Measurements of the W-pair production rate and the W mass using four-jet events at LEP
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Summary

Weak nuclear interactions play a role in phenomena like nuclear fusion inside the sun, $\beta$ decay and many other decays of unstable particles. Remarkably, a consistent gauge theory of weak nuclear interactions can only be constructed by a unified description of both weak interactions and electromagnetism: the Standard Model of electroweak interactions. In this model, weak interactions are mediated by spin-1, massive bosons: the charged W bosons, and the neutral Z boson. Both were discovered in 1983 in $p\bar{p}$ collisions at CERN, but their exact properties were not very accurately known until the advent of the $e^+e^-$ collider LEP in 1989.

In the first phase of LEP, the center-of-mass energy was set to be approximately equal to the Z boson mass. In this period, until 1995, the properties of the Z boson were studied in detail. In 1996, the center-of-mass energy of LEP was increased to the threshold of W-pair production, and above that threshold in the years that followed. In this phase of LEP, the properties of the W boson and its production process could be studied. It is this phase of LEP, and more precisely the data taken from 1996 to 1998, that is the topic of this thesis. In this thesis, a measurement of the production cross section of W-pairs is presented, as well as a measurement of the W boson mass, for events where both W’s decay hadronically.

This thesis consists of several parts. In Chapter two a brief summary of the relevant theory is given. Subsequently, the LEP accelerator and the L3 detector are described in Chapter three. Chapter four describes how the information from the individual subdetectors is combined. In this chapter the energy determination of clusters and jets is described, and properties of individual W’s are derived. Since the initial state is fully known, up to the overall relatively small effects of photon radiation, the accuracy of the reconstruction is improved by fitting the event under the constraints of energy and momentum conservation. For the W mass reconstruction further fits are performed, constraining the two reconstructed W masses to be equal.

In Chapter five, this information is used to select fully hadronically decaying W-pair events from the data, i.e. events with four hadronic jets. The dominant background for this process is the production of $q\bar{q}$-pair events with one or more hard gluons. The event selection therefore starts by requiring a clear four-jet signature, with a high multiplicity and little missing energy and momentum. This selection is 92% efficient for signal and reduces the background considerably. The remaining background resembles the signal closely. A
multivariate analysis, in this thesis implemented in the form of a neural network, is used to separate this background from the signal. This yields a single variable with a low value for background-like events and a high value for signal-like events. This event-by-event information is used in a fit to the data to derive the respective signal and background production rates with their statistical uncertainties. Systematic uncertainties are estimated using Monte Carlo studies and are dominated by fragmentation uncertainties. The cross section results for the various centre-of-mass-energies are given in Tables 5.2 and 5.4, and are illustrated graphically in Figure 5.13 on page 80.

As the W cross section at the production threshold at $\sqrt{s} = 161\text{ GeV}$ is strongly dependent on the W mass, the measured cross section at this energy has been used to determine the W mass. A value of $m_W = 81.33^{+0.72}_{-0.72} \pm 0.03\text{ GeV}$ is derived.

In Chapter six, the W mass is determined directly using the W decay products. To select W pair events a minimum value for the neural network output value is required. The W mass is determined from the event sample using a likelihood fit. The event-by-event likelihood is determined using a Monte Carlo reweighting technique. The W mass result using the data from $\sqrt{s} = 172\text{ GeV}$ to $\sqrt{s} = 189\text{ GeV}$ is

$$m_W = 80.571 \pm 0.107\text{ (stat)} \pm 0.034\text{ (syst)} \pm 0.055\text{ (FSI)} \pm 0.017\text{ (LEP)}\text{ GeV}.$$ 

The dominant systematic error is due to uncertainties in the modelling of color reconnection, a process that can occur between the quarks in the final state.

The implications of the measurements are discussed in Chapter seven. Several models different from the Standard Model predict, among other things, a different W-pair production rate. Using the measured W-pair production cross section, limits can be found for several anomalous couplings. These are possible differences of observed particle-particle interactions with respect to Standard Model predictions. In particular, three limits are found:

$$-0.45 < \Delta g_1^Z < 0.50 \text{ at 95\% CL}$$
$$-0.47 < \lambda_{\gamma} < 0.56 \text{ at 95\% CL}$$
$$-0.7 < \Delta \kappa_{\gamma} < 1.6 \text{ at 95\% CL}.$$ 

Using the measured cross sections for W-pair production where one or two of the W bosons decays leptonically, the W branching fractions can be determined. Assuming lepton universality, the following results are obtained:

$$B(W \to q\bar{q}) = (68.20 \pm 0.68 \pm 0.33)\%$$
$$B(W \to t\nu) = (10.60 \pm 0.23 \pm 0.11)\%.$$ 

The W branching fractions are dependent on the six elements $V_{ij}$ of the Cabibbo-Kobayashi-Maskawa quark mixing matrix not involving the top quark, in particular $V_{cs}$. Using the measured W branching fractions, we derive:

$$|V_{cs}| = 1.008 \pm 0.032 \pm 0.016.$$ 

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In certain models beyond the Standard Model the W boson can decay to final states unobservable to the detector. Using the measured and predicted cross sections, it can be shown that, at 95% CL, the invisible W width is less than 52 MeV.

A recent model involving gravity has hypothesised the existence of extra dimensions, which are curled up to very small sizes, not observable to us. The existence of these dimensions influences the $W^+W^-$ cross sections due to the existence of gravitons, whose interactions are described in terms of the scale $M_S$ and a factor $\lambda$ which is of the order of unity. For values of $\lambda = \pm 1$ the following limits are obtained:

$$
\lambda = -1 : \quad M_S > 0.68 \text{ TeV} \quad \text{at 95\% CL},
$$

$$
\lambda = +1 : \quad M_S > 0.79 \text{ TeV} \quad \text{at 95\% CL}.
$$

The W mass derived in this thesis can be used as a check of the validity of the Standard Model. In Figure 7.6, the direct W and top quark mass measurements are compared to the predictions calculated using a multitude of measurements. The agreement between these quite differently derived results beautifully confirms the consistency of the Standard Model.

Taking a different approach, we can assume the validity of the Standard Model and use the world data set, including the direct W and top mass measurements, to obtain a prediction for the mass $m_H$ of the at this moment still unobserved Higgs Boson:

$$
m_H^{\text{All Data}} = 85^{+54}_{-34} \text{ GeV}.
$$