EUROPEAN LABORATORY FOR PARTICLE PHYSICS (CERN)

CERN-EP/99-?
February 28, 2000

Measurement of W-pair production in e^+e^- collisions at 189 GeV

The ALEPH Collaboration

Abstract

The production of W^+W^- pairs is analysed in a data sample collected by ALEPH at a mean centre-of-mass energy of 188.63 GeV, corresponding to an integrated luminosity of 174.20 pb^{-1}. Cross sections are given for different topologies of W decays into leptons or hadrons. Combining all final states and assuming Standard Model branching fractions, the total W-pair cross section is measured to be $15.71 \pm 0.34(\text{stat.}) \pm 0.18(\text{syst.})$ pb. Using also the W-pair data samples collected by ALEPH at lower centre-of-mass energies, the decay branching fraction of the W boson into hadrons is measured to be $B(W \to \text{hadrons}) = 66.97 \pm 0.65(\text{stat.}) \pm 0.32(\text{syst.})\%$, allowing a determination of the CKM matrix element $|V_{cs}| = 0.951 \pm 0.030(\text{stat.}) \pm 0.015(\text{syst.})$.

(to be Submitted to Physics Letters B)

1 Introduction

This letter presents results on W-pair production in e^+e^-collisions using data collected with the ALEPH detector at a centre-of-mass energy around 189 GeV, during the 1998 data taking period.

The experimental conditions and data analysis follow those used in the cross section measurement at lower LEP2 energies. As they are already described in detail in [1], attention will be focused on changes in selection procedures other than a simple rescaling of cuts with the increased collision energy.

The separation of WW events in all possible W decay channels allows the determination of the W branching fractions and, indirectly, the coupling of the W to cs pairs.

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], with an accepted Bhabha cross section of approximately 4.25 nb [5]. An integrated luminosity of 174.20 ± 0.20 (stat.) $\pm$ 0.73 (syst.) pb^{-1} was recorded at a mean centre-of-mass energy of 188.63 ± 0.04 GeV [6].

In the following, all signal cross sections are defined by the production of four-fermion final states only through two resonating W bosons in t-channel ν_{e} exchange and s-channel Z/γ exchange, referred to as CC03 cross sections [7]. The measured cross sections are corrected for the difference, denoted the"4f-CC03 correction", in the accepted cross sections for CC03 processes and all Standard Model four-fermion final states consistent with W-pair decays.

The `KORALW` [8] version 1.21 Monte Carlo event generator is used to simulate the signal events. The `JETSET` [9] package takes care of hadronisation. Comparison samples are generated with `EXCALIBUR` [10] and `grc4f` [11] for the CC03 and all four-fermion diagrams are used for systematic error evaluation. Samples of events are generated with different W masses, both for CC03 diagrams and for all WW-like four-fermion diagrams, with `KORALW`. `EXCALIBUR` was used to generate events with and without colour reconnection effects following the ansatz of Ref. [12].

The `KORALZ` [13] Monte Carlo program is used to generate background events coming from the $q\bar{q}$ process, with a cross-check using `PYTHIA 5.7` [14].

Other background events are generated with `PYTHIA 5.7` for ZZ, Zee and Weν processes, `PHOT02` [15] for $\gamma\gamma$ interactions, `KORALZ` for μ and τ pair production and `BHWIDE` [16] and `UNIBAB` [17] for Bhabha scattering events.

The CC03 Standard Model cross section is calculated using the program `GENTLE` [18] which gives $\sigma_{\mathrm{WW}} = 16.65$ pb for $\sqrt{s} = 188.63$ GeV and $m_{\mathrm{W}} = 80.35\ \mathrm{GeV}/c^2$ [19].

2 Selection of W-pair candidates

2.1 WW $\rightarrow \ell\nu\ell\nu$ events

The selection of fully leptonic W-pair decays follows exactly the two selections used for the cross section and branching fraction measurements at 183 GeV [1].

Beam related background and detector noise that is not simulated in Monte Carlo events, affect the efficiencies of the cut that removes $\gamma\gamma$ events depositing energy at angles below 12° around the beam. The inefficiency introduced is measured from random triggers and found to be $8.2 \pm 0.5\%$. It is applied as a correction factor lowering the Monte Carlo efficiencies.

The CC03 efficiencies in the individual $\ell\nu\ell\nu$ channels are given in Table 1 and are corrected for the beam related effect. The inclusive combination of the two selections has an efficiency of $64.2 \pm 0.4\%$ for the fully leptonic WW channels, combined assuming lepton universality. The total background amounts to $131 \pm 7(\mathrm{stat.}) \pm 8.5(\mathrm{syst.})$ fb and is dominated by $\gamma\gamma \to \ell\ell$ and non-WW-like four-fermion events, mainly $\mathrm{ZZ} \to \ell\ell\nu\nu$. In the data, the inclusive combination selects 220 events.

The systematic uncertainty on lepton identification amounts to 0.6% for electrons and 1.6% for muons, to cover residual discrepancies in identification efficiency and purity between data and Monte Carlo. The sources of systematic errors are listed in Table 2. The effect on the total cross section amounts to 24 fb and is dominated by the Monte Carlo statistical errors, the uncertainties on the background cross sections and the uncertainty introduced by the cut on energy detected close to the beam axis.

Events are classified into six di-lepton channels making use of electron and muon identification criteria. A jet or a track is classified as a tau either if no lepton identification is fulfilled or if the identified lepton has an energy lower than 25 GeV. A maximum likelihood fit is applied to determine the cross section for each fully leptonic decay channel using efficiency matrices for CC03 and backgrounds, as in Table 1. WW-like four-fermion processes are taken into account in the 4f-CC03 correction for each individual channel. For all channels together, this correction amounts to -10 ± 10 fb, where the uncertainty comes from Monte Carlo statistics.

The results of the fit are

$$\begin{aligned}
\sigma(\mathrm{WW} \to \mathrm{e}\nu\mathrm{e}\nu) &= 0.19 \pm 0.05(\mathrm{stat.}) \pm 0.01(\mathrm{syst.})\ \mathrm{pb},\\
\sigma(\mathrm{WW} \to \mu\nu\mu\nu) &= 0.20 \pm 0.05(\mathrm{stat.}) \pm 0.01(\mathrm{syst.})\ \mathrm{pb},\\
\sigma(\mathrm{WW} \to \tau\nu\tau\nu) &= 0.22 \pm 0.08(\mathrm{stat.}) \pm 0.02(\mathrm{syst.})\ \mathrm{pb},\\
\sigma(\mathrm{WW} \to \mathrm{e}\nu\mu\nu) &= 0.43 \pm 0.07(\mathrm{stat.}) \pm 0.01(\mathrm{syst.})\ \mathrm{pb},\\
\sigma(\mathrm{WW} \to \mathrm{e}\nu\tau\nu) &= 0.36 \pm 0.08(\mathrm{stat.}) \pm 0.02(\mathrm{syst.})\ \mathrm{pb},\\
\sigma(\mathrm{WW} \to \mu\nu\tau\nu) &= 0.38 \pm 0.08(\mathrm{stat.}) \pm 0.01(\mathrm{syst.})\ \mathrm{pb}.
\end{aligned}$$

The systematic errors are obtained by varying all input parameters in the fit according to their uncertainties.

The total fully leptonic cross section is obtained with the same fit, assuming lepton universality:

$$\sigma(\mathrm{WW} \to \ell\nu\ell\nu) = 1.78 \pm 0.13(\mathrm{stat.}) \pm 0.02(\mathrm{syst.})\ \mathrm{pb}.$$

This result agrees with the Standard Model expectation of 1.76 ± 0.04 pb [21].

2.2 WW $\to \ell\nu$qq events

Similarly to the lower energy measurements, the three $\ell\nu$qq selection procedures are applied. One selection is optimised for WW events with an electron or a muon, and

Table 1: Summary of results of the different event selections on Monte Carlo and data events. Efficiencies are given in percent of CC03 processes. The qqqq column refers to events with a NN output greater than 0.3. The listed backgrounds do not include the 4f-CC03 corrections. In the qqqq column the backgrounds include non-qqqq WW decays.

		Event selection and classification										
		ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$	eqq	μqq	τqq	qqqq	All
Eff. for WW→ (%)	eνeν	57.8	-	8.8	-	-	0.5	-	-	-	-	67.1
	e$\nu\mu\nu$	-	59.0	4.7	-	4.6	0.3	-	-	-	-	68.6
	e$\nu\tau\nu$	3.0	4.2	50.1	-	0.3	4.3	-	-	-	-	61.9
	$\mu\nu\mu\nu$	-	0.1	-	61.9	8.3	0.3	-	-	-	-	70.6
	$\mu\nu\tau\nu$	-	4.2	0.3	3.5	52.9	3.5	-	-	-	-	64.4
	$\tau\nu\tau\nu$	0.2	0.4	7.7	0.4	6.0	36.5	-	-	-	-	51.2
	eνqq	-	-	-	-	-	-	82.4	-	5.4	0.2	88.0
	$\mu\nu$qq	-	-	-	-	-	-	-	87.5	4.1	0.2	91.9
	$\tau\nu$qq	-	-	-	-	-	-	3.7	3.8	59.0	0.9	68.0
	qqqq	-	-	-	-	-	-	-	-	-	91.7	91.7
Backgrounds (fb)		18	7	43	11	15	36	99	26	189	1854	2299
Observed Events		24	51	48	26	46	25	381	382	303	1435	2721

requires an identified electron or muon track. The other two are designed to select $\tau\nu$qq events, based on global variables and topological properties of events.

2.2.1 WW $\rightarrow$ eνqq and WW $\rightarrow$ $\mu\nu$qq selections

The selection of eνqq and $\mu\nu$qq events is changed with respect to the previous analysis [1]. The preselection is still based on the event total charged energy and multiplicity. Further, a cut on the total longitudinal momentum and visible energy is applied to reject Zγ events where the photon is undetected along the beam line.

With increased $\sqrt{s}$, the two W's are produced with a larger initial boost, and the identification of the lepton as the track with the highest momentum component antiparallel to the missing momentum is much less efficient. In this analysis, the selection of the lepton track therefore relies on the fact that it is expected to be more energetic and isolated than the other charged tracks in the hadronic system, and ignores any correlation with the missing momentum. The candidate lepton is chosen as the charged track that maximises $p_\ell^2(1-\cos\theta_{\ell j})$, where p_ℓ is the track momentum and $\theta_{\ell j}$ the angle of the track to the closest of the jets clustered using the remaining charged tracks, with the Durham-P [20] algorithm ($y_{\rm cut}=0.0003$).

The same electron or muon identification criteria as for the fully leptonic channel are required for this lepton candidate track. No cut is applied on the lepton energy, so that

Table 2: Systematic error summary in fb.

	WW cross section		
Source	$\ell\nu\ell\nu$	$\ell\nu$qq	qqqq
Calibration of calorimeters			32
Jet energy calibrations			9
WW generator and m_{W} dependence			25
WW fragmentation			17
QCD generator			23
background shape			50
Final state Interactions			38
Background normalisation	13	30	84
Luminosity	9	35	39
Monte Carlo statistics	15	61	36
Beam background	11	30	40
Lepton identification	2	45	
Lepton isolation		56	
Probability discrimination		46	
Total	24	118	134

$\tau\nu$qq events where the τ decays to a softer lepton (as $\tau \to \mathrm{e}\nu\nu$ or $\tau \to \mu\nu\nu$) will also be selected by this analysis.

For electron candidates the lepton energy is corrected for possible bremsstrahlung photons detected in the electromagnetic calorimeter. The isolation of the lepton is then evaluated as $\log(\tan\theta_C/2) + \log(\tan\theta_F/2)$ where θ_C and θ_F are, respectively, the angle of the lepton to the closest charged track, and the opening angle of the largest cone centred on the lepton direction that contains a total energy smaller than 5 GeV.

The probability for an event to come from each of the three eνqq, $\mu\nu$qq or $\tau\nu$qq signal processes is determined from Monte Carlo reference samples using the lepton energy, the lepton isolation and the event total transverse momentum (Fig. 1). An event is classified as eνqq or $\mu\nu$qq, if its corresponding probability is greater than 0.40, in which case it is not considered in the tau search presented below.

2.2.2 WW $\to \tau\nu$qq events

The selection of $\tau\nu$qq events is based on global event variables and is combined with a topological selection attempting to identify the τ jet. As the selections were described in detail in previous papers [1], only the changes other than a rescaling of the energy-based cuts values with $\sqrt{s}$ will be mentioned in the following:

(i) In the global analysis the visible mass is now required to be greater than 85 GeV/c^2 and less than 155 GeV/c^2 to cope with the increasing boost of the W boson. The estimated energy of the "primary" neutrino must be smaller than 70 GeV.

(ii) In the topological analysis, the energy of the most energetic quark jet must be less than 75 GeV. Additionally the mass of the hadronic system, i.e., the mass excluding the tau jet, is required to be less than 100 GeV/c^2.

If an event has been rejected by e, μ and $\tau\nu$qq algorithms, but contains a well identified e or μ, it is classified in the $\tau\nu$qq channel if its probability to be a $\tau\nu$qq event is greater than 0.40. This classification reduces the correlation between e and τ or μ and τ channels (see section 4).

2.2.3 Results

Table 1 gives the efficiencies for each selection. The inclusive efficiencies for the three semileptonic decay channels are $87.8 \pm 0.4\%$ for the electron channel, $91.6 \pm 0.4\%$ for the muon channel and $66.5 \pm 0.5\%$ for the tau channel, giving $82 \pm 0.3\%$ average efficiency on WW $\rightarrow \ell\nu$qq, with a background of 314 ± 12(stat.) $\pm$ 25(syst.) fb. The overall 4f-CC03 correction is $+8 \pm 40$ fb. A total of 1066 events are selected in the data.

The systematic uncertainties on the cross sections (Table 2) are dominated by the Monte Carlo statistical error in the 4f-CC03 correction. The uncertainty on the background shape comes mainly from remaining $\gamma\gamma$ events and beam background as observed at the preselection level. In the eνqq channel, residual e^+e^- Bhabha background affects the isolation and probability distributions. The effects of these differences on the cross sections are evaluated by reweighting Monte Carlo events used for the computation of efficiencies after the ratios of data and Monte Carlo distributions in each bin of the most relevant variables. The uncertainty introduced by the cut on energy detected close to the beam axis affects the $\tau\nu$qq analyses. A model for local energy deposits due to beam background was obtained with random trigger events. Such deposits were then added to the simulated events to estimate their effect on the measurement. Another estimate of this effect was obtained by locking out from the analysis all energy deposits below a polar angle of 12 degrees.

A similar fit as for fully leptonic events is used here with the corresponding matrix of efficiencies and backgrounds. The partial cross sections are then extracted from such a maximum likelihood fit to the number of events in each selection, leading to

$$\begin{aligned}
\sigma(\mathrm{WW} \rightarrow \mathrm{e}\nu\mathrm{qq}) &= 2.41 \pm 0.14(\mathrm{stat.}) \pm 0.07(\mathrm{syst.})\ \mathrm{pb}, \\
\sigma(\mathrm{WW} \rightarrow \mu\nu\mathrm{qq}) &= 2.39 \pm 0.13(\mathrm{stat.}) \pm 0.06(\mathrm{syst.})\ \mathrm{pb}, \\
\sigma(\mathrm{WW} \rightarrow \tau\nu\mathrm{qq}) &= 2.23 \pm 0.17(\mathrm{stat.}) \pm 0.08(\mathrm{syst.})\ \mathrm{pb},
\end{aligned}$$

where the systematic errors are obtained by varying all input parameters of the fit according to their uncertainties.

The total $\ell\nu$qq cross section is extracted by means of the same fit, under the assumption of lepton universality:

$$\sigma(\mathrm{WW} \rightarrow \ell\nu\mathrm{qq}) = 7.07 \pm 0.23(\mathrm{stat.}) \pm 0.12(\mathrm{syst.})\ \mathrm{pb}.$$

This result agrees with the Standard Model expectation of 7.31 ± 0.15 pb [21].

2.3 WW $\rightarrow$ qqqq events

The analysis of WW decays to four jets is updated from Ref. [1] and consists of a simple preselection followed by a fit to the distribution of the output of a neural network (NN).

For each event, particles are clustered into four jets with the DURHAM-PE algorithm [20]. A first preselection cut rejects events with a real Z and large undetected initial state radiation, requiring that the total longitudinal momentum be smaller than 1.5 times the difference between the visible mass and the mass of the Z. The value y_{34} of the jet resolution parameter where a four-jet becomes a three-jet event, is required to be greater than 0.001. A further requirement that none of the four jets contain more than 95% of electromagnetic energy in a one degree cone around any particle included in a jet rejects $\mathrm{q\bar{q}}$ events with a visible initial state radiation photon. Four-fermion final states with one of the fermions being a charged lepton are rejected by requiring that the maximum energy fraction of a single charged particle in a jet be smaller than 0.9.

At this level of the selection, 3438 events are selected in the data while 3593 ± 7 events are expected from Standard Model processes. This preselection has an efficiency of 98.4% on CC03 events and a purity of 35.9%. The WW $\rightarrow \ell\nu$qq processes are considered here as background and amount to 0.99 pb at this level.

The input variables for the NN are described in the Appendix and are related to the global event properties, the properties of jets, WW kinematics and the b-tag probabilities for the four jets. The NN is simplified with respect to that used for the analysis of the 183 GeV data [1], with fewer input variables and a slightly improved performance. Figure 2 gives the distribution of the NN output values for all backgrounds and signal Monte Carlo events compared with the data. Results are given in Table 1 for a cut at 0.3 on the NN output value

The cross section is extracted by means of a binned maximum likelihood fit to the full NN output distribution of data events where only the normalisation of the Monte Carlo signal is allowed to vary. The mainly QCD background is kept fixed in shape and normalisation. The fit result is $\sigma(\mathrm{WW} \rightarrow \mathrm{qqqq}) = 6.84 \pm 0.23(\mathrm{stat.})$. However, systematic studies at the Z show that small but significant discrepancies exist between data and Monte Carlo in the distributions of jet variables in hadronic events forced to four jets. These differences are quantified using the 14 NN variables taking correlations and energy rescaling to 189 GeV into account. For example, Fig 3 shows the effect of these adjustments in the case of the maximum jet energy distribution from 4-jet events at 189 GeV where the agreement with data is improved where the QCD background dominates. Assuming that these adjustments are independent of $\sqrt{s}$, the Monte Carlo events in the background NN distribution are reweighted accordingly. The corrected fit result is:

$$\sigma(\mathrm{WW} \rightarrow \mathrm{qqqq}) = 6.89 \pm 0.23(\mathrm{stat.}) \pm 0.13(\mathrm{syst.})\ \mathrm{pb}.$$

If only events with a NN output greater than 0.3 are kept a value of 6.89 ± 0.23 pb is found showing no significant bias due to the QCD background. The measured cross section is 2.3 standard deviations lower than the Standard Model expectation of 7.59 ± 0.15 pb [21].

The sources contributing to the systematic error are summarised in Table 2. The uncertainties related to the variables used for the event preselection cuts and for the

NN input are assessed by changing jet directions and energies according to possible residual differences between LEP1 Z data and Monte Carlo, and by allowing for a possible miscalibration of the calorimeters. The beam background was studied in the same way as described in section 2.2.3.

Uncertainties in the WW generator are evaluated by comparing `KORALW` and `EXCALIBUR` Monte Carlo samples; `EXCALIBUR` is also used to evaluate the effects of colour reconnection. The effect of Bose-Einstein correlations is estimated according to the scheme denoted BE_3 as proposed in the `LUBOEI` [22] implementation in `JETSET`. Finally, for the QCD fragmentation uncertainty, the `HERWIG` [23] generator, tuned at the Z peak for non-b quark flavors, is used to produce different samples of $q\bar{q}$ background events and, coupled to the parton level of `KORALW`, WW signal events. The background normalization assumes a 5% variation in its cross section.

Several cross checks have been performed on the fit result to search for possible biases arising in the selection and full simulation of the WW events. The previous version of the NN [1], which has a different preselection, gives 6.81 ± 0.23 pb. Another estimate with a preselection based mostly on charged tracks and a NN using only charged tracks to construct six input variables gives 6.83 ± 0.25 pb. Along the same line, a selection based on calorimeter measurements with six input variables to a linear discriminant gives 6.80 ± 0.27 pb. A variety of linear discriminant analyses using from 4 up to 14 variables give results which vary from 6.65 to 6.77 pb.

3 Total cross section

The total cross section is obtained from a fit assuming the Standard Model branching fractions, the only unknown being the total cross section. The fit is applied to all data selected as described in the previous sections and uses the matrices of efficiencies and backgrounds of the various analyses, yielding

$$\sigma_{\mathrm{WW}} = 15.71 \pm 0.34(\mathrm{stat.}) \pm 0.18(\mathrm{syst.})\ \mathrm{pb}.$$

New calculations with the double pole approximation (DPA) [25] have recently appeared, and two Monte Carlo programs, `YFSWW3` [26] and `RacoonWW` [27], are being developed. The DPA consists in isolating the contributions of the poles at the complex squared masses and projecting onto the respective gauge-invariant residues. The expected uncertainty is of the order of 0.5%. It is currently believed that the $\mathcal{O}(\alpha)$ WW(CC03) cross section is lower than the calculation using the improved Born approximation by 1 to 2% due to non-leading EW radiative corrections [28]. Figure 4 shows the total cross section measured as a function of the centre-of-mass energy. The predictions of these two new calculations are in better agreement with the experimental results than the calculation from `GENTLE`.

4 Branching fractions and V_{cs}

The same fit as for the total cross section is performed combining the data samples collected at 161, 172, 183 and 189 GeV centre-of-mass energies.

Without assuming lepton coupling universality, the seven unknowns are the three individual leptonic branching fractions and the four total cross sections at 161, 172, 183 and 189 GeV. The hadronic branching fraction is set to $1 - \mathrm{B_e} - \mathrm{B}_\mu - \mathrm{B}_\tau$. The fitted leptonic branching fractions are

$$\begin{aligned}
\mathrm{B(W \to e\nu)} &= 11.35 \pm 0.46(\mathrm{stat.}) \pm 0.17(\mathrm{syst.})\%, \\
\mathrm{B(W \to \mu\nu)} &= 11.10 \pm 0.44(\mathrm{stat.}) \pm 0.16(\mathrm{syst.})\%, \\
\mathrm{B(W \to \tau\nu)} &= 10.51 \pm 0.55(\mathrm{stat.}) \pm 0.22(\mathrm{syst.})\%,
\end{aligned}$$

and are consistent with lepton universality and the Standard Model expectations. The QCD part of the systematic error is defined as coming from the effect of different QCD generators for the background and for the signal fragmentation as well as from final state interactions. It amounts to 0.04% in each channel. Due to cross-contaminations in the identification of W decays to $\tau\nu$ versus $\mathrm{e}\nu$ or $\mu\nu$, the measured $\mathrm{B(W \to \tau\nu)}$ is 26% anticorrelated with $\mathrm{B(W \to e\nu)}$ and 24% anticorrelated with $\mathrm{B(W \to \mu\nu)}$. The $\mathrm{B(W \to e\nu)}$ is 4.6% anticorrelated with $\mathrm{B(W \to \mu\nu)}$.

If lepton universality is assumed ($\mathrm{B_e} = \mathrm{B}_\mu = \mathrm{B}_\tau = (1 - \mathrm{B_q})/3$), a fit to $\mathrm{B(W \to qq)}$ and the four total cross sections as unknowns yields the measurement of the hadronic branching fraction

$$\mathrm{B(W \to qq)} = 66.97 \pm 0.65(\mathrm{stat.}) \pm 0.32(\mathrm{syst.})\%.$$

The QCD part of the systematic error is 0.12%.

This result can be expressed in terms of the individual couplings of the W to quark-antiquark pairs:

$$\frac{\mathrm{B(W \to qq)}}{1 - \mathrm{B(W \to qq)}} = (|V_{\mathrm{ud}}|^2 + |V_{\mathrm{cd}}|^2 + |V_{\mathrm{us}}|^2 + |V_{\mathrm{cs}}|^2 + |V_{\mathrm{ub}}|^2 + |V_{\mathrm{cb}}|^2)(1 + \alpha_s(m_{\mathrm{W}}^2)/\pi). \tag{1}$$

The world average value of $\alpha_s(m_{\mathrm{Z}}^2)$ evolved to m_{W}^2 is taken as $\alpha_s(m_{\mathrm{W}}^2) = 0.121 \pm 0.002$. The other measured CKM matrix elements [24] give a squared sum of 1.05 ± 0.01. The measured hadronic branching fraction is then interpreted as

$$|V_{\mathrm{cs}}| = 0.951 \ \pm 0.030(\mathrm{stat.}) \pm 0.015(\mathrm{syst.}).$$

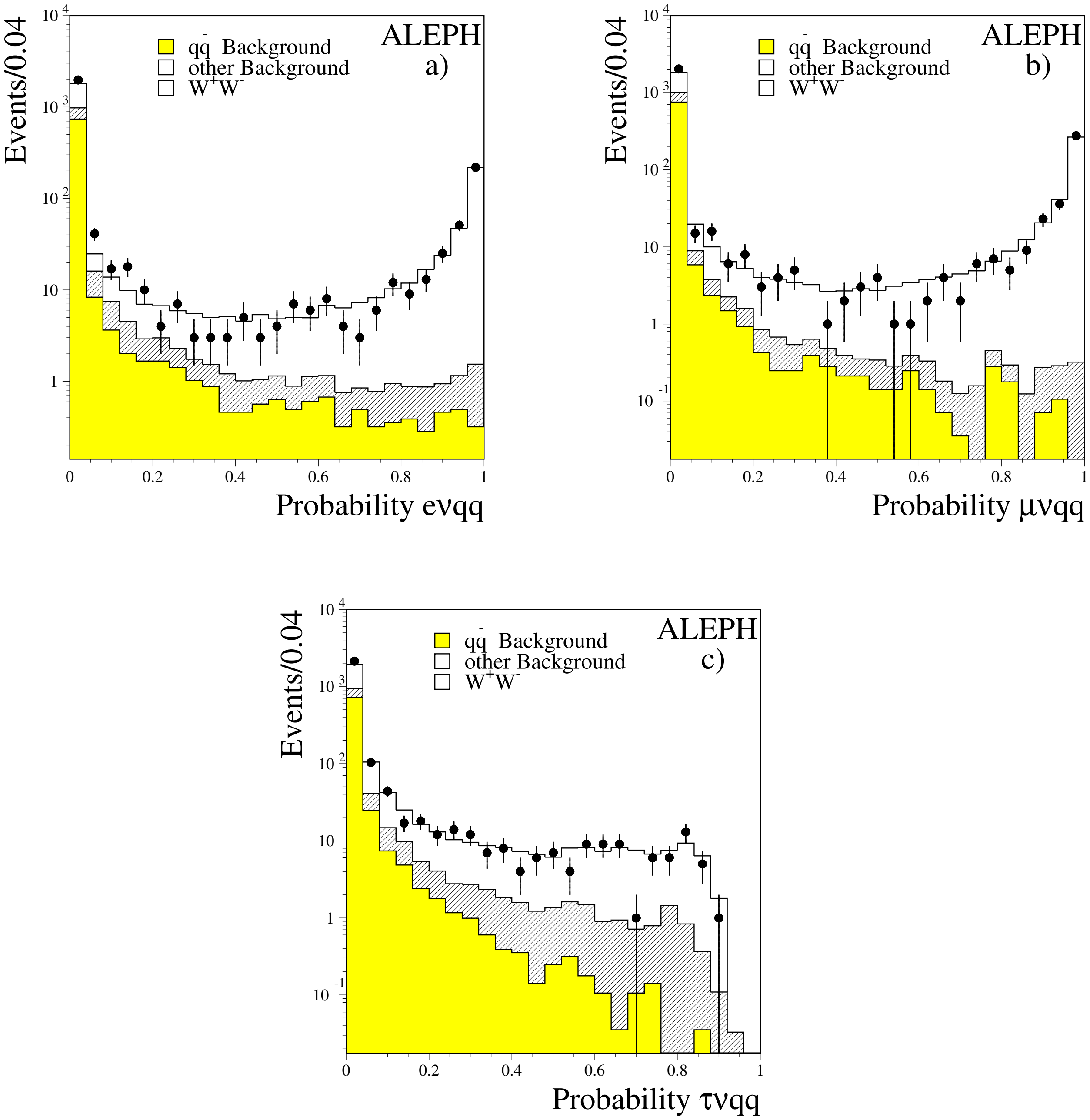

Figure 1: Probability distribution of preselected events for the (a) $e\nu$qq, (b) $\mu\nu$qq and (c) $\tau\nu$qq selections. The points are the data and the histograms the Monte Carlo predictions. The light shaded histogram shows the expected q$\bar{\text{q}}$ background contribution, the dark shaded histogram shows the expected signal contribution, and the medium shaded histogram shows the amount expected from other sources.

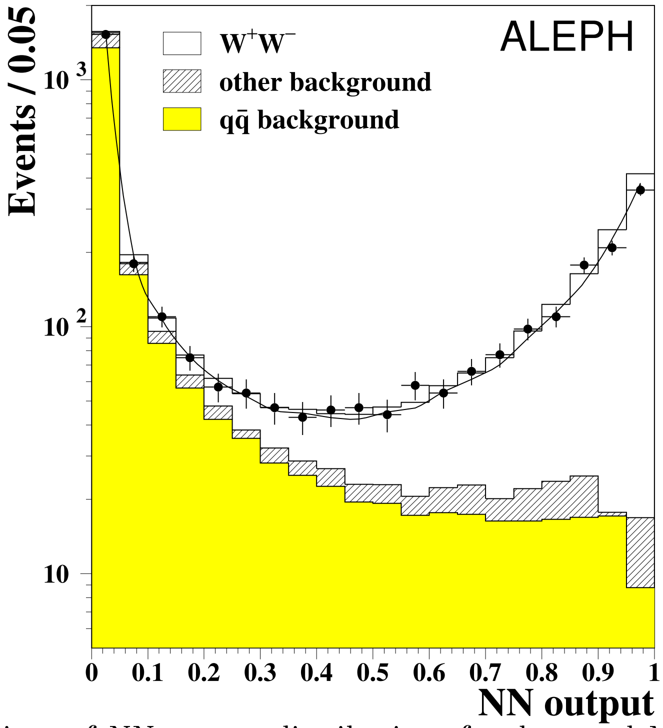

Figure 2: Comparison of NN output distributions for data and Monte Carlo after the four-quark preselection. The points are the data and the histograms the Monte Carlo predictions. The light shaded histogram shows the expected background contribution. The line shows the fit result.

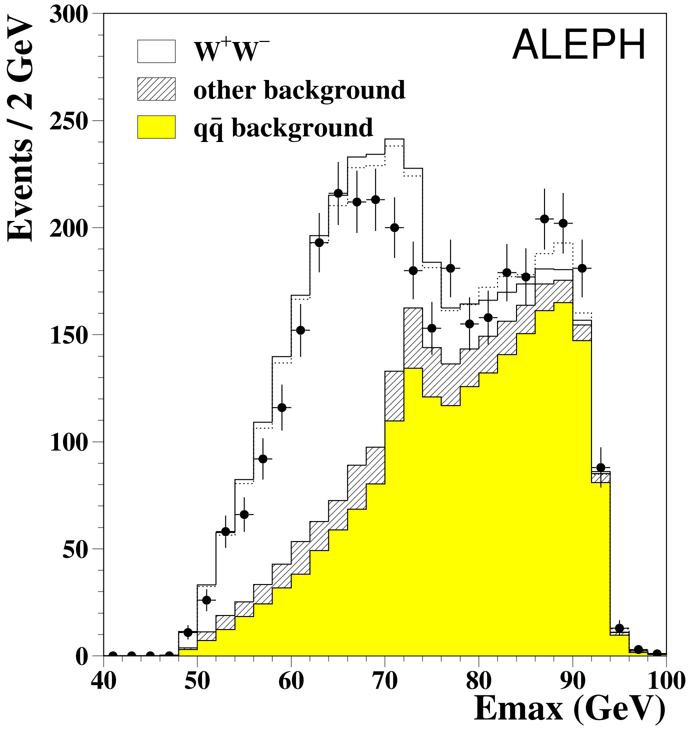

Figure 3: Comparison of the highest jet energy distributions for data and Monte Carlo after the four-quark preselection. The points are the data and the histograms the Monte Carlo predictions. The light shaded histogram shows the expected background contribution. The dotted histogram shows the effect of reweighting the $q\bar{q}$ background.

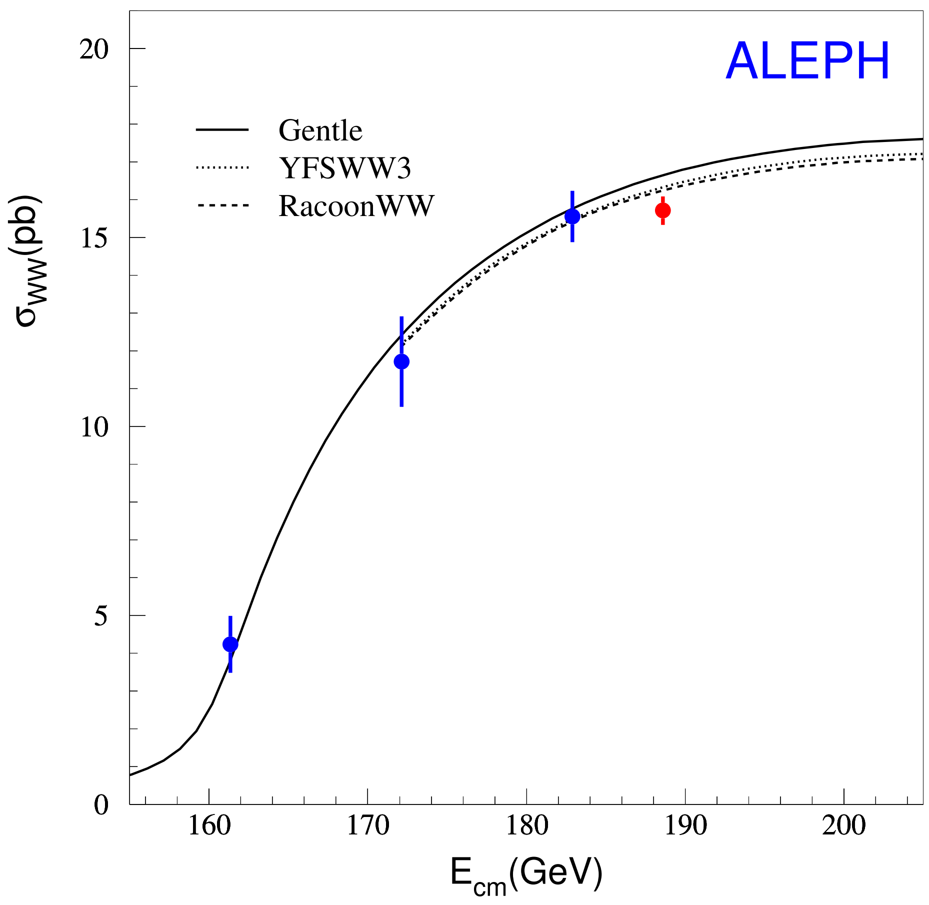

Figure 4: Measurements of the W-pair production cross section at four centre-of-mass energies, compared to the Standard Model predictions from `GENTLE`, `YFSWW3` and `RacoonWW`, for the LEP average value of the W mass [19].

5 Conclusions

The W-pair production cross section at $\sqrt{s} = 188.63$ GeV has been measured in all decay channels with an integrated luminosity of 174.20 pb^{-1}. The determination of individual branching fractions has been performed. The total cross section is $15.71 \pm 0.34(\text{stat.}) \pm 0.18(\text{syst.})$ pb. This result is 1.9 standard deviations away from the Standard Model expectation of 16.65 ± 0.33 pb [21]. After inclusion of the data taken at centre-of-mass energies of 161, 172 and 183 GeV, the hadronic decay branching fraction is found to be $66.97 \pm 0.65(\text{stat.}) \pm 0.32(\text{syst.})\%$ which is used to determine the CKM matrix element $|V_{\text{cs}}| = 0.951 \pm 0.030(\text{stat.}) \pm 0.015(\text{syst.})$.

Acknowledgements

We would like to thank S. Dittmaier and W. Placzek for invaluable discussions on DPA. It is a pleasure to congratulate our colleagues from the CERN accelerator divisions for the successful operation of LEP at 189 GeV. We are indebted to the engineers and technicians in all our institutions for their contributions to the excellent performance of ALEPH. Those of us from non-member countries thank CERN for its hospitality.

Appendix: Hadronic neural network input variables

The neural network hadronic event selection uses 14 variables. These are based on global event properties, heavy quark flavour tagging, jet properties and WW kinematics and are listed below. The four jets are numbered in order of decreasing energy.

Global event properties

- Thrust
- Sphericity
- Missing Energy
- Sum of the four smallest interjet angles

Heavy flavour tagging

- Probability of an event being a light quark (uds) event based upon impact parameter significance of tracks in the event

Jet properties

- Maximum electromagnetic energy fraction of a jet in any one degree cone
- Maximum charged track energy fraction of a jet
- Minimum number of good charged tracks in a jet

WW kinematics

- Angle between Jet2 and Jet3

  The following jet related variables are determined from kinematically fitted jet momenta.

- Energy of Jet1
- Energy of Jet3
- Energy of Jet4
- Smallest jet mass
- Second smallest jet mass

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