Measurement of the W-pair cross section in e^+e^- collisions at 172 GeV

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Abstract

The $e^+e^- \to W^+W^-$ cross section is measured in a data sample collected by ALEPH at a mean centre–of–mass energy of 172.09 GeV, corresponding to an integrated luminosity of 10.65 pb^{-1}. Cross sections are given for the three topologies, fully leptonic, semi-leptonic and hadronic of a W-pair decay. Under the assumption that no other decay modes are present, the W-pair cross section is measured to be $11.7 \pm 1.2(\text{stat.}) \pm 0.3(\text{syst.})$ pb. The existence of the triple gauge boson vertex of the Standard Model is clearly preferred by the data. The decay branching ratio of the W boson into hadrons is measured to be $B(W \to \text{hadrons}) = 67.7 \pm 3.1(\text{stat.}) \pm 0.7(\text{syst.})$ %, allowing a determination of the CKM matrix element $|V_{cs}| = 0.98 \pm 0.14(\text{stat.}) \pm 0.03(\text{syst.})$.

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1 Introduction

This letter presents results on W-pair production using data collected with the ALEPH detector at centre–of–mass energies of 170.3 and 172.3 GeV in November 1996.

The experimental conditions and data analysis follow closely those used in the cross section measurement at threshold [1]. As they are already described in detail in [1], attention will be focused on changes other than a simple rescaling of cuts with the increased collision energy. These changes are mainly meant to take advantage of the higher signal over background ratio by increasing the selection efficiencies.

At these energies, the cross section has little sensitivity to the W mass, but it is large enough that over 100 W-pairs are expected in the data sample collected, allowing determinations of the W hadronic and leptonic branching ratios. The total production rate constitutes a test of the Standard Model, while the hadronic branching ratio is sensitive to the yet poorly known coupling of the W to cs pairs $|V_{\mathrm{cs}}|$.

A detailed description of the ALEPH detector can be found in Ref. [2] and of its performance in Ref. [3]. The luminosity is measured with small-angle Bhabha events, using lead-proportional wire sampling calorimeters [4]. The accepted Bhabha cross section is approximately 5.2 nb [5]. An integrated luminosity of 10.65 ± 0.05 (stat.) $\pm$ 0.06 (syst.) pb^{-1} was recorded, at a mean centre–of–mass energy of 172.09 ± 0.06 GeV [6] (1.10 pb^{-1} and 9.55 pb^{-1} at 170.28 GeV and 172.30 GeV, respectively).

2 Physics processes and definition of the W-pair cross section

WW events are produced through three doubly resonant diagrams (s-channel γ and Z^0 exchange and t-channel ν exchange), called "CC03 diagrams", leading to a four-fermion final state. Many additional diagrams can lead to the same four-fermion final states as the decay modes of a W-pair [7]. The interference between the CC03 and the additional diagrams is treated by means of correction factors and the results are presented as CC03 cross sections, following the same procedure as in [1].

As for the threshold measurement, two Monte Carlo event generators were used to simulate the signal events. Samples of events were generated with different W masses, both for CC03 diagrams and for all four-fermion diagrams, with `KORALW` [8]. A comparison sample was generated with `EXCALIBUR` [9] with and without colour reconnection effects (following the ansatz of [10]). The `KORALW` sample with $m_{\mathrm{W}} = 80.25$ GeV/c^2 serves to determine the efficiencies used to obtain the central value of the final result. The other samples are used to check the m_{W} dependence of the selection procedures and of the four-fermion–to–CC03 correction. The `EXCALIBUR` samples are used as a check of the Monte Carlo simulation of the physics processes, and to assess the effects of colour reconnection. The `PYTHIA 5.7` [12] Monte Carlo program is used to simulate the various backgrounds. Monte Carlo samples corresponding to integrated luminosities at least twenty times as large as that of the data were fully simulated for all background reactions.

3 Selection of W-pair candidates

3.1 $W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ events

The two selections for the $W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ signal (ℓ = e, μ or τ) developed for the threshold measurement are used. Details of the two analyses are given in [1]. They have similar overall efficiencies (65% and 69%) and background levels (0.035 pb and 0.058 pb), but differ in their sensitivities to the individual dilepton channels. The first analysis is based on topological information and is sensitive to all channels. Events are accepted if they contain two or four charged tracks with zero total electric charge. The four-track case is reduced to a two-jet topology by merging the three tracks with the smallest invariant mass. This triplet is interpreted as coming from a three-prong tau decay, and its mass is required to be smaller than 1.5 GeV/c^2. The second analysis requires from two to six charged tracks and the presence of at least one high momentum electron or muon, identified using the standard ALEPH algorithms [3]. In the first analysis, the photon veto against radiative dilepton events has been increased from 1 to 4 GeV and an acollinearity cut of more than 2° between the charged tracks is introduced to reject doubly radiative returns to the Z events with gamma conversion in the detector. In the second analysis, the most energetic jet must lie between 20% and 80% of the beam energy (was 35% and 68% at threshold).

Events are accepted as WW candidates if they pass either of the two selections. The combined efficiency is 74%, for a background of 0.065 pb. In the data, 10 events pass one of the selections, 9 pass both. The residual background amounts to 0.7 events and is dominated by $\gamma\gamma \to \tau\tau$ and non-CC03 four-fermion events.

The largest detector related systematic effects come from the photon vetoes. Events triggered at random beam crossings are used to assess the losses due to beam related background and detector noise. The loss of efficiency due to the requirement that no energy be measured in a cone of 12° around the beam axis is measured to be 2%. In addition, a systematic uncertainty of ±2% is assigned for the large angle photon vetoes. The overall systematic error, detailed in Table 1, amounts to ±0.07 pb and is dominated by Monte Carlo statistics.

The four-fermion–to–CC03 correction is -0.018 ± 0.053 pb, giving

$$\sigma_{\rm CC03}(\mathrm{WW} \to \ell^+\nu\ell^-\bar{\nu}) = 1.22^{+0.46}_{-0.37}(\mathrm{stat.}) \pm 0.07(\mathrm{syst.})\ \mathrm{pb}. \quad (1)$$

Table 1: *Contributions to the systematic error on the cross section for* $\mathrm{WW} \to \ell^+\nu\ell^-\bar{\nu}$.

Source	Error (pb)
Signal efficiency	0.05
Backgrounds	0.02
Four-fermion–to–CC03 correction	0.05
Luminosity	0.01
Total (in quadrature)	0.07

3.2 $W^+W^- \to \ell\nu q\bar{q}$ events

The typical final state of semileptonic WW events consists of an energetic lepton, large missing momentum and two energetic hadronic jets. The three selection procedures developed for the threshold measurement have been applied. As in the previous section, one selection is optimised for WW events with electrons or muons and requires an energetic identified electron or muon, while the other two are designed for $\tau\nu q\bar{q}$ events, based on global variables and topological properties of events.

3.2.1 $WW \to e\nu q\bar{q}$ and $WW \to \mu\nu q\bar{q}$ selections

At least five tracks are required, with a total charged energy greater than $0.12\sqrt{s}$, and the missing four-momentum is used to reduce the non-radiative $q\bar{q}$ background and to remove most of the radiative component. The charged track with the highest momentum component antiparallel to the missing momentum is chosen as the lepton candidate. Loose electron or muon identification criteria and an energy of at least 15 GeV are required. For electrons, the charged energy is corrected for possible bremsstrahlung photons detected in the electromagnetic calorimeter. The remaining particles are clustered into two jets with the Durham (*P-scheme*) algorithm [11].

After this preselection, the probability for an event to come from the signal process is built from the energy of the lepton, the total missing transverse momentum and the lepton isolation with the procedure defined in [1].

Events are selected if they have a probability larger than 0.55 to be an $e\nu q\bar{q}$ event, or a probability larger than 0.65 to be a $\mu\nu q\bar{q}$ event. These cut values are designed, based on Monte Carlo studies, to minimise the statistical uncertainty on the WW cross section. The probability distributions of preselected $e\nu q\bar{q}$ and $\mu\nu q\bar{q}$ Monte Carlo and data candidates are shown in Fig. 1. With these cuts, the selection efficiencies for $e\nu q\bar{q}$ and $\mu\nu q\bar{q}$ are 84% and 91%, respectively, on a total background of 0.135 pb; 14 electrons and 20 muons are selected in the data.

3.2.2 $WW \to \tau\nu q\bar{q}$ events

The analysis optimised for the selection of $WW \to \tau\nu q\bar{q}$ events is based on two complementary approaches: the global selection uses global event variables, such as the acoplanarity and the missing mass, while the topological selection attempts to identify the tau jet.

A common preselection requires high multiplicity events, energy in a cone of 12° around the beam axis less than $0.025\sqrt{s}$, no energetic isolated photon, the polar angle of the missing momentum to be greater than 18.2°. The event is divided into two hemispheres by the plane perpendicular to the thrust axis and the acollinearity calculated from the directions of the total momenta of all particles in the two hemispheres, is required to be less than 170°.

In the global analysis the events are required to be acoplanar and the missing momentum isolated in space and in projection in the plane transverse to the beam axis, therefore the acoplanarity between the event hemispheres is required to be less than 170° and the energy contained in an azimuthal wedge of half-angle 30° with respect to the

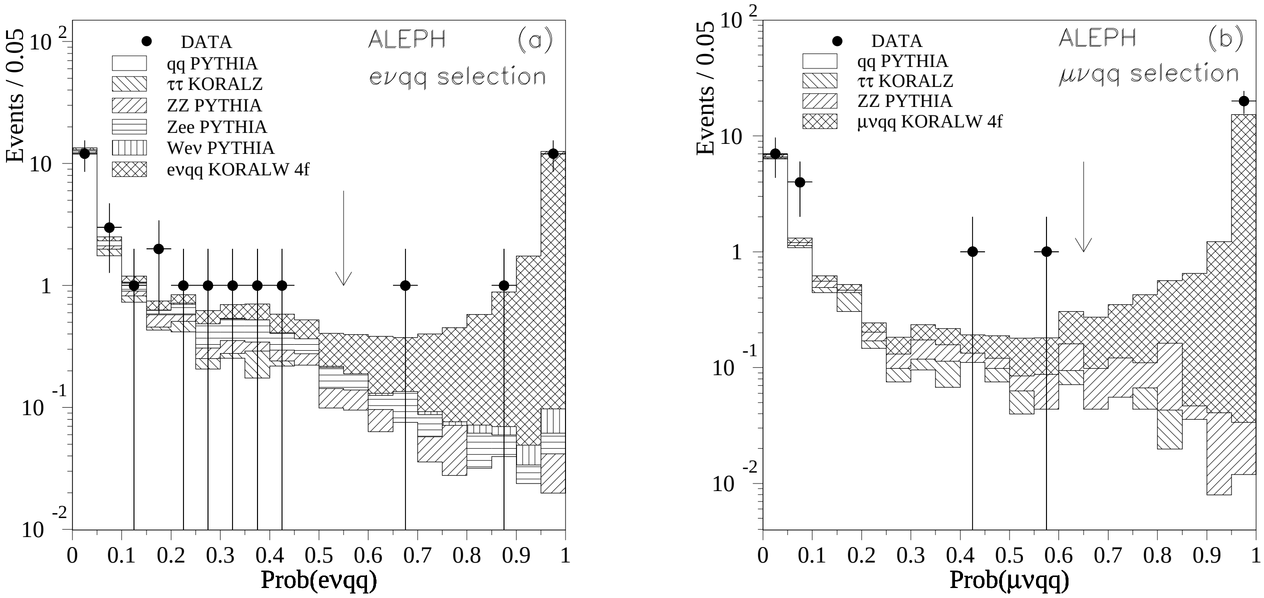

Figure 1: *Probability distribution of preselected ALEPH events for the* eνq$\bar{\text{q}}$ *(a) and the* $\mu\nu$q$\bar{\text{q}}$ *(b) selections. The arrows show the cuts above which events are kept in the selection.*

plane defined by the beam and the missing momentum directions is required to be less than $0.10\sqrt{s}$. Moreover, the energy in a cone of half-angle 20° around the direction of the missing momentum is required to be less than $0.025\sqrt{s}$. In order to reduce the background from single W production, the average of the missing momentum and missing energy is required to be less than 60 GeV, the missing mass less than 80 GeV/c^2. Finally the visible mass is required to be greater than 80 GeV/c^2 and less than 130 GeV/c^2.

In the topological analysis, jets are constructed with the JADE algorithm. The tau jet is a low multiplicity jet containing at least one and at most three tracks, with a charged momentum of at least $0.025\sqrt{s}$ and is the most antiparallel jet to the missing momentum. The tau jet must be separated by more than 25° from the the other jets. The acollinearity of the q$\bar{\text{q}}$ jets is required to be greater than 125°, the quark jet energies must be less than 60 GeV and the invariant mass of the quark-jets must be greater than 60 GeV/c^2. The energy in a wedge (defined as above in the global analysis) must be less than $0.20\sqrt{s}$.

The inclusive combination of these two selections has an efficiency of 59% on the WW $\rightarrow \tau\nu$q$\bar{\text{q}}$ channel, with a non W background of 0.110 pb (dominated by q$\bar{\text{q}}$ events); 33 events are selected in the data (23 are already in the electron and muon samples).

3.2.3 Combined results for the semileptonic channels

The three analyses are combined inclusively. A total of 44 events is selected, of which 14 have a high energy identified electron, 20 have a high energy identified muon, and 10 are likely to contain a tau. The combined efficiency is 89% for the electron channel, 94% for the muon channel and 61% for the tau channel, giving 81% overall. The individual sensitivities

Table 2: *Efficiencies for the three semileptonic WW decay channels to be inclusively selected by just one of the electron* (e)*, muon* (μ) *or tau* (τ) *selections. Also given, the efficiencies to be simultaneously selected by both the electron and tau* (e.τ) *or muon and tau* ($\mu.\tau$) *selections. These five efficiencies are summed to give the combined efficiencies in the final column. Also shown are the number of selected data events* (N_{data}).

	Selection					
	e	μ	τ	e.τ	$\mu.\tau$	
Channel	Efficiencies (%)					Combined (%)
eνq$\bar{\mathrm{q}}$	28.4	0.1	5.2	55.5	0.1	89.3
$\mu\nu$q$\bar{\mathrm{q}}$	0.0	32.0	3.3	0.0	58.7	94.0
$\tau\nu$q$\bar{\mathrm{q}}$	0.8	0.8	54.2	2.6	2.6	60.9
N_{data}	5	6	10	9	14	

of each selection to the semileptonic channels, eνq$\bar{\mathrm{q}}$, $\mu\nu$q$\bar{\mathrm{q}}$ or $\tau\nu$q$\bar{\mathrm{q}}$, are summarised in Table 2 together with the numbers of selected events. Systematic uncertainties on signal efficiencies are evaluated to be $\pm 2.2\%$, coming from i) Monte Carlo statistics, ii) errors from the photon vetoes, iii) uncertainties in the lepton identification, iv) uncertainties on the lepton isolation variable, and v) possible variations of the probability discrimination procedure.

The background amounts to 0.244 pb; it is dominated by q$\bar{\mathrm{q}}$, ZZ* and Ze$^+$e$^-$events. A systematic uncertainty of ± 0.062 pb is assigned by summing the following contributions: i) Monte Carlo statistics; ii) q$\bar{\mathrm{q}}$ modelling, assessed by the deviations of Monte Carlo from LEP1 data, using the same selections with cuts rescaled by the ratio of centre–of–mass energies; iii) comparison of the normalisation and distributions of preselected Monte Carlo and data candidates with signal probabilities smaller than 0.10; and iv) overall normalisation of the q$\bar{\mathrm{q}}$ background, assessed using radiative returns to the Z peak. In this channel the four-fermion–to–CC03 correction is estimated as $+0.042$ pb with an uncertainty of ± 0.051 pb coming from Monte Carlo statistics. The various sources of systematic uncertainty are summarised in Table 3.

The resulting cross section for the semileptonic WW channel is

$$\sigma_{\mathrm{CC03}}(\mathrm{WW} \rightarrow \ell\nu\mathrm{q}\bar{\mathrm{q}}) = 4.73 \pm 0.76(\mathrm{stat.}) \pm 0.16(\mathrm{syst.})\ \mathrm{pb}. \quad (2)$$

Table 3: *Contributions to the systematic error on the cross section for* $\mathrm{WW} \rightarrow \ell\nu\mathrm{q}\bar{\mathrm{q}}$.

Source	Error (pb)
Signal efficiency	0.13
Backgrounds	0.08
Four-fermion–to–CC03 correction	0.05
Luminosity	0.04
Total (in quadrature)	0.16

3.3 $W^+W^- \to q\bar{q}q\bar{q}$ events

A simple preselection is used to remove obvious backgrounds and is followed by a multivariable analysis to obtain the cross section. Due to a factor four increase of the signal to background ratio at 172 GeV compared with 161 GeV, only the weighting technique [1] is used, the other multivariable analyses serving as cross checks.

The preselection cuts applied are: i) total visible energy > 118 GeV ; ii) missing longitudinal momentum < 27 GeV/c; iii) minimum jet mass of 0.6 GeV/c^2 to remove converted photons in the detector; and iv) maximum fraction of a jet energy carried by a single particle < 0.85. After the preselection, 186 events are observed for 170 expected from standard processes.

Each preselected event is weighted according to its location in a binned multidimensional space of discriminating variables [13]. The weight in each bin, estimated using signal and all background Monte Carlo samples, is the fraction of WW events in that bin. Five variables are used: i) y_{34}, the jet-resolution parameter at which the transition from three to four jets occurs; ii) the sphericity of the event; iii) the sum of squared transverse particle momenta with respect to their jets axes; iv) the lowest jet energy; and v) the sum of the cosines of the angles between all pairings of jets. The changes compared to the threshold analysis are the replacement of the JADE jet algorithm [14] by the Durham algorithm and the use of the the sum of the cosines of the angles instead of the average fitted dijet mass. The distribution of weights for the preselected events is shown in Fig. 2, compared with Monte Carlo expectations. The hadronic WW cross section is extracted by a binned log-likelihood fit to this distribution. A selection that applies a cut at a minimum weight value of 0.35 would select 65 events with an efficiency of 82% for a background cross section of 1.04 pb (mainly from $q\bar{q}$ events).

The four-fermion–to–CC03 correction is -0.11 ± 0.03 pb. The background contributions are evaluated with Monte Carlo events.

The different sources of systematic uncertainties, estimated as at 161 GeV [1], are summarised in Table 4. They are added in quadrature to obtain a total systematic uncertainty of 0.21 pb.

The CC03 cross section for the hadronic channel is

$$\sigma_{\mathrm{CC03}}(\mathrm{WW} \to q\bar{q}q\bar{q}) = 5.76 \pm 0.88(\mathrm{stat.}) \pm 0.21(\mathrm{syst.})\ \mathrm{pb}. \tag{3}$$

This result has been checked by an independent analysis based on a neural network, yielding $\sigma_{\mathrm{CC03}}(\mathrm{WW} \to q\bar{q}q\bar{q}) = 6.04 \pm 0.88(\mathrm{stat.}) \pm 0.27(\mathrm{syst.})$ pb, which is consistent within the errors.

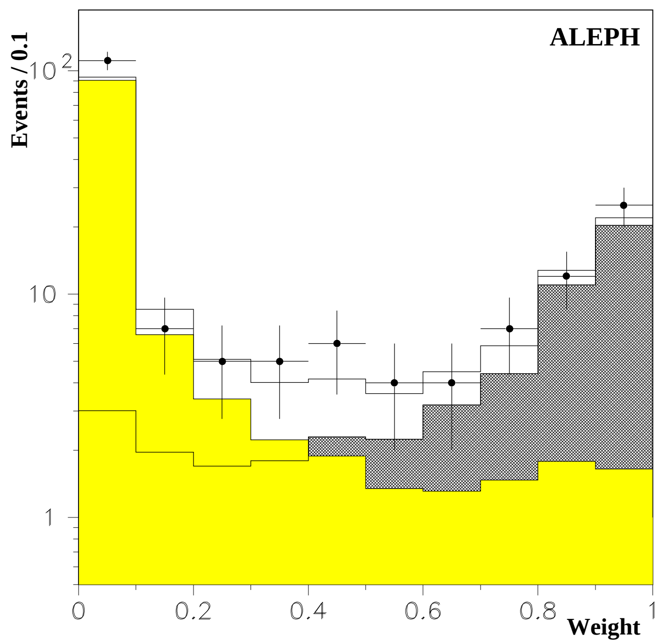

Figure 2: *Comparison of weight distributions for data and Monte Carlo after the preselection. The points are the data, the open histogram the total Monte Carlo prediction. The light shadowed histogram shows the expected background and the dark shadowed histogram the expected* $\mathrm{WW} \to \mathrm{q\bar{q}q\bar{q}}$ *contribution for* $m_{\mathrm{W}} = 80.25\ \mathrm{GeV}/c^2$.

Table 4: *Contributions to the systematic error on the cross section for* $\mathrm{WW} \to \mathrm{q\bar{q}q\bar{q}}$.

Source	Error (pb)
Preselection	0.07
Colour reconnection	0.03
QCD background normalisation	0.08
QCD generator	0.06
WW generator	0.02
Four-fermion–to–CC03 correction	0.03
Simulation of discriminating variables	0.13
Detector calibration	0.02
MC statistics	0.08
Luminosity	0.05
Total (in quadrature)	0.21

4 Results

In the following it is assumed that the W boson does not decay into modes other than $\ell\nu$ and $q\bar{q}$ pairs. The cross section from the three channels are summed to obtain the total CC03 W-pair cross section:

$$\sigma_{WW} = 11.71 \pm 1.23(\text{stat.}) \pm 0.28(\text{syst.})\ \text{pb}, \tag{4}$$

where the systematic error is dominated by the uncertainties in the $q\bar{q}q\bar{q}$ channel. The result agrees with the expected cross section (computed with the program GENTLE [15]) for the current world average value of $m_W = 80.356 \pm 0.125$ GeV/c^2 [16], of $12.39 \pm 0.09 \pm 0.25$ pb, where the first term corresponds to the error on m_W and the second to a $\pm 2\%$ theoretical uncertainty on this cross section calculation [17].

At 172 GeV centre-of-mass, the WW cross section is already sensitive to the large cancellations typical of the non-abelian gauge theory structure of the Standard Model. In Fig. 3 the radiatively corrected cross section calculated with GENTLE is compared with the ALEPH measurements of σ_{WW} at threshold and at 172 GeV. On the same figure are shown i) the cross section that would be obtained from the t-channel neutrino exchange only, and ii) the cross section obtained by including in addition only the s-channel photon exchange diagram and not the Z exchange one. The existence of the triple gauge boson vertex of the Standard Model is clearly preferred by the data.

Within the framework of the Standard Model, the WW cross section near threshold depends chiefly on the W mass. However, the cross section at 172 GeV retains some dependence on the W mass, yielding $m_W = 81.17^{+1.15}_{-1.62}$ (stat.). Combining this with the W mass measurement made at threshold [1] gives

$$m_W = 80.20 \pm 0.33 \pm 0.09 \pm 0.03(\text{LEP})\ \text{GeV}/c^2, \tag{5}$$

where the first error is statistical and the second comes from systematic errors in the cross section. The last systematic error comes from the uncertainty in the LEP beam energy [6].

Under the assumption of lepton universality, the three cross sections for $\ell\nu\ell\nu$, $\ell\nu q\bar{q}$ and $q\bar{q}q\bar{q}$ channels can be written as a function of the total WW cross section σ_{WW} and the hadronic W branching ratio B as

$$\begin{aligned} \sigma_{\ell\nu\ell\nu} &= \sigma_{WW}(1-B)^2 \\ \sigma_{\ell\nu q\bar{q}} &= 2\sigma_{WW}B(1-B) \\ \sigma_{q\bar{q}q\bar{q}} &= \sigma_{WW}B^2. \end{aligned}$$

A maximum likelihood fit to the data collected at 161 and 172 GeV gives

$$\text{B}(\text{W} \to \text{hadrons}) = 67.7 \pm 3.1(\text{stat.}) \pm 0.7(\text{syst.})\ \%, \tag{6}$$

in agreement with direct measurements performed at LEP [18] and with both the Standard Model expectation of 67.5% and the indirect measurements performed at proton colliders of 67.9 ± 1.5 % [19].

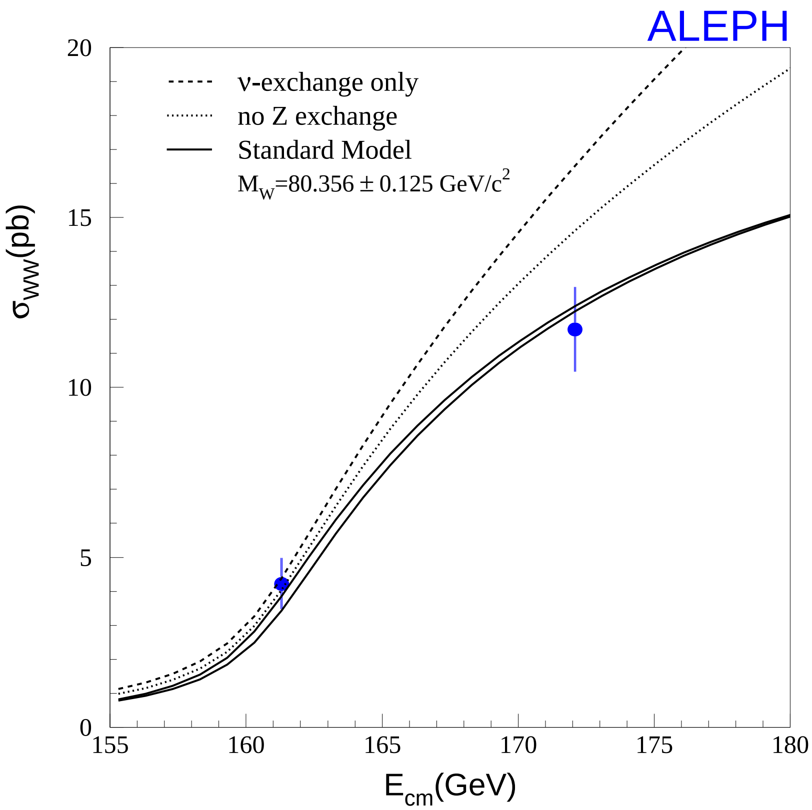

Figure 3: *Measurement of the W-pair production cross section at the two centre–of–mass energies, compared to the Standard Model prediction from* GENTLE *for the world average value of the W mass (the two curves correspond to the* ± 125 MeV/c^2 *error on* m_{W}*). Also shown are the cross sections that would be obtained i) from the t-channel neutrino exchange diagram only or ii) by including in addition only the s-channel photon exchange diagram and not the Z exchange one.*

This result can be expressed in terms of the individual branching ratios of the W to quark–antiquark pairs:

$$\mathrm{B(W \to hadrons)} = \frac{(|V_{\mathrm{ud}}|^2 + |V_{\mathrm{cd}}|^2 + |V_{\mathrm{us}}|^2 + |V_{\mathrm{cs}}|^2 + |V_{\mathrm{ub}}|^2 + |V_{\mathrm{cb}}|^2) \times (1 + \alpha_s(M_W^2)/\pi)}{1 + (1 + \alpha_s(M_W^2)/\pi) \sum_{ij} |V_{\mathrm{ij}}|^2} \tag{7}$$

Higher-order corrections to this formula are below 1%. Using the world average value of $\alpha_s(M_Z^2) = 0.118 \pm 0.003$ [19] evolved to M_W^2, $|V_{\mathrm{ud}}| = 0.9736 \pm 0.0010$, $|V_{\mathrm{cd}}| = 0.224 \pm 0.016$, $|V_{\mathrm{us}}| = 0.2205 \pm 0.0018$, $|V_{\mathrm{cb}}| = 0.041 \pm 0.003$ [19] and $|V_{\mathrm{ub}}| = 0.0033 \pm 0.0008$ [20] a constraint on the least well measured CKM matrix element is obtained: $|V_{\mathrm{cs}}| = 0.98 \pm 0.14(\mathrm{stat.}) \pm 0.03(\mathrm{syst.})$. This result is consistent with, but also improves on the existing direct measurement from D meson decay, $|V_{\mathrm{cs}}| = 1.01 \pm 0.18$ [19]. It is in agreement with the more precise value derived from the unitarity of the CKM matrix under the assumption of only three generations [19].

Without the assumption of lepton coupling universality, the individual leptonic branching ratios of the W boson can be derived from the observed number of leptons of different flavour in $\ell\nu q\bar{q}$ and $\ell\nu\ell\nu$ events and the $W^+W^- \to q\bar{q}q\bar{q}$ cross section, using the data collected at 161 and 172 GeV. The results are

$$\begin{aligned} B(W \to e\nu) &= 9.7 \pm 2.0(\text{stat.}) \pm 0.5(\text{syst.})\ \%, \\ B(W \to \mu\nu) &= 11.2 \pm 2.0(\text{stat.}) \pm 0.6(\text{syst.})\ \%, \\ B(W \to \tau\nu) &= 11.3 \pm 2.7(\text{stat.}) \pm 0.6(\text{syst.})\ \%, \end{aligned}$$

in agreement with lepton universality and the Standard Model value of 10.8%. $B(W \to \tau\nu)$ is 25% anticorrelated with the other two branching ratios.

5 Conclusions

Using an integrated luminosity of 10.65 pb^{-1} collected in the ALEPH detector at centre–of–mass energies of 170.3 and 172.3 GeV, all combinations of standard W decay channels are analysed. The W-pair cross section is measured to be $11.7 \pm 1.2(\text{stat.}) \pm 0.3(\text{syst.})$ pb. It is combined with the threshold measurement to improve the W boson mass. The existence of the triple gauge boson vertex of the Standard Model is clearly preferred by the data. The hadronic decay branching ratio of the W is directly measured and is found to agree with the minimal Standard Model expectation. This allows a determination of the CKM matrix element $|V_{cs}| = 0.98 \pm 0.14(\text{stat.}) \pm 0.03(\text{syst.})$. Individual leptonic branching ratios of the W are consistent with lepton universality.

Acknowledgements

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