 0.29$
L3	$1.53 \pm 0.24 \pm 0.05$	$6.82 \pm 0.42 \pm 0.11$	$8.25 \pm 0.46 \pm 0.25$
OPAL	$1.69 \pm 0.20 \pm 0.06$	$6.65 \pm 0.39 \pm 0.13$	$7.15 \pm 0.43 \pm 0.31$

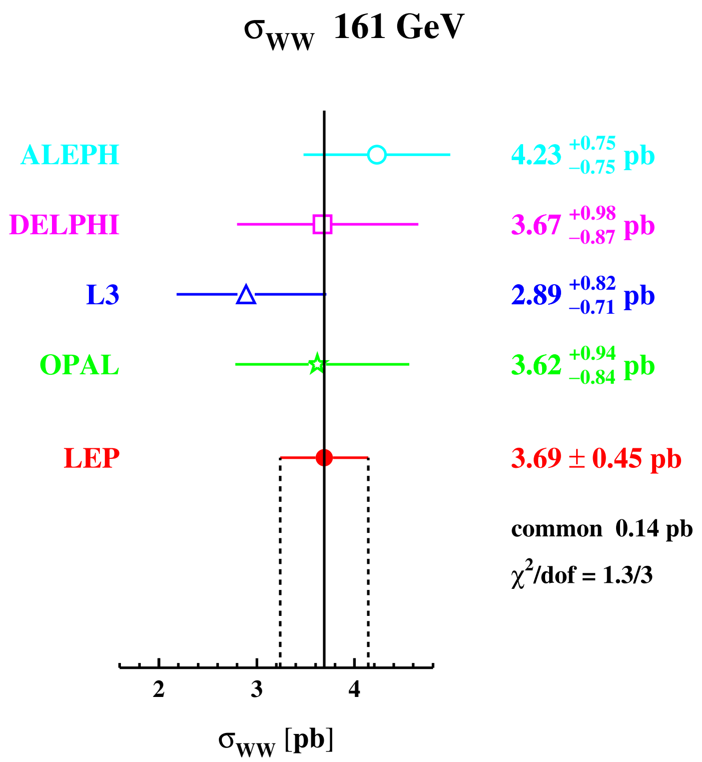
Assuming the SM branching ratio's, one can fit the total CC03 WW production cross section at 183 GeV. Here, care has been taken to treat common systematic errors (QCD background) between channels correctly:

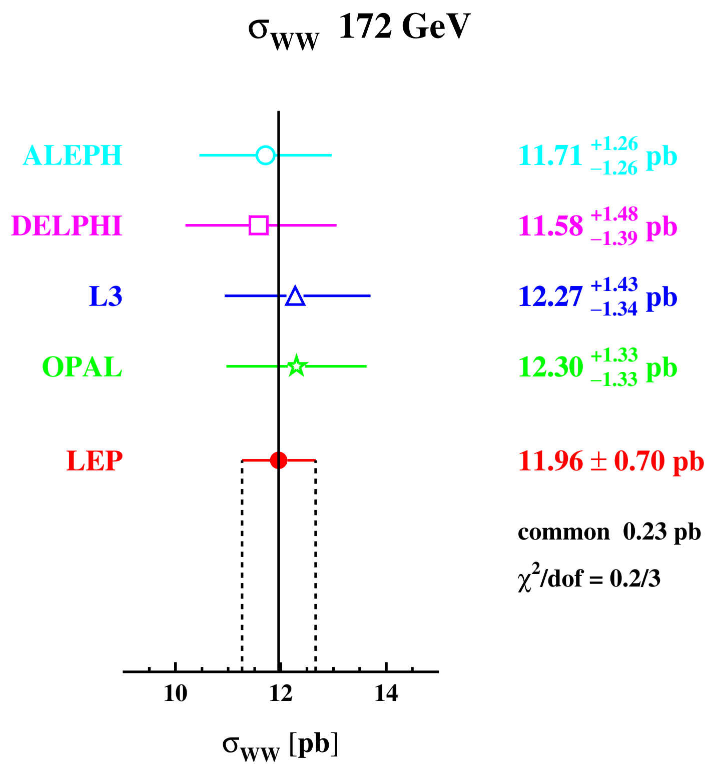
	$\sigma_{WW}(183\,\mathrm{GeV})$ (pb)
ALEPH	$15.51 \pm 0.61 \pm 0.36$
DELPHI	$16.01 \pm 0.71 \pm 0.43$
L3	$16.66 \pm 0.66 \pm 0.30$
OPAL	$15.52 \pm 0.62 \pm 0.35$

Combining the 4 experiments, and taking into account correlations between experiments, one obtains the LEP average:

$$\sigma_{WW}(183\,\mathrm{GeV}) = 15.90 \pm 0.41\,\mathrm{pb}$$

WW Cross Sections at 161 and 172 GeV



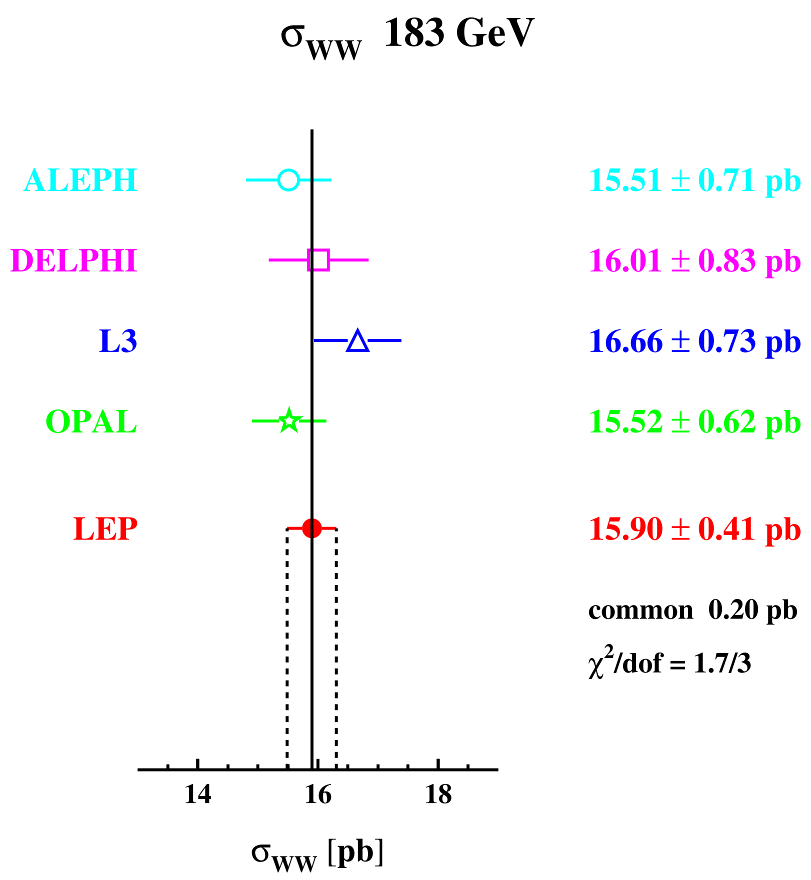


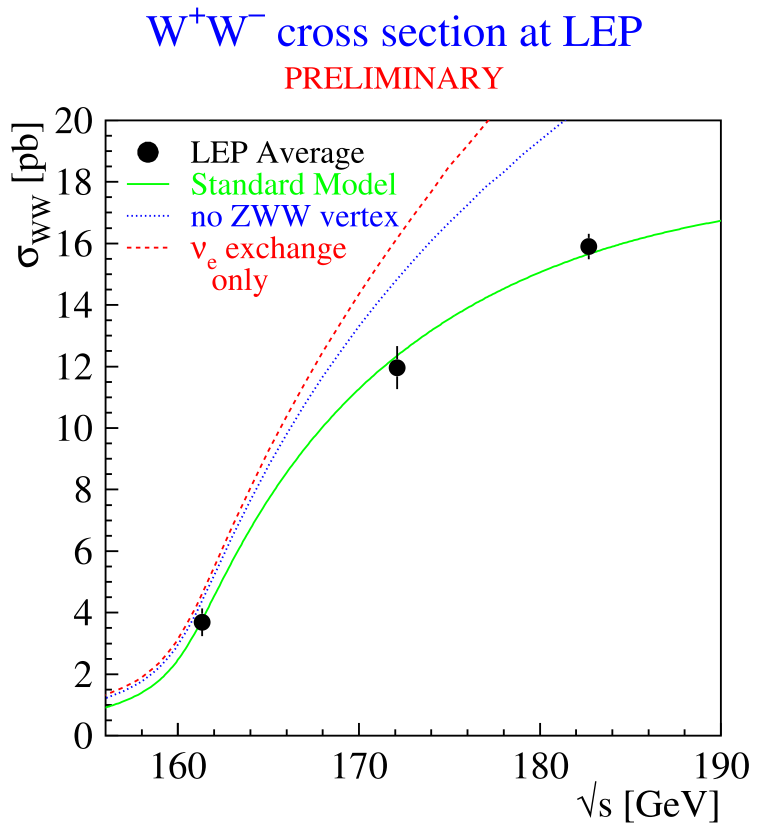
At 161 GeV: use $\sigma_{\mathrm{WW}}(\mathrm{m_W})$ to measure $\mathrm{m_W}$:

$$\mathrm{m_W} = 80.40^{+0.22}_{-0.21}\,\mathrm{GeV}$$

At 172 GeV: sensitivity to $\mathrm{m_W}$ much reduced to $\mathcal{O}(2)$ GeV per experiment.

σ_{WW} at 183 GeV and WW Excitation Curve





The measurements are in good agreement with the Standard Model expectations; the predictions of models with no ZWW vertex, or t-channel ν_e exchange only are excluded.

Interpretation

The W Hadronic Branching Ratio can be written in terms of elements of the CKM matrix:

$$\frac{\mathrm{Br}(\mathrm{W} \to \mathrm{q\bar{q}})}{1 - \mathrm{Br}(\mathrm{W} \to \mathrm{q\bar{q}})} = (1 + \frac{\alpha_s}{\pi}) \sum_{\mathrm{i}=u,c;\,\mathrm{j}=d,s,b} |\mathrm{V_{ij}}|^2$$

Using the LEP measurements of $\mathrm{Br}(\mathrm{W} \to \mathrm{q\bar{q}})$ one obtains:

$$\sum_{\mathrm{i}=u,c;\,\mathrm{j}=d,s,b} |\mathrm{V_{ij}}|^2 = 2.10 \pm 0.08$$

which is a measurement of the unitarity of the CKM matrix.

It is most interesting to derive the least well known element, $|\mathrm{V_{cs}}|$, using measured values of other elements:

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

Charm in W Decay

A direct derivation of $|\mathrm{V}_{\mathrm{cs}}|$ can be made by measuring the charm content in W decays. Since $|\mathrm{V}_{\mathrm{cb}}|$ is small, c quarks are the heaviest copiously produced quarks in W decay. However, even in the absence of b quarks, c tagging is hard!

In c tagging, one exploits the c mass and lifetime, leptons from semileptonic c decays, and reconstructed D and D^* mesons.

Measure:

$$R_c = \frac{\Gamma(W \to cX)}{\Gamma(W \to qq)} = \frac{|\mathrm{V}_{\mathrm{cd}}|^2 + |\mathrm{V}_{\mathrm{cs}}|^2 + |\mathrm{V}_{\mathrm{cb}}|^2}{\sum_{\mathrm{i}=u,c;\mathrm{j}=d,s,b} |\mathrm{V}_{\mathrm{ij}}|^2}$$

Analyses: ALEPH, L3 at 183 GeV, DELPHI at 172 GeV

DELPHI in fact measures $R_{cs} = \frac{\Gamma(W \to cs)}{\Gamma(W \to qq)}$ via charm and strange quark tagging.

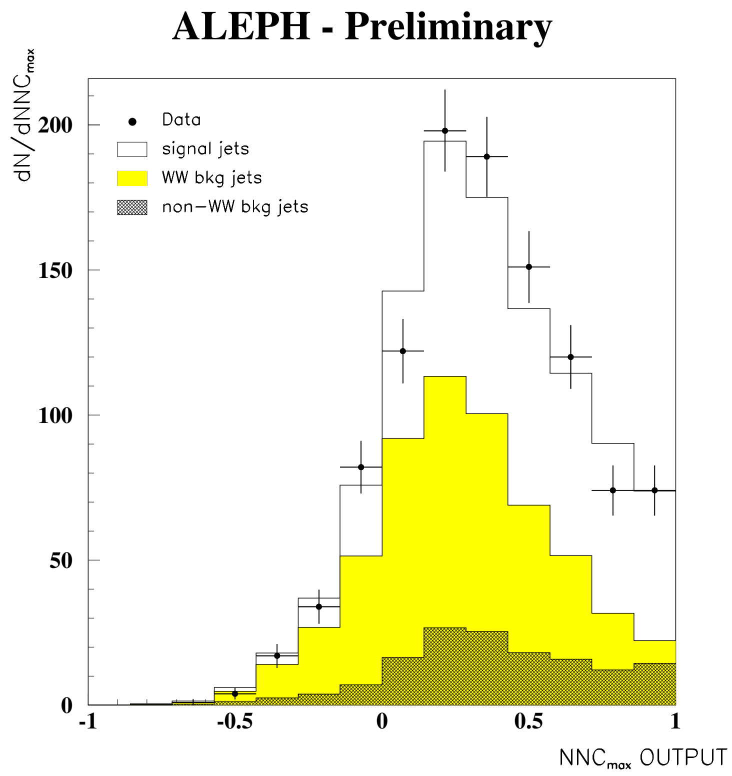
R_c Analyses ALEPH and L3

ALEPH, L3 : use $qqqq$ and $qq\ell\nu$ events at 172 and 183 GeV.

ALEPH: c tagging via neural network, or via linear (Fisher) discriminant analysis, both with 12 input variables. The neural network gives slightly better performance; linear discriminant analysis gives relative weight of input variables.

L3: 4 categories of events: e or μ from c decay, D^* candidate, and the remaining events. Each category analyzed via neural network.

ALEPH: NN output for jets in the pair with the highest NN output:



$|\mathrm{V_{cs}}|$ *Overview*

Summary of $|\mathrm{V_{cs}}|$ Results:

	R_c	$\lvert\mathrm{V_{cs}}\rvert$
$D \to K\ell\nu$ (PDG)		1.04 ± 0.16
ALEPH direct (183)	$0.51 \pm 0.05 \pm 0.03$	$1.00 \pm 0.10 \pm 0.06$
L3 direct (183)	$0.50 \pm 0.11 \pm 0.04$	$0.98 \pm 0.22 \pm 0.08$
DELPHI direct (172)	$0.42 \pm 0.13 \pm 0.06$	$0.87 \pm 0.24 \pm 0.11$
Average direct		0.98 ± 0.11
LEP $\mathrm{Br(W \to q\bar{q})}$		1.03 ± 0.04
CKM unitarity		0.9745 ± 0.0005

WW production at LEP now gives best $|\mathrm{V_{cs}}|$ measurement without assuming CKM matrix unitarity.

W Hadronic Final States

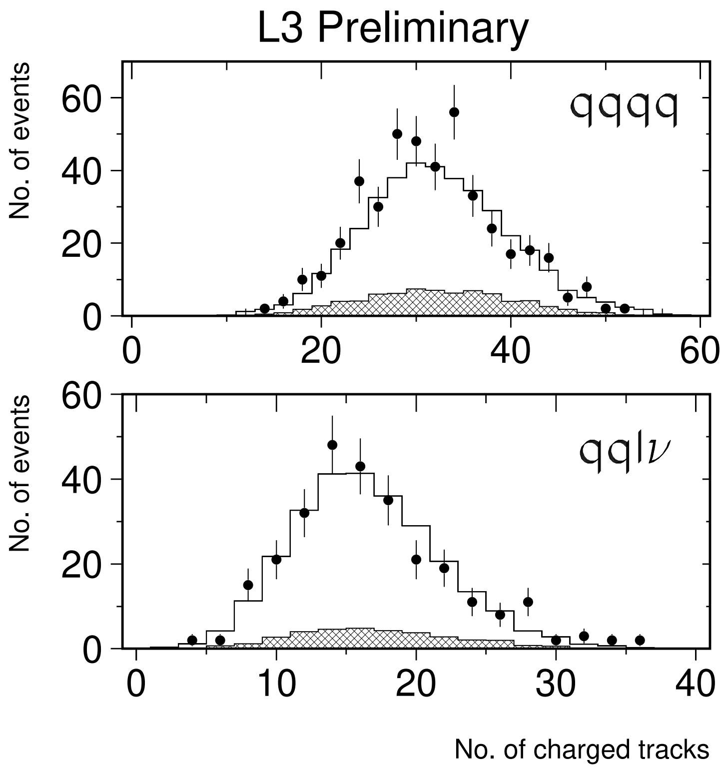
Charged tracks in W hadronic final states: possible sign of colour reconnection effects or Bose-Einstein correlations.

Investigate $qqqq$ vs $qq\ell\nu$ events. If fragmentation and hadronization of each W is independent: $qqqq = 2qq\ell\nu(-2\ell\nu)$. (Or in other notation: WW $=$ 2W).

If, however, colour reconnection effects are sizable, they typically decrease the charged multiplicity in $qqqq$ events (at low particle momentum and rapidity), and may influence the measurement of $\mathrm{m_W}$ in the $qqqq$ channel.

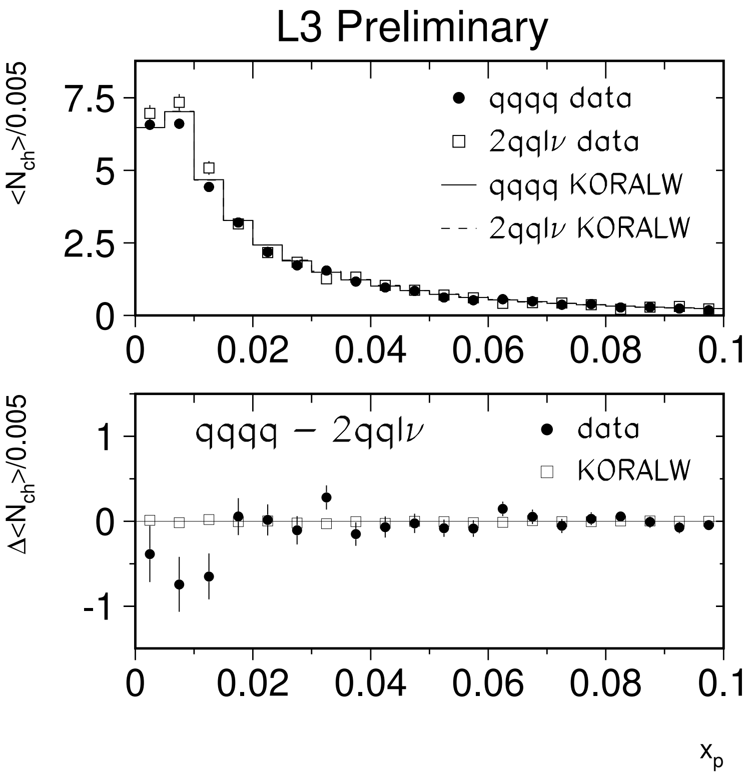
Analyses: L3, DELPHI at 183 GeV, DELPHI, OPAL at 172 GeV.

L3: Charged track multiplicity distribution:

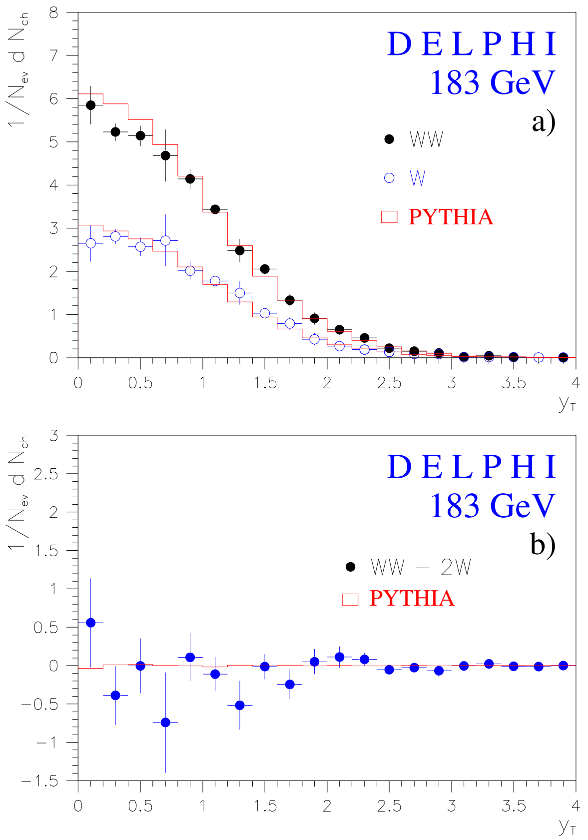


L3 and DELPHI charged track analyses

L3: Distribution of scaled charged particle momentum $x_p = 2p/\sqrt{s}$:



DELPHI: Distribution of track rapidity with respect to thrust axis:



All indications: no significant differences between $qqqq$ and $qq\ell\nu$ events.

Bose-Einstein Correlations in WW Events

BEC well established in nucleus-nucleus, hadron-hadron, e^+e^- interactions: interference between identical bosons leading to enhanced production close in phase space.

Define correlation function

$$C(Q) = \frac{\rho(Q)}{\rho_0(Q)}, \qquad Q^2 = M^2(\pi\pi) - 4m_\pi^2$$

with $\rho(Q)$ 2-particle density function, and $\rho_0(Q)$ idem for reference sample without BEC.

Reference sample: unlike-sign pairs or mixed-events.

Fit with function

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

with $\lambda =$ correlation strength, $R =$ source radius.

Question relevant here: do BEC exist between decay products of different W's? If yes: may compromise $\mathrm{m_W}$ measurement in $qqqq$ channel.

Analyses: OPAL at 183 GeV, DELPHI, ALEPH at 172 GeV

Analyses of BEC in WW events

OPAL: Select $\mathrm{WW} \to \mathrm{q\bar{q}}\ell\bar{\nu}$, $\mathrm{WW} \to \mathrm{q\bar{q}q\bar{q}}$ and $(\mathrm{Z}^*/\gamma) \to \mathrm{q\bar{q}}$ samples, and fit simultaneously for $\lambda^{\mathrm{same\ W}}$, $\lambda^{\mathrm{diff\ W}}$ and λ^{Z^*}, taking into account cross-feed between channels.
Results:

$$\lambda^{\mathrm{diff\ W}} = 0.40 \pm 0.50 \pm 0.39$$

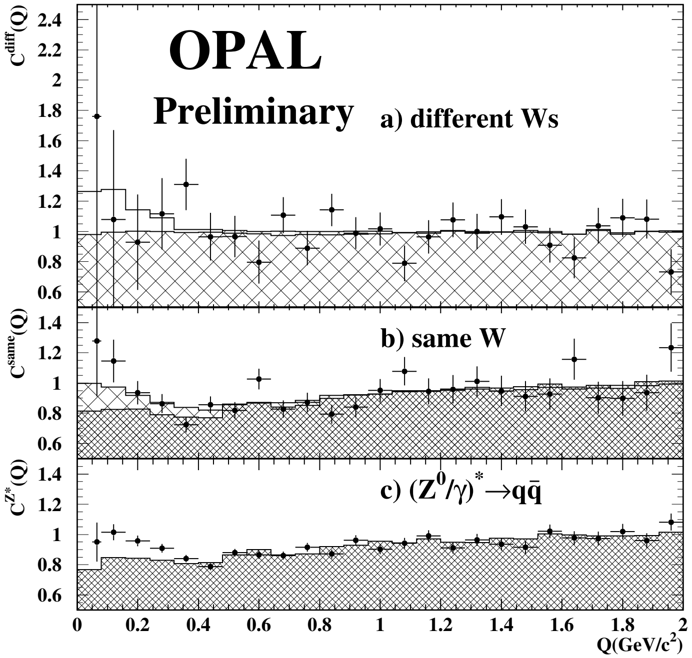
and other parameters in agreement with Z data.

ALEPH, DELPHI: Construct $C^{\mathrm{diff}}(Q)$ by subtracting $q\bar{q}\ell\bar{\nu}$ from $q\bar{q}q\bar{q}$.
Results:

$$\mathrm{DELPHI:}\quad \lambda^{\mathrm{diff\ W}} = -0.20 \pm 0.23$$

$$\mathrm{ALEPH:}\quad \lambda^{\mathrm{diff\ W}} = -0.64 \pm 1.14$$

OPAL: after unfolding of the 3 classes:



Open histogram: BEC different W's only
Wide hatched histogram: BEC same W's only
Fine hatched histogram: no BEC

Summary Properties WW Events

Summary of hadronic charged multiplicity measurements:

	$< N_{had}^{qqqq} >$	$< N_{had}^{qq\ell\nu} >$	$\Delta < N_{had} >$
DELPHI (183 GeV)	$37.4 \pm 0.5 \pm 0.9$	$19.5 \pm 0.4 \pm 0.6$	-0.6 ± 0.6
L3 (183 GeV)	$36.1 \pm 0.4 \pm 0.8$	$18.8 \pm 0.4 \pm 0.4$	-1.5 ± 0.9
DELPHI (172 GeV)	$40.6 \pm 1.7 \pm 1.1$	$18.0 \pm 0.9 \pm 0.6$	$+3.9 \pm 1.6$
OPAL (172 GeV)	$38.3 \pm 1.1 \pm 0.6$	$18.4 \pm 0.9 \pm 0.4$	$+1.5 \pm 2.3$

Results consistent with no differences: rule out most extreme colour reconnection scenario's.

Summary of BEC measurements:

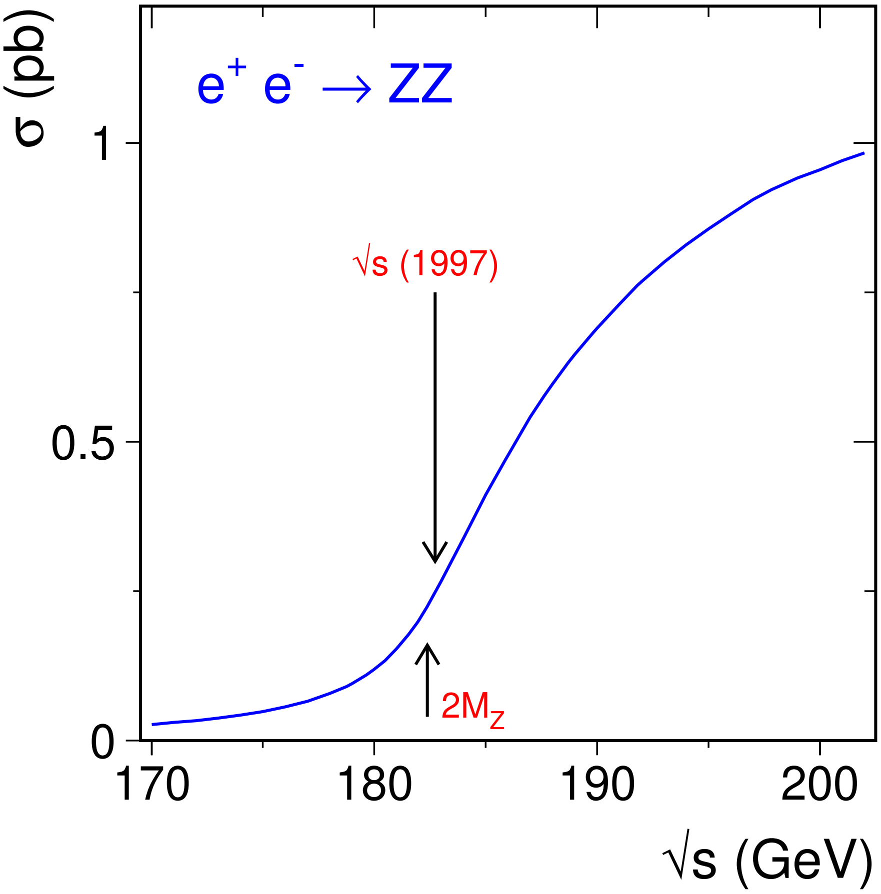
	$\lambda^{\mathrm{diff\ W}}$	$\lambda^{\mathrm{same\ W}}$	R (fm)	λ^{Z}	R^{Z} (fm)
OPAL (183)	0.40 ± 0.63	0.72 ± 0.35	0.94 ± 0.16	0.67 ± 0.03	0.96 ± 0.02
DELPHI (172)	-0.20 ± 0.23	0.41 ± 0.13	0.5 (fixed)	0.40 ± 0.06	0.62 ± 0.20
ALEPH (172)	-0.64 ± 1.14	0.96 ± 0.84	1.7 ± 2.0	0.51 ± 0.12	0.65 ± 0.16

Warning: Results at Z are often inconsistent between analyses, comparisons to be done with care (definitions?). $\lambda^{\mathrm{diff\ W}}$ and $\lambda^{\mathrm{same\ W}}$ from OPAL obtained with a different method than ALEPH and DELPHI.

ZZ Production at LEP

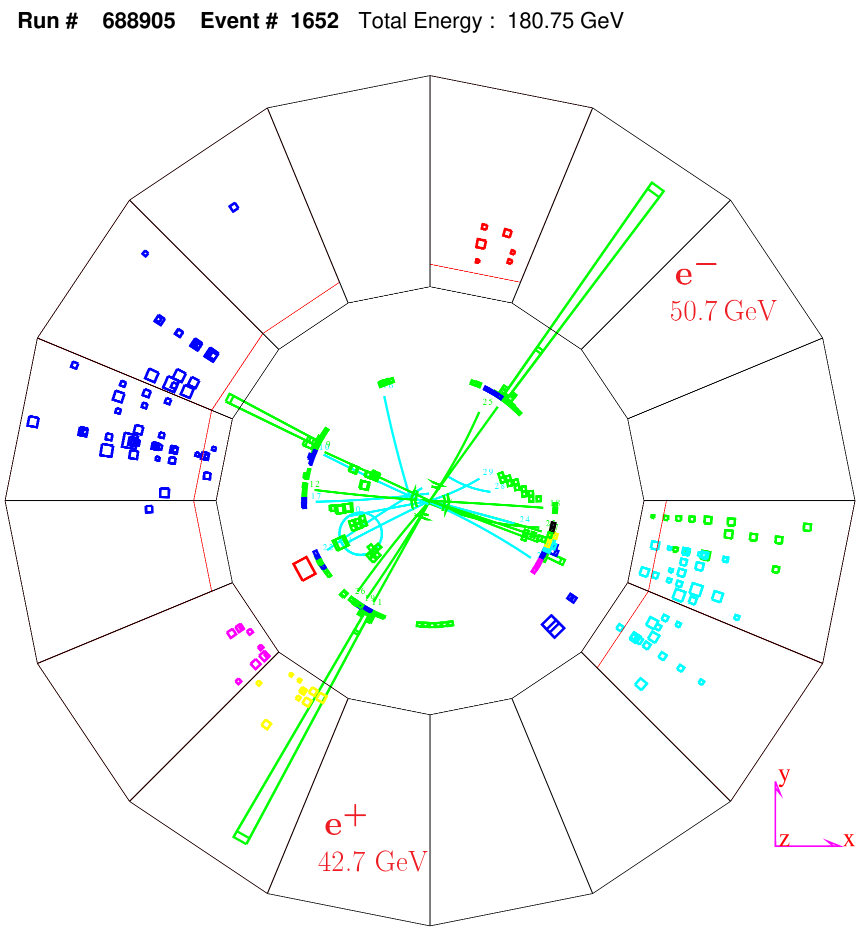
Little brother of WW production: ZZ production.

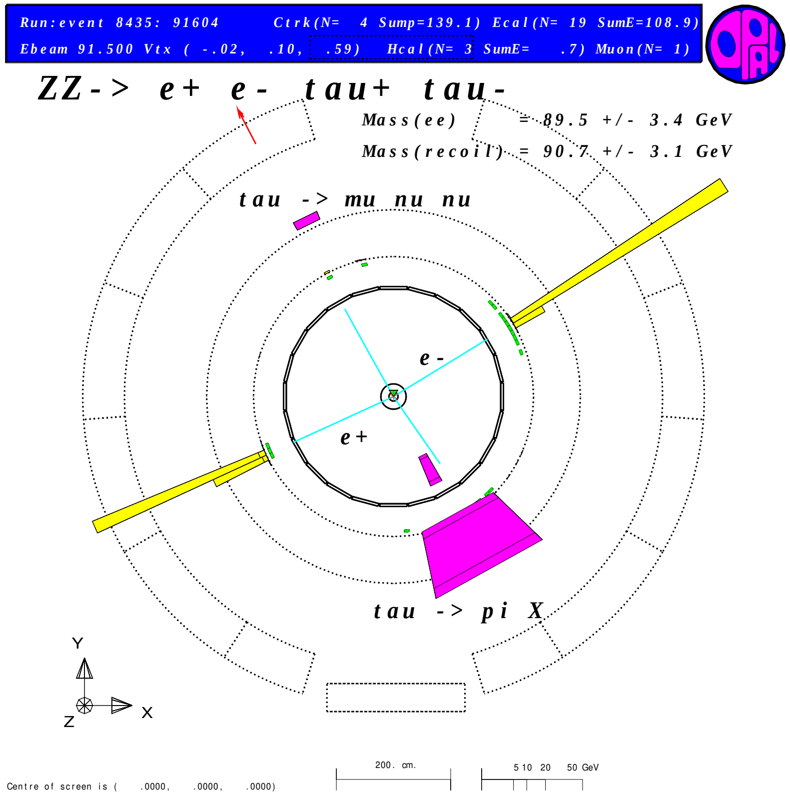
LEP in 1997: $\sqrt{s} > 2M_Z$ (barely): first observation of ZZ production at LEP.



Cleanest final states: $q\bar{q}\ell^+\ell^-$, $\ell^+\ell^-\ell^+\ell^-$.

Example of Observed ZZ Events at 183 GeV (L3, OPAL)





$m_{\mathrm{ee}} = 92.8\,\mathrm{GeV}$ $m_{\mathrm{jj}} = 88.8\,\mathrm{GeV}$

Summary and Conclusions 1

From the data taken at $\sqrt{s} \approx 183$ GeV, some 3260 WW candidate events have been selected by the 4 LEP experiments.

The WW production cross section at 183 GeV is measured to be:

$$\sigma_{WW}(183\,\mathrm{GeV}) = 15.90 \pm 0.41\,\mathrm{pb}$$

Combined with earlier data, W branching fractions have been determined:

$$Br(e\nu) = 10.97 \pm 0.49\%$$

$$Br(\mu\nu) = 10.33 \pm 0.47\%$$

$$Br(\tau\nu) = 9.99 \pm 0.61\%$$

Or, assuming lepton universality:

$$Br(\ell\nu) = 10.46 \pm 0.26\%$$

$$Br(qq) = 68.61 \pm 0.78\%$$

From WW production at LEP the CKM matrix element $|\mathrm{V_{cs}}|$ is measured to be:

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

Summary and Conclusions 2

No significant differences have been observed in the hadronic final state of $WW \rightarrow qqqq$ and $WW \rightarrow qq\ell\nu$ events. Within statistics, charged particle distributions are well described by Monte Carlo. This rules out the most extreme colour reconnection scenario's.

Sizable Bose-Einstein correlations between decay products of different W's are disfavoured (ALEPH, DELPHI), but can not be excluded with the present statistics (OPAL).

First ZZ events at LEP have been observed.

In 1998, we expect to almost quadruple the data sample, with 150 pb^{-1} at $\sqrt{s} = 189$ GeV.