We present the measurements on 2-fermion and 4-fermion production in $e^+e^-$ collisions at centre-of-mass energies ranging from 192 to 202 GeV as collected by the 4 LEP experiments in 1999. For processes with 2-fermions in the final state we present both production cross sections and asymmetries for event samples at low and high effective centre-of-mass energies, where the latter process is sensitive to possible contributions from various non-SM physics, like contact interactions or $Z'$ exchange, and can therefore be used to set limits on parameters in those models. We also report on the measured cross sections for a subset of processes leading to 4 fermions in the final state: pair production of heavy vector bosons $W^+W^-$ (NC03) and $ZZ$ (NC02) followed by single-$W$ production. A measurement of the leptonic branching ratio of the $W$-boson is used to extract information on $|V_{us}|$.

1 Introduction

In 1999 LEP delivered almost 1 fb$^{-1}$ to the 4 experiments at energies ranging from 192 to 202 GeV, doubling the total luminosity collected at LEP2 during the period 1996-1998. The total cross section at these energies is more than two orders of magnitude smaller than at the $Z$ peak, but all cross sections are well predicted within the Standard Model (SM). There are many diagrams leading to 4-fermions in the final state where a special subset produces 4 fermions in the final state via pair production of two on-shell heavy vector bosons. In looking for new physics it is important to understand and control all known SM processes.
2 2-fermion production

In the processes $e^+e^- \rightarrow 2$ fermions there is a large fraction of events in which an initial state radiation (ISR) photon has lowered the effective centre-of-mass energy, $\sqrt{s'}$, of the annihilation process to values close to the $Z$-boson mass ($\text{radiative return}$ events). This can be clearly seen from the distribution of this effective-centre-of-mass energy (Fig. 1). The second and more interesting class of events are the so-called non-radiative (or high energy) sample defined as having $\sqrt{s'} > 0.85\sqrt{s}$ where we have all available energy contained in the annihilation, entering a new energy regime in $e^+e^-$ interactions.

For each fermion species a cross section and production asymmetry is measured\(^1\). Errors on both measurements are statistically dominated. The hadronic cross section for the non-radiative sample is slightly high (2.3 standard deviations when combining all 1999 data into a (luminosity averaged) single-energy point). All other measured cross sections and asymmetries are in excellent agreement with the SM expectation (Fig. 2).

![Diagram](image1.png)

Figure 1: The annihilation diagram for 2-fermion production (electrons also have large t-channel contributions) and the reconstructed effective centre-of-mass energy, $\sqrt{s'}$ for the selection of $e^+e^-$ hadrons ($\gamma$) at 200 GeV. The arrow indicates the cut used in the selection of the non-radiative sample.

![Diagram](image2.png)

Figure 2: LEP combined measured cross section and asymmetries for 2-fermion production for the high-energy ($\sqrt{s'} > 0.85\sqrt{s}$) event sample for different fermion species as a function of the centre-of-mass energy.

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3 4-fermion production

3.1 W⁺W⁻ production

Since 1996 W bosons are pair-produced at LEP, where the production cross section has been measured up to energies of 202 GeV. Since a single W boson decays into either a quark anti-quark pair (~ 68%) or into a lepton and a neutrino (~ 32%) there are 3 different event topologies. Events are selected with high efficiency and purity. Even the fully hadronic channel in which both W's decay hadronically, experiments typically reach selection efficiencies of 90% at purities of around 80%, despite the large QCD background.

In 1998 the LEP combined experimental error on the cross section was comparable to the theoretical uncertainty of about 2% (GENTLE). This triggered a large theoretical effort to reduce these uncertainties resulting in two new calculations: RACOONWW and YFSWW. The theoretical error of both calculations is around 0.5% with a central value of both calculations being about 2-3 % low with respect to the old GENTLE prediction. The new calculations describe well the measured cross sections at all energies (Fig. 3).

The combined LEP measurement of the W leptonic branching ratio \( \text{BR}(W \to l \nu) = 10.71 \pm 0.10 \) % when assuming lepton universality gives a handle on the elements of the CKM matrix:

\[
\frac{1}{\text{Br}(W \to l \nu)} = 3 \left[ 1 + \frac{\alpha_s(M_W^2)}{\pi} \right] \sum_{l=u,c,j=d,s,b} |V_{ll}|^2
\]

Using the current world-average values and errors of the other matrix elements, not assuming the unitarity of \( V_{cK}\) and \( \alpha_s(M_W^2) = 0.121 \pm 0.002 \) it allows to extract a LEP combined value of \( |V_{c}\) = 0.993 ± 0.016.

3.2 ZZ cross section

Since 1998 the centre-of-mass energy is high enough to create two on shell Z bosons. The cross section is small (~ 1 pb) but this process has some very distinct final states with low background from other SM processes. All detectable final states are covered. To reduce the background coming from QCD events with hard gluon radiation and W⁺W⁻ events in the 4-quark final state, the experiments use the fact that the W boson almost never produces a b-quark
in the final state whereas the Z decays in about 21% into a pair of b and anti-b quark. These events can be selected with high purity and are comparable both in cross section and signature to that of the SM Higgs boson. Measuring this cross section shows the ability to detect a SM Higgs boson like signal if it is there and one controls one of the most important backgrounds. The measured cross section has a statistics dominated error and is in good agreement with the theoretical predictions (Fig. 4).

3.3 Other 4-fermion cross sections

For single-W production the LEP experiments adopted a common definition of the signal. This makes a direct comparison between the 4 different experiments possible and furthermore it includes a gauge invariant set of diagrams concentrating on a region in phase space where the theoretical errors are relatively small.

Common single-W signal definition

- all t-channel diagrams
- $\sqrt{s} > 45$ GeV/c$^2$ for $q\bar{q}e^-\bar{\nu}_e$,
- $E_T > 20$ GeV for the $e\nu\nu$ final states (with $l=\mu, \tau$)
- $|\cos(\theta_-)| > 0.95, |\cos(\theta_+)| < 0.95$ for the $e\nu\nu$ final state

References

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3. CERN Yellow Report (in preparation)
4. The LEP WW Working Group, LEPEWWG/WW/00-02

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