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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. Under Standard Model assumptions for the W-pair production and decay, the W-pair cross section is measured to be $15.69 \pm 0.34(\text{stat.}) \pm 0.17(\text{syst.})$ pb. Using also the W-pair data samples collected by ALEPH at lower centre-of-mass energies, the decay branching ratio of the W boson into hadrons is measured to be $B(W \to \text{hadrons}) = 66.89 \pm 0.67(\text{stat.}) \pm 0.31(\text{syst.})\%$, allowing a determination of the CKM matrix element $|V_{cs}| = 0.947 \pm 0.031(\text{stat.}) \pm 0.015(\text{syst.})$.

(ALEPH contribution to 1999 summer conferences)

PRELIMINARY

*contact person : Patrice Perez (Patrice.Perez@hep.saclay.cea.fr)

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 measurement of cross-sections in all possible W decay channels allows the determination of the W branching ratios and 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 the t-channel ν_e exchange and s-channel Z/γ exchange referred to as CC03 cross sections [7].

The effect of the non-CC03 diagrams is accounted for by the difference, denoted "4f-CC03 correction", in accepted cross-sections from CC03 processes and all Standard Model four-fermion final states compatible with W-pair decays.

The `KORALW` [8] Monte Carlo event generator is used to simulate the signal events. Comparison samples are generated with `EXCALIBUR` [9] and `grc4f` [10] for the CC03 and all four fermion diagrams showing an excellent agreement. Samples of events are generated with different W masses, both for CC03 diagrams and for all WW-like four-fermion diagrams, with `KORALW`. A comparison sample is generated with `EXCALIBUR` with and without colour reconnection effects (following the ansatz of Ref. [11]).

The `KORALZ` [12] Monte Carlo program is used to generate background events coming from the $q\bar{q}$ process, with a cross-check using `PYTHIA 5.7` [13].

Other background events are generated with `PYTHIA 5.7` for ZZ, Zee and $We\nu$ processes, `PHOT02` [14] for gamma-gamma interactions, `KORALZ` for μ and τ pair production, `BHWIDE` [15] and `UNIBAB` [16] for Bhabha scattering events.

The CC03 Standard Model cross section is calculated using the program `GENTLE` [17] which gives for $\sqrt{s} = 188.63$ GeV and m_W =80.39 GeV/c^2 [18], σ_{WW} =16.65 pb.

2 Selection of W-pair candidates

2.1 $WW \to \ell\nu\ell\nu$ events

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

Beam related backgrounds reduce the efficiency of the cut which removes gamma-gamma induced events depositing energy at angles below 12° around the beam. The inefficiency introduced is measured from random triggers and found to be 8.2±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 ± 7 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.

Lepton identification efficiency has a 0.6% (resp. 1.6%) systematic uncertainty for electrons (resp. muons), to cover residual discrepancies in identification efficiency and purity between LEP1 or LEP2 data and Monte Carlo. The final 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 in the subtraction of backgrounds and in the signal efficiencies.

Events are classified according to electron and muon identification criteria, a jet or a track being assigned to a tau if no lepton identification is fulfilled or if the identified lepton has an energy lower than 25 GeV. A likelihood fit is applied to determine individual cross sections 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 yield:

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

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 procedure, assuming lepton universality:

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

2.2 WW → $\ell\nu$qq events

The three selection procedures developed for the lower energy measurements are applied. 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 $\tau\nu$qq events, based on global variables and topological properties of events. As the electron and muon selections have a sizeable efficiency to keep $\tau\nu qq$ events, as well as the tau selection towards $e/\mu\nu qq$ events, a reclassification is then performed.

2.2.1 WW $\to$ eνqq and WW $\to$ $\mu\nu$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 the increased $\sqrt{s}$ energy 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. Therefore, in this analysis, the selection of the lepton track 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. For this purpose the topology of the reconstructed charged tracks in the event is considered. The candidate lepton is chosen as the charged track that maximises $p_l^2(1-\cos\theta_{lj})$, where p_l is the track momentum and θ_{lj} the angle of such track to the closest of the jets clustered using the remaining charged tracks, with the Durham-P [19] algorithm ($y_{\mathrm{cut}} = 0.0003$).

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 also $\tau\nu$qq events where the τ decays to a softer lepton (as $\tau \to \mathrm{e}\nu\nu$ or $\tau \to \mu\nu\nu$) will 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 5GeV.

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 previous papers in detail [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 72 GeV.

(ii) In the topological analysis, the energy of the higher energy of the two quark jets 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.

2.2.3 Results

The probability for an event to come from a signal process is determined from Monte Carlo reference samples using the lepton energy, the lepton isolation and the event total transverse momentum (Fig. 1). If an event is selected only with the $e\nu qq$ (resp. $\mu\nu qq$) algorithm it is kept in this channel if its corresponding probability is greater than 0.40.

If an event is selected only with the $\tau\nu qq$ algorithm, it is kept in the $\tau\nu qq$ class. Finally, if an event is selected both with the $\tau\nu qq$ and e or $\mu\nu qq$ algorithms 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 improves the correlation between e and τ or μ and τ channels (see section 4).

Table 1 gives the efficiencies coming from each selection. The inclusive combined efficiencies for the three semileptonic decay channels are $87.8 \pm 0.4\%$ for the electron channel, $91.7 \pm 0.4\%$ for the muon channel and 67.1 ± 0.5 % for the tau channel, giving 82.2% average efficiency on WW $\rightarrow \ell\nu$qq, with a background of 282 ± 11 fb. The overall 4f-CC03 correction is $+15 \pm 40$ fb. A total of 1072 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 subtraction of backgrounds, and by the uncertainty coming from the cut on energy around the beam for $\tau\nu$qq events.

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

$$\begin{aligned}
\sigma(\mathrm{WW} \rightarrow \mathrm{e}\nu\mathrm{qq}) &= 2.43 \pm 0.14(\mathrm{stat.}) \pm 0.07(\mathrm{syst.})\ \mathrm{pb}, \\
\sigma(\mathrm{WW} \rightarrow \mu\nu\mathrm{qq}) &= 2.40 \pm 0.13(\mathrm{stat.}) \pm 0.06(\mathrm{syst.})\ \mathrm{pb}, \\
\sigma(\mathrm{WW} \rightarrow \tau\nu\mathrm{qq}) &= 2.25 \pm 0.17(\mathrm{stat.}) \pm 0.08(\mathrm{syst.})\ \mathrm{pb},
\end{aligned}$$

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:

$$\sigma(\mathrm{WW} \rightarrow \ell\nu\mathrm{qq}) = 7.11 \pm 0.23(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})\ \mathrm{pb}.$$

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 net (NN).

For each event, particles are clustered into four jets with the DURHAM-PE algorithm [19]. 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 contains 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 3580 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 Appendix A, 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 the one used for the analysis of the 183 GeV data [1], with less 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 [20].

The cross-section is extracted by means of a binned maximum likelihood fit to the distribution of the NN output for data events.

The fit result is

$$\sigma(\mathrm{WW} \rightarrow \mathrm{qqqq}) = 6.83 \pm 0.23(\mathrm{stat.}) \pm 0.13(\mathrm{syst.})\ \mathrm{pb}.$$

This result is 2.5 standard deviations lower than the Standard Model expectation of 7.59 ± 0.15 pb for which a 2% error is quoted [21]. Several cross-checks have been performed. The previous version of the NN [1], which has a different preselection, gives an identical result. Another estimate with a preselection based mostly on charged tracks and a NN using only charged tracks to construct six input variables gives a 10fb lower cross section with a 10% higher error. A variety of linear discriminant analyses using from 4 up to 14 variables give results which vary from 6.65 to 6.77 pb. In order to check for a possible bias coming from the $\mathrm{q\bar{q}}$ and non four quark W decays, only events with a NN ouput greater than 0.3 are kept and give a value of 6.84 ± 0.23 pb.

Systematic errors are summarised in Table 2. The uncertainty on the variables used for the event preselection cuts, and for the NN input is assessed by changing jet directions and energies according to possible residual differences between LEP1 Z data and MC, and by allowing for a possible mis-calibration of the calorimeters.

Uncertainties with the WW generator have been evaluated comparing `KORALW` and `EXCALIBUR` MC samples, `EXCALIBUR` has also been used to evaluate the effects of colour reconnection. Finally, for the QCD fragmentation uncertainty, the `HERWIG` [22] generator, tuned at the Z peak for non b quark flavors, was used to produce different samples of $\mathrm{q\bar{q}}$ background events and, coupled to the parton level of `KORALW`, WW signal events.

3 Total cross section

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

$$\sigma_{\mathrm{WW}} = 15.69 \pm 0.34(\mathrm{stat.}) \pm 0.17(\mathrm{syst.})\ \mathrm{pb}.$$

The simple sum of the different channels obtained assuming lepton universality only is: $\sigma_{\mathrm{WW}} = 15.72 \pm 0.35(\mathrm{stat.}) \pm 0.17(\mathrm{syst.})$ pb. Figure 3 shows the total cross section measured as a function of the c.m. energy.

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→ (in %)	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	4.2	0.2	91.9
	$\tau\nu$qq	-	-	-	-	-	-	3.8	3.8	59.5	0.9	68.0
	qqqq	-	-	-	-	-	-	-	-	-	91.7	91.7
Backgrounds (in fb)		18	7	43	11	15	36	84	21	176	1854	2266
Observed Events		24	51	48	26	46	25	381	382	309	1435	2727

4 Branching ratios and V_{cs}

The same fit as for the total cross section is performed adding together 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 ratios and the four total cross sections at 161, 172, 183 and 189 GeV. The hadronic branching ratio is set to $1 - \mathrm{B_e} - \mathrm{B}_\mu - \mathrm{B}_\tau$. The fitted leptonic branching ratios are

$$\begin{aligned}\mathrm{B(W \to e\nu)} &= 11.34 \pm 0.46(\mathrm{stat.}) \pm 0.17(\mathrm{syst.})\%,\\ \mathrm{B(W} \to \mu\nu) &= 11.29 \pm 0.44(\mathrm{stat.}) \pm 0.15(\mathrm{syst.})\%,\\ \mathrm{B(W} \to \tau\nu) &= 10.48 \pm 0.56(\mathrm{stat.}) \pm 0.22(\mathrm{syst.})\%,\end{aligned}$$

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.

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 ratio

$$\mathrm{B(W \to qq)} = 66.89 \pm 0.67(\mathrm{stat.}) \pm 0.31(\mathrm{syst.})\%.$$

Table 2: *Systematic errors summary in fb.*

	WW cross section		
Source	$\ell\nu\ell\nu$	$\ell\nu$qq	qqqq
Calibration of calorimeters			32
Jet corrections			9
WW generator and m_{W} dependence			25
WW fragmentation			17
QCD generator			23
Final State Interactions			38
Background normalisation	13	30	84
Luminosity	9	35	39
MC statistics	15	61	20
Beam background	11	30	40
Lepton id	2	45	
Lepton isolation		56	
Probability discrimination		46	
Total	24	114	125

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 [23] give a squared sum of 1.05 ± 0.01. The measured hadronic branching ratio is then interpreted as

$$|V_{cs}| = 0.947 \pm 0.031(\mathrm{stat.}) \pm 0.015(\mathrm{syst.}).$$

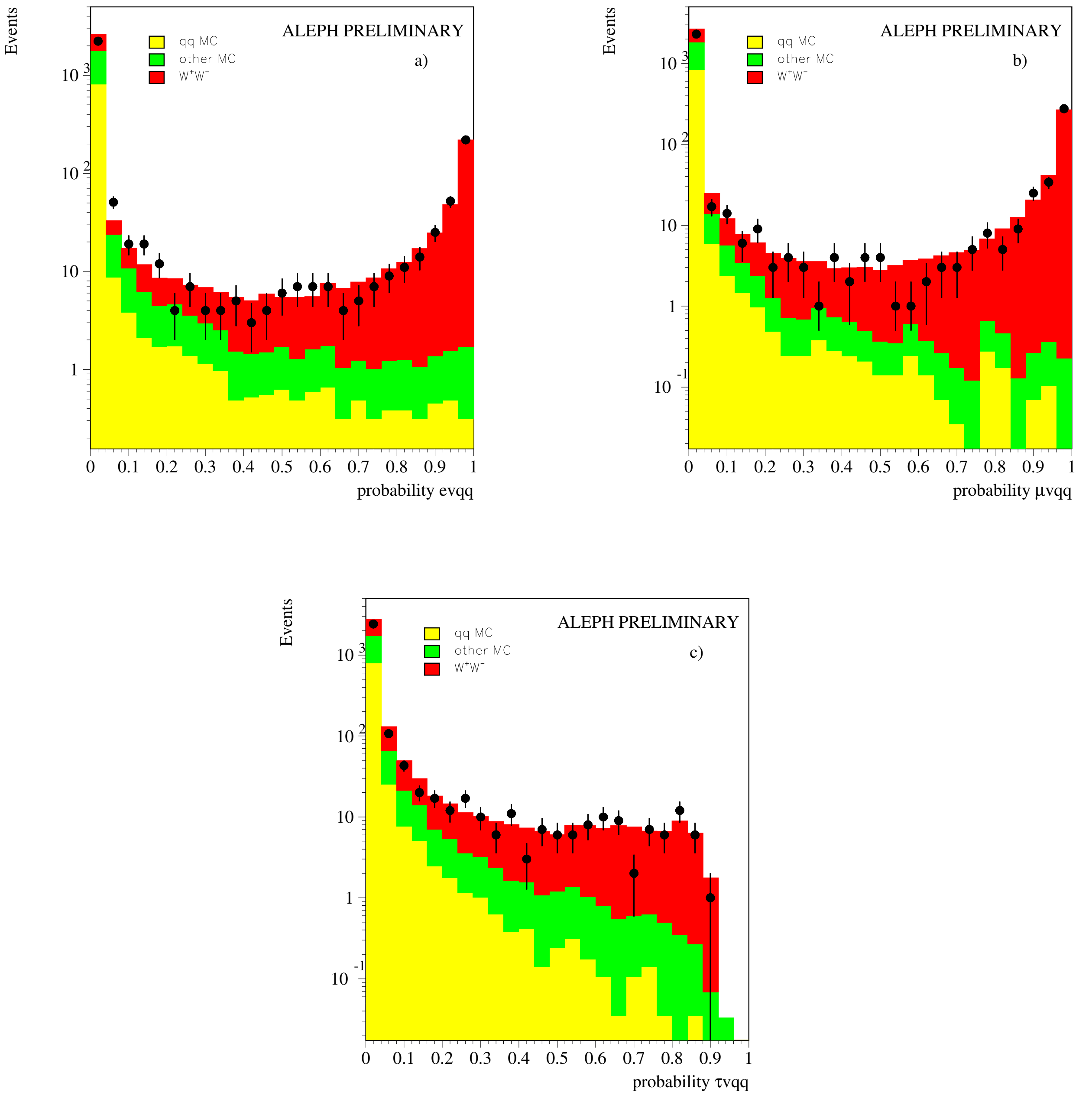

Figure 1: *Probability distribution of preselected events for the* eνqq *(a) the* $\mu\nu$qq *(b), and the* $\tau\nu$*qq (c) selections. The points are the data and the histograms the Monte Carlo predictions. The light shaded histogram shows the expected* q$\bar{\mathrm{q}}$ *background contribution.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

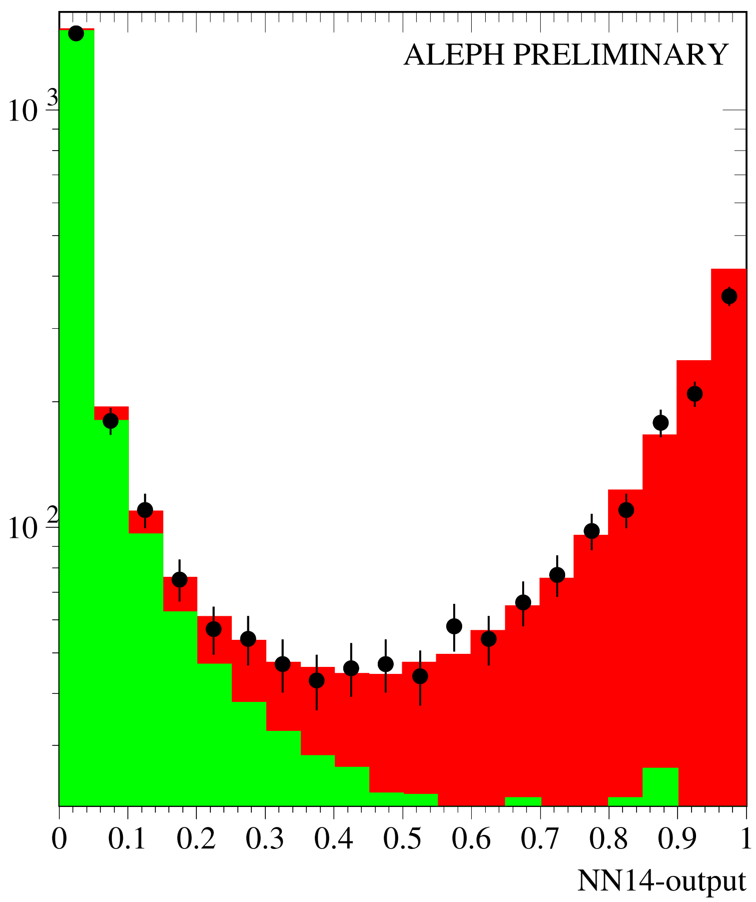

Figure 2: *Comparison of NN output distributions for data and Monte Carlo in the four quark channel after the preselection. The points are the data and the histograms the Monte Carlo predictions. The light shaded histogram shows the expected background contribution.*

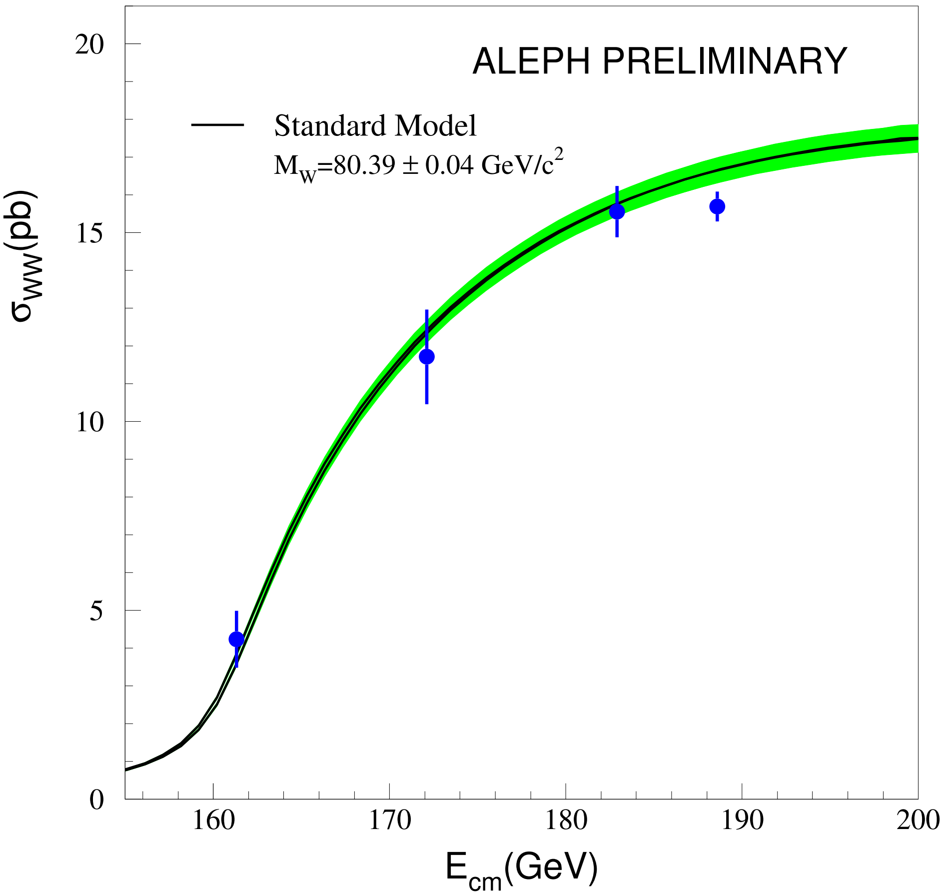

Figure 3: *Measurements of the W-pair production cross section at three centre-of-mass energies, compared to the Standard Model prediction from* `GENTLE` *for the world average value of the W mass [18]. The two curves correspond to the 42* MeV/c^2 *error on* m_{W} *, the shaded area around the two curves represents a possible theoretical error (±2%) on the* `GENTLE` *calculations.*

5 Conclusions

Using an integrated luminosity of 174.20 pb^{-1} the W pair production cross section at $\sqrt{s}$ = 188.63 GeV has been measured in all decay channels. The determination of individual branching ratios has been performed. The total cross section is 15.69 ± 0.34(stat.) $\pm$ 0.17(syst.) pb. This result is 1.9 standard deviations away from the Standard Model expectation of 16.65 ± 0.33 pb [21]. After adding the data taken at 161, 172 and 183 GeV c.m. energy, the hadronic decay branching ratio is 66.89 ± 0.67(stat.)± 0.31(syst.)% which is used to determine the CKM matrix element $|V_{cs}| = 0.947 \pm 0.031(\text{stat.}) \pm 0.015(\text{syst.})$.

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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 A. 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
- Minimum jet mass
- Second minimum jet mass

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