W Pair Production at LEP II

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W-pair production processes are reviewed, based on the complete LEP 2 data set. The W-pair cross section is measured, the leptonic and hadronic branching ratios are extracted and the CKM matrix element $|V_{cs}|$ is calculated.

1. Introduction

In 1996, the W-pair production threshold has been reached. Since 1996, an integrated luminosity of roughly 700 pb^{-1} has been delivered by the LEP machine to each of the four LEP experiments. The data sets presented in this note are given in Table 1. The year 2000 data set is composed of several different centre-of-mass energies, between 200 and 209 GeV, but average in two data sets at 205 GeV and 207 GeV. The method to determine the W-pair cross section is presented and the experimental results are then compared with recent [1] theoretical predictions. The W branching ratio into hadrons and leptons is extracted and the CKM matrix element $|V_{cs}|$ is then derived.

2. Event Selections

Since the W boson can decay either leptonically or hadronically, there are three possible final states:

- Fully leptonic channels (WW $\rightarrow l\nu l\nu, 11\%$ of the decays) are characterised by 2 acoplanar charged leptons and missing momentum. The selection is based on cut criteria.
- Semileptonic channels (WW $\rightarrow l\nu q\bar{q}, 44\%$ of the final states) are characterised by a high momentum, isolated lepton along with some missing momentum and 2 hadronic jets. To maximise the efficiency of the selection, multi-variable discriminant techniques are used to select semileptonic events.
- Fully hadronic channel (WW $\rightarrow q\bar{q}q\bar{q}, 46\%$ of final states) is characterised by no missing momentum and four jets in the event. The QCD background has a large contribution in this channel, therefore very complicated statistical tests like a neural network technique or a likelihood test are used.

The average efficiency and purity are summarised in Table 2.

3. Results

The WW (signal) cross section is extracted from a maximum likelihood fit given by the product of Poisson-probabilities:

$$L_i = P(N^i_{obs}, N^i_{exp})$$

where N^i_{obs} is the number of observed events in the channel i. The expected number of events, N_{exp}, is given by:

$$N^i_{exp} = \mathcal{L}\left(\sum_i^n \epsilon_{ij}\sigma_j + \sigma_i^{bg}\right)$$

where σ_j is the expected cross section, ϵ_{ij} the efficiency of selection j to accept event from process i, L the integrated luminosity and σ_i^{bg} the residual background.

3.1. WW cross sections

The four LEP experiments [2] have presented preliminary results at all energies, which are combined to obtain a LEP preliminary cross section. This result is shown in figure 1. The plotted line

Table 1
Energy and average luminosity per experiment.

Year	1996		1997	1998	1999				2000	
$\sqrt{s}$ [GeV]	161	172	183	189	192	196	200	202	205	207
$\int \mathcal{L}dt[pb^{-1}]$	10	10	55	180	30	80	80	40	80	130

Table 2
Average efficiency and purity of the 4 LEP experiments.

Channel	efficiency	purity
$l\nu l\nu$	50%-80%	80%-90%
$e\nu q\bar{q}$	75%-90%	$\sim$ 95%
$\mu\nu q\bar{q}$	75%-90%	$\sim$ 95%
$\tau\nu q\bar{q}$	50%-80%	80%-85%
$q\bar{q}q\bar{q}$	75%-80%	75%-80%

represents the theoretical predictions of the W-pair cross section from RacoonWW [3] and YFSWW [4] calculations for centre-of-mass energy larger than 170 GeV. These calculations are performed in the Leading Pole Approximation (LPA) [5] for both models. The LPA is not valid at and near threshold hence the predictions of the cross section for centre-of-mass energies below 170 GeV are obtained using the GENTLE [6] calculation. The shaded area represents the theoretical uncertainty of the prediction, which is approximately 0.4% above a centre-of-mass energy of 180 GeV and 2% near threshold. To verify the agreement between the LEP measured W-pair cross section and the different predictions, the ratio:

$$R_{WW} = \sigma_{CC03}(EXP)/\sigma_{CC03}(TH)$$

is defined. At each centre-of-mass energy larger than 180 GeV, the ratio is calculated for RacoonWW and YFSWW. The results are shown in figure 2. The data are in a good agreement with both models.

3.2. W branching ratios

For the determination of the cross section of an individual channel, the W branching ratios are first determined without assuming the lepton universality. The results of each experiment are listed in Table 3. The branching ratios are in agreement between the different experiments. Secondly, assuming lepton universality, the measured hadronic and leptonic branching ratios are found to be:

$$B(W \to l\nu) = 10.69 \pm 0.06(\text{stat.}) \pm 0.07(\text{syst.})\%,$$
$$B(W \to q\bar{q}) = 67.92 \pm 0.17(\text{stat.}) \pm 0.21(\text{syst.})\%.$$

These results are consistent with the Standard Model expectations.

3.3. $|V_{cs}|$ from $B(W \to l\nu)$

Within the Standard Model, the leptonic branching ratio of the W boson depends on the six matrix elements of the Cabbibo-Kobayashi-Maskawa (CKM) quark mixing matrix not involving the top quark:

$$\frac{1}{Br(W \to l\nu)} = 3\left(1 + \left(1 + \frac{\alpha_s}{\pi}\right) \sum_{i=u,c,j=d,s,b} |V_{ij}|^2\right),$$

where $\alpha_s(\mathrm{M_W^2}) = 0.121 \pm 0.002$ is the strong coupling constant. The value of the sum $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 + |V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2$ can be deduced from the strong coupling constant and the leptonic branching ratio [2]:

$$\sum_{i=u,c,j=d,s,b} |V_{ij}|^2 = 2.039 \pm 0.025\ (\mathrm{Br})\ \pm 0.001\ (\alpha_\mathrm{s}).$$

The first error is coming from the uncertainty of the leptonic branching ratio. The second term

Table 3
Measured branching ratio (in %) of the 4 LEP experiments and the LEP combined value using all the LEP 2 data.

Exp.	$W \to e\nu$	$W \to \mu\nu$	$W \to \tau\nu$	$W \to q\bar{q}$
ALEPH	10.95 ± 0.31	11.11 ± 0.29	10.57 ± 0.38	67.33 ± 0.47
DELPHI	10.36 ± 0.34	10.62 ± 0.28	10.99 ± 0.47	68.10 ± 0.52
L3	10.40 ± 0.30	9.72 ± 0.31	11.78 ± 0.43	68.34 ± 0.52
OPAL	10.40 ± 0.35	10.61 ± 0.35	11.18 ± 0.48	67.91 ± 0.61
LEP	10.54 ± 0.17	10.54 ± 0.16	11.09 ± 0.22	67.92 ± 0.27

represents the uncertainty on the strong coupling constant. Using the experimentally obtained five terms [7] $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 + |V_{cd}|^2 + |V_{cb}|^2 = 1.0477 \pm 0.0074$, one can extract:

$$|V_{cs}| = 0.996 \pm 0.013,$$

which is the most accurate measurement of $|V_{cs}|$. The error is dominated by the uncertainty of the W leptonic branching ratio.

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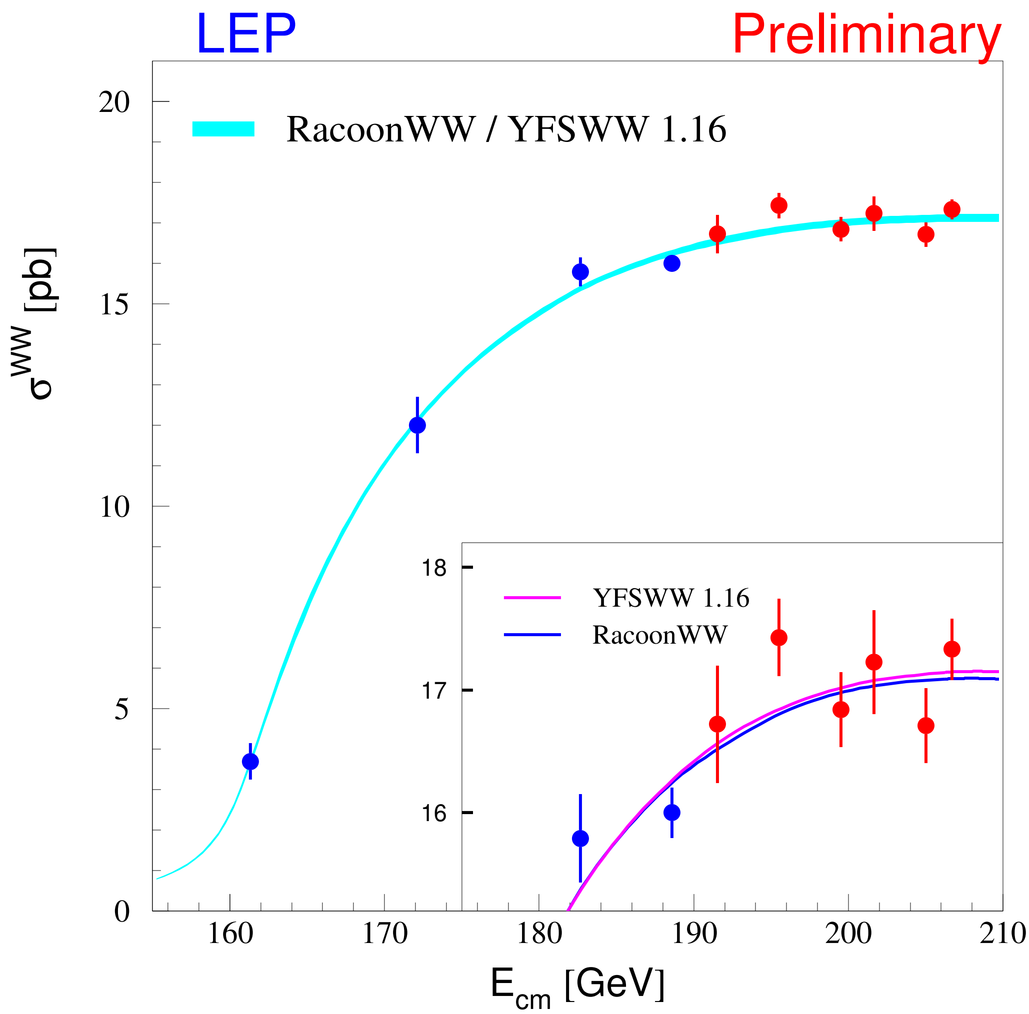

Figure 1. WW cross section results of the LEP combined data compared to the prediction of RacoonWW, YFSWW and GENTLE

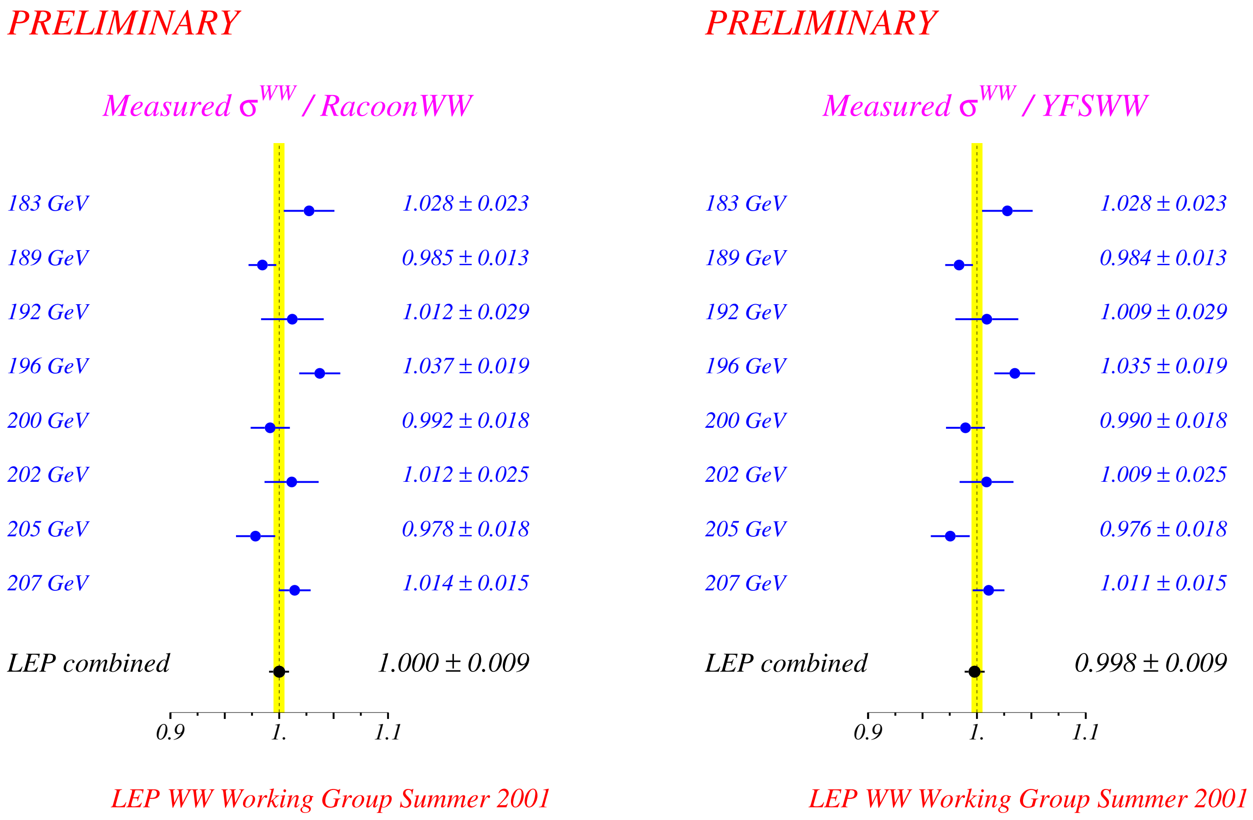

Figure 2. Ratio of LEP combined W-pair cross section to the expectations according to RacoonWW (left) and YFSWW (right) predictions. The shaded bands represent an uncertainty of 0.5% on the cross section prediction.