A STUDY OF THE POLARIZATION AND DECAY OF THE TAU LEPTON AT L3

BAD, JIANZHONG
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The Johns Hopkins University, 1992
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A Study of the Polarization and Decay of the Tau Lepton At L3

by

Jianzhong Bao

A dissertation submitted to The Johns Hopkins University in conformity with the requirements for the degree of Doctor of Philosophy

March 1992
Baltimore, Maryland
Abstract

A study with $e^+e^- \rightarrow \tau^+\tau^-$ events collected at the $Z^0$ resonance with the L3 detector at LEP has been carried out. From approximately 10,000 $\tau$-pair events, the leptonic decay branching ratios of the $\tau$ lepton are measured to be: $Br(\tau \rightarrow e\nu\bar{\nu}) = 0.1772 \pm 0.0036^{+0.0041}_{-0.0037}$, $Br(\tau \rightarrow \mu\nu\bar{\nu}) = 0.1760 \pm 0.0039^{+0.0039}_{-0.0036}$. The longitudinal polarization asymmetry of the tau is measured in the decay $\tau \rightarrow e\nu\bar{\nu}$ by fitting the electron energy spectrum to the expected theoretical distribution from the Standard Model. The polarization is found to be: $A_{pol} = -0.006 \pm 0.091 \pm 0.066$, which corresponds to a value of the electroweak mixing angle $\sin^2 \theta_W = 0.238 \pm 0.011 \pm 0.008$, in good agreement with other measurements of $\sin^2 \theta_W$ and the prediction from the Standard Model for electroweak interactions.
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During the past 30 years, significant theoretical and experimental advances have been made in elementary particle physics. An outstanding example is the development of our present understanding of the weak and electromagnetic interactions, and their unification. This is best summarized in the Standard Model, a model which describes the properties of leptons and quarks, and successfully predicted the existence and physical properties of the massive $W^\pm$ and $Z^0$ vector bosons.

The construction and successful operation of the Large Electron-Positron Collider (LEP) have provided excellent opportunities for carrying out high precision tests of the Standard Model. The high center of mass energy of LEP provides a relatively clean environment for studying the $\tau$ lepton. Decay branching ratios can be measured with low systematic errors, which makes the results comparable with measurements done at lower energy machines with larger statistics. Moreover, higher sensitivity to weak interaction effects also makes the studies of the weak neutral current coupling constants of different fermions more precise. Since in the Standard Model such constants are different for left- and right-handed fermions, a longitudinal polarization of the final state fermions occurs, it is proportional to the product of vector and axial vector coupling constants involved. From the measurement of the polarization one can determine the weak mixing angle with high accuracy. At the present, such effect can be effectively measured only in the $e^+e^- \rightarrow \tau^+\tau^-$ process.

This thesis reports the measurements of the leptonic decay branching ratios of the $\tau$ and its polarization in its electron decay mode, made with the data taken at the L3 detector at LEP during the 1990 and 1991 run periods. It is organized as follows: Chapter 1 gives a brief introduction of the field; Chapter 2 summaries the Standard Model and the main properties of the $\tau$ lepton; Chapter 3 presents a description the L3 experiment at LEP; In Chapter 4, the event selection and Monte Carlo studies of backgrounds are discussed; Chapter 5 contains analysis of decay branching ratios of the leptonic $\tau$ decays and polarization measurement in the electron channel; Chapter 6 summarizes the results and presents some comparisons with the Standard Model and results from other experiments.
Throughout the entire period of graduate study at Johns Hopkins, I benefited immensely from many people. It is beyond my ability to fully express my gratitude to all the help they gave me. I thank all the members of the L3 collaboration, it is their heroic efforts which turned such a wonderful experiment into reality. In particular I thank Dr. A.Pevsner and Dr. C.Y.Chien for providing me the opportunity of working in their group, and for their relentless support during the past five and a half years; I thank Dr. P.Fisher for his guidance, patience, and physics insight which initiated and greatly influenced my interests in $\tau$ physics; I owe a lot to Dr. K.Kumar, most of my $\tau$ analysis work was done in close co-operation with him; During the development and installation of the Plastic Scintillating Fiber readout system, I worked with Dr. H.Akbari, her passion in physics was most impressive; I would like to thank Mr. J.Spangler, his rich knowledge and highly skillful hands fulfilled many unrealistic schedule; I benefited a great deal from many discussions with Drs. L.Madansky, B.Barnett, and B.Blumenfeld. I thank Dr.Blumenfeld for careful reading of the manuscripts and many suggestions in various aspects of the analysis. I am grateful to Dr. J.C.Sens, who introduced the L3 analysis software to me. I am indebt to the following colleagues in the TEC group: G.Viertel, M.Pohl, J.Mnich, B.Betev, M.Macdermott, L.Taylor, A.Gougas, I.Leedom and C.Spartiotis. This thesis contains analysis work done at CERN in the past two years, with the help of many people. I thank Drs. J.M.Qian and J.F.Zhou for their suggestions on the studies of the BGO energy scale; Dr. A.Gougas helped me a great deal at the final stage of the analysis; I thank Dr. T.S.Dai for sharing tricks in PAW. Many thanks go to Mrs. N.Anderson and E.Hankin for administrative helps. Finally I wish to thank the American tax payers for making my study in the U.S. possible, and for their steady support to fundamental researches, without which none of these would have been possible.

This thesis is dedicated to my parents.
Chapter 1

Introduction

The main objective of elementary particle physics is to find out the basic building blocks of matter and to describe the nature of the interactions among them. At present we know that elementary particles can be classified into two distinct groups. One group consists of leptons and quarks. These are spin $\frac{1}{2}$ particles, called fermions. They obey Fermi-Dirac statistics. There are six quarks, u, d, c, s, t, b, and six leptons, e, $\mu$, $\tau$, $\nu_e$, $\nu_\mu$, and $\nu_\tau$. All except the t quark and $\nu_\tau$ have been found experimentally, there is also indirect evidence of the existence of the t quark and $\nu_\tau$. In addition, each particle has a corresponding antiparticle. All these particles can be grouped into three generations according to a mass progression. The first generation consists of the electron and its neutrino and of the up and down quarks. The second generation consists of the muon and its neutrino and of the charm and strange quarks. The third generation consists of the tau and its neutrino and of the bottom and top quarks.

The other group consists of the gauge bosons. These are integer spin particles following Bose-Einstein statistics. The gauge bosons mediate the interaction between quarks and leptons. Experimental results indicate that there are four types of interaction in nature. They are the strong, electromagnetic, weak and gravitational interaction. The quarks interact with each other via the strong interaction, which is mediated by gauge bosons called gluons. The quarks and leptons interact with one another via the electro-weak interaction, which is mediated by the gauge bosons $\gamma$, $W^+$, $W^-$, and $Z^0$. In Table 1.1 we list the currently known elementary particles and their main properties.
<table>
<thead>
<tr>
<th>Particle</th>
<th>Charge</th>
<th>Spin</th>
<th>Colors</th>
<th>Mass (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron (e)</td>
<td>-1</td>
<td>1/2</td>
<td>0</td>
<td>$0.511 \times 10^{-3}$</td>
</tr>
<tr>
<td>Electron neutrino ($\nu_e$)</td>
<td>0</td>
<td>1/2</td>
<td>0</td>
<td>$&lt; 0.94 \times 10^{-8}$</td>
</tr>
<tr>
<td>Up quark (u)</td>
<td>2/3</td>
<td>1/2</td>
<td>3</td>
<td>$5 \times 10^{-3}$</td>
</tr>
<tr>
<td>Down quark (d)</td>
<td>-1/3</td>
<td>1/2</td>
<td>3</td>
<td>$9 \times 10^{-3}$</td>
</tr>
<tr>
<td>Muon ($\mu$)</td>
<td>-1</td>
<td>1/2</td>
<td>0</td>
<td>0.106</td>
</tr>
<tr>
<td>Muon neutrino ($\nu_{\mu}$)</td>
<td>0</td>
<td>1/2</td>
<td>0</td>
<td>$&lt; 0.25 \times 10^{-3}$</td>
</tr>
<tr>
<td>Charm quark (c)</td>
<td>2/3</td>
<td>1/2</td>
<td>3</td>
<td>1.25</td>
</tr>
<tr>
<td>Strange quark (s)</td>
<td>-1/3</td>
<td>1/2</td>
<td>3</td>
<td>0.175</td>
</tr>
<tr>
<td>Tau ($\tau$)</td>
<td>-1</td>
<td>1/2</td>
<td>0</td>
<td>1.784</td>
</tr>
<tr>
<td>Tau neutrino ($\nu_{\tau}$)</td>
<td>0</td>
<td>1/2</td>
<td>0</td>
<td>$&lt; 0.035$</td>
</tr>
<tr>
<td>Top quark (t)</td>
<td>2/3</td>
<td>1/2</td>
<td>3</td>
<td>&gt; 89</td>
</tr>
<tr>
<td>Bottom quark (b)</td>
<td>-1/3</td>
<td>1/2</td>
<td>3</td>
<td>4.3</td>
</tr>
<tr>
<td>Photon ($\gamma$)</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$W$ boson ($W^\pm$)</td>
<td>$\pm1$</td>
<td>1</td>
<td>0</td>
<td>$80.14 \pm 0.31$</td>
</tr>
<tr>
<td>$Z$ boson ($Z$)</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>$91.18 \pm 0.01$</td>
</tr>
<tr>
<td>Gluon ($g$)</td>
<td>0</td>
<td>1</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Higgs scalar ($H$)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>$57 \leq m_H \leq 1000$</td>
</tr>
</tbody>
</table>

Table 1.1: Elementary Particles

The electromagnetic and weak interactions can be described by local gauge theories [1]. The relativistic field theory of Quantum Electrodynamics (QED) provides a highly precise description of processes involving photons and charged leptons, the incorporation of weak phenomena in this theory led to the establishment of the Standard Model [2]. This model describes the electroweak properties of leptons and quarks, and successfully predicted the existence of vector bosons $W^\pm$ and $Z^0$ [5]. At this time no significant contradiction between experimental observations and Standard Model predictions has been found. Since the model is a renormalizable quantum field theory, radiative corrections to physical processes are finite and calculable. Thus one can fix some measured input parameters and then calculate the values of some precisely measurable quantities and compare them with experimental results. If the accuracy of the experiment is good enough to match the size of electroweak corrections, then the Standard Model can be tested at the one loop level. This is of particular interest, since any sizeable discrepancy would hint at ‘new physics’ beyond the Standard Model.
Despite its success so far, the Standard Model is not entirely satisfactory. In particular, it is not a theory which unifies all known forces, and by introducing a large number of additional free parameters, such as the fermion masses and the number of lepton/quark generations, it fails to explain the family problem. Besides, the Higgs mechanism, which is responsible for providing masses for all particles, is far from being understood.

The discovery of the $\tau$ lepton [6] and of the b quark [14] proved the existence of a third generation of leptons and quarks. During the past 15 years, the $\tau$-lepton has been studied extensively at many experiments, most notably at $e^+e^-$-colliders. Deviations from electron and muon properties have been carefully searched for, but no significant difference has yet been found. It is generally accepted that the $\tau$ is a 'sequential' lepton (i.e. it possesses its own unique lepton number). Its interaction with the neutral current is identical to those of the electron and muon. However, the accuracy of the $\tau$ properties is rather poor compared with high precision experiments performed with the lighter leptons, and there is still room for deeper understanding and perhaps new physics. Besides, in contrast to muon decay, the $\tau$-lepton can also decay into hadrons. The character of the hadronic $\tau$ decays provides a unique tool for the study of the couplings of the light mesons to the vector and axial-vector currents. On the other hand, the leptonic decays, together with the $\tau^+\tau^-$ production cross section, probe the structure of the weak currents and the universality of their couplings to the gauge bosons. Here the term universality implies that all coupling constants for the charged and neutral current interactions are the same for the different generations.

A subject which remains to be understood, is the existence of a 2$\sigma$ discrepancy between the world average value of the measured $\tau$ lifetime and the value calculated from the measured leptonic branching ratios (which are in good agreement with Standard Model predictions). From the measured $\tau$ leptonic branching ratios, one can also extract the strong coupling constant, $\alpha_s$, which provides an independent and complimentary measurement of this important parameter in QCD. Furthermore, the weak decay of the $\tau$ can be used to analyze its polarization, which is at present the only effective way to measure the ratio of the vector and axial-vector coupling constants of the $\tau$ to the weak current. At the $Z^0$ resonance, the measurement of the $\tau$ spin polarization asymmetry $A_{pol}$ in the reaction $e^+e^- \rightarrow \tau^+\tau^-$ has the advantage of being more sensitive to the Weinberg angle than the forward-backward asymmetry measurement. The results are also less dependent on the center of mass energy than the latter.
Chapter 2

Theory

This chapter begins with a brief discussion of the theoretical framework of the electroweak Standard Model, followed by some of its applications in weak neutral current processes (especially in the production and decay of the $\tau$ leptons) and of the technique of the measurement of the $\tau$ polarization.

2.1 The Standard Model

One of the goals of theoretical physics is to explain all interactions in the universe by a single theory. As an intermediate step, the Standard Model is a theory which unifies weak and electromagnetic interactions, and describes the two interactions in a single formalism.

2.1.1 Weak Interaction

In contrast to the strong and electromagnetic interactions, the weak interaction can involve a change of the particle type, with transitions such as $u \leftrightarrow d, e^- \leftrightarrow \nu_e$, etc. Some examples of weak interactions are:

\[
\begin{align*}
\mu^+ & \rightarrow \nu_\mu \epsilon^+ \nu_e, \\
\bar{d} & \rightarrow u e^- \bar{\nu}_e.
\end{align*}
\] (2.1)
All such weak processes can be successfully described by an effective interaction of the form
\[ \mathcal{L}_W = -\frac{4G_F}{\sqrt{2}} J^\mu J_\mu, \]  
\hspace{1cm} (2.2)

where
\[ J^\mu = \bar{\nu}_e \gamma_\mu \frac{1}{2} (1 - \gamma^5) e + \bar{u}_\mu \gamma_\mu \frac{1}{2} (1 - \gamma^5) \mu + \bar{d}' \gamma_\mu \frac{1}{2} (1 - \gamma^5) d' + \bar{c}' \gamma_\mu \frac{1}{2} (1 - \gamma^5) s' \]  
\hspace{1cm} (2.3)
is the current, and
\[ G_F = 1.16637(2) \times 10^{-5} GeV^{-2} \approx 10^{-5}/m_p^2 \]  
\hspace{1cm} (2.4)
is the Fermi coupling constant \((m_p\) is the proton mass). Here particle names are used to denote Dirac spinors, \(d'\) and \(s'\) are related to the \(d\) and \(s\) quarks as follows:
\[ d' \equiv d \cos \theta_c + s \sin \theta_c, \]
\[ s' \equiv -d \sin \theta_c + s \cos \theta_c. \]  
\hspace{1cm} (2.5)

where \(\theta_c\) is the Cabibbo angle which is determined experimentally as \(\theta_c \sim 13.2^\circ\).

The presence of term \(\frac{1}{2} (1 - \gamma^5)\) explains the parity violation effects observed in experiments. It indicates that only left-handed fermions and right-handed antifermions participate in charge-current interactions. So the weak interactions are chiral, i.e. they do not treat the left- and right- handed components of the fermions equally and hence they do not conserve parity and helicity. In the lowest order (tree level), \(\mathcal{L}_W\) gives a successful description of low-energy charged-weak interactions. However, this theory is not renormalizable, due to the fact that higher order corrections produce an infinite sequence of interactions of higher and higher dimension and increasingly divergent integrals, which require many arbitrary constants to converge them to finite. To solve this problem, massive vector bosons \(W^\pm\) were introduced, and eq.(2.2) is replaced by:
\[ \mathcal{L}_W = -\frac{g}{\sqrt{2}} (J^\mu W^{\mu +} + J^{\mu} W_{\mu}^-), \]  
\hspace{1cm} (2.6)

where \(g\) is a dimensionless coupling constant. The propagator of the \(W\) boson can be written as
\[ \frac{g_{\mu\nu} - q_{\mu} q_{\nu}/M_W^2}{q^2 - M_W^2}, \]  
\hspace{1cm} (2.7)

which approaches a constant as \(q^2 \to \infty\) rather than decreasing as \(\frac{1}{q^2}\), because of the fact that the polarization vectors which describe the \(W\) boson behave as
\[ c^L_\mu \to \frac{q_\mu}{M_W} \]  
\hspace{1cm} (2.8)
when $q \to \infty$. Therefore the theory is still not renormalizable. However, a similar problem does not arise from the longitudinally polarized virtual photons in QED, since owing to gauge invariance, two polarization vectors that differ by some multiple of the 4-momentum describe the same photon, i.e., when doing the displacement

$$\epsilon_\mu \to \epsilon_\mu + a q_\mu,$$

the components of the photon polarization that are proportional to $q$ do not contribute to physical processes. It is therefore natural to ask whether a gauge theory can similarly be applied to weak interaction. A related problem exists in the process $e^+e^- \to W^+W^-$, when the $W$s are produced in longitudinally polarized states. The amplitude behaves like $\frac{q^2}{M_W^2}$ at very high energy. One solution to the problem was to introduce a massive neutral vector boson, $Z$. In the meantime this breaks gauge invariance, since it requires the vector boson to be massless. This leads to the concept of spontaneous symmetry breaking which provided a way for the $W^\pm$'s and $Z$ to acquire masses without destroying gauge invariance. The idea is to introduce a complex scalar field $\phi$ (the Higgs field) which couples to the gauge fields, spontaneously breaking the gauge symmetry to give mass to the three gauge bosons.

### 2.1.2 The Glashow-Weinberg-Salam Model

The standard theory of electroweak interactions is based on the gauge group $SU(2)_L \otimes U(1)$ and is known as the Glashow-Weinberg-Salam (GWS) model. In 1961 Glashow [2] proposed a formalism for the unification of weak and electromagnetic interactions using this group. Later Weinberg [3] and Salam [4] showed how the weak gauge bosons could acquire their masses without violating gauge invariance. The interactions of the $SU(2)_L \otimes U(1)$ gauge fields are described by the electroweak theory and the couplings are determined by the electric charge $e$, and the mixing angle $\sin^2 \theta_W$, defined by the masses of the gauge bosons as shown below. In Born approximation, the currents and coupling constants for the vector and axial vector currents can be summarized as follows:

$$g_{vf} = I_{3f}, \quad g_{vf} = I_{3f} - 2Q_f \sin^2 \theta_W,$$

where $g_{vf}$ and $g_{vf}$ are called axial and vector current coupling constants, respectively, $Q_f$ refers to the particular fermion charge ($Q_f = -1$ for leptons), and $I_{3f}$ is the third
component of fermion weak isospin. Symmetry breaking and mixing lead to the existence of two physical particles: a massless photon responsible for electromagnetic interactions
\[ \gamma = \sin \theta_W W^0 + \cos \theta_W B^0, \] (2.11)
and a massive mediator of the weak neutral current
\[ Z^0 = \cos \theta_W W^0 - \sin \theta_W B^0. \] (2.12)

\( B^0 \) is the field corresponding to \( U(1) \). The mixing angle, \( \sin^2 \theta_W \), is given by the \( Z^0 \) and \( W^\pm \) masses:
\[ \sin^2 \theta_W = 1 - \frac{M_{Z^0}^2}{M_W^2}. \] (2.13)

### 2.2 The \( \tau \) Lepton and its Decay Properties

Much has been learned about the \( \tau \)-lepton since its discovery at SLAC in 1975 [6]. In the Standard Model, \( \tau \) pair production in \( e^+e^- \) annihilation proceeds through both the electromagnetic and neutral weak currents, \( e^+e^- \rightarrow \gamma, Z \rightarrow \tau^+\tau^- \). At low energies \( (s \ll M_Z^2) \), contributions from \( Z \) are negligible. The production cross-section is sensitive to the coupling of the \( \tau \) to the photon alone. From the energy dependence of the production cross-section near threshold, the spin of the \( \tau \) was determined to be \( \frac{1}{2} \) and its mass was measured to be \( m_\tau = 1784.1^{+2.7}_{-3.6} \text{ MeV} \) [43].

At higher \( e^+e^- \) energies, where contributions from the \( Z \) become important, the study of \( \tau \) production and decay allows one to extract information about the electroweak
parameters. The Z coupling to the neutral lepton (see eq.(2.10)) can be written as

\[ \mathcal{L}_{NC} = \frac{g}{4 \cos \theta_W} Z_{\mu} \sum_l \bar{l} \gamma^\mu (v_l - a_l \gamma_5) l, \]  

(2.14)

where the weak charges are,

\[ v_e = v_\mu = v_\tau = -1 + 4 \sin^2 \theta_W, \]

\[ a_e = a_\mu = a_\tau = -1. \]  

(2.15)

For unpolarized e\(^+\) and e\(^-\) beams, the differential production cross-section in the lowest order is [11]

\[ \frac{d\sigma}{d\Omega} = \frac{\alpha^2}{8s} \{ A(1 + \cos^2 \theta) + B \cos \theta - h_r [C(1 + \cos^2 \theta) + D \cos \theta] \}, \]  

(2.16)

where \( s \) is the center of mass energy squared, \( \theta \) is the angle between e\(^-\) and \( \tau^- \), and \( h_r (\pm 1) \) is the \( \tau^- \)-helicity, and

\[ A = 1 + 2 v_e v_\tau \text{Re}(\chi) + (v_e^2 + a_e^2)(v_\tau^2 + a_\tau^2)|\chi|^2, \]

\[ B = 4 a_e a_\tau \text{Re}(\chi) + 8 v_e a_\tau a_\tau |\chi|^2, \]

\[ C = 2 v_e a_\tau \text{Re}(\chi) + 2 (v_e^2 + a_e^2) v_\tau a_\tau |\chi|^2, \]

\[ D = 4 a_e v_\tau \text{Re}(\chi) + 4 v_e a_\tau (v_\tau^2 + a_\tau^2)|\chi|^2. \]  

(2.17)

\( \chi \) in eq.(2.17) is the Z propagator

\[ \chi = \frac{\sqrt{2} G_F M_Z^2}{4 \pi \alpha} \frac{s}{s - M_Z^2 + i M_Z \Gamma_Z}, \]  

(2.18)

where \( M_Z \) is the mass of the Z boson. If the \( \tau \) helicity is not measured, one has

\[ \sigma = \frac{4 \pi \alpha^2}{3s} A. \]  

(2.19)

Therefore, \( A \) represents the normalization of the \( \tau \) production cross section with respect to the QED point cross section. Only the terms proportional to \( (1 + \cos^2 \theta) \) contribute to the total cross section. Since the vector coupling, \( v_l \), is very small, the contribution of the \( \gamma - Z \) interference term to \( A \) is considerably suppressed. At center of mass energies far below the Z mass, the purely weak contribution is negligible due to the propagator term \(|\chi|^2\).

The Z-exchange amplitude introduces a linear dependence on \( \cos \theta \) in the cross section, which leads to a forward-backward asymmetry, defined as:

\[ A_{FB}^{\tau\tau}(s) \equiv \frac{N_F - N_B}{N_F + N_B} = \frac{3B}{8A}. \]  

(2.20)

11
Here, \( N_F \) and \( N_B \) are the number of negative \( \tau \)'s in the forward and backward hemispheres, respectively, with respect to the electron direction. At \( s \ll M_Z^2 \), this asymmetry is proportional to the product of the axial-vector couplings of the electron and the tau to the \( Z \),

\[
A_{\tau\tau}^{FB}(s \ll M_Z^2) \approx \frac{3}{2} a_e a_\tau \text{Re}(\chi).
\]  

(2.21)

The propagator \( \chi \) determines the sign of this asymmetry to be negative.

### 2.2.1 \( \tau \) Production at the \( Z^0 \) Peak

For \( s = M_Z^2 \), the real part of the \( Z \)-propagator vanishes and the photon exchange terms can be neglected in comparison with the \( Z \)-exchange contributions (\( \Gamma_2^2 / M_Z^2 \ll 1 \)). We therefore have,

\[
\sigma_{\text{peak}} = \frac{12\pi \Gamma_e \Gamma_\tau}{M_Z^2 \Gamma_2^2},
\]

(2.22)

where

\[
\Gamma_l = \frac{G_F M_Z^2}{24\sqrt{2}\pi} (v_l^2 + a_l^2)
\]

(2.23)

is the \( Z \) partial decay width to the \( l^+ l^- \) final state, and \( \Gamma_2 \) is the total decay width of the \( Z^0 \) boson. The cross section formula (2.22) is valid only in the lowest order and fermion mass effects have been neglected. In order to compare measured values with theoretical predictions, higher order electroweak radiative corrections must be taken into account.

### 2.2.2 Decay Branching Ratios

In the Standard Model, the \( \tau \)-lepton decays via the \( W \)-emission diagram shown in figure 2.1. The Lagrangian of \( W \)-coupling to the charged current is:

\[
\mathcal{L}_{cc} = -\frac{g}{2\sqrt{2}} W^+_{\mu} \left\{ \sum_l \bar{\nu}_l \gamma^\mu (1 - \gamma_5) l + \bar{u} \gamma^\mu (1 - \gamma_5) d_0 \right\} + \text{h.c.}
\]

(2.24)

If one neglects final state masses and gluonic corrections, the contributions to the \( \tau^- \)-decay width are equally shared by the two leptons and three quark flavors, i.e. two of them correspond to the decay modes \( \tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e \) and \( \tau^- \rightarrow \nu_\tau \mu^- \bar{\nu}_\mu \), while the other three are associated with the three possible colors of the quark-antiquark pair in the \( \tau^- \rightarrow \nu_\tau d_0 \bar{u} \) decay mode \( (d_0 \equiv \cos \theta_c d + \sin \theta_c s) \). Therefore, the branching
Figure 2.1: Feynman diagram for the decay of the $\tau$-lepton

ratios for the different channels are expected to be approximately:

$$B_l \equiv Br(\tau^- \rightarrow l^- \bar{\nu}_l) \simeq \frac{1}{3} = 20\% (l = e, \mu),$$  \hspace{1cm} (2.25)

$$R_\tau \equiv \frac{\Gamma(\tau^- \rightarrow \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \rightarrow \nu_\tau \tau^- \bar{\nu}_\tau)} \simeq N_e = 3.$$  \hspace{1cm} (2.26)

Experimentally, the world averages are [40]:

$$B_e = (17.73 \pm 0.23)\%.$$  \hspace{1cm} (2.27)

$$B_\mu = (17.41 \pm 0.24)\%.$$  \hspace{1cm} (2.28)

$$R^{\text{exp,B}}_\tau = \frac{1 - B_e - B_\mu}{B_e} = (3.66 \pm 0.05).$$  \hspace{1cm} (2.29)

Leptonic Decays

The $SU(2)_L \otimes U(1)$ gauge symmetry implies $\epsilon - \mu - \tau$ universality. Hence the electroweak radiative corrections in the case of $\tau$ decays are similar to those in the $\mu$ decays [7]. In general the decay partial width can be written as follows:

$$\Gamma_{\text{tot}} = \Gamma(\tau \rightarrow l\nu_l\bar{\nu}_l) + \Gamma(\tau \rightarrow l\nu_l\gamma\gamma) + ...$$  \hspace{1cm} (2.30)

Assuming a massless $\nu_l$, this leads to [7]:

$$\Gamma_{\tau \rightarrow l} \equiv \Gamma(\tau^- \rightarrow l^- \bar{\nu}_l) = \frac{G_F^2 m_e^5}{192\pi^3} f(\frac{m_e^2}{m_\tau^2}) r,$$  \hspace{1cm} (2.31)

where $f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x$; $l = e, \mu$, it is approximately 1 for electron. The factor $r$ takes into account radiative corrections not included in the
Fermi coupling constant $G_F$, and the non-local structure of the $W$-propagator. These effects have been shown to be small [37]:

$$r = \left[ 1 + \alpha \left( \frac{25}{4} - \pi^2 \right) \right] \left[ 1 + \frac{3}{5} \frac{m_e^2}{M_W^2} \right] \approx 0.9960,$$

(2.32)

where,

$$\alpha(m_r) \approx \frac{1}{138}; \quad m_r = 1784.2 \pm 3.2\text{MeV}.$$

Therefore,

$$\Gamma(\tau \to e\nu_r\bar{\nu}_e(\gamma)) = (4.115 \pm 0.037) \times 10^{-13}\text{GeV},$$

and,

$$\Gamma(\tau \to \mu\nu_r\bar{\nu}_\mu(\gamma)) = (4.003 \pm 0.036) \times 10^{-13}\text{GeV}.$$ 

From eq. (2.31) and the world average measured $\tau$-lifetime [25], $\tau_\tau = (3.025 \pm 0.059) \times 10^{-13}s$, we obtain the branching ratio $B^\text{th}_e = (18.9 \pm 0.4)\%$, which is about two standard deviations higher than the measured value. Given the present limit of $m_{\nu_e} < 35\text{MeV}$ (95% C.L.) [29], it is unlikely for such a discrepancy to be due to a non-zero value of $m_{\nu_e}$. The agreement is slightly better in the muonic channel: taking into account the phase-space mass correction, $f\left(\frac{m_{\nu_e}^2}{m_r^2}\right) = 0.9728 \pm 0.0001$, one has $B^\text{th}_\mu = (18.4 \pm 0.4)\%$. However, in both cases the experimental branching fractions are below the values extracted from the measured lifetime. Generally speaking, experimentally the systematic errors in the branching ratio measurements are easier to control than in the case of lifetime measurements, thus great care must be taken when averaging lifetime results from different experiments. To probe the lifetime-branching ratio puzzle, a better than 1% measurement of $\tau_\tau$ in a single experiment is much to be desired.

Precise measurements of the $\tau$ lifetime and its leptonic decay branching fractions can be used to test $e - \mu - \tau$ universality. Allowing the value of the coupling $g$ in eq. (2.14) to be flavor dependent, one has

$$\frac{B_\mu}{B_\tau} = \left(\frac{g_\mu}{g_\tau}\right)^2 \cdot f\left(\frac{m_{\nu_e}^2}{m_r^2}\right).$$

(2.33)
From the present world average of the measured $\tau$ leptonic branching fractions, we have

$$\left| \frac{g_{\mu}}{g_{\tau}} \right| = 1.005 \pm 0.010.$$  \hfill (2.34)

The error is nearly twice as large as the value obtained from pion decay experiments, which yield $\left| \frac{g_{\mu}}{g_{\tau}} \right| = 1.006 \pm 0.006$.

Hadronic Decays

The semileptonic decay modes of the $\tau$, $\tau^{-} \rightarrow \nu_{\tau} H^{-}$, probe the matrix element of the left-handed charged current between the vacuum state ($\langle 0 \rangle$) and the final hadronic state ($\langle H^{-} \rangle$),

$$\langle H^{-}\rangle \bar{d}_u \gamma^\mu (1 - \gamma_5) u |0 \rangle.$$  \hfill (2.35)

Contrary to the $e^+ e^- \rightarrow \gamma \rightarrow$ hadrons process, which is suitable for testing only the electromagnetic vector current, the semileptonic $\tau$-decay modes offer the possibility to study the properties of both vector and axial-vector weak currents.

For decay modes $\tau^{-} \rightarrow \nu_{\tau} \pi^{-}$ and $\tau^{-} \rightarrow \nu_{\tau} K^{-}$, the relevant matrix elements are known from the measured decays $\pi^{-} \rightarrow \mu^{-} \bar{\nu}_\mu$ and $K^{-} \rightarrow \mu^{-} \bar{\nu}_\mu$. Assuming the matrix elements depend only on the four-vector $p^\mu$, and the structure function $f_\pi$ and $f_K$, which is measured in the experiments, one has,

$$\langle \pi^{-}(p) | \bar{d}_u \gamma^\mu \gamma_5 u |0 \rangle \equiv i\sqrt{2} f_\pi p^\mu,$$  \hfill (2.36)

$$\langle K^{-}(p) | \bar{s}_u \gamma^\mu \gamma_5 u |0 \rangle \equiv i\sqrt{2} f_K p^\mu.$$  \hfill (2.37)

The corresponding $\tau$-decay widths can then be predicted rather accurately. Taking all electroweak radiative corrections into account, the theoretical predictions for these two decay modes are [45],

$$R_{\tau - \pi} \equiv \frac{\Gamma(\tau^{-} \rightarrow \nu_{\tau} \pi^{-})}{\Gamma_{\tau^{-}}} = 0.601$$  \hfill (2.38)

$$R_{\tau - K} \equiv \frac{\Gamma(\tau^{-} \rightarrow \nu_{\tau} K^{-})}{\Gamma_{\tau^{-}}} = 0.034,$$  \hfill (2.39)

which are in good agreement with the experimental ratios: $(0.634 \pm 0.023)$ and $(0.038 \pm 0.011)$ respectively [40]. In the Calibbo allowed modes with $J^P = 1^-$, the matrix element of the vector charged current can also be obtained, through an isospin rotation, from the isovector part of the $e^+ e^-$ annihilation cross-section into
hadrons, which measures the hadronic matrix element of the $I = 1$ component of the electromagnetic current,

$$< H^0 | (\bar{u}\gamma^\mu u - \bar{d}\gamma^\mu d) | 0 >. $$ (2.40)

The $\tau$-decay particle widths for these modes can be expressed as an integral over the corresponding $e^+e^-$ cross-section [31], and using the available $e^+e^- \rightarrow$ hadrons data, one can then predict the $\tau$-decay widths for these modes.

For $\tau$-decays into final hadronic states with $J^P = 1^+$, or Cabibbo suppressed modes with $J^P = 1^-$, only model-dependent estimates can be made at present, with an accuracy which depends on our knowledge of strong interactions at low energies. Due to their semileptonic character, the hadronic $\tau$-decay data can then be unique and extremely useful tools to learn about the couplings of the light mesons to the weak currents [43] [10].

2.2.3 $\alpha_s$

In $e^+e^-$-annihilation, the ratio of the hadronic cross section to the leptonic cross section can be defined as:

$$R_{ve}(Q^2 = s) = \frac{\sigma(e^+e^- \rightarrow hadrons)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)},$$ (2.41)

where $s$ stands for the center-of-mass energy squared. This expression can be modified to hold for the $W$-boson:

$$R_W(Q^2 = s) = \frac{\Gamma(W \rightarrow hadrons)}{\Gamma(W \rightarrow l\bar{\nu}_l)}.$$ (2.42)

It can then be generalized to $\tau$ decay by integrating over $s$ of $\Gamma(W \rightarrow hadrons)$ and $\Gamma(W \rightarrow l\nu_l)$, using the proper phase space and $\tau \rightarrow \nu, \tau$ vertex factors:

$$R_{\tau} = \frac{\Gamma(\tau \rightarrow hadrons)}{\Gamma(\tau \rightarrow l\nu_l)}.$$ (2.43)

Experimentally, this ratio can be expressed in terms of the leptonic branching ratios as follows:

$$R_{\tau} = \frac{1 - B_e - B_\mu}{B_l} = \frac{1 - f_e B_l - f_\mu B_l}{B_l} = \frac{1}{B_l} - f_e - f_\mu$$ (2.44)

where $f_e$ and $f_\mu$ are phase-space factors associated with the electron and muon masses respectively ($f_e \simeq 1$ and $f_\mu \simeq 0.9728$), and $B_l$ is the leptonic branching ratio. It
has been shown [39] that the uncertainties in the theoretical calculations of $R_\tau$ are very small, and the value of $R_\tau$ can therefore be accurately predicted as a function of $\alpha_s(m^2_\tau)$. Experimentally, measurements of the leptonic decay rates of the $\tau$ can be used to determine the value of $\alpha_s(m^2_\tau)$. Once the running coupling constant $\alpha_s(\mu = m^2_\tau)$ is determined at the scale $m_\tau$, it can be evolved to higher energies using the renormalization group. The size of the error on $\alpha_s(\mu)$ scales roughly as $(\alpha_s(\mu))^2$, and it therefore decreases as $\mu$ increases. Therefore, a modest precision in the determination of $\alpha_s$ at low energies results in a very high precision in the coupling constant at high energies. The advantage of determine the running coupling constant in the $\tau$ decay is that it avoided the complications from nonperturbative effects. If the universality of the $Wl_l$ ($l = e, \mu, \tau$) couplings is assumed ($B_\mu = 0.9728 B_\tau$), the measured leptonic branching fractions imply a value of $R_\tau$ lower than the one given in Eq. (2.29). Taking an average of the available experimental data, one gets $R^{\exp}_\tau = 3.59 \pm 0.05$, which corresponds to $\alpha_s(m_\tau) = 0.33 \pm 0.03$. This running coupling constant decreases to $\alpha_s(M_2) = 0.119^{+0.003}_{-0.004}$, in very good agreement with the present LEP average, $\alpha_s(m^2_Z) = 0.120 \pm 0.007$, and with a smaller error.

The small size of the non-perturbative contributions allows us to make an accurate prediction of $R_\tau$ in terms of $\alpha_s(m^2_\tau)$. This can be used to infer a value of the QCD-scale $\Lambda_{\overline{MS}}$ from the measured tau hadronic-width. Table 2.2 [45] shows the results obtained for different values of $\Lambda_{\overline{MS}}$. The quoted errors are due to the small uncertainties associated with the electroweak corrections and the non-perturbative contributions.

<table>
<thead>
<tr>
<th>$\Lambda_{\overline{MS}}$ (MeV)</th>
<th>$\alpha_s(m^2_\tau)/\pi$</th>
<th>$R_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.06111</td>
<td>3.29 ± 0.02</td>
</tr>
<tr>
<td>200</td>
<td>0.07818</td>
<td>3.40 ± 0.02</td>
</tr>
<tr>
<td>300</td>
<td>0.09418</td>
<td>3.52 ± 0.02</td>
</tr>
</tbody>
</table>

Table 2.1: Values of $\Lambda_{\overline{MS}}$ for different $R_\tau$.

The ratio $R_\tau$ is related to the total $\tau$-decay width through the equation

$$\Gamma(\tau^-) = \Gamma(\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e) \{1.9728 + R_\tau\}. \tag{2.45}$$

Therefore, $R_\tau$ can be obtained experimentally either from the leptonic branching ratios or from the lifetime measurement, if the theoretical prediction for the leptonic width is assumed.
2.3 Polarization of the $\tau$

In the process $e^+e^- \rightarrow \tau^+\tau^-$, the longitudinal polarization of the $\tau$ pairs is reflected in the distorted distribution of the decay products. Therefore, the $\tau$-polarization can be determined from a measurement of the shape of the final charged particle energy spectrum in the decay channels $\tau^- \rightarrow \nu_\tau \pi^- , \nu_\tau e^- \bar{\nu}_e , \nu_\tau \mu^- \bar{\nu}_\mu , \nu_\tau \rho^- , \nu_\tau a^-$. The coefficients $C$ and $D$ in eq.(2.17) can then be extracted, by measuring the asymmetries

$$A_{\text{pol}}(s) \equiv \frac{\sigma(h_\tau = +1) - \sigma(h_\tau = -1)}{\sigma(h_\tau = +1) + \sigma(h_\tau = -1)}$$

$$= -\frac{C}{\mathcal{A}} \approx \left\{ \begin{array}{ll}
-2v_e a_\tau \text{Re}(\chi) & (s \ll M_\tau^2) \\
\mathcal{P}_r & (s = M_\tau^2)
\end{array} \right., \quad (2.46)$$

$$A_{\text{FB}}^{FB}(s) \equiv \frac{N_F(h_\tau = +1) - N_F(h_\tau = -1) - N_B(h_\tau = +1) + N_B(h_\tau = -1)}{N_F(h_\tau = +1) + N_F(h_\tau = -1) + N_B(h_\tau = +1) + N_B(h_\tau = -1)}$$

$$= -\frac{3D}{\mathcal{A}} \approx \left\{ \begin{array}{ll}
-\frac{3}{2} a_\tau v_\tau \text{Re}(\chi) & (s \ll M_\tau^2) \\
\frac{1}{2} \mathcal{P}_r & (s = M_\tau^2)
\end{array} \right., \quad (2.47)$$

where $A_{\text{pol}}$ is the average longitudinal polarization of the lepton $l \ (l = e, \tau)$, and $A_{\text{FB}}^{FB}$ is the forward-backward polarization asymmetry. At the $Z^0$ pole, the Born level forward-backward asymmetry, as defined in eq. (2.20) can be written as

$$A_{rr}^{FB}(M_\tau^2) = \frac{3}{4} \mathcal{P}_r \mathcal{P}_r. \quad (2.48)$$

$$\mathcal{P}_r = \frac{-2v_\tau a_\tau}{v_\tau^2 + a_\tau^2} \approx -2 \frac{v_\tau}{a_\tau} = -2(1 - 4 \sin^2 \theta_W). \quad (2.49)$$

Thus, the $\tau$ polarization depends on the ratio of the vector and axial-vector couplings, and is directly related to $\sin^2 \theta_W$. A non-zero lepton polarization produced in $e^+e^-$ annihilation indicates that parity is violated both in the $e^+e^- \rightarrow \tau^+\tau^-$ production process and in the subsequent $\tau$-decays, without which a $\tau$-polarization could not be observed. Two pioneering measurements of $\tau$-polarization asymmetry were carried out by CELLO and MAC [9], but since at PEP/PETRA energies the expected value of $A_{\text{pol}}$ is only about 1 %, their sensitivity was not sufficient to obtain a non-zero result.

In the $\tau$ rest frame, the energy-angular distribution for one-charged particle final state can be written as follows:

$$\frac{d\sigma}{dx_0 d\cos(\theta)} = C(F_1(x_0) + F_2(x_0) \cos(\theta)). \quad (2.50)$$
Here, \( x_0 \) is the ratio between the energy of the decay particle and the maximum possible energy (beam energy), \( \theta \) is the angle between the decay particle and the \( \tau \) spin (see Fig. 2.2a), \( F_1 \) and \( F_2 \) are structure functions which depend on the spin and mass of the decay particle, and \( C \) is a normalization constant.

![Diagram of angular relationships between decay products.](image)

**Figure 2.2: Angular relationships between decay products.**

### 2.3.1 Hadronic Channels

We take the process \( \tau \to \pi^- \nu_\tau \) as an example. Fig 2.2a shows the preferred spin orientations relative to the momentum of the particles in the \( \tau \) rest frame. For unpolarized \( \tau \)'s the decay angular distribution is isotropic in the \( \tau \) rest frame, resulting a flat energy distribution for the decay pion in the lab frame. For polarized \( \tau \)'s, since the \( \pi^- \) has a spin of 0, if one assumes a left-handed \( \nu_\tau \), then in the laboratory system the emission of the \( \pi^- \) in the direction opposite to that of the left-handed \( \tau^- \) is preferred. This results in the \( \pi^- \) getting less momentum than the one from a right-handed \( \tau^- \) decay. Therefore, on average, for \( \tau^- \)'s in negative helicity states, the energy spectrum of their decay product \( \pi^- \)'s have a negative slope, as shown in Fig 2.3. Measuring the polarization thus involves determination of this slope. In the
laboratory frame, the $\pi^-$ energy distribution is given by

$$\frac{1}{N} \frac{dN}{dx} = 1 + P(2x - 1)$$

(2.51)

where $x = E_\tau/E_{\text{max}}$ and $P =$ average polarization.

### 2.3.2 Leptonic Channels

There are three spin $\frac{1}{2}$ particles in the leptonic decays of the $\tau$. Figure 2.2b shows the case of $\tau$ decays to $\epsilon$ in which the electron carries the whole recoil momentum of the two neutrinos and goes along the direction of the $\tau$ momentum seen in the lab frame. If one assumes a left-handed $\nu_\tau$ and a right-handed $\bar{\nu}_\epsilon$, then the electron will have to be in the same helicity state as the $\tau^-$. The V-A theory requires the electron to have negative helicity, only $\tau^-$ of negative helicity can the electron be in such a state, which is why in fig. 2.4, at the higher end of the energy region, electrons from $\tau^-$'s with negative helicity are more numerous than those of positive helicity. The energy spectrum of the final state leptons is given by

$$\frac{1}{N} \frac{dN}{dx} = \frac{1}{3}[(5 - 9x^2 + 4x^3) + P(-1 + 9x^2 - 8x^3)].$$

(2.52)
2.3.3 Comparison of Sensitivities of Various $\tau$ Decay Modes to $P_r$

Experimentally, the sensitivity to the polarization varies between different decay channels. This can be estimated as follows [44]. Assuming the distribution of the decay particle energy spectrum can be expressed as

$$H(x) = f(x) + Pg(x),$$

(2.53)

with $\int f(x) = 1$ and $\int g(x) = 0$, and $P$ is the value of the polarization. The error on $P$ can be written as:

$$\Delta P = \frac{1}{\sqrt{N}} \left[ \int \frac{g^2}{f + Pg} \right],$$

(2.54)

where $N$ is the number of $\tau$ decays in the mode. The sensitivity to $P$ for a particular decay channel is then inversely proportional to $\Delta P$, i.e.,

$$S = \frac{1}{\sqrt{N} \Delta P}.$$

(2.55)

Taking into account the decay branching ratios, the weight of a given decay mode $i$ (with branching ratio $Br_i$) is

$$W_i = S^2 Br_i.$$

(2.56)
\[ \sum \Pi_i = 1. \] (2.57)

The results for five major decay channels are listed in Table 2.7. Here detector effects or radiative corrections are not included.

<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>ev \bar{v}</th>
<th>\mu \nu \bar{\nu}</th>
<th>\pi \nu</th>
<th>\rho \nu</th>
<th>a_1 \nu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>0.22</td>
<td>0.22</td>
<td>0.60</td>
<td>0.52</td>
<td>0.24</td>
</tr>
<tr>
<td>Branching Ratio</td>
<td>0.18</td>
<td>0.18</td>
<td>0.11</td>
<td>0.23</td>
<td>0.07</td>
</tr>
<tr>
<td>Weight</td>
<td>0.07</td>
<td>0.07</td>
<td>0.32</td>
<td>0.50</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Table 2.2: Sensitivities and weights for various decay channels

Another way of comparing sensitivities between different decay channels is by calculating the asymmetry \( A_x \) defined as

\[
A_x(P_r) = \frac{S(x > x_c, P_r)}{S(x > x_c, P_r = 0)} - \frac{S(x < x_c, P_r)}{S(x < x_c, P_r = 0)},
\] (2.58)

where \( x_c \) is the cross over point of the two different helicity spectra, \( S(x > x_c, P_r) \) and \( S(x < x_c, P_r) \) are, for given polarization \( P_r \), the area for the regions above and below \( x_c \), respectively, and \( S(x > x_c, P_r = 0) \) and \( S(x < x_c, P_r = 0) \) correspond to the same quantities of a zero polarization. In fig. 2.5 the normalized spectra for \( P_r = 1, 0 \), and \(-1\) are shown, the crossing point of \( P_r = 1, -1 \) in this case is at \( x_c = 0.5 \). The \( A_x(P_r) \) can be readily calculated to be 1. Similarly, for Born level electron spectra shown in fig. 2.4, one gets \( A_x(P_r) \sim 0.3 \). This indicates that the sensitivity of the electron channel is about 1/3 of the pion channel.

### 2.3.4 Radiative Corrections

Since the measurement of the polarization involves analysing the shape of the energy spectrum of the decay particles, any changes in this shape will affect the results. Loss of energy due to radiation, for example, will distort the spectrum and thus has to be properly taken in to account. There are mainly two kinds of radiative corrections which affect the measurement: 1) QED corrections, which consist of all one-loop diagrams with real and virtual photons. They are gauge invariant and depend on the actual experimental setup and cuts; 2) Electroweak corrections, which contain the box diagrams with massive gauge boson exchange and modifications of the propagator for \( \gamma, Z^0 \). They are detector independent and can be taken into account by introducing flavor dependent coupling constants.
QED Corrections

There are three types of radiated photons to be considered in the $e^+e^- \rightarrow \tau^+\tau^-$ process and subsequent decays.

- Initial state radiation; Photons from this process are normally collinear with the incoming beam and thus escape undetected into the beam pipe. This radiation affects the total measured cross section, but does not strongly affect the shape of the energy spectrum and final state polarization.

- Final state radiation from the $\tau$ pair; Affects the polarization measurement.

- Radiation from the decay products. It reduces the energy of the decay particle which is measured, if the energy of the radiated photon is incorrectly estimated.

A Monte Carlo program KORALZ [26] was used to model the above QED effects. It simulates the process $e^+e^- \rightarrow \mu^+\mu^-, e^+e^- \rightarrow \tau^+\tau^-$ at energies around the $Z^0$ pole including the radiative corrections. In Fig. 2.6 the influence of the initial state radiation on the polarization and forward-backward asymmetry is plotted. The solid lines represent Born level results and the dashed lines include the initial state radiation. The dotted line shows the $A_{pol}$ using the $\pi$ energy spectrum including both initial

![Graph](image)

Figure 2.5: Pion energy spectra for $P_\tau = 1.0$, and -1.
and final state corrections. Clearly, the polarization is not very much dependent on the center-of-mass energy. The effects of final state radiation on the polarization measurement will be discussed in detail in Chapter 4. Fig 2.7 shows the influence of QED corrections to the $\mu$ momentum spectrum in the decay $\tau \to \mu \nu \bar{\nu}_\mu$. The solid curve is Born level result. The dashed curve includes initial state bremsstrahlung effects and the dotted curve includes, in addition, final state radiation.

**Electroweak Corrections**

If we use the following three constants: $\alpha$, $G_F$, and $M_Z$, which are experimentally known with high accuracy, then the mass of the $W$ boson can be written in terms of them as:

$$M_W^2 \sin^2 \theta_W = \frac{\pi \alpha}{\sqrt{2} G_F} \equiv A^2 = (37.281 \text{GeV})^2,$$

(2.59)

and eq.(2.13) becomes

$$\sin^2 \theta_W = \frac{1}{2} [1 - \sqrt{1 - \frac{4A^2}{M_Z^2}}].$$

(2.60)

The electroweak corrections affect the above tree-level relations. They can be included by modifying the coupling $\alpha$. (This is also referred to as the improved Born approximation.)

$$\alpha(M_Z^2) = \frac{\alpha}{1 - \Delta \alpha} = 1.064 \alpha,$$

(2.61)

and the ratio of the relative strength of the neutral to charged weak currents, $\rho$, is

$$\rho = \frac{1}{1 - \Delta \rho},$$

(2.62)

$$\Delta \rho = \frac{3G_F m_t^2}{8 \pi^2 \sqrt{2}}.$$

(2.63)

where $m_t$ represents the mass of the top quark. We then obtain,

$$\sin^2 \theta_W = \frac{1}{2} (1 - \sqrt{1 - \frac{4A^2}{\rho M_Z^2 (1 - \Delta \alpha)}}).$$

(2.64)

The value of $\Delta \rho$ depends on the top quark mass which is experimentally unknown. Therefore the corrections are strongly model-dependent. In Fig. 2.8, the effects of electroweak radiative corrections on the muon momentum spectrum in the decay $\tau \to \mu \nu \bar{\nu}$ is shown. The events are generated using the KORALZ Monte Carlo program, with the solid histogram corresponding to radiative corrections fully included, and the dashed histogram corresponding to all but the final state radiation included.
Figure 2.6: Effects of QED bremsstrahlung on the $\tau$ polarization and forward-backward asymmetry.
Figure 2.7: Effects of QED bremsstrahlung on the $\mu$ momentum spectrum at the $Z^0$ pole.

Figure 2.8: Effects of final state radiation on the muon momentum spectrum
Chapter 3

The L3 Detector

The L3 detector at LEP [15] consists of a central tracking chamber, an electromagnetic and a hadron calorimeter, and a 3-layer muon chamber system. L3 has 97% of acceptance for electron, photon and hadrons, and 70% acceptance for muons. The whole detector is surrounded by a conventional solenoid magnet which provides a uniform field of 0.5 Tesla. Designed to study $e^+e^-$ collisions at 90-200 GeV center of mass energy, it is based on the success of past experiments which detected electrons, muons, and photons and measured their energy with high precision. The following is a list of the major components of the L3 detector [13] and their characteristics (see Fig. 3.1):

- A vertex chamber (Time Expansion Chamber, TEC), which measures the charged particle tracks with a 50 $\mu$m average single wire resolution in the bending plane and 600 $\mu$m double track resolution. In the non-bending plane, it provides 500 $\mu$m single track resolution and 7 mm double track resolution on the Z coordinates;

- An electromagnetic calorimeter (ECAL) of 22 radiation lengths, made of BiGeO (BGO) crystals, which has an energy resolution of close to 1% for electrons and photons at energies above 2 GeV;

- A layer of scintillation counters, located between the electromagnetic and the hadron calorimeter, with a time resolution of $< 1$ns;

- A hadronic calorimeter (HCAL), made of depleted uranium absorber plates interspersed with proportional wire chambers. It is about 4 interaction lengths
Figure 3.1: L3 Detector overview.

in depth, and measures hadronic energy with resolution of \((55/\sqrt{E} + 5)\%\), and an angular resolution of \(\delta \theta = 2.5^\circ\), \(\delta \Phi = 3.5^\circ\);

- A muon filter of 1.03 absorption length made of brass absorber with proportional chamber.

- A muon chamber (MUCH) consists of three layers of large drift chambers, which measures muon momentum with 2% resolution at 45 GeV.

- A luminosity monitor, consisting of a charged particle tracking chamber with good position resolution and BGO crystal array with good energy resolution for electrons and photons.

3.1 Central Tracking Chamber

The L3 central tracking chamber as shown in fig. 3.4, is 960 cm long and extends from 9 cm to 49 cm radially from the interaction point. It consists of a Time Expansion Chamber (TEC), a Z-Chamber with cathode strip readout and a Plastic Scintillating
Figure 3.2: L3 Detector endview.

Figure 3.3: L3 Detector sideview.
Fiber (PSF) calibration system. The TEC covers the polar angle $|\cos \theta| \leq 0.8$. The design goals of the TEC are:

- To measure the transverse momentum with respect to the beam direction and determine the sign of charged particles with momentum up to 50 GeV/c at 95% confidence level;
- To determine the track multiplicity originating from the interaction region at the trigger level;
- To reconstruct the interaction point and of secondary vertices for particles with lifetime greater than $10^{-13}$ s, or decay lengths of a few mm.

In the TEC, by introducing a zero potential grid plane near the anode wire plane, the small high field detection region at sense wire plane is separated from the low field drift region (with a drift velocity of $\sim 6 \mu m/ns$). This structure allows the choice of a low electric field in the drift region to optimize the spatial resolution as well as a high electric field in the detection gap for necessary signal amplification. Using so-called cool gas ensures low longitudinal diffusion and low drift velocity with linear dependence on the electric field, the gas pressure and the temperature. A low drift velocity, achieved by a gas mixture of 80% CO₂ and 20% C₄H₁₀ at 2 atm, results in more accurate drift time measurement and a small Lorentz angle ($\sim 2.4^\circ$) in the presence of a magnetic field. 100 MHz Flash Analog to Digital Converters (FADC) determine the drift time of ionized electrons by a center of gravity method. To improve the tracking resolution, a shaping circuit is used on the analog pulses coming from the anodes by removing the ion tails.

The TEC has two main parts: inner chamber and outer chamber. The inner chamber, extends from 9 cm to 15 cm in radius, is mounted on the beam pipe and it is subdivided into 12 sectors, each with 30° coverage in $\Phi$. The outer chamber, extends from 15 cm to 46 cm in radius, is subdivided into 24 sectors, each with 15° coverage in $\Phi$. This layout helps in resolving the left-right ambiguity for the pattern recognition in the offline analysis. There are three types of signal wires, all with sensitive length of 982 mm: the Sense wires (anode wires) for measuring the R-$\Phi$ coordinates; Charge Division sense wires (CD) to determine the Z coordinates of the tracks by measuring the charge asymmetry at both ends of the wire; groups of five grid wires, located on each side of an anode, in the amplification region to further resolve the left-right
ambiguity (LR). Each inner sector contains 8 standard and 2 CD wires, while each outer sector has 54 standard, 9 CD and 14 LR wires.

A Z-chamber which consists of two layers of cylindrical proportional chambers with cathode readout was built outside the shell of TEC outer chamber and has a gas mixture of 80% Argon and 20% CO₂. When combined with the charge division wire measurements, it provides a spatial resolution in the Z direction of better than 2mm.

A plastic scintillating fiber (PSF) system was installed between the outer TEC shell and the Z-chamber as an external calibration device. It is comprised of 24 fiber ribbons placed along the axial direction of the TEC, each covers one outer sector. A ribbon is formed by 143 scintillating fibers of 1.2 meters long and $0.7 \times 1.0 \text{mm}^2$ cross section. The fibers are read out by ITT multi-anode microchannel plate photo multiplier tubes (MCPMTs). Each ribbon is coupled to two MCPMTs. When a charged particle passes through the active region of a ribbon, it induces ionization, thus photons are released and start to travel along the fiber. By measuring the signals from the fiber one can determine the exact position of the track crossing point in $r \phi$, which is then translated into drift distance. Plotting the drift distances obtained from the PSF for all the tracks against the measured drift time, one can obtain the drift velocities and use it to estimate the corrections to the values from the TEC. Applying this method to all sectors (all wires), an external calibration on a sector by sector (wire by wire) basis can be achieved.

The photoelectronic signals from a MCP tube are buffered into a CMOS microplexer (MX-4) chip, which contains 128 DC coupled differential low noise (2,000e⁻/channel), high speed (of better than 5 MHz) differential amplifier; the analog signals from the MX-4 are then converted by a CMOS 8-bit flash converter(75C58), with its outputs internally buffered so it can be directly connected to a 4-bit arithmetic logic unit, which manipulates the outputs from the A/D converter and provides three different operation modes, according to the run condition. More details about the PSF system can be found in Appendix C.

Four drift chambers (FTC) are installed at each end of the TEC in front of the BGO endcaps. The FTC measures the position and direction of charged particles with a spatial resolution of better than 200 $\mu$m and angular precision better than 10 mrad.
3.2 Electromagnetic Calorimeter

The L3 Electromagnetic Calorimeter (ECAL) consists of ~ 12,000 BGO (Bismuth Germanium Oxide, Bi₄Ge₃O₁₂) crystals pointing to the interaction region, the BGO was chosen because of its short radiation length for electrons and photons, high density, high intrinsic resolution ((0.5)%/√E for low energies, 1% for E > 1 GeV) and good linearity. The design goals for the ECAL are:

- A energy resolution of 1% from 2 GeV up to 100 GeV for e and γ, good energy measurement and angular determination (position resolution of better than 2 mm using weighted light output) for photons with energy down to 50 MeV;

- Rejection power against hadrons of the order of 10³ for electrons above 1 GeV;

The ECAL (as shown in fig.3.5) surrounds the Central Tracking Chamber and is composed of a cylindrical barrel and two endcaps. The barrel is made of 7680 BGO crystals, arranged in 48 rings of 160 crystals each (Figure ), covering the polar angular region from 42° to 138°. The two endcaps extend the polar angular coverage to 12° and 168°, each contains 1536 crystals. Each crystal is a truncated pyramid with a
cross-section of $2 \times 2 \text{cm}^2$ at the inner end and $3 \times 3 \text{cm}^2$ at the outer end. The length of each crystal is 24 cm, corresponding to 22 radiation lengths. The Hamamatsu 1.5cm$^2$ photodiodes, which are insensitive to the magnetic field, are used to collect the scintillation light. Two silicon photodiodes, together with its linear electronics are mounted on the rear face of each crystal. Signals from the crystals are readout by ADCs of large dynamic range (200,000:1). In order to maintain a stable running environment, the crystal temperature is monitored by 128 temperature sensors, which are read out through the same BGO readout system. The crystal temperature is kept at constant to a few tenths of a degree.

The crystals were calibrated at CERN in the SPS X3 electron beam, with two fully equipped half barrels at 2, 10 and 50 GeV/c momentum points. During the calibration, the dependence of calibration constants on the impact point and the temperature was also measured. The light collection efficiency of each crystal, together with the gain of the corresponding readout chain are monitored by means of Xenon light pulses distributed by optical fibers. Each crystal can receive two different lights, one for high energy pulses (35 GeV equivalent), the other for low energy (1.5 GeV) equivalent). The energy resolution obtained from test beam, 4% at 180 MeV, 1.5% at 2 GeV and 0.6% at 50 GeV [20].
3.3 Scintillation Counter

The barrel scintillation counters (see fig. 3.6) were installed between the electromagnetic and hadron calorimeters. BICRON BC-412 plastic scintillators of 1 cm thick were used, each is 167 mm wide in the middle and 182 mm at the ends. The counters were divided into 32 sectors in $\phi$, with every two of them covering a hadron calorimeter $\phi-$sector. Due to the rail of the BGO calorimeter, there is only one wider counter both at $\phi = 0$ and $\phi = \pi$. Thus in total there are 30 barrel counters. The barrel scintillation counters cover the acceptance of the middle muon chambers (MM), i.e. a polar angle region of $30^\circ \leq \theta \leq 150^\circ$. Each counter has two phototubes at both ends and is read out by high precision TDCs and ADCs. The endcap counters are located in front of the endcap hadronic calorimeter. There are 16 counters on either side of the detector, each counter covers one of the 16 $\phi$ sectors of the hadronic calorimeter endcaps. They are perpendicular to the beam line, each of them is 10 mm thick, 270 mm long, 275 mm wide and 180 mm on both side respectively. Each counter has a phototube. The endcap counters extend the coverage down to $25^\circ \leq \theta \leq 155^\circ$. In the azimuthal angle $\phi$, 93% is covered by scintillators, they are used effectively to reject beam gas events and cosmic rays.
3.4 Hadron Calorimeter

The Hadronic Calorimeter (HC) barrel, as shown in fig. 3.7, extends from 88 cm to 213 cm radius. It was designed to measure the total hadronic energy by the absorption technique, determine the energy flow and act as muon filter in $e^+e^-$ interactions. It contains three parts: the barrel, the endcaps and the Muon Filter. The barrel covers the polar range $35^\circ \leq \theta \leq 145^\circ$. The endcaps cover the polar angle region $5.5^\circ \leq \theta \leq 35^\circ$, and $145^\circ \leq \theta \leq 174.5^\circ$. Both barrel and endcaps are over the full azimuthal range $0^\circ \leq \phi \leq 360^\circ$. The coverage of the hadronic calorimeter is 99.5% of $4\pi$ solid angle. The energy resolution versus energy was obtained from test beam as well as from $Z^0$ events and has the form:

$$
\frac{\sigma}{E} = \frac{0.55}{\sqrt{E(\text{GeV})}} + 0.05
$$

(3.1)

The barrel and endcaps were constructed with depleted uranium absorber plates sandwiched with proportional wire chambers. The uranium radioactivity offers a $\gamma$ source for the calibration of the proportional wire chamber. The gas wire proportional chambers were made of planes of brass tubes with 0.3 mm thick walls and 5mm x 10mm inner dimensions. The gas mixture is 80% Argon and 20% CO$_2$. All wires are read out by FASTBUS ADCs.

The barrel consists of 9 rings of 16 modules each, 6 outer rings of long modules and 3 inner rings of short modules. Each long module contains 60 chambers and 58 uranium plates, while each short module contains 53 chambers and 51 uranium plates. The innermost ring is centered at the interaction vertex and followed by four rings on either side. The anode wires in adjacent chamber planes are oriented at right angle to each other to determine both $z$ and $\phi$ coordinate. The signal wires are grouped into readout towers, each tower includes only wires from alternate, parallel layers. In the $\phi$ projection the towers point to the beam axis with a constant angular interval ($\approx 2.5^\circ$ from interaction vertex). In the $Z$ projection, they have constant width of about 5 cm, also corresponding to about $2.5^\circ$ in the central region. The spatial resolution is $\Delta \theta = 2.5^\circ$ and $\Delta \phi = 2.5^\circ$ for jets.

Each of the two HC endcaps contains one outer and two inner rings, for mechanical reasons, each ring is split vertically into two half-rings. The chamber wires are stretched azimuthally to measure the polar angle $\theta$ directly. Neighbouring chamber
layers are oriented at 22.5° with respect to each other and the gaps between chambers do not coincide. As in the barrel, the chamber wires are grouped to form towers for each view separately. They are pointing to the interaction region with an angular width about 1° in $\theta$.

The Muon Filter is mounted on the inside wall of the support tube and adds 1.03 absorption length to the Hadronic Calorimeter. It consists of 8 identical octants, each made of six 1 cm thick, 4 m long and 1.4 m wide brass (65% Cu+35% Zn) absorber plates interleaved with five layers of proportional chambers and followed by five 1.5 cm thick absorber plates matching the circular shape of the supporting tube. The chambers use the same gas mixture as the Barrel Hadronic Calorimeter and the signals are read out by FASTBUS TDCs. Charge is measured at both ends for three central layers of each octant, therefor the $z$-coordinate along the wire can be obtained. The precision on this coordinate is close to 4 cm, and the overall chamber efficiency is 91%. It is used to reduce punchthroughs and sail throughs.
3.5 Muon Chambers

The L3 Muon Chamber (MUCH) is designed to measure muon momentum with high precision, $\Delta p/p \approx 2\%$ at 45 GeV/c, corresponding to a mass resolution of about 1.4% at the $Z^0$ peak. This is achieved using three layers of high precision drift chambers which measure the curvatures of the muon tracks in the large volume between the support tube and the magnet coil. The spectrometer covers the polar angle range of $44^\circ \leq \theta \leq 136^\circ$, 2.5 meter at the inner radius and 5.4 meter at outer radius.

Each chamber is subdivided into 16 independent modules called octant, each octant has a special mechanical structure to support five chambers: one inner chamber (MI), two middle chambers (MM) and two outer chambers (MO). They measure track coordinate in the bending plane. Thus the muon momentum, and are called P chambers. The MI, MM and MO is physically divided into 19, 15 and 21 drift cells respectively. Each cell of MI and MO contains 16 sense wires, MM cell has 24 sense wires. In addition, each of the top and bottom P-chambers (MI, MO) is covered by 2 Z-chambers with wires perpendicular to the beam direction to measure z coordinate along the beam. In order to reduce the effect of multiple scattering, there are no z-chambers for the middle chambers (MM) which were closed by thin aluminum honeycomb with 0.9% radiation length per 2 layers. Fig. 3.8 is a view of an octant of the Muon chambers.

The transverse momentum of a muon track, $P_T$ (GeV/c), can be written as:

$$P_T = \frac{0.3BL^2}{8s}$$

(3.2)

where $B$ is the magnetic field in Tesla, $L$ is the distance between the inner and the outer chambers in meter and $s$ is the sagitta of the track in mm. For a 45 GeV/c muon, the sagitta is 3.5 mm in the 0.5 T magnetic field and $L \approx 2.91m$. Since $\Delta P/P = \Delta s/s$, for 2% momentum resolution at 45 GeV, $\Delta s$ is required to be not more than 70 $\mu m$.

The P-chambers are filled with a gas mixture of 61.5% Argon and 38.5% Ethane. At normal high voltage settings, the chamber cell has a uniform electric field of 1140V/cm in the drift region. In the 0.5 T magnetic field, the drift velocity is $51 \mu m/nsec$, and the Lorentz angle is $18.8^\circ$. Sense wires are spaced 9 mm apart and are sandwiched with field wires. Eight additional guard wires beyond the last sense wires equalize the drift time behavior of all the sense wires. A plane of cathode wires
Figure 3.8: Muon chambers.

(mesh) spaced 2.25 mm apart locates 50.75 mm away from the sense wire plane. All wires are put into position along the Pyrex glass plates which are glued onto carbon fiber bridges. The internal optical alignment system integrated into the structure of the bridges positions the wires to an accuracy of 10 \( \mu m \). The single wire resolution is 220 \( \mu m \) throughout the entire drift region. Z-chambers are composed of two layers of drift cells offset by one half cell with respect to each other to resolve the left-right ambiguity. Chamber gas mixture is 91.5% Argon and 8.5% Methane. The mean drift velocity is 30\( \mu m/\text{nsec} \). Typical single wire resolution is 500 \( \mu m \). All wires are connected via amplifiers to discriminators, then digitized by FASTBUS TDCs with a resolution of 2.2nsec/bit. Parallel TDCs outputs without time information are used for fast road-scan muon trigger.

3.6 Luminosity Monitor

The luminosity monitor is designed for luminosity measurements with better than 1% precision using small angle Bhabha scattering events. It consists of two identical cylindrical BGO electromagnetic shower detectors and two identical charged parti-
cle tracking chambers with good position resolution situated on either side of the interaction point, at $z = \pm 2765$mm. The luminosity monitor covers forward angular region, $24.7\text{ mrad} \leq \theta \leq 69.3\text{ mrad}$.

The BGO crystals are arranged in eight rings, each of 15 mm thick, parallel to the beam pipe. Azimuthally, they are divided into 16 sectors, each sector contains 19 crystals which are 26 cm long (corresponding to 24 radiation lengths), $1.5 \times 1.5\text{cm}^2$ to $1.5 \times 3.0\text{cm}^2$ in cross section. The light outputs of the BGO are collected by silicon photodiodes mounted on the rear of each crystal, and read out by ADCs which are identical to the barrel BGO calorimeter.

A tracking chamber is placed in front of the BGO array and consists in a stack of four planar multiwire proportional chambers with cathode strip readout. The cathode strips are arranged both in $r - \phi$ (2 chambers) and $x-y$ (2 chambers) The spatial resolution per track is better than 250 $\mu m$. Table 3.9 lists the resolution of the system.

<table>
<thead>
<tr>
<th>Tracking Chamber</th>
<th>BGO detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta E/E$ [%]</td>
<td>0.5 - 1.0</td>
</tr>
<tr>
<td>$\Delta R$ [$\mu m$]</td>
<td>&lt; 250 &lt; 800</td>
</tr>
<tr>
<td>$\Delta \theta$ [mrad]</td>
<td>&lt; 0.1 &lt; 0.3</td>
</tr>
<tr>
<td>$\Delta \phi$ [degree]</td>
<td>= 0.6 &lt; 0.6</td>
</tr>
</tbody>
</table>

Table 3.1: Main Characteristics of the L3 Luminosity Monitor

To ensure the best shower coverage, a software cut limits the acceptance to the inner six of the eight rings, $30\text{ mrad} \leq \theta \leq 62\text{ mrad}$ with full efficiency, corresponding to an effective Bhabha cross section 100 nb. This also matches the full efficiency range of the forward tracking chamber. The main source of systematic errors are: detector inefficiency, beam background, uncertainty of LEP beam parameters at the interaction point, and theoretical uncertainties. During the 1991 physics run, the integral luminosity measurement has an estimated total systematic error of 0.9%.
3.7 Trigger and Data Acquisition System

The L3 Trigger [18] is composed of three levels of triggers. After each beam crossing at a rate of 45 KHz (or 90 KHz from the 1992 physics run as planned), the trigger decides if an e⁺e⁻ interaction took place and reduces the rate to a few Hz. The FASTBUS is chosen for Data Acquisition (DAQ) due to its high speed and flexibility. A VAX 8800, clustered with small VAX for each of main detector components and many VAX stations, are used for data handling. The quality of the accepted data is monitored online, as well as the detector parameters for the purpose of detector calibration and safety.

3.7.1 Level-1 Trigger

The Level-1 Trigger consists of Calorimeter Trigger, Muon Trigger, Scintillator Trigger and TEC Trigger, its decision is the logical OR of above subtriggers. It operates at 45 KHz, and decides within 21 μs either starting to digitize and store detector data or clearing the front end electronics. A negative decision at level 1 does not contribute to the dead time. A Trigger Control BOX (TBOX) synchronizes data acquisition and level-1 trigger with the beam crossing.

Calorimeter Trigger

The Calorimeter Trigger processes the information given by the BGO, Hadron Calorimeter and Luminosity monitor. It has following subtriggers:

- **Total energy trigger:**
  The total amount of energy detected is required to be greater than a predefined threshold value, which is different for different region of the detector:

  1. The energy in the ECAL is no less than 20 GeV.
  2. Total calorimeter energy must be larger than 20 GeV;
  3. The sum of the energies in the barrel ECAL and HCAL must be larger than 15 GeV;
  4. The energy in the barrel ECAL alone is more than 10 GeV;
• Cluster trigger:
The number of energy clusters found should be larger than 7.

• Single photon:
A cluster in the ECAL is accepted, if the ratio between the energy of the cluster and the total BGO energy in the event is greater than 0.8.

• Luminosity trigger:
There are more than 15 GeV energy deposition in each of the two luminosity monitors, or one monitor energy is above 25 GeV and the other more than 5 GeV.

• Single tag trigger:
Energy deposition in one luminosity monitor is more than 30 GeV. It serves as the Luminosity Trigger Monitor.

Muon Trigger

The Muon Trigger uses the trigger cells information from the muon chambers and searches for tracks originated from the interaction region. It accepts events with $P_T > 1\text{GeV/c}$. The main subtriggers are:

• Single Muon trigger:
A track with 2 P-chamber hits out of 3 and 3 Z-chamber fired out of 4, this covers angular range of $44^\circ \leq \theta \leq 136^\circ$.

• Dimuon trigger:
A track with 2 P-chamber hits and 1 II/IM Z-chamber fired in the same octant. In addition, there is at least one other track with 2 P-chamber hits in one of the five opposite octants. This covers the angular region of $36^\circ \leq \theta \leq 144^\circ$.

• Small Angle Muon trigger:
One P-chamber hit in MI and One Z-chamber hit in II/IM together with another track of the same condition in one of opposite three octants. One track must be in the forward region ($+z$), another in the backward region ($-z$). The angular regions $36^\circ \leq \theta \leq 44^\circ$ and $136^\circ \leq \theta \leq 144^\circ$, where only one layer of P chambers is available, are covered by this trigger.
Scintillator Trigger

The Scintillator Trigger, based on the signals of 30 barrel and 32 endcap counters, serves as a backup for the energy trigger and for monitoring the latter's efficiency. The multiplicity trigger asks for the coincidence of 6 out of the 30 barrel counters. In the meantime, the scintillator signals are also sent to the energy trigger for tighter trigger.

TEC Trigger

The TEC Trigger requires two tracks in the TEC with opening angle greater than 120° in the R − φ plane. It serves as a backup trigger for dimuon trigger and energy trigger.

Trigger Control

The Trigger Control Box implements the final level-1 trigger decision and distribute it to all subdetectors and high level trigger. It synchronizes the whole data acquisition system. If the event is accepted by level-1 trigger, TBOX sends an ACCEPT signal to subdetectors to start the data conversion and buffering and active the level-2 trigger. Otherwise, the CLEAR signal is sent out.

3.7.2 Level-2 and Level-3 Trigger

The Level-2 Trigger is based on the decisions from all level-1 triggers to make further more complex coincidence. As shown in fig. 3.9, after each beam crossing, all data from the level one triggers are stored in parallel in a multiport multievent buffer (MMB), which is an 8 events deep, 256 words per event input memory runs on a first in/first out basis. The MMB status word are then read by one of the four fast trigger processors (XOP) work in round robin mode between two FASTBUS segments. (When at idle, the XOPs compete for mastership of the input crate segment.) If positive, it reads the earliest event in each memory and decrements each MMB status register, thus building a complete event with its event number. This readout is decoupled from level 1 operation since the MMB memory provides a simultaneous
random read/write access. When the readout is completed the XOP releases mastership and starts analysing the event information in order to reduce the event rate. After the computation is finished, the XOP arbitrates for mastership on the output segment in order to write data and final decision on the acceptance of the event, into the DSM on the central crate.

The Level-3 Trigger is embedded in the main flow of the data acquisition. Unlike the level-1 and level-2 triggers, which only have coarse granularity and lower resolution trigger data, the level-3 trigger access to the complete digitized data with finer granularity and higher resolution. A complicated algorithm is applied to reject background events. The selection of good events is based on

- the correlation of the energy deposited in the ECAL and HCAL,
- the reconstruction of muon track in the Z chambers,
- the reconstruction of the vertex in the TEC.

A positive level-3 decision starts the tape writing.

For each of the above subtriggers, typical trigger rates at Level-3 are: Calorimeter trigger: \( \sim 3 \) Hz; Muon trigger: \( \sim 1.5 \) Hz after requiring at least one scintillating counter (typical scintillating counter rate is 9.5 Hz); TEC trigger: \( \sim 1.5 \) Hz.

### 3.7.3 Data Acquisition System

The L3 DAQ system, as shown in fig. 3.9, is a combination of all subdetectors electronics readouts, FASTBUS modules and online VAX system. The system also includes ample buffering capacity to allow asynchronous operation without contributing to the dead time. Starting, stopping, etc., of both the event data flow and monitoring processes is under control via a master process. During data taking, a slow control program monitors the whole detector is monitored for its overall safety and integrity.
Figure 3.9: The L3 DAQ data flow.
Chapter 4

Event Selection

This chapter contains three sections, in the first section $\tau^+\tau^-$ event selection is presented; the second section is devoted to the identification of $\tau$ decays to electrons; and in the last section the selection of $\tau$ decays to muon events is described.

4.1 Tau Pair Selection

This section starts with a brief description of the event reconstruction procedure, some general considerations in the selection of $e^+e^- \rightarrow \tau^+\tau^-$ events, followed by detailed discussions on the selection criteria, acceptance, and background estimation.

4.1.1 Event Reconstruction

Offline event selection is done in several steps. First, for each event, the raw detector information (hits) recorded during online data acquisition is reconstructed by the L3 reconstruction program. The reconstruction process is one through which information from individual detectors are analyzed, summarized, and combined together to give a picture of the physical processes happened in the event, from which one can then decide to keep or discard the event, according to physics interests. The event reconstruction proceeds in two stages. First, an event is reconstructed in each subdetector separately, then in the second stage it is reconstructed globally, by combining
information from each subdetector.

At first, hits in the calorimeters which are above certain thresholds (2MeV in the BGO and 9MeV in the HCAL) are identified, the geometrical centers of the towers or crystals are taken as the coordinates. In the next step the hits are grouped into clusters, which is then classified as either hadronic or electromagnetic according to transverse and longitudinal shower profile, and the energy partition in the two calorimeters. The direction of the cluster is defined as the weighted sum of all the hits within the cluster.

In the TEC and the muon chambers, hits are formed first into local segments and then tracks are reconstructed based on the segments. The global event reconstruction starts with the most energetic cluster. An axis is determined by summing up all the energy weighted vector of all clusters within a 30° cone of this axis, these clusters form a Jet, and the axis is called the jet-axis. The procedure is repeated with the remain clusters until there is no more clusters left. Finally the jets are classified as: hadronic, electromagnetic, single muon, single electron, etc., depending on information from subdetectors, their energies are also calculated accordingly. A few of the reconstruction objects generated in the second stage are [12] [19]:

1. ASRC’s, which are smallest resolvable clusters reconstructed from the ECAL bumps (local maxima in the energy flow) and HCAL clusters, each ASRC corresponds to roughly one measured particle;

2. AMUI’s, which are muon tracks reconstructed from muon chamber tracks, TEC tracks, and preprocessed data in the calorimeters;

3. ASJT’s, which are jets reconstructed from ASRC’s and AMUI’s,

4. AJET’s, which are jets reconstructed from calorimeter hits.

During normal data acquisition, a typical online tape records ~ 4,000 event triggers (which takes roughly 30 minutes at the typical trigger rate of ~ 2 Hz), of which 300 ~ 400 are saved as good hadronic Z⁰ decays after the event reconstruction process.
4.1.2 Selection of $e^+e^- \rightarrow \tau^+\tau^-$ Events

The objective of the selection is to obtain a clean sample of $\tau$-pair events with a high efficiency with well understood acceptance. For the polarization measurement, additional care must be taken: due to helicity conservation, the energies of the two taus in an event are strongly correlated, therefore cuts on the event energies must not be such that it will introduce bias to one helicity. The selection is based on cutting the event topologies and energy deposition in various subdetectors: first from a given type of event we form the test statistics, then a value of some element from each characteristic distribution of the physics quantities is obtained, this element is then compared with a cut parameter, depending on the sign of the difference between the cut parameter and the function value, the event is classified as a good candidate or background event. A set of cut parameters are obtained in this fashion (referred as cuts from now on). The cuts are well simulated by Monte Carlo simulations which are used for background and efficiency estimation.

At first some very loose (called pass 1) selection cuts are applied to all reconstructed events in order to reject junk events (cosmic rays, beam gas events, etc) and to reduce the data set. This reduces the size of the sample by approximately a factor of 10. The events which survived these cuts are then split into different data streams according to physics interests, finally a pass 2 selection, which contains more specific cuts is applied to the interested stream (in our case the tau stream) to select clean samples for physics analysis. The main data streams are: $e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$, $q\bar{q}$, inclusive muon, new particles, and single gamma. For the $\tau$ stream the rejection rate at pass 2 is close to 80%. Fig. 4.1 is a typical $Z^0 \rightarrow \tau^+\tau^-$ event, in which one tau decays to an electron, characterized by a single track in the hemisphere and a near 100% energy deposition in the ECAL, resulting an energetic BGO bump which matches very well with the track in the $\tau^0$ plane; the other tau decays to three charged hadrons, which are indicated by three charged tracks in the TEC and a significant amount of energy deposition in the HCAL.

In the vicinity of the $Z^0$ resonance, $\tau$ pair events are relatively easier to distinguish from backgrounds than is the case of lower center of mass energy, this is mainly due to the fact that hadronic events, which are the major backgrounds, are of higher multiplicity. The main sources of backgrounds are:
Figure 4.1: A $Z^0 \rightarrow \tau^+\tau^-$ event observed in the L3 detector.

- $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \mu^+\mu^-$ events; These are events with two very high momentum, almost back-to-back charged particles, for $e^+e^- \rightarrow e^+e^-$ with full center of mass energy deposited in the ECAL, and for $e^+e^- \rightarrow \mu^+\mu^-$ with the scaler sum of the muon momentum close to center of mass energy, whereas very little energy deposition in the ECAL.

- $e^+e^- \rightarrow q^+q^-$ events; At LEP energies this type of background is reduced by the fact that particle multiplicity rises with center of mass energy (and peaks at $\sim 20$ at LEP), while the multiplicity of $\tau$-pair events remains constant with $E_{cm}$. It is therefore less likely for a low multiplicity hadronic events to occur and being identified as $\tau$-pairs.

- Two photon processes: $e^+e^- \rightarrow (e^+e^-)X$ where the final-state electron and positron escape the detector at low angles and the $X(e^+e^-, \mu^+\mu^-, \pi^+\pi^-)$ is misidentified as a low energy $\tau$-pair event. At LEP the hadronic part of the $X$ is (relatively) reduced compared to low-energy experiment since, as a pure 2nd order QED process, it lacks a resonance such as $Z^0$ which enhances $e^+e^- \rightarrow \tau^+\tau^-$ production. The dominant backgrounds from two photon events are therefore those with $X$ components as $e^+e^-$ and $\mu^+\mu^-$, with typical topology of two charged tracks with nearly equal but opposite momenta transverse
to the beam.

The details of selection cuts will be discussed in the following sections.

Data Sample

The data used in this analysis were collected in the 1990 and 1991 physics runs, corresponding to an integrated luminosity of 18.4 $pb^{-1}$. During this period energy scan around $Z_0$ resonance, with center-of-mass energies ranging from 88.22 to 94.22 GeV was performed by LEP, with a beam energy calibration of better than 20 MeV, and an energy spread of $\sim 10$ MeV per beam [17].

Selection Cuts

We start with introducing the definition of the thrust axis. A direction $n_T$ is found such that $\sum_i |P_{i\parallel}i|$ is maximized, where $P_{\parallel} = P \cdot n_T$ is the longitudinal momentum and $i$ runs over all particles in an event, charged or neutral. The event thrust is defined as

$$T = \frac{\max \sum_i |P_{i\parallel}i|}{\sum_i P_i}.$$  

(4.1)

For a spherically symmetric event $T = 0.5$, for collinear particles it equals to 1. $n_T$ is called the thrust axis.

To identify $\tau$ pair events, combined information from all subdetectors is used. Since the study is restricted in the barrel region (where $|\cos \theta_{\text{thrust}}| < 0.7$, $\theta_{\text{thrust}}$ is the angle between the direction of the thrust and that of the electron beam), it is possible to apply relatively tight requirements on the quality of the TEC tracks and thus reject backgrounds due to partial TEC sector failure and two-photon processes which are more severe at low polar angles.

The following cuts are applied for the selection of $e^+e^- \rightarrow \tau^+\tau^-$-events:

1. The event thrust must satisfy

$$|\cos \theta_{\text{thrust}}| < 0.7$$

i.e. only events in the barrel region are considered.
2. There is at least 1 scintillator counter fired within a time interval, after correcting for time of flight, within 5ns of the beam gate. This cut is to reject backgrounds from cosmic rays.

3. There is at least one ASJT in the event (see Section 4.1.1 for the definition of the ASJT’s). To qualify as an ASJT, the sum of the energies in a jet is required to be greater than 3.0GeV. For events with only one ASJT, a second jet is formed by summing up all tracks and calorimeter energies within 30° of the most energetic cluster not associated to the ASJT, the visible energy of this jet is required to be greater than 2.0GeV. Both jets are required to have a polar angle of greater than 45°, i.e. they are confined to be within the barrel region.

4. The angle between the two most energetic jets in the event is required to be greater than 165°; this is to reject backgrounds from q̄q events which contain more than two jets, and low energy two photon events. Typically, in two photon processes, due to imbalanced missing energy in the event, the two tracks are highly acollinear. In fig. 4.2 the acollinearity distributions for data and Monte Carlo events are shown. To further reject q̄q backgrounds, the maximum opening angle in the rφ plane formed by a track and the thrust axis must not exceed 23°, as shown in fig. 4.3.

5. The sum of the number of tracks and the number of ASRCs in an event should be less than 22. As shown in fig. 4.4, there is a distinct separation between τ pair and q̄q events, due to the difference of their multiplicities. In Fig. 4.5 the distribution for data and Monte Carlo τ pair and q̄q events are plotted.

6. The number of good TEC tracks in each hemisphere of the event, defined by the plane which passes through the interaction point and transverse to the thrust axis, must be between 1 and 3, while the total number of tracks in a event is required to be not more than 6. A good TEC track must satisfy the following criteria:

\[ DC\Delta < 10.0mm \]
\[ N_{hits} \geq 30 \]
\[ Span \geq 40 \]
\[ P_t \geq 100.0 MeV \]
where $N_{\text{hits}}$ is the number of used hits on the track, span is the difference between the first and the last wire number for the track. For a track in the barrel region, maximum span is 61. $P_t$ is the transverse momentum of the track. This cut further rejects $e^+e^- \rightarrow q^+q^-$-events. As shown in fig. 4.7, there is a good agreement between data and Monte Carlo distributions.

7. At least one track has $P_t$ of greater than $2.0 GeV/c$. This is to reject backgrounds from two photon processes where the $e^+e^-$ escape in the beam pipe undetected, the remain fermion pair is misidentified as a $\tau$ pair, with very low total event energy.

8. To reject background from $e^+e^- \rightarrow e^+e^-(\gamma)$, it is required that the ECAL energy in the event be less than $0.8\sqrt{s}$, where $s$ is the center-of-mass energy squared. Shown in fig. 4.6 is the distributions of the total ECAL energy from data, Monte Carlo $e^+e^- \rightarrow \tau^+\tau^-$, and Bhabha events, where the Monte Carlo $e^+e^- \rightarrow \tau^+\tau^-$-distribution has a input polarization of $-13.42\%$. Only the data collected at the $Z^0$ energy are used. Since the shape of the electron energy spectrum strongly depends on the value of the $P_t$, one would expect that the distribution of the total ECAL energy in an event also varies with respect to different $P_t$. It is therefore worthwhile to point out that the Bhabha background are estimated with respect to the above polarization value. In the next chapter the same Monte Carlo events are used for fitting the polarization in the decay $\tau \rightarrow ev\bar{v}$. For this study, this cut has the potential of losing high energy electron candidates whose opposite side have large BGO energy deposition. (Events with both tau decays identified as electrons are not used for the polarization measurement). Similar discussion applies to the next cut.

9. To reject background from $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$, the scalar sum of the muon momenta must be less than $0.7\sqrt{s}$ for events contain two muons.

10. To suppress background from $e^+e^- \rightarrow \mu^+\mu^-$ process in which both muons are not reconstructed by the muon chambers, owing to detection gaps, an event is rejected if in both hemisphere there is a minimum ionizing track in the HCAL (with energy deposition of less than $4.0 GeV$), along with a BGO energy deposition which is consistent with a muon ($\sim 250 MeV$ for MIP, but a cut at $< 2.0 GeV$ is used in stead, to take into account of bremsstrahlung photons).

In order to ensure the quality of the data set, events collected during runs that were
Figure 4.2: Distribution of the acollinearity between the two jets in an event.

Figure 4.3: Maximum opening angle between a TEC track and the thrust axis in the rφ plane.
Figure 4.4: Number of tracks vs. number of ASRCs in $\tau\tau$ and $q\bar{q}$ events.

Figure 4.5: Sum of the number of tracks and ASRCs.
under bad detector conditions, such as subdetector malfunctions, incorrect luminosity measurement, etc. are removed. A total of 10217 events passed the above criteria and are selected as $\tau$ pair events. The number of events accepted at each center of mass energy point are given in Table 4.1.

Luminosity

The luminosity $\mathcal{L}$ is measured and monitored throughout the running period using small angle Bhabha events. It can be expressed as the following:

$$\mathcal{L} = \frac{N_{ee}}{\epsilon \delta \sigma_{ee}}. \quad (4.2)$$

where $N_{ee}$ is the number of accepted Bhabha events, $\epsilon$ is the luminosity trigger efficiency, $\delta$ is the acceptance of the luminosity monitor and $\sigma_{ee}$ is the theoretical Bhabha cross section. A total systematic uncertainty of 0.9% is achieved in the luminosity measurement [17].

Trigger Efficiency

The measurement of the polarization can be biased if the event trigger efficiency shows an energy or direction dependence. The triggers used in the selection of $e^+e^- \rightarrow \tau^+\tau^-$ events are total energy and TEC two charged track triggers. In events contain $\tau \rightarrow \mu\nu\bar{\nu}$ decay(s), the muon trigger bit is also checked. For a given event, the trigger is true if the logical OR of these trigger bits equals to one, therefore the trigger efficiency can be written as:

$$\epsilon_{\text{trigger}} = 1 - \prod_{k=1}^{N}(1 - \epsilon_k) \quad (4.3)$$

where $k$ ($k = 1, ... N$) stands for trigger type, $\epsilon_k$ is the corresponding efficiency. Of the total 10,217 selected $\tau^+\tau^-$ events, 10,063 were triggered by the TEC trigger, 5 have no energy triggers. We thus obtained a TEC trigger efficiency of $(98.50 \pm 0.12)\%$, an energy trigger efficiency of $(99.95 \pm 0.02)\%$, and the combined trigger efficiency is $(99.99 \pm 0.02)\%$, The corresponding inefficiency is too small to have any significant effects on the energy spectrum, thus the polarization measurements.
Scintillator Efficiency

The inefficiency of the scintillator counters is studied with both data and Monte Carlo dimuon events, through counting the fraction of events in which only one and in-time scintillator hit while neither one of the two muons passes through dead or missing counters. To suppress cosmic ray contributions, in this study it is required for the TEC tracks to have DCA in the $r\phi$ plane of less than $5.0\, mm$. This constraint has an estimated efficiency of $(98.64 \pm 0.25)\%$. Taking this correction into account, it is found that $(1.29 \pm 0.17)\%$ of all data events and $(1.01 \pm 0.08)\%$ of the Monte Carlo events have one scintillator hit. Assuming the excess in data comes from scintillator inefficiency, this leads to an inefficiency of $(0.28 \pm 0.20)\%$.

Acceptance

The acceptance, determined from Monte Carlo simulation, is defined as:

$$
\epsilon_{acceptance} = \frac{N_{sele}}{N_{tot}},
$$

(4.4)

where $N_{tot}$ is the total number of Monte Carlo events which have passed the detector simulation, $N_{sele}$ is the number of events selected after applying selection cuts. The
error on the acceptance follows binomial distribution and can be expressed as:

\[
\Delta e_{\text{acceptance}}^{mc} = \sqrt{\frac{e_{\text{acceptance}}^{mc}(1 - e_{\text{acceptance}}^{mc})}{N_{\text{tot}}}} = \sqrt{\frac{N_{\text{sel}}(N_{\text{tot}} - N_{\text{sel}})}{N_{\text{tot}}^2}}
\]  

(4.5)

To determine the acceptance of the $\tau^+\tau^-$ selection, events are generated in $4\pi$ solid angle at the $Z^0$ peak ($\sqrt{s} = 91.2 \text{GeV}$) using the KORALZ Monte Carlo program with full radiative corrections, i.e. initial and final state radiations, as well as their interference. The generated events are then passed through detector simulation program based on GEANT which includes the effects of energy loss, multiple scattering, detector resolution, etc., resulting in a complete simulation. Later the simulated events are analyzed with the same program used for analyzing the real data. For a well understood detector one would expect the Monte Carlo events to be able to reproduce the behavior of the real data, which is crucial for using it as an acceptance estimator. As shown in Figures 4.4 the data are well simulated by the Monte Carlo. From 58,500 Monte Carlo $Z^0 \rightarrow \tau^+\tau^-$ events generated in $4\pi$ solid angle, 29,660 are accepted as tau-pair candidates, which yields an acceptance of $e^{mc} = (50.7 \pm 0.2)\%$.

Selection Efficiency

The selection efficiency of $e^+e^- \rightarrow \tau^+\tau^-$ events are calculated as follows:

\[
\epsilon_{\tau^+\tau^-} = e_{\text{acceptance}}^{mc} \epsilon_{\text{trigger}},
\]  

(4.6)

and the error on $\epsilon_{\tau^+\tau^-}$ is:

\[
\Delta \epsilon_{\tau^+\tau^-} = \epsilon_{\tau^+\tau^-} \sqrt{\left(\frac{\Delta e_{\text{acceptance}}}{\epsilon_{\text{acceptance}}}\right)^2 + \left(\frac{\Delta \epsilon_{\text{trigger}}}{\epsilon_{\text{trigger}}}\right)^2}.
\]  

(4.7)

From this we obtain the selection efficiency to be: $\epsilon_{\tau^+\tau^-} = (50.7 \pm 0.2)\%$, or, within the fiducial volume($|\cos \theta_{\text{thrust}}| < 0.7$), $\epsilon_{\tau^+\tau^-} = (83.0 \pm 0.2)\%$.

Background

The background is estimated using fully reconstructed Monte Carlo detector simulation events, as well as real data where possible.

1. Background From $q\bar{q}$ Events The background contribution from $q\bar{q}$ events is estimated with LUND Monte Carlo events. A total of 100,000 $e^+e^- \rightarrow q\bar{q}$ events
are used for this study, 236 of them survived after all the cuts, yielding a background contamination of 0.2% within the fiducial volume.

2. **Background From $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \mu^+\mu^-$ Events**

To estimate the influence of Bhabha and dimuon backgrounds, both Monte Carlo events and real data are used. The contamination from $e^+e^- \rightarrow e^+e^-$ is estimated to be 0.8%, from $e^+e^- \rightarrow \mu^+\mu^-$ is estimated to be 0.7%.

3. **Background From Two Photon Processes**

To estimate the backgrounds from two photon processes, a total of simulated 6,000 Monte Carlo events are used, corresponding to a cross section of 33 nb. No events passed the selection. We thus estimate the background from two photon processes to be less than 0.1%.

4. **Background From Cosmic Rays**

Background from cosmic rays is estimated to be less than 0.1%, and is dominated by the inefficiency of the scintillators.

To summarize, the overall background is not dominated by any particular source(s) and is estimated to be (1.7±0.4)% of the $\tau$ pair sample, the error is from Monte Carlo statistics. In fig. 4.8 the total event visible energy, normalized to the center-of-mass

<table>
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<th>Number of events</th>
<th>$\sqrt{s}$(GeV)</th>
<th>Number of events</th>
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<td>93.70</td>
<td>244</td>
</tr>
<tr>
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<td><strong>2636</strong></td>
<td><strong>Total (1991)</strong></td>
<td><strong>7581</strong></td>
</tr>
</tbody>
</table>

Table 4.1: Number of tau pair candidates at each center of mass energy

energy is shown. Only events at the $Z^0$ peak are used. There is a small displacement between the data and the Monte Carlo which is believed to be due to the errors on the estimates of the single pion G-factors.
Figure 4.7: Number of TEC tracks in the two hemispheres of an event.

Figure 4.8: Total visible energy distribution.
4.1.3 Selection of $\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau$ Events

In the analysis of all $\tau$ decay channels in this thesis, each event is split into two hemispheres by a plane which contains the production point and is perpendicular to the thrust axis, particle identification is performed in each hemisphere. Since processes $e^+ e^\rightarrow e^+ e^-, e^+ e^- \rightarrow \mu^+ \mu^-$ form the major background to events in which both $\tau$ decays to electrons or muons, for $P_T$ measurement in this thesis events which the two $\tau$'s decay into the same leptonic channel are excluded. This introduces a loss of statistics of about 3.2% in total, but the gain in systematic errors justifies it. For the measurement of the polarization, it helps reduce bias to the electron energy spectrum. To be consistent, all distributions in the following two sections are made with the second type of events.

Electron Identification

The selection of $\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau$ events is based mainly on requiring a low charged multiplicity ($\leq 2$ in each candidate $\tau$ decay) and an ECAL shower shape consistent with that of an electron, in addition there be minimum energy deposition in the HCAL region behind the electron candidate. For each $\tau$ jet in an event, electromagnetic clusters in the ECAL are searched and then associated with a charged track. To qualify an electromagnetic cluster, an energy cluster in the BGO must contain at least 9 adjacent crystals each with more than 10 MeV. The ratio of the energy measured in the $3 \times 3$ array(E9) centered on the most energetic crystal and the energy measured in the $5 \times 5$ array(E25), defined as $E_9/E_{25}$, where both energy measurements have a position-dependent leakage correction applied, should have a value close to 1, since for an isolated electromagnetic shower, its width normally is very narrow and thus the majority of the shower energy is deposited in the $3 \times 3$ array, the amount of energy in the rest surrounding crystals are small and can be treated as statistical fluctuations. Therefore $E_9/E_{25}$ has an approximately Gaussian distribution centered at 1.0 with a width of $\sim 1\%$. For hadronic showers and for electromagnetic showers that have been contaminated by a nearby shower, $E_9/E_{25}$ will be smaller than 1.0, as shown in fig. 4.9. To identify the electromagnetic cluster as an electron, we require a close match in the azimuthal angle between the centroid of the electromagnetic shower and a good track (as defined in the previous section) in the TEC, and there be no more than a few GeV energy deposition in the HCAL behind the matched
bump.

The following cuts are applied to select electron candidates.

1. The number of good charged tracks in the hemisphere contains the candidate must satisfy: \( N_{trk} \leq 2 \). Here up to one extra track is allowed in order to reduce inefficiency due to \( \gamma \) conversions from radiation emitted by the electron. When there are two tracks in the hemisphere, the one has the higher transverse momentum and close to the more energetic ECAL bump (see below) is taken as the electron candidate.

2. For the ECAL bump associated to the candidate track, it is required that \( E_0/E_{25} \) be greater than 0.95. Fig. 4.9 shows the distribution of \( E_0/E_{25} \) after all other cuts have been applied.

3. The shower profile of a candidate in the ECAL be consistent with what is expected from a purely electromagnetic shower, i.e. \( \frac{\sigma_{xx}}{\sigma_{zz}} > 0.2 \), where,

\[
\sigma_{xy} = \sum_{i=1}^{n} \frac{E_i(x - \bar{x})(y - \bar{y})}{E_i}.
\]

Here \( E_i \) is the measured energy in crystal \( i \), \( x_i, y_i \) are the coordinates of the crystal, and \( \bar{x}, \bar{y} \) are the average position of the shower center. The sum is done with all crystals in the shower. In Fig. 4.10 distributions of \( \frac{\sigma_{xx}}{\sigma_{zz}} \) for e, \( \pi \) and \( \rho \) are plotted in the same scale. The main purpose of this cut is to reject one-prong hadronic \( \tau \) decays.

4. To further reject hadronic \( \tau \) decay backgrounds and backgrounds with \( \pi^0 \)'s, the candidate track must match with the center-of-gravity of the BGO bump within 10 mrad in the transverse plane, i.e.

\[
|\phi_{trk} - \phi_{BGO}| < 10.0 \text{mrad},
\]

where \( \phi_{trk} \) is the \( \phi \) angle of the track at the TEC-BGO intercept point, \( \phi_{BGO} \) is the \( \phi \) angle of the best matched BGO bump.

5. The total bump energy within a 60° cone formed with the bump direction of the electron candidate, excluding those of the cluster associated to the candidate track, must satisfy: \( E_{excess} < 0.04 E_{beam} \). \( E_{beam} \) represents beam energy. This cut suppresses hadronic \( \tau \) decays accompanied by \( \pi^0 \), as well as \( e^+e^- \rightarrow \tau^+\tau^-\gamma \) events. In Fig. 4.12 the distribution of the excessive bump energy distribution.
6. The energy deposition in the HCAL behind the candidate cluster is required to be less than \(2.5 GeV\). This cut suppresses backgrounds from \(\tau \rightarrow \pi(K)\nu\) and \(\tau \rightarrow \rho\nu\). Since the ECAL is of \(\sim 1\) interaction length for the pions and kaons, roughly \(2/3\) of these particles will deposit a large fraction of their energies in the BGO before reaching the HCAL, whereas the electrons are expected to interact fully in the BGO, with little or no energy leakage into the HCAL, as shown in fig. 4.13. This cut also helps eliminating \(\tau \rightarrow \mu\nu\bar{\nu}\) where the muon track is not reconstructed by the muon chambers.

7. There must be no muon candidate in the hemisphere.

8. To remove contaminations from \(e^+e^- \rightarrow e^+e^-\) events where the energy of one electron is mismeasured, an electron candidate is rejected if the opposite hemisphere contains a single track of electromagnetic energy greater than \(0.75E_{beam}\). Due to spin-spin correlations of the two \(\tau\)'s in an event, this cut may introduce bias to the polarization measurement, which will be discussed in the next chapter.

9. The energy of the electron candidate must satisfy:

\[
E_{electron} > 0.02E_{beam}.
\]

The lower limit helps reject backgrounds from two photon processes as well as hadronic tau decays misidentified as electrons, the upper limit rejects backgrounds from Bhabha events.

10. The \(\chi^2\) of the best matched bump to be an electron, defined as:

\[
\chi^2 = \sum_{i=1}^{6} \frac{(E_i - \bar{E}_i)^2}{\sigma_i^2}
\]

should not exceed 50. Here \(E_i\) is the energy deposited in the \(i\)th most energetic crystal, \(\bar{E}_i\), and \(\sigma_i\) is the average value and standard deviation of the energy deposited in the \(i\)th crystal, determined from \(Z^0 \rightarrow e^+e^-\) events. The crystals are ordered according to measured energy. In order to reject events in which the center of gravity of the best matched bump is associated with a dead crystal in the ECAL, a candidate bump is required to contain at least 4 crystals.

After applying the above cuts, 3110 \(\tau \rightarrow e\nu\bar{\nu}\) decay candidates are selected for the measurement of decay branching ratios, events with both \(\tau\)'s identified as decay \(\tau \rightarrow \nu\nu\) are counted once.
Figure 4.9: $E_\gamma^{E_{25}}$ distribution.

Selection Efficiency

To estimate the selection efficiency for $\tau \to e\nu\bar{\nu}$ events, the above selection cuts are applied to a sample of Monte Carlo $e^+e^- \rightarrow \tau^+\tau^-$ events which have passed full detector simulation. The calculated selection efficiency is $(79.1 \pm 0.8)\%$. Fig. 4.15 shows the energy dependence of the selection efficiency. At energies below $2GeV$ the efficiency drops sharply, this is mainly due to the increase of backgrounds in the $\tau$ sample. A fit to the flat region of the energy dependence of the efficiency gives $(82.3 \pm 0.8)\%$.

Backgrounds

The main background for the decay $\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\gamma$ comes from one-prong hadronic $\tau$ decays, in events where both $\tau$'s decay to an electron the major background source is Bhabha events. The selection cuts are applied to Monte Carlo events with full detector simulation to estimate various background contributions. To estimate the Bhabha backgrounds, real data are used. The backgrounds from other tau decay channels are estimated from 58,500 simulated Monte Carlo events in the full solid
Figure 4.10: $\frac{S_{\text{uu}}}{S_{\text{ss}}}$ for different decay channels.

Figure 4.11: $\Delta \phi$ distribution.
Figure 4.12: Excess energy inside a 60° cone around the electron candidate.

Figure 4.13: HCAL energy behind the electron candidates.
Figure 4.14: $\chi^2$ of a bump to be electron for selected candidates.

Figure 4.15: Electron selection efficiency vs energy.
angle. A summary of the background contaminations is given in Table 4.2. The numbers in the second column are accepted backgrounds before scaled to data, which yield the percentage backgrounds in the selected candidates shown in the third column.

1. Misidentification These are mainly from hadronic one-prong tau decays accompanied with one or more $\pi^0$s, where the charged and neutral pions become very collinear, and substantial amount of energy goes to the the photons from the $\pi^0$s, resulting a well measured BGO bump. Another background source is the charged pions misidentified as electrons.

2. Backgrounds From $e^+e^- \rightarrow e^+e^-$ are determined from 12,000 real data Bhabha events. Given the relatively low Bhabha background level in the $\tau$-pair sample, these are mainly contributions from Bhabha events where the energy if one of the electrons was badly measured.

3. Other Backgrounds Based on limited Monte Carlo data, the background from two photon process is less than 0.1 %.

<table>
<thead>
<tr>
<th>Background Source</th>
<th>Number of events</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \pi\nu$</td>
<td>151</td>
<td>1.4 ± 0.6</td>
</tr>
<tr>
<td>$\tau \rightarrow \rho\nu$</td>
<td>238</td>
<td>2.2 ± 1.1</td>
</tr>
<tr>
<td>$\tau \rightarrow$ others</td>
<td>22</td>
<td>0.2 ± 0.2</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow e^+e^-$</td>
<td>18</td>
<td>0.3 ± 0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>429</strong></td>
<td><strong>4.1 ± 1.3</strong></td>
</tr>
</tbody>
</table>

Table 4.2: Backgrounds in electron identification

TEC Efficiency

The TEC global inefficiency and inefficiency of individual sector is determined using hadronic $Z^0$ decays. The TEC global inefficiency is defined as the fraction of the hadronic events without TEC tracks. Among 12,000 hadronic events, there are about 1% events which do not have TEC tracks. For the Monte Carlo events, this number is less 0.1%. Therefore the TEC global inefficiency is: $\epsilon_{\text{ineff}} = (1.00 \pm 0.20)\%$. Figure 4.16 shows the number of tracks in each TEC sector from hadronic events in the 1990 period. Sector 12 was switched off throughout of the 1990 run, due to a broken high
Figure 4.16: Number of tracks vs TEC sector in hadronic $Z^0$ decays.

voltage wire. The overall TEC efficiency, after excluding the bad sectors, and 1.5% tracks without inner chamber hits, is $(98.8 \pm 0.2)\%$ during the 1990 run and $(99.2 \pm 0.2)\%$ during the 1991 run.

**ECAL Efficiency**

There are an estimated total of 1.5% bad BGO crystals, including 45 dead and some noisy ones, resulting a detector efficiency of BGO 98.5%. The effects of the bad crystals are included in the reconstruction of the Monte Carlo events (by switching off suspected crystals), and hence the estimates of selection efficiencies. In data processing, noisy crystals are switched off at the pass 1 reconstruction level. The goodness of the Monte Carlo bad crystal correction is checked with real data $e^+e^-$ events by counting the number of time an event has at least one electron with substantially lower bump energy. The two agree within statistics of the samples.
4.1.4 Selection of $\tau^− → \mu^- + \bar{\nu}_\mu + \nu_\tau$ Events

Muon Identification

A good identification of the decay $\tau → \mu\nu\bar{\nu}$ largely depends on the detector’s excellent muon detection. Due to the hadronic decays of the $\tau$'s it is important to separate $\pi$'s from $\mu$ candidates, which requires cuts on energy deposition and shower profile in the HCAL. For muons at energies below several hundred $GeV$ ionization is the main source of energy loss, the weak interaction is negligibly small, and bremsstrahlung is strongly suppressed due to the high mass. The energy loss in BGO is $\sim 0.010 GeV/cm$, which yields a total energy deposition in the ECAL of $\sim 0.23 GeV$ for a muon passing through; for the HCAL the deposition is about $2.5 GeV$, assuming the average energy loss to be $0.015 GeV/cm$. On the other hand while about $1/4$ of all the $\pi$'s leaves the ECAL with minimum ionizing energy, they almost always being completely stopped in the HCAL (there is about $1\%$ of all the $\pi$'s sail through the detector misidentified as a muon), therefore the shower development in the HCAL are very different from the case of muons. To avoid backgrounds from cosmic rays and badly measured muon tracks due to multiple scatterings in the calorimeter, a muon candidate is required to be pointing to the interaction region within $3\sigma_zy$ in the $r - \phi$ plane, and within $4\sigma_z$ in the $r - z$ plane, $\sigma_zy$ and $\sigma_z$ are the errors on the muon DCA in the two planes, respectively.

To select $\tau^- → \mu^- + \bar{\nu}_\mu + \nu_\tau$ events, the following cuts are applied to the selected $\tau$ pair data sample:

1. There is one well reconstructed muon in the hemisphere, with a momentum of

$$P_{muon} > 0.01 E_{beam}/c.$$ 

The lower cut is mainly for rejecting backgrounds from two photon process and punch throughs. To avoid misidentification, a well reconstructed muon track should consist of at least 2 P-segments out of 3 layers of muon chambers, and should have one or more Z-segments.

2. When extrapolated back to the interaction region, the distance of closest approach (DCA) of the muon track must be within $20 cm$ of the nominal vertex in the transverse ($r - \phi$) plane, and within $25 cm$ of the nominal vertex along the
beam direction (z). This cut further rejects backgrounds from cosmic rays, it also suppresses backgrounds from hadronic punchthrough, which are produced at large distances from the vertex and thus usually have large DCA's. The errors on the muon DCA comes from three sources: the beam size, multiple scattering in the inner detector, and reconstruction errors. The uncertainty of the LEP beam size is typically of the order of 25μm in the horizontal plane and 5μm in the vertical plan, which is small compared to other errors. Multiple scattering changes the muon trajectory and therefore smears the DCA distribution. For a 45 GeV/c muon originating from the interaction region, its DCA has an r.m.s. of ~ 15.0mm. The error of reconstruction usually is negligibly small.

3. The energy deposition in the HCAL corresponding to the muon candidate is required to be less than 6GeV. This cut rejects contaminations from hadronic punchthroughs, minimum ionizing hadrons (sailthroughs) and decay muons.

4. To remove background from dimuon events in which one muon has poorly reconstructed momentum, the recoil side must not be comprised of a muon candidate with momentum greater than 0.7E_{beam}/c.
Figure 4.18: Muon vertex distribution in the rz plane.

Figure 4.19: Energy deposition in the HCAL.
A total of 2683 events survived the above cuts, and are selected as $\tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau$ candidates used for the decay branching ratio measurement later.

Selection Efficiency

Fig. 4.20 shows the selection efficiency as a function of the muon momentum, determined from the Monte Carlo events. A fit to this curve with a linear function, excluding the first bin, yields an average selection efficiency of $(74.5 \pm 1.0)\%$.

Background Contamination

The main sources of backgrounds for $\tau \rightarrow \mu \nu \bar{\nu}$ selection are: misidentification and events from $e^+ e^- \rightarrow \mu^+ \mu^-$. There is also a small possible contribution from $\pi$ punch throughs and cosmic rays.

1. **Misidentification** $\tau \rightarrow \rho \nu \bar{\nu}$ or $\tau \rightarrow \pi \chi$ where one pion punchthroughs form the dominant background. Another major source of background is the so-called sailthrough, the probability of a pion to become a sailthrough muon is
approximately 1%, the momentum of the sailthrough muons are often rather low. The combination of the two processes gives a total background of 1.8%.

2. **Backgrounds from** $e^+e^- \rightarrow \mu^+\mu^-$ **This is the major background source for events in which both taus decay into a muon, and the momentum of at least one of the tracks is not well reconstructed.**

3. **Other Backgrounds** Background from cosmic rays are negligibly small, due to the requirements on the scintillator timing and the muon vertex cuts. The possibility of electrons being misidentified as muons are studied using 8,000 Bhabha event in the barrel. none of the electrons is identified as muon. The corresponding misidentification probability is $< 0.1\%$ with 95% confidence level. Given the Bhabha rejection cuts in the $\tau$ pair selection, the background from electron is negligible.

The background from hadronic tau decays are estimated with 58,500 KORALZ Monte Carlo $e^+e^- \rightarrow \tau^+\tau^-$ events, and 8,000 dimuon data are used for estimates of background from $e^+e^- \rightarrow \mu^+\mu^-$. The results are listed in 4.3. The entries in the second column has not been scaled to data, whereas the third column shows the percentage of backgrounds in the selected candidates.

<table>
<thead>
<tr>
<th>Background Source</th>
<th>Number of events</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow h\nu$</td>
<td>178</td>
<td>1.8 ± 1.1</td>
</tr>
<tr>
<td>$e^+e^- \rightarrow \mu^+\mu^-$</td>
<td>9</td>
<td>0.4 ± 0.3</td>
</tr>
<tr>
<td>Other</td>
<td>0</td>
<td>&lt; 0.1 ± 0.2</td>
</tr>
<tr>
<td>Total</td>
<td>187</td>
<td>2.3 ± 1.1</td>
</tr>
</tbody>
</table>

Table 4.3: Backgrounds in muon identification

**Muon Chamber Efficiency**

A muon has to be reconstructed in at least two of the three chambers to be identified, efficiencies due to detection or reconstruction will result in event loss. The inefficiency of the muon chamber is estimated by comparing the probabilities of a muon track being reconstructed in each layer of the chambers between data and Monte Carlo dimuon events. The overall inefficiency for detecting dimuon events is found to be $(4.0 \pm 0.5)\%$ [46]. The inefficiency is nearly momentum independent for
$p_\mu > 5.0 GeV$, but rises sharply for the region of $p_\mu < 5.0 GeV$. From the shape of the muon momentum spectrum, we estimate a single muon detection efficiency for $\tau \rightarrow \mu \nu \bar{\nu}$ of $\sim (2.5 \pm 0.5)\%$. The error is set larger, allowing uncertainties in the Monte Carlo simulation at low energy region.
Chapter 5

Measurement

This chapter contains two parts. The measurements of the leptonic decay branching ratios are presented in the first part; the second part is devoted to the measurement of the \( \tau \) polarization in \( \tau \) decays to electron channel.

5.1 Decay Branching Ratios

5.1.1 Branching Ratio Measurements

The final results of \( \tau \to e\nu\bar{\nu} \), \( \tau \to \mu\nu\bar{\nu} \) event selections from Chapter 4 are listed in Table 5.1, the errors on the background contaminations are obtained by adding contributions from various background sources in quadrature.

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Number of candidates</th>
<th>backgrounds (%)</th>
<th>Efficiency(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau \to e\nu\bar{\nu} )</td>
<td>3110</td>
<td>4.1 ± 1.3</td>
<td>82.3 ± 0.8</td>
</tr>
<tr>
<td>( \tau \to \mu\nu\bar{\nu} )</td>
<td>2683</td>
<td>2.3 ± 1.1</td>
<td>74.5 ± 1.0</td>
</tr>
</tbody>
</table>

Table 5.1: Number of observed candidates in each decay channel and corresponding estimated background fractions

Decay branching ratios are calculated by taking into account all possible combinations of event topologies, and by estimating the selection efficiency in each case. Let \( N_{sel} \)
represents the total number of electron candidates selected, \( N_\tau \) be the total number of \( \tau \) pairs, \( \varepsilon_\tau \) be the selection efficiency for \( \tau \) pairs within the acceptance, and \( B_i \) the decay branching ratio of decay mode \( i \). \( N_{\mathcal{MC}} \) can be expressed in terms of \( N_\tau \), \( B_i \), and \( \varepsilon_i \) as the following:

\[
N_{\mathcal{MC}} = \frac{N_\tau}{\varepsilon_\tau} \left[ \varepsilon_1 B_1^2 + \varepsilon_2 B_2 (1 - B_1) + \varepsilon_3 (1 - B_1)^2 + \varepsilon_4 \right],
\]

where \( \varepsilon_1 \) is the selection efficiency for events with both \( \tau \)'s decay into the interested mode \( i \); \( \varepsilon_2 \) is the efficiency for selecting events in which one \( \tau \) decays into mode \( i \), the other decays differently; \( \varepsilon_3 \) is the efficiency for selecting events which both \( \tau \)'s decay via modes other than the interested one; \( \varepsilon_4 \) is the efficiency for selecting events from \( e^+e^- \rightarrow e^+e^- \) (in the case of \( \tau \rightarrow e\nu\bar{\nu} \) decay) and \( e^+e^- \rightarrow \mu^+\mu^- \) (in the case of \( \tau \rightarrow \mu\nu\bar{\nu} \) decay) background. These efficiencies are estimated with Monte Carlo events which have passed the real detector simulation. Monte Carlo \( \tau \)-pair events are used to estimate \( \varepsilon_1 \), \( \varepsilon_2 \) and \( \varepsilon_3 \), whereas \( \varepsilon_4 \) is estimated using Bhabha or \( e^+e^- \rightarrow \mu^+\mu^- \) Monte Carlo, by applying electron selection cuts on them, and counting the number of events accepted. The results are listed in table 5.2. All numbers are referred to the barrel region of the detector. The decay branching ratio in the Monte Carlo for \( \tau \rightarrow e\nu\bar{\nu} \) is 18.5%, and for \( \tau \rightarrow \mu\nu\bar{\nu} \) is 18.0%.

<table>
<thead>
<tr>
<th>( \varepsilon_i ) (( \tau \rightarrow e ))</th>
<th>Total MC used</th>
<th>Number of candidates</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \varepsilon_1 ) (( \tau \rightarrow e ))</td>
<td>1223</td>
<td>513</td>
<td>0.4195</td>
</tr>
<tr>
<td>( \varepsilon_2 ) (( \tau \rightarrow e ))</td>
<td>5395</td>
<td>4196</td>
<td>0.7778</td>
</tr>
<tr>
<td>( \varepsilon_3 ) (( \tau \rightarrow e ))</td>
<td>23734</td>
<td>283</td>
<td>0.0119</td>
</tr>
<tr>
<td>( \varepsilon_4 ) (( \tau \rightarrow e ))</td>
<td>13000</td>
<td>54</td>
<td>0.0042</td>
</tr>
<tr>
<td>( \varepsilon_1 ) (( \tau \rightarrow \mu ))</td>
<td>1157</td>
<td>340</td>
<td>0.2038</td>
</tr>
<tr>
<td>( \varepsilon_2 ) (( \tau \rightarrow \mu ))</td>
<td>5274</td>
<td>3720</td>
<td>0.7053</td>
</tr>
<tr>
<td>( \varepsilon_3 ) (( \tau \rightarrow \mu ))</td>
<td>24026</td>
<td>151</td>
<td>0.0063</td>
</tr>
<tr>
<td>( \varepsilon_4 ) (( \tau \rightarrow \mu ))</td>
<td>18000</td>
<td>45</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

Table 5.2: estimated background fractions

Using the data from table 5.1 the leptonic branching ratio is calculated to be:

\[
Br(\tau \rightarrow e\nu\bar{\nu}) = 0.1772 \pm 0.0036, \\
Br(\tau \rightarrow \mu\nu\bar{\nu}) = 0.1760 \pm 0.0039.
\]

(5.2)

The errors are statistical only.
5.1.2 Systematic Errors

The systematic errors on the decay branching ratios are calculated from the errors on the selection efficiencies, backgrounds in the decay mode and in the $\tau$-pair sample.

To estimate the systematic error due to uncertainty in the selection efficiency, in the case of $\tau \rightarrow e\nu\bar{\nu}$ decay, first the selection efficiency obtained from Monte Carlo simulation has to be corrected to the inefficiency of the TEC as given in Chapter 4. The errors on the TEC efficiency and the electron selection efficiency are then combined to give an error on the selection efficiency of 1.0%. Since the Monte Carlo events used in this study were simulated under real detector conditions with bad crystals taken into account, inefficiency due to this source is included. To estimate the uncertainties on the bad crystal simulation, a comparison of $e^+e^- \rightarrow e^+e^-$ data and Monte Carlo events are carried out by counting the number of events with at least one jet energy of $< 30 GeV$. The result shows that the effect is well simulated within $\sim 0.5\%$. Therefore the final uncertainty on the selection efficiency is $\sim 1.2\%$. The systematic error on $B_\tau$ is then estimated by varying the selection efficiency by this amount.

The selection efficiency of $\tau \rightarrow \mu\nu\bar{\nu}$ decays obtained from Monte Carlo estimates is corrected to the estimated inefficiency of the muon chamber given in the last section of Chapter 4, which yields a final selection efficiency of $(72.6 \pm 1.1)\%$. The systematic error on $B_\mu$ is estimated via varying the efficiency by its $\pm 1$ standard deviation.

The systematic error due to uncertainty in the background estimates are determined by varying the background contents by $\pm 1$ standard deviation.

The results are listed in 5.3.

The final results on the leptonic branching ratios are:

$$Br(\tau \rightarrow e\nu\bar{\nu}) = 0.1772 \pm 0.0036^{+0.0041}_{-0.0037}$$

$$Br(\tau \rightarrow \mu\nu\bar{\nu}) = 0.1760 \pm 0.0039^{+0.0039}_{-0.0036}$$

(5.3)

where the first error is statistical and the second systematic.
<table>
<thead>
<tr>
<th>Error Source</th>
<th>$\tau \rightarrow e\nu\bar{\nu}$</th>
<th>$\tau \rightarrow \mu\nu\bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency (%)</td>
<td>+0.29</td>
<td>+0.28</td>
</tr>
<tr>
<td>($%$)</td>
<td>-0.27</td>
<td>-0.27</td>
</tr>
<tr>
<td>$\tau\tau$ Backgrounds (%)</td>
<td>+0.11</td>
<td>+0.10</td>
</tr>
<tr>
<td>($%$)</td>
<td>-0.07</td>
<td>-0.07</td>
</tr>
<tr>
<td>$\tau$ decay backgrounds (%)</td>
<td>+0.27</td>
<td>+0.26</td>
</tr>
<tr>
<td>($%$)</td>
<td>-0.25</td>
<td>-0.22</td>
</tr>
<tr>
<td>Total (%)</td>
<td>+0.41</td>
<td>+0.39</td>
</tr>
<tr>
<td>($%$)</td>
<td>-0.37</td>
<td>-0.36</td>
</tr>
</tbody>
</table>

Table 5.3: Systematic errors on decay branching ratios

5.2 Polarization

In this thesis the $\tau$ polarization is determined from the shape of the energy spectrum of the decay products. A number of issues have to be addressed before this can be done. Namely, the observed spectrum has first to be corrected to any changes in the detector energy scale and resolution; then the radiative effects in the decay process have to be properly taken into account.

5.2.1 Energy Scale

The measurement of the $\tau$ polarization involves fitting the energy distribution of the decay products to some expected distribution. It is therefore important to understand the absolute energy scale, resolution, their variation with respect to the electron energies, and the uncertainties on these values in both distributions, then make proper correction to the efficiency on a bin by bin basis.

Monte Carlo events are used to estimate the effects of absolute energy scale on the polarization measurements. Three sets of $\tau$-pair events at the $Z^0$ pole in which both $\tau$'s decays to electrons are generated without radiative effects, each contains 20,000 events, the first one has the natural energy distribution as predicted; in the second set electron energies are artificially increased by 1%, whereas in the third set they are decreased by the same amount. Using the Born level formula (2.52), a maximum likelihood fit was performed to each of the three spectra with $P_\tau$ as free parameter, the results are listed in Table 5.4. Clearly a 1% change in the energy scale would
\begin{table}
\begin{tabular}{|c|c|}
\hline
$\Delta E/E(\%)$ & $P_r(\%)$ \\
\hline
0.0 & $-16.93 \pm 0.03$ \\
+0.01 & $-22.20 \pm 0.03$ \\
-0.01 & $-12.22 \pm 0.03$ \\
\hline
\end{tabular}
\caption{Effects of absolute energy shifts on polarization values, errors are statistical only.}
\end{table}

introduce a change on $P_r$ of 0.05 and thus is a significant source of systematic error. To estimate the shift in the energy scale, $e^+e^- \rightarrow e^+e^-$ events are used for the higher energy region, figure 5.1 shows the electron energy distributions for data events, a gaussian fit is performed to extract the peak position. For the data this yields a peak position of: $(1.001 \pm 0.001)\%$ which is consistent with no shift. For the Monte Carlo the peak position is at $(1.004 \pm 0.001)\%$. There is also a difference in the resolution between data and Monte Carlo events, which is due to imperfection in the simulation and nearly energy independent. Fig. 5.2 shows the comparision of data and Monte Carlo distribution after correct the resolution in the latter.

To find out whether the difference between the two peak positions is due to a linear shift in the energy or caused by scaling, studies with low energy electrons and photons in both data and Monte Carlo are carried out. In the first approach, electron energy distribution from $J/\psi \rightarrow e^+e^-$ is used. A total of 15 such decays were collected during the 1991 physics run [47], the standard deviation of the mass peak is $\sim 60MeV$, or $\sim 2.0\%$, this yields an uncertainty on the peak position of approximately 0.5\%, or $\sim 15MeV$. Given that the average electron energy in such events is less than half of the beam energy, a linear shift of $180MeV$ (which corresponds to 0.4\% of the Bhabha peak) will result in a shift of the mass peak by more than 60MeV, this is not observed in either data nor Monte Carlo distributions. Therefore a linear shift of the energy scale is excluded. Figure 5.3 is a plot of the invariant mass distribution of the selected $J/\psi \rightarrow e^+e^-$ events [47].

A more precise estimate of the energy scale in the lower region used the $e^+e^- \rightarrow e^+e^-\gamma$ process. Since for any three body final stat the three particles (in this case the $e^+e^-\gamma$) must lie in a plane, their energies can be defined in terms of their total energy (which equals to $E_{cm}$) and the angles between them. Let $E_\gamma$ be the photon energy, $E_{e^+}, E_{e^-}$ be the energy of the $e^+$ and $e^-$, respectively, the corresponding momenta be
Figure 5.1: Energy distribution of Bhabha events.

Figure 5.2: Energy distribution of Bhabha events after smearing the MC resolution
Figure 5.3: Invariant mass distribution of $J/\psi \rightarrow e^+e^-$ events.

$p_1, p_2,$ and $p_3$, the angle between the photon and the $e^+$ be $\theta_{12}$, between the photon and the $e^-$ be $\theta_{13}$, and between the $e^+$ and $e^-$, $\theta_{23}$, conservation of momentum in the center of mass system requires that the three momentum vectors to form a closed triangle as shown in figure 5.4, the interior angles $\alpha_{ij}$ are related to the angles between the momentum vectors as follows:

$$\alpha_{ij} = \pi - \theta_{ij},$$  \hspace{1cm} (5.4)

whereas,

$$E_{cm} = |p_1| + |p_2| + |p_3|.$$  \hspace{1cm} (5.5)

we then have:

$$E_\gamma = E_{cm} \frac{\sin \theta_{12}}{\sin \theta_{12} + \sin \theta_{23} + \sin \theta_{13}}.$$  \hspace{1cm} (5.6)

Comparing the difference between $E_\gamma$ and the measured photon energy, one gets the shift in the energy scale and its error. This method provides a ‘calibrated’ source of photons, since photons in the BGO which do not correspond to the radiated photon can be excluded by their energy. The accuracy of the method is limited only by the angular resolution. Figure 5.5 shows the distribution of the cosine of the angle ($\beta$) between the photon and the normal vector to the event plane. A cut requiring the opening angle between the direction of the photon and the direction of its nearest track
to be greater than 60 mrad was been applied to ensure a well defined event plane. The width of this distribution gives the experimental resolution with which the event plane can be defined. For an acollinearity between the two tracks of > 60 mrad, the resolution is found to be $\sigma \leq 10 mrad$. A cut at $|\cos \beta| < 0.15$ is applied. Define:

$$K = 2 \frac{\sin \theta_{12}}{\sin \theta_{12} + \sin \theta_{23} + \sin \theta_{13}},$$

(5.7)

it is the ratio of the photon energy to the beam energy. In figure 5.6 K is plotted for various values of acollinearity angle $\alpha_{12}$. Clearly, the threshold energy of the photon is related to the acollinearity of the charged tracks. Figure 5.7 shows the normalized event energy distribution

$$E_{tot} = \frac{E_{\gamma} + E_{e+} + E_{e-}}{E_{cm}},$$

(5.8)

obtained with 1991 Bhabha data sample. Also shown is a fit to the Gaussian distribution which yields $E_{tot} = 1.001 \pm 0.001$.

Figure 5.8 is a plot of the difference between the measured photon energy and calculated value normalized to the latter for selected events. In this plot the photon is required to be separated from the nearest track by larger than 60 mrad, which corresponds to an energy of greater than 2.0 GeV (see fig. 5.6). The width of the distribution is well explained by the energy resolution of the ECAL and the resolution.
Figure 5.5: Cosine of the angle between the photon and the normal of the event plane.

Figure 5.6: Distribution of function K.
Figure 5.7: Normalized total event energy in $e^+e^- \rightarrow e^+e^-\gamma$ events.

of the event plane. In order to increase statistics, $e^+e^- \rightarrow \mu\mu\gamma$ are also studied. The direction of the $\mu$'s are determined from the matched TEC tracks.

From the combined statistics we conclude that the BGO energy scale is known within 1.0% for data, and within statistical error there is no displacement of the relative energy scale between data and the Monte Carlo in the energy range considered. In the Monte Carlo, there is a 0.5% scale shift towards the high energy end which will be corrected before fitting the polarization.

Low energy electrons are also used to determine a global offset of the energy scale, not such evidence was fonunction. Appendix B provides more details of the analysis using $e^+e^- \rightarrow e^+e^-\gamma$ and $e^+e^- \rightarrow \mu\mu\gamma$ events.

5.2.2 Radiative Corrections

Since the Born level expression (Eq. (2.52)) does not hold when radiative corrections are incorporated, semianalytical calculations are performed and implemented into Monte Carlo programs to obtain a measurement of the relevant parameters. Radia-
Figure 5.8: Differences between measured photon energy and kinematic predictions.

Figure 5.9: Energy spectrum of observed photons.
tive corrections are taken into account at the simulation level, which simplified the analysis, however the drawback is one thus becomes heavily rely on the simulation and Monte Carlo statistics. For this study, in the Monte Carlo program KORALZ \(e^+e^- \rightarrow \tau^+\tau^-\) events are generated with positive and negative helicity separately for the two \(\tau\)'s in the final state. Let \(f_+(x)\) and \(f_-(x)\) represent their corresponding momentum distributions from the Monte Carlo, then the final distribution \(f(x)\) is a linear combination of the two. From Eq.(2.50) the differential cross section depends linearly on the \(P_\tau\), this still holds after taking into account radiative corrections. i.e.,

\[
\frac{1}{N}f(x) = \frac{1}{2}[(1 + P_\tau) f_+(x) + (1 - P_\tau) f_-(x)].
\]

(5.9)

The basic idea of the semianalytical treatment of the QED radiative effects in the \(e^+e^- \rightarrow \tau^+\tau^-\) process is the following: Since in principle effects at all stages interfere with each other, they have to be handled all as a whole, which is very complicated and difficult. A good approximation is to look at the process as a noninterfering fragmentation process. At the start of the reaction the initial-state \(e^+e^-\) pair is allowed to radiate \(n\) photons which carry a total energy of \(\sqrt{s}\), the remaining energy \(\sqrt{s(1 - \gamma)}\) is available for producing the \(\tau^+\tau^-\) pair. Consider the case of \(\tau^- \rightarrow \mu^-\nu\bar{\nu}\), the \(\tau^-\) radiates a photon according to the fragmentation function \(D_\nu\) which follows the Altarelli-Parisi distribution, and thus loses fraction \((1 - z)\) of its energy. The subsequent \(\tau\) decay is described by a fragmentation function \(h_\mu\), in which a the \(\nu_\tau - \bar{\nu}_\mu\) system takes a fraction \(u\) of the \(\tau\) energy. Finally a bremsstrahlung photon can be radiated from the muon, and the muon energy is therefore \(x = uzt\sqrt{1 - \gamma}\sqrt{3}/2\).

The initial-state radiation is calculated by taking a convolution over the improved Born cross-section with the multi-photon spectrum to give the effect to \(O(\alpha^2)\). It has been shown that such a parameterization agrees with the full second-order exponentiated cross-section calculations to a precision of the order 0.1%. As shown in Fig. 2.6 in Chapter 2, since \(A_{pol}\) depends only weakly on \(\sqrt{s}\) the influence of initial-state radiation is small: the variation of \(A_{pol}\) across the energy range of this experiment is roughly 4%, compared to the size of the current statistical error. The effect of radiation from the initial and/or final state is to soften the differential cross section \(d\sigma/dx\) and to reduce the total cross section.

For the leptonic modes, the differential cross section can be expressed in the following semianalytical form:

\[
\frac{d\sigma}{du} = (2\pi_0 + \frac{2\pi^3}{3})(W_0(s, u) + W_2(s, u))
\]

(5.10)
where $W_0(s, x), W_2(s, x)$ are structure functions, given in Appendix A. $x_0$ is the cosine of the polar acceptance angle of the detector.

Generally speaking, the final state radiation, characterized by the fragmentation functions $H_0^r$ and $H_2^r$ (see Appendix A) does not change the total cross section, but dramatically changes the shape of the spectrum, thus has a larger influence on the measured value of polarization (inclusion of the final state radiation changes $P_e$ from -0.16 to -0.13, therefore photons from the final states must be handled properly.

As an illustration of the effects of radiative corrections, a fit is done first with the muon momentum spectrum for polarization of about $-16\%$ (Born level), and then to one which has all radiation effects included. Fitting the second curve with Born level formula Eq.(2.52) gives $(-8.5 \pm 5.1)\%$, while using eq.(5.9) yields $(-18.2 \pm 5.2)\%$.

### 5.2.3 Fitting Methods

To extract the polarization information, the measured electron energy distribution from decay $\tau \rightarrow e\nu\bar{\nu}$ is compared with the expected distribution from the Monte Carlo events accepted using the same selection cuts. A $\chi^2$ fit is performed with the Monte Carlo distribution taken as the theoretical prediction.

The energy distributions of $\tau$'s with positive and negative helicities, $f_+(x_e)$ and $f_-(x_e)$, as functions of the electron energy $x_e = E_e/E_{beam}$, can be expressed as follows:

$$f_{\pm}(x_e) = \frac{\Delta n_{\pm}(x_e)}{\Delta x_e}, \quad (5.11)$$

with:

$$\sum f_+(x_e)\Delta x_e = n_+$$
$$\sum f_-(x_e)\Delta x_e = n_- \quad (5.12)$$

where $n_+$ and $n_-$ are the accepted number of Monte Carlo events with positive and negative helicity, respectively. $n_+ + n_- = n_\tau$. $n_\tau$ is the total number of accepted Monte Carlo events.

Let $N_{\pm}$ represent the number of helicity $\pm 1$ events in the Monte Carlo before the selection, $P_\tau^0$ be the input polarization of the Monte Carlo, and $N_\tau$ be the total
number of Monte Carlo events before the selection, one has:

\[ N_{\pm} = \frac{(1 \pm P_0^2)}{2} N_r. \]  
\[ \text{(5.13)} \]

From these a probability function can be built:

\[ f(P_r, x_e) = N(P_r) \left\{ \frac{1 + P_r}{1 + P_0^2 f_+(x_e)} + \frac{1 - P_r}{1 - P_0} f_-(x_e) \right\}, \]

\[ \text{(5.14)} \]

with \( P_r \) as the polarization to be determined. \( N(P_r) \) is the normalization parameter.

The above probability function can be used to weigh the measured data distribution, but before doing so two factors have to be taken into account. First the background from other \( \tau \) decays have to be subtracted according to the estimates from Monte Carlo. Second, background from \( e^+e^- \to e^+e^- \) events has to be taken into account independently. Given the relatively high sensitivities to \( P_r \) at the higher \( x_e \) bins where this background is more severe, it is inappropriate to subtract it according to the given Monte Carlo distribution with certain input polarization, since this will then introduce bias to the measurement. One therefore needs to float the \( e^+e^- \to e^+e^- \) background with a distribution of proper luminosity obtained from the Bhabha data. Let \( f_{ee}(x_e) \) be the distribution of \( e^+e^- \to e^+e^- \), \( N(ee) \) be its normalization factor, we can therefore build the following \( \chi^2 \) function:

\[ \chi^2 = \sum_i \frac{\left[ n_{\text{data}}^i - n_{\text{background}}^i - f(P_r, x_e) - N(ee)f_{ee}(x_e) \right]^2}{\sigma_i^2}, \]

\[ \text{(5.15)} \]

where \( n_{\text{data}}^i \) is the number of data events observed at bin \( i \), \( \sigma_i \) is the corresponding error; \( n_{\text{background}}^i \) is the estimated number of background events at bin \( i \). This \( \chi^2 \) is then minimized using the function minimizing program MINUIT to extract \( P_r \).

The advantage of this method lies in its simplicity, so long as the Monte Carlo simulates the data well. Since the measurement is performed by comparing the difference between the data and Monte Carlo, some of the systematic errors will be canceled out. However it is based on the assumption that all radiative corrections are well understood; it also requires a large number of events to obtain a good accuracy on the probability functions \( f_{\pm} \). The error on the \( P_r \) due to Monte Carlo statistics can be expressed as:

\[ (\Delta P_r)_{MC} = \frac{(\Delta P_r)^{\text{stat}}}{\sqrt{n_{MC}}}, \]

\[ \text{(5.16)} \]

where \( \Delta P_r^{\text{stat}} \) is the statistical error obtained from the fit, \( n_{MC} \) is the total number of selected Monte Carlo events that are used to build \( f_{\pm} \), \( n_{\text{data}} \) is the total number of
selected data events used in the fit. This error will introduce fluctuations on \( f_\pi \) and thus the final result on \( P_\tau \). It therefore can be classified as systematic error.

A sample of 100,000 Monte Carlo generator level \( \tau \rightarrow e\nu \bar{\nu} \) decay events were used to test the fitting method. When fitting the same sample to itself, the result is: \( P_\tau = -0.1385 \pm 0.0144 \), which is consistent with the input polarization \( P_\tau = -0.1342 \).

### 5.2.4 Fitting Results

For the polarization measurement, in order to minimize systematic errors, events in which both side are identified as \( \tau \rightarrow e\nu \bar{\nu} \) decays are not used. Since the main objective in this study is to obtain an unbiased electron energy spectrum with large statistics, some concession to the level of the backgrounds is allowed, provided the backgrounds are well simulated by the Monte Carlo. Therefore the \( \tau \)-pair selection cuts are tuned to accept more events at lower energy.

Applying the procedure described in above section, a 20-bin fit is performed to a sample of 2,532 events. The result is:

\[
P_{\tau \rightarrow \pi} = -0.096 \pm 0.091. \tag{5.17}
\]

The errors are statistical only. The fitting result using the Monte Carlo reweighting method is shown in fig. 5.10, where the dotted histogram represents the measured spectrum, the hatched histogram is the estimated backgrounds, the open histogram is the result of the fit. Also shown are the expected distribution from the two helicities for the measured value of polarization.

The fitting bin size is chosen based mainly on the total number of data entries in the fit, varying the bin size from 15 to 25 the fitting result behaves stable. Given the high resolution of the ECAL, with more data a finer bin size will help improve the sensitivity of the result.

### 5.2.5 Systematic Errors

The systematic uncertainties consist of: Uncertainties on acceptance and efficiency; on the relative difference in the energy calibration of the BGO; uncertainties on
misidentification and background contamination, uncertainties due to the fitting method; and uncertainties due to limited Monte Carlo statistics.

Acceptance and efficiency

The uncertainties on the $P_T$ due to energy dependent variation of acceptance are estimated in the following way: first, the slope of the acceptance vs energy curve determined from MC is varied by the amount of its error, the amount of corresponding changes in the $P_T$ is assigned as the first contribution to systematic errors; then, at each bin of the acceptance curve, a random number which normalized to one is multiplied to the amount of the variation at that bin; this is repeated 20 times, and the width of the distribution is assigned as the second contribution to systematic errors. Finally the two contributions are combined.
Energy scale

To estimate the systematic error due to the uncertainties on the energy calibration of the BGO, we scale the measured electron energy by ±1.0% which is the amount obtained in the analysis of 3-body final states. A new fit to the $P_r$ is done and the difference from the previous value of $P_r$ is found to be ±0.038. This value is then assigned as the systematic error due to uncertainties of energy calibration. The effects of the error on the BGO resolution on the measurement of the $P_r$ is studied by smearing the resolution within its error: ±0.01% and redo the fitting. No changes on the $P_r$ was found.

Backgrounds and misidentification

Systematic errors due to background contaminations are estimated in two steps: first the absolute height of the background spectrum is varied within the uncertainties on the background contents, then the slope of the background spectrum is varied in a similar fashion as in the case of the efficiency slope. The two contributions are combined in quadrature to give an estimate on the systematic error.

One unique background is the electrons coming from the two photon process, which contributes to the excess in data at the first two bins (see fig. 5.10). To estimate this background level, first an electron identification is done to the data set after pass 1 selection, which contains mostly low multiplicity events, including two photon processes. The electron energy spectrum of the events passed the electron cuts have a shape similar to that of the $\tau \rightarrow e\nu\bar{\nu}$, with the exception of two very high peaks at each end of the energy range. The peak at near the beam energy comes from the electrons in $e^+e^- \rightarrow e^+e^-$ process, whereas the one at low energy corresponds to two photon processes. This distribution is then compared with the electron energy spectrum from Monte Carlo $\tau \rightarrow e\nu\bar{\nu}$ decays, with the latter normalized to the mid-region of the data spectrum. The excess at the lower end in the data is then estimated. To correspond this to the real data $\tau \rightarrow e$ decay spectrum, we then start from the $\tau$-pair sample to select $\tau \rightarrow e$ decay, and require in each event the opposite side of the electron candidate to be a soft electron which looks like coming from two photon process, the electron energy distribution will thus have a rise at the lower end. Its height is compared with that of the two photon peak and a fixed two photon background normalization of 8.0% for the first two bins is obtained. The effect of
this background to the $P_r$ is estimated by varying the background content by 10%, and refit the $P_r$. The difference in the values of the $P_r$ is found to be 1.0% and is assigned as the systematic error to $P_r$.

**Monte Carlo statistics**

Systematic error due to Monte Carlo statistics is calculated according to eq. (5.16). A total of $n_{MC} = 12,822$ Monte Carlo $\tau \rightarrow e\nu\bar{\nu}$ decays were used in the fitting. From this, $n_{data}$ and the value of $\Delta(P_r)^{stat}$ we obtain the systematic error to be 0.040.

In Table 5.5 contributions from various sources discussed above are listed. Since the contributions from different sources are largely uncorrelated, they are added in quadrature to obtain the total systematic error. At present the systematic error is about 60% of the statistical error, and can be improved via more Monte Carlo statistics and better understanding of the background and ECAL calibration.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta P_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance</td>
<td>0.017</td>
</tr>
<tr>
<td>Backgrounds + Misidentification</td>
<td>0.025</td>
</tr>
<tr>
<td>Energy Calibration</td>
<td>0.038</td>
</tr>
<tr>
<td>Radiative corrections</td>
<td>0.020</td>
</tr>
<tr>
<td>Monte Carlo statistics</td>
<td>0.040</td>
</tr>
<tr>
<td>Total</td>
<td>0.066</td>
</tr>
</tbody>
</table>

Table 5.5: Systematic errors on $P_r$

**5.2.6 Final Result**

The final result on $P_r$ in the decay $\tau \rightarrow e\nu\bar{\nu}$ is:

$$P_r = -0.096 \pm 0.091(stat) \pm 0.066(syst),$$

(5.18)

where the first error is statistical, the second systematic.
Chapter 6

Discussion

6.1 Decay Branching Ratios

The results on the leptonic $\tau$ decay branching ratios presented in this thesis confirm once again the $\tau$ decay puzzle described in Chapter 2. From the recent LEP measurements of the $\tau$ lifetime, the current world average of $\tau_{\text{mim}}$ is $3.04 \pm 0.07 \times 10^{-13}$s, or $(2.165 \pm 0.050 \times 10^{-12} \text{GeV})^{-1}$; and the $\tau$ mass (measured by the DELCO collaboration) is $1784.1^{+4}_{-3.9} \text{MeV}$. Based on these numbers one can calculate the leptonic decay branching ratios from the following expression:

$$B_l = \frac{\tau_l}{\tau_\mu} (\frac{G_F}{G_F^\mu})^2 (\frac{m_l}{m_\mu})^5$$

(6.1)

where $l = e, \mu$. This relation is affected by Standard Model radiative corrections at the percent level. The combined result is $\sim 2.2\sigma$ higher than measured values.

Using the $B_e$ obtained in this thesis, the above equation predicts a $\tau$ lifetime of $(0.283 \pm 0.007) \times 10^{-12}$s for equal coupling constants to the weak neutral current.

From the results on $B_e$ and $B_\mu$ in this thesis, using eq. (2.33) we obtain the ratio of the coupling constants to be:

$$\frac{G_F^\mu}{G_F^e} = 1.01 \pm 0.03.$$  

(6.2)

Assuming the measured values of $\tau_{\text{mim}}$ and $m_\tau$ are correct, one possible explanation for the $\tau$ lifetime discrepancy involves the introduction of a heavy 4th generation
neutrino which mixes with $\nu_3$, written as:

$$\nu_\tau = \nu_3 \cos \theta_{3-4} + \nu_4 \sin \theta_{3-4}$$  \hspace{1cm} (6.3)

there $\theta_{3-4}$ is the mixing between the two generation, similar to the Cabibbo mixing in the $d-s$ quark sector. A heavy neutrino will reduce the tau decay rates by $\cos^2 \theta_{3-4}$. $\theta_{3-4}$ can be estimated as follows: Since the mixing is expected to be small, $\nu_\tau$ is mostly $\nu_3$. Therefore to the first order one can apply the current limit on $\nu_\tau$, $m_{\nu_\tau} < 35 MeV$ to $m_{\nu_3}$. From the LEP results on the $Z^0$ width we know that $m_{\nu_4} > 45.6 GeV$. Inserting these numbers in the above equation, one has:

$$\cos^2 \theta_{3-4} = 0.943.$$  \hspace{1cm} (6.4)

### 6.1.1 $\alpha_s$ Measurements

The measured leptonic branching ratios can be used to estimate the value of $\alpha_s(Q^2)$ at $Q^2 = m_\tau^2$. The QCD expression for $R_\tau$ is:

$$R_\tau = 3 F_{\text{weak}} (1 + a K_\tau(1) + a^2 K_\tau(2) + a^3 K_\tau(3) + \delta_{\text{weak}} + \delta_{m_\pi}(a) + \delta_\tau(a))$$ \hspace{1cm} (6.5)

where $a$ is the color factor, $F_{\text{weak}} = 1.0194$ is an weak correction factor, including the factor $|V_{ud}|^2 + |V_{us}|^2$ which is close to 1. $\delta_{\text{weak}} \approx 0.001$ is a small electroweak correction term, $\delta_{m_\pi}(a) \sim -0.01$ accounts for the non-zero running coupling masses of the $u, d, s$ quarks, $\delta_\tau(a) \sim -0.01$ accounts for non-perturbative effects, $a = \frac{a_s(m_\tau^2)}{\pi}$, and $K_\tau(i)$ are the QCD predictions for the perturbative expansion, they depend on the $f$ scale through $x = ln \sqrt{f}$ and are given by:

$$K_\tau(1) = 1, \hspace{1cm} (6.6)$$

$$K_\tau(2) = 1.0857 - 0.1153 n_f + \frac{19}{21} \beta_0, \hspace{1cm} (6.7)$$

$$K_\tau(3) = -6.6368 - 1.2001 n_f - 0.0052 n_f^2 + \frac{19}{21} \beta_1 \left[ n_f \left( 1.9857 - 0.1153 n_f \right) + \frac{265}{288} \beta_0^2 \right] + 2 \beta_0 (1.9857 - 0.1153 n_f) \hspace{1cm} (6.8)$$

where

$$\beta_0 = \frac{1}{6} (33 - 2 n_f) \hspace{1cm} (6.9)$$

$$\beta_1 = \frac{1}{12} (153 - 19 n_f) \hspace{1cm} (6.10)$$

$$\beta_2 = \frac{1}{2} \left( 2837 - \frac{5033}{9} n_f + \frac{325}{27} n_f^2 \right) \hspace{1cm} (6.11)$$

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The only input needed to extract $\alpha_s(m_Z^2)$ is the leptonic branching ratio of the $\tau$ obtained in the previous section. Adding in quadrature the statistical and systematic errors, we have,

$$B_i = 0.177 \pm 0.004 R_{\tau}^{\text{exp}} = 3.61 \pm 0.12$$

(6.12)

Using eq.(6.5) with $f = 1$ and $n_f = 3$, we obtain:

$$\alpha_s(m_Z^2) = 0.34^{+0.08}_{-0.07}$$

(6.13)

which translates into a strong coupling constant $\alpha_s(m_Z^2)$:

$$\alpha_s(m_Z^2) = 0.117^{+0.008}_{-0.006}$$

(6.14)

The value is in good agreement with other L3 determinations of $\alpha_s$, $\alpha_s = 0.115 \pm 0.009$ [41] [42].

### 6.2 Determination of $\sin^2 \theta_W$

From the measured $\tau$ polarization values in Chapter 5, the $\tau$ couplings to the $Z^0$ can be determined using eq. (2.49) to be

$$\frac{n_\tau}{\alpha_\tau} = 0.048 \pm 0.045 \pm 0.033,$$

(6.15)

and the value of $\sin^2 \theta_W$ is

$$\sin^2 \theta_W = 0.238 \pm 0.011 \pm 0.008.$$

(6.16)

These results agree well with other measurements of $\sin^2 \theta_W$ at L3 [17] and other LEP experiments [34] [35] [36].

#### 6.2.1 $P_\tau$ Results From Other Decay Modes

Measurements of $P_\tau$ has been carried out with other $\tau$ decay channels at L3, the results are listed in 6.1, together with the result obtained in this thesis. The values in the $\tau \rightarrow \mu$ and $\tau \rightarrow \pi$ decays correspond only to the 1991 data.

Since the systematic errors from each decay channel are largely uncorrelated, the results from different decay channels can be combined using weighted average, i.e.

$$P_\tau = \frac{\sum_{l=e,\mu,\pi} \frac{P_{\text{exp}}}{\alpha}}{\sum_{l=e,\mu,\pi} \frac{1}{\alpha}}$$

(6.17)
<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Measured $P_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow e\nu\bar{\nu}$</td>
<td>$-0.096 \pm 0.091 \pm 0.066$</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu\nu\bar{\nu}$</td>
<td>$-0.108 \pm 0.117 \pm 0.065$</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi\nu$</td>
<td>$-0.147 \pm 0.056 \pm 0.048$</td>
</tr>
</tbody>
</table>

Table 6.1: Polarization results from various $\tau$ decay channels

with

$$\sigma_\tau^2 = \frac{1}{\sum_{\mu,\mu\nu} \sigma_i^2}.$$  \hspace{1cm} (6.18)

From this we obtain the average polarization of the $\tau$-lepton to be:

$$P_\tau = -0.129 \pm 0.044 \pm 0.034.$$  \hspace{1cm} (6.19)

Since the helicities of the two $\tau$'s in an event are completely correlated, if one uses both of them to measure the polarization the result will be correlated. If we write the distribution for positive and negative helicity particles separately:

$$H_+(h^+) = f_+(h^+) + P_\tau g(h^+)$$  \hspace{1cm} (6.20)

and

$$H_-(h^-) = f_-(h^-) + P_\tau g(h^-),$$  \hspace{1cm} (6.21)

then the correlation of the two helicities will be $c = H_+ H_-$, or

$$c = f_+(h^+) f_-(h^-) + P_\tau^2 g(h^+) g(h^-) + P_\tau [f_+(h^+) g_-(h^-) + f_-(h^-) g_+(h^+)].$$  \hspace{1cm} (6.22)

Consider the simplest case in which both $\tau$'s in a event decays in the $\tau \rightarrow \pi\nu$ mode, for $P_\tau \sim 0$, one has: $f_+(h^+) = x$ and $f_-(h^-) = 1 - x$, where $x = \frac{E_{\text{beam}}}{E_{\text{beam}}}$, $E_{\text{beam}}$. Put these into the above expression of $c$ and integral over $x$, we obtain: $c = \frac{1}{6}$. Therefore, assuming ideal acceptance, the error on the measurement of $P_\tau$ will be larger by the same amount, than treating each side of the event completely independent.

### 6.2.2 Comparison with other measurements

These results are consistent with previous measurements by L3 and other LEP and SLC experiments of electron and tau neutral-current couplings from leptonic partial widths $\Gamma(Z^0 \rightarrow l^+l^-)$ and forward-backward charge asymmetries, the values also agree with results from electron-neutrino scattering experiments. Assuming lepton
Figure 6.1: Comparison of different measurements

universality, the measurements of $A_{FB}$ and $\Gamma_{ll}$ in all three leptonic final states can be combined to get a value of $\tilde{\alpha}_l$ and $\tilde{\alpha}_l$. From the preliminary analysis of the data in all three leptonic channels of the $Z^0$ decay, it is found:

\[
\tilde{\alpha}_l = -0.4903 \pm 0.0023,
\]

\[
\tilde{\xi}_l = -0.0462 \pm \frac{0.0080}{0.0080}.
\]  

Using the value for $\tilde{\alpha}_l$, and the result in eq.(6.15), we obtain the value for $\tilde{\alpha}_l$ to be: $-0.963 \pm 0.953$. In fig. 6.1 a contour plot shows the results from the $A_{FB}$ and $\Gamma_{ll}$ obtained from 1990 data (the 1991 data has not yet been processed at the time of the writing), and the result of $\frac{\tilde{\alpha}_l}{\tilde{\alpha}_l}$ from this thesis. Clearly, the result from the polarization measurement resolved the ambiguity of the relative sign of $\tilde{\alpha}_l$ and $\tilde{\alpha}_l$.

In table 6.2 measurements of the $\tau$-polarization performed at $\sqrt{s} < M_Z$ are listed. A good agreement with the result from this thesis is seen, while the accuracy in the latter is about one order of magnitude higher.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$P_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CELLO</td>
<td>$-0.2 \pm 5.6$</td>
</tr>
<tr>
<td>MAC</td>
<td>$a_e v_\tau = (0.26 \pm 0.31)(1 \pm 0.011)$</td>
</tr>
<tr>
<td>AMY</td>
<td>$1.0 \pm 1.4$</td>
</tr>
</tbody>
</table>

Table 6.2: Measurements of $P_\tau$ at low energies

At the present the values of $\sin^2 \theta_w$ measured from $\tau$ polarization still has a larger error compared to other methods, which is due to mainly statistics. However from
eq.(2.49) it is clear that $P_\tau$ is linear in $v_\tau \propto 1 - 4\sin^2 \theta_w$ and the corresponding error on the electroweak parameter is $\Delta \sin^2 \theta_w \approx \Delta P_\tau / 8$, whereas the forward-backward asymmetry is quadratic in $v_\tau$, which gives an error $\Delta \sin^2 \theta_W \approx \Delta A_{FB} / 2$, the gain of a factor 4 in the error on $\sin^2 \theta_w$ with respect to $A_{FB}$ therefore make it possible for the $P_\tau$ measurement be competitive with even limited statistics in determining the electroweak mixing parameter.

6.2.3 Conclusions

Measurements of the leptonic branching ratios of the $\tau$ decays have been performed with $10,217 e^+e^- \rightarrow \tau^+\tau^-\nu\bar{\nu}$ events collected near the $Z^0$ resonance, the results are:

$$Br(\tau \rightarrow e\nu\bar{\nu}) = 0.1772 \pm 0.0036^{+0.0041}_{-0.0037},$$
$$Br(\tau \rightarrow \mu\nu\bar{\nu}) = 0.1760 \pm 0.0039^{+0.0039}_{-0.0036}. \quad (6.24)$$

Within error, they agree with the current world average values, and are compatible with expectations from the Standard Model based on the assumption of $e - \mu - \tau$ universality of the weak charged current couplings. From the measured $\tau$ leptonic decay branching ratios, the QCD running coupling constant $\alpha_s(Q^2 = m_\tau^2)$ is calculated to be $\alpha_s(Q^2 = m_\tau^2) = 0.34^{+0.08}_{-0.04}$, which corresponds to a value of the coupling at the $Z^0$ resonance: $\alpha_s(Q^2 = m_\tau^2) = 0.117^{+0.03}_{-0.02}$, in good agreement with the measurements done with hadronic $Z^0$ decays at the L3 experiment.

A measurement of the average longitudinal polarization asymmetry of the $\tau$ lepton is done with $2,532 \tau \rightarrow e\nu\bar{\nu}$ decays. The result is:

$$P_\tau = -0.096 \pm 0.001 (stat) \pm 0.006 (syst). \quad (6.25)$$

From this we obtain a value of the ratio of the vector - axial vector coupling constant: $v/a = 0.048 \pm 0.045 \pm 0.033$, and the weak mixing angle $\sin^2 \theta_W = 0.238 \pm 0.011 \pm 0.008$. The results are consistent with the Standard Model prediction.
Appendix A

Formulae for Radiative Corrections

The structure function $W_i(s,u)(i = 0,1)$ in Chapter 5 is defined as:

$$W_0(s,u) = \int_0^{1-u^2} \frac{dv}{\sqrt{1-v}} \rho(v) F_0(s(1-v)) H_0^r \left( \frac{u}{\sqrt{1-v}} \right), \quad (A.1)$$

and

$$W_2(s,u) = \int_0^{1-u^2} \frac{dv}{\sqrt{1-v}} \rho(v) F_2(s(1-v)) H_1^r \left( \frac{u}{\sqrt{1-v}} \right), \quad (A.2)$$

where $F_i$ are the Born form-factors. The term $\rho(v)$ describes the finitial state bremsstrahlung and can be written [22] as follows:

$$\rho(v) = \frac{e^{-C_\gamma}}{\Gamma(1+\gamma)} e^{\Delta_{YFS} \gamma v^{-1}} (1 + \Delta_s + \Delta_H(v)), \quad (A.3)$$

where

$$\Delta_{YFS} = \frac{\alpha}{\pi} \left( \frac{L}{2} - 1 + \frac{\pi^2}{3} \right), \quad (A.4)$$

$$\Delta_s = \frac{\alpha}{\pi} (L - 1) + \frac{1}{2} \left( \frac{\alpha}{\pi} \right)^2 L^2, \quad (A.5)$$

$$\Delta_H(v) = v(-1 + \frac{1}{2} v) + \frac{\alpha}{\pi} L \left\{ -\frac{1}{4} (4 - 6 v + 3 v^2) \ln(1-v) - v \right\}, \quad (A.6)$$

$$L = \ln \frac{s}{m^2}, \quad (A.7)$$

$$\gamma = 2 \frac{\alpha}{\pi} (L - 1), \quad (A.8)$$

$$C = 0.37721566. \quad (A.9)$$

This expression is the second order sub-leading approximation with the proper resummation of soft photons. It neglects the effects of the production of additional
light fermion pairs which is small and affects only the overall normalization of the cross section.

The fragmentation functions $D$ are given by:

$$D_{\tau}(-\frac{m_r^2}{s(1-v)}, x) = \delta(1-z) + \gamma_{\tau}d_{\tau}(z), \quad (A.10)$$

$$\gamma_{\tau} = \frac{\alpha}{\pi} (\ln \frac{s(1-v)}{m_r^2} - 1), \quad (A.11)$$

$$d_{\tau}(z) = \left(\frac{1}{1-z}\right)_+ + \frac{3}{4} \delta(1-z) - \frac{1}{2}(1+z), \quad (A.12)$$

$$D_{\mu}(\frac{m_\mu^2}{m_r^2}, z) = \delta(1-z) + \gamma_{\epsilon}d_{\epsilon}(z), \quad (A.13)$$

$$\gamma_{\epsilon} = \frac{\alpha}{\pi} (\ln \frac{m_\epsilon^2}{m_r^2} - 1). \quad (A.14)$$

From these fragmentation functions one can derive the general decay functions $H_i(x)$ as:

$$H_i(x) = \int_0^1 \frac{dz}{z} D_{\tau}(\frac{m_r^2}{s(1-v)}, x) \int_0^1 \frac{dt}{t} D_{\mu}(\frac{m_\mu^2}{m_r^2}, t) h_i(x) \theta(1 - \frac{x}{zt}), \quad (A.15)$$

where $h_i(x)$ are the nonradiative decay functions. In the above equation the term of order $\gamma_{\tau}\gamma_{\epsilon}$, which corresponds to the simultaneous photon emission from the $\tau$'s and it's decay product is neglected. For $\tau \rightarrow e$ decay the final results are:

$$H_0^e(x) = \frac{2 - 6x^2 + 4x^3 + \frac{4}{9}}{9} \rho(-1 + 9x^2 - 8x^3)$$

$$+ (\gamma_{\tau} + \gamma_{\epsilon})\{(-1 - 9x^2 + 4x^3)\ln(1-x)$$

$$+ \frac{4}{9} \rho(-1 + 9x^2 - 8x^3)\ln(1-x) - (1 - 6x^2 + 4x^3)\ln x$$

$$- \frac{4}{9} \rho(\frac{1}{2} + 9x^2 - 8x^3)\ln x$$

$$- \frac{1}{3}x + 4x^2 - \frac{8}{3}x^3 + \frac{4}{9} \rho(\frac{2}{3} + 2x - 8x^2 + \frac{16}{3}x^3)\}$$

$$H_1^e(x) = \frac{-2}{3} + 4x - 6x^2 + \frac{8}{3}x^3$$

$$+ \frac{4}{9} \delta(1 - 12x + 27x^2 - 16x^3)$$

$$+ (\gamma_{\tau} + \gamma_{\epsilon})\{(-\frac{2}{3} + 4x - 6x^2 + \frac{8}{3}x^3)\ln(1-x)$$

$$+ \frac{4}{9} \delta(1 - 12x + 27x^2 - 16x^3)\ln(1-x)$$

$$- (-\frac{1}{3} + 2x - 6x^2 + \frac{8}{3}x^3)\ln x$$

$$- \frac{4}{9} \delta(\frac{1}{2} - 6x + 27x^2 - 16x^3)\ln x + \frac{7}{9}$$
\[-\frac{5}{3}x + \frac{8}{3}x^2 - \frac{16}{3}x^3 \]
\[+ \frac{4}{9} \delta \left( -\frac{5}{3} + 7x - 10x^2 + \frac{32}{3}x^3 \right) \]
Appendix B

BGO linearity

To quantify the possible offset and scaling effect in the energy measurement of the ECAL, we start from the comparison between the measured and the kinematic prediction of the photon energy in the $e^+e^-\gamma$ sample. In fig. B.1 such a distribution is shown. A fit to a straight line yields a slope of $0.9961 \pm 0.0100$, and an offset of $-0.3995 \pm 0.1881$, which is consistent with zero within error. The first bin was not fitted because of uncertainties on the energy calculation at low energies.

Similar study was carried out with Monte Carlo Bhabha events, where hard radiative photons are searched and their energy are compared with kinematic predictions, as shown in fig. B.2. In this plot the entries at each bin for measured photon energy are grouped into four bins and fitted to a gaussian. The mean position from each fit is taken as the y-coordinate, and the error bars are calculated from the widths of the distribution. This is necessary especially at low energies, where radiation tends to stretch the energy distribution and thus shift the mean position to higher scale. From the fit we obtain a scale factor of $1.014 \pm 0.007$, which agrees with what has been found in the Bhabha Monte Carlo (see Chapter 5). An offset is excluded at the level of a few MeV.

As a cross check, in fig. B.3 we plotted the electron energy from Monte Carlo $\tau \rightarrow e$ decays. The x-axis is the generator level energy, the y-axis is the energy reconstructed by the BGO. Once again a slope consistent with previous plot is found, and the amount of the offset is negligible. Fig. B.4 shows how the ratio of reconstructed and generator energy changes with respect to the generator level energy.
Figure B.1: Measured photon energy vs. prediction from kinematics from $ee\gamma$ data

Therefore, the scale factor observed in Bhabha events (+0.004) is verified by studies at low energy region. Within statistical error such a scale can be treated as independent of the electron energy.

The amount of offset in the BGO energy scale is consistent with zero.
Figure B.2: Measured photon energy vs. prediction from kinematics for Monte Carlo events

Figure B.3: Reconstructed vs. generator level electron energy for $\tau \rightarrow e\nu\bar{\nu}$ events
Figure B.4: Reconstructed vs. generator level electron energy for $\tau \rightarrow e\nu\bar{\nu}$ events
Appendix C

PSF System

In order to achieve an accuracy of 0.1% on the drift velocity in the TEC, an external calibration system made of Plastic Scintillating Fibers (PSF) is implemented. It provides an independent measurement of the track position in the $r - \phi$ plane at the outer TEC surface. By fitting the measured average drift time as a function of the track coordinates determined from the signals in the fibers, the drift velocity can be calculated and used to calibrate the values obtained from the TEC. A detailed discussion of the calibration method can be found in [48]. This appendix contains a description of the PSF readout system hardware.

C.1 Overview of the PSF system

Every one of the 24 outer sectors of the TEC is covered by a ribbon in azimuth. Each ribbon contains 143 plastic scintillating fibers of 1.3 mm, 1 mm thick and 0.7 mm wide. The fibers have a doping of 1% butyl-PBD and 0.02% BDB with a polystyrene base. Their spectral range is between 300 – 500 nm. The photoelectron yield of the fibers are measured in the laboratory with a $^{90}$Sr source and an RCA 8850 Quantacon photomultiplier tube. At a distance of 1.2 m the average number of photoelectron was found to be $\sim 2$.

The ribbons are polished at both ends. At one end, each is optically coupled to two 100-anode micro-channel-plate (MCP) phototubes which are then readout via a multiplex amplifier chip (MX4). The fiber-MCP interface is carefully aligned to
ensure a one-to-one fiber-anode correspondence. The other end of the ribbons are mirrored to reduce light loss.

The CMOS MX4 chip is triggered externally to sample and multiplex the signals from all anodes of the MCP tube. The outputs are then digitized by the 75C58 CMOS 8-bit flash converters, and recorded by the TEC readout system. A signal in a fiber is registered as a bit 1 at its corresponding anode.

### C.2 The MCP tube

The MCP phototube (manufactured by ITT) used in this system has an average electron gain of $10^6$ in a 5KG magnetic field. It has 100 anodes arranged in a $10 \times 10$ array. The tube has a diameter of 52mm and a length of 18mm. The quantum efficiency of the photocathodes varies between 10 – 40% at 450nm, and the dark current rate is $\sim 10$ kcounts/s at $23^\circ$C. In application, the photocathode is set at $-200V$, the three stage microchannel plates is set at $-2,000V$ to $-2,500V$ and the anode is at $-50V$. Since the manufacturing processes for the MCPs could not be kept constant, their performance varies over a large range [49]. Individually customized HV bleeder chains are made to correct the voltage differentials needed to optimize each tube’s performance.

A prototype single-anode MCP tube was used to test the characteristics of the microchannel plates. Shown in fig C.1 is the photoelectron spectrum from such a tube, as a comparison, a spectrum from an RCA 8850 Quantacon was also shown. One finds the resolution in the case of the MCP is worse compared with that of the Quantacon. This is due to electron multiplication of the three microchannel plates spreads over many channels, resulting an electron cloud with a higher density at the center and produces a broader and less resolved photoelectron peaks.

Lab test was conducted to understand the behavior of the MCP tubes in magnetic fields. Fig. C.2 shows the response of the MCP tube as a function of the magnetic field strength. There is a loss of the gain at 5KG (the L3 environment) which is consistent with the theory of the MCP [50]. This is recovered by increasing the voltage on the microchannel plates by $\sim 50V$ over their nominal value at 5KG.
Figure C.1: (a). Photoelectron spectrum from an ITT single anode MCP tube; (b). Photoelectron spectrum from an 8850 Quantican

Figure C.2: Gain variation of the MCP tube as a function of magnetic field
The 143 fibers of each ribbon is grouped into two 10 x 10 arrays similar to that of the anode array on the MCP tube. One array has 71 fibers, the other 72. each array is then mounted in a DELRIN plate, which could be coupled to an alignment ring that was glued to the photocathode surface of the MCP. This method provides a plug type of optical connection which maintains positional alignment for each fiber to its photocathode sensitive area.

Prior to installation, each MCP tube was aligned to a prototype 10 x 10 fiber array with fibers at only the four corners, the crosstalk between anodes were checked and minimized during the the alignment. Finally an alignment ring was glued onto the MCP. The tube was then tested with a setup which has 10 x 10 fibers mounted in a DELRIN plate, each fiber can be fired off individually to examine for crosstalk.

C.3 Analog electronics

The CMOS MX4 microplexer chip is chosen because of its capability of readout large number of channels (128) in serial at a high speed, and its low electronic noise. Fig. C.3 is a simplified circuit diagram for one channel of the chip. The readout of the PSF system works as follows: The cycle time at LEP is 22.2μs. When a positive trigger is issued, the information from all subdetectors are collected and transferred to the data buffers within 500μs. If instead a negative trigger is issued, a fast clear signal is sent out at about 2.2μs prior to the next collision by the level one trigger to reset all readout devices. The PSF readout uses the fast clear to start its data taking cycle. The RESET signal opens the amplifier switch and charges are stored on the two capacitors C1 and C2 (see fig. C.3). After ~1μs C1 stops charging and C2 continues to sample the signal for another 500ns. The beam collision occurs within this sampling time. By comparing the charges on the two capacitors a good signal to noise ratio can be obtained.

When a positive trigger is issued, the stored charges from the two capacitors are then subtracted and the reminder is transferred to the digitization circuits (see next section) at a rate of 1MHz. If a fast clear is issued, a new data taking cycle starts.

The MX4 chips are microbonded onto a substrate with a pad separation of 88μm. The substrate is mounted on a circuit board (PSF-100) which contains the driving
amplifiers, coupling capacitors and resistors, and a $10 \times 10$ brass tube array of 1cm long for connecting to the anode pins of the MCP tube.

C.4 Digitization and DAQ

A/D boards and their operation modes

The PSF A/D Board is a 233mm x 160mm (6U) VME four layer printed circuit board. Each A/D board has two analog to digital (A/D) converters for digitizing the output signals from the PSF-100 boards. Total of 24 boards are installed to process signals from the 48 MCP tubes. Fig. C.4 is the block diagram of an A/D board.

The analog input signal is connected to J4, a front panel connector, using a coaxial cable between the PSF-100 box mounted on the TEC and the blockhouse. An OPA620 high speed amplifier (U4) is used to invert and buffer the input signal to the A/D.

The 75C58 CMOS 8-Bit flash converter is used because of its high speed (20MHz)
and relatively low power consumption. The output of the converter is internally buffered to couple it to a pair of 74F181 4-Bit Arithmetic Logic Units (ALU).

Prior to data taking, the PSF A/D board is programmed to store the pedestals from the MX-4 output, plus a threshold value in the Static Random Access Memory (SRAM). This will allow the ALU's to discriminate between valid data and background signals. The pedestal value varies for each of the 128 channels due to the differences in the zero level of the MX-4 for each channel.

The ALU's are used for three different functions: $F = A + B$, $F = A - B - 1$ (for $A > B$), and $F = A$. There are four modes of operation:

- Pedestal plus threshold storage mode: This is done before the global data taking begins. To set up the data path for this mode, U15 and U17 will be enabled (see fig. C.4). The ALU's are set to the $F = A + B$ function so the converter output $A$ (data value) will be added to the threshold value $B$ and stored in the SRAM. The threshold value can be supplied from the on board switch (local) or from the control board (remote) depending on the status of the remote signal. This operation will be repeated for all of the 128 channels on each MX-4 chip.
Run mode: In this mode the analog input is digitized, and compared to the pedestal plus threshold value stored previously for each channel. The data path for this operation is set up by enabling U16 and disabling U15 and U17 (Figure 3), to connect the SRAM output to the B inputs of the ALU's. The ALU's will be set for the \( F = A - B - 1 \) (for \( A > B \)) function and the \( C_{n+4} \) bit will be monitored for each channel. The \( C_{n+4} \) bit is high only if the analog input is greater than the previously stored value of the pedestal plus threshold for that specific channel. The data consists of a serial string of 128 bits, each corresponds to a specific fiber mounted on the TEC. The bit is set to 1 if a fiber has detected a particle.

The run mode generates two data streams per A/D board each consisting of 128 bits. The data from eight boards is packed into a 16-bit word and converted to differential ECL logic to drive the 70-meter long cable connected to the data storage electronics. Three of these data blocks are necessary to handle all the information generated from the 48 MCP-PMT's.

There are two other operation modes which allow raw data or pedestal data to be stored for diagnostic purposes.

- **Raw data output mode:** This mode is set up by enabling U24 and setting the ALU's to the \( F = A \) function. Only one A/D board at a time can be addressed in this mode since the data is read out on a common BUS (J1 of the VME BUS). Channel A uses D00-D07 of the VME BUS and Channel B uses D08-D15.

- **Pedestal output mode:** This mode is set up by disabling the A/D (U3) so that its output is tri-stated and enabling U16 and U24. The ALU's are set to the \( F = A + B \) function but since A is disabled the output is equivalent to \( F = B \). This allows the pedestal plus threshold value stored in the SRAM to be read out on the VME BUS. Only one A/D board is enabled at a time.

In the last two modes the TTL to ECL translator can only be activated in the offline state because its data form is different and is stored in a separate data base. There are two 8-bit data busses which are common to all A/D J1 data lines. Each A/D board has two tri-state buss drivers which are activated sequentially from board to board, allowing only the selected A/D board to access the two busses. Depending on the function code sent to the ALU, either the threshold SRAM (8 X 128) or the 8 bit A/D conversion data from the PSF-100 electronics is applied to the dual busses and then transmitted to the data storage electronics.
Two 26C31 differential line drivers are used to send control and timing signals to the PSF-100 boards mounted on the TEC. Adjustable voltage regulators are used to send three voltages to the PSF-100 boxes. The voltages are set slightly higher than the nominal values to compensate for the voltage drop over the 40-meter cable between the voltage regulators and the PSF-100 boards. Each A/D board can supply power control signals for three PSF-100 boxes. Every PSF-100 box has two data outputs which are connected to one A/D board.

**Control board**

The PSF Control Board is a 233mm x 160mm (64U) VME board with J1 and J2 connectors. Fig. C.6 is a block diagram of the control board. The J1 connector follows the VME BUS specification and J2 is defined specifically for this application. Only one control board is used for the whole PSF readout system. The control board is located in Crate 1, and is connected with Crate 2 through a 64 conductor flat ribbon cable from Crate 1 to Crate 2.

A list of the signal names and their functions are provided in table B.4. In table B.5 the functions of the jumpers on the control board is explained. The timing diagram of the PSF system is shown in C.5.

The control board accepts timing and synchronization signals from the BGO and Trigger groups. It also provides an interface to the PSF-DIP located about 70m away from the PSF digitization electronics. Differential ECL to TTL receivers and TTL to differential ECL drivers are used for these signals. The operator's terminal communicates with the control board via an RS-232C serial link to the CY-233 serial I/O board. The PSF A/D boards are driven from the control board which has separate BUS drivers for each crate.

The control board uses variable pulse generators to generate the reset and sampling signals to the PSF-100 boards. These signals are sent to the PSF-100 board via the differential line drivers located on the PSF A/D boards. The sampling signals are synchronized to the beam crossing (TLO) so that the MX-4 chip samples the MCP outputs during the proper time for the event. This timing is adjusted to taking into account of the delays in the logic and the 40 meter cable from the blockhouse to the TEC detector.
A programmable logic sequencer, the PLS-105, is used to generate the two phase clock (PHI1, PHI2) and the Start Readout (SIN) PSF signals to the MX-4 chips located on the PSF-100 boards. These signals are delayed to account for cable propagations and used to synchronize the A/D converters to the 128 channel serial analog outputs from each MX-4. The sequencer is only started if the control board receives a TL1 accept after being properly initialized. The MX-4 readout does not begin until after a 5 micro-second hold off signal is received from the BGO group. This prevents any electronic interference with the BGO electronics.

A thumbwheel switch is provided for manual control of the threshold that drives the A/D boards. The threshold can also be supplied from an external source via the port on the CY-233 I/O board. The control board has several built in diagnostic features to test the system. The PLS-105 can be used to supply S1, S2, and RESET signals to perform a self test. A calibration signal "CAL" is also generated by the PLS-105 and sent to the PSF-100 board via the A/D board. This signal will be used when testing the system to verify the MX-4 response.

The A/D board select lines are driven by a counter or from the CY-233 I/O board. These 5 lines sequentially select 1 of the 24 A/D boards for raw data output or
pedestal readout. Only one board is enabled at a time since the boards share a common data BUS for these operations. The A/D board address can also be manually incremented with a front panel mounted pushbutton switch for diagnostic testing. The front panel has two LEDs to indicate status; one for the 5V power supply and one to indicate that the system is at ONLINE. The two VME Crates in which the system is installed each have a standard VME J1 backplane. They each have a J2 backplane that is built from a standard VME backplane with custom wire-wrapped circuit additions for this application. Each of the 24 A/D boards is identical, but they are installed in slots that have unique wiring to the control board for the board select (/Raw) line. Each A/D board slot also has unique wiring for the two data output channels, Data A and Data B. Eight A/D boards with 16 outputs are wired to one PSF TTL to ECL board that contains 16 TTL to differential ECL drivers. Three TTL to ECL boards are used in the system, and they each supply data to one PSF-DIP located in P4.
PSF-DIP

The Data Reduction Processor (DRP) used for the TEC is designed to provide multiple microcomputer processing to refine the information from the detector and thus to reduce the amount of computer storage. The input side of the DRPs are composed of Flash Analog to Digital converters (FADC) that digitize the analog signals generated by the TEC. Both time and amplitude information can be processed via these FADC-DRP units.

The DRP units used in handling the data from the PSF system have been modified to accept parallel differential ECL information in the form of 256, 16 bit words per event for each unit. Three units are necessary to handle all the data from the PSF system. The PSF-DRP's front end was named the Plastic Scintillating Fiber Data Input Port (PSF-DIP). The advantage of using the same DRP device allows the PSF data to be incorporated in the common data base for the entire L3 detector, thus reducing complicated computer book keeping.

PSF logics

In tables B.6-8 the logics for different operation modes are listed.

C.5 Summary

The readout system for the PSF has been functional successfully since first installation. The results from the 1990 and 1991 LEP physics run periods have shown that the PSF system reached its design goal. A signal to noise ratio of 20:1 and a fiber-to-fiber crosstalk of negligible amount ensures correct locating of the fiber hits, thus a high single fiber resolution of 245μm [51] which agrees with the design value. The efficiency of the PSF system was ~ 21% and ~ 17% during the 1990 and 1991 run period, respectively, which is lower than expected ~ 30% (the drop of efficiency in 1991 was due to improper adjustment of the threshold), and remains to be improved through better tuning of the threshold settings. Preliminary calibration results using the PSF have shown improvements in the error of the TEC global drift velocity [52].
<table>
<thead>
<tr>
<th>Signal name</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0,C1,C2,C3</td>
<td>Control the logical operation of the ALU</td>
</tr>
<tr>
<td>CEN</td>
<td>Convert enable for the A/D board</td>
</tr>
<tr>
<td>RUN</td>
<td>Connect the RAM to the ALU</td>
</tr>
<tr>
<td>WRITE</td>
<td>Switch on the WRITE enable to RAM</td>
</tr>
<tr>
<td>READ</td>
<td>Switch on the READ enable to RAM</td>
</tr>
<tr>
<td>CRATE 1</td>
<td>enable/disable CONTROL and DATA for crate 1</td>
</tr>
<tr>
<td>CRATE 2</td>
<td>enable/disable CONTROL and DATA for crate 2</td>
</tr>
<tr>
<td>BOARD SELECT</td>
<td>enable raw data output of the A/D board</td>
</tr>
<tr>
<td>TW</td>
<td>Select MASTER or EXTERNAL threshold</td>
</tr>
<tr>
<td>RST</td>
<td>System reset</td>
</tr>
<tr>
<td>ABORT</td>
<td>Stop data transmission to PSF-DIP</td>
</tr>
<tr>
<td>OE</td>
<td>Enable TTL to ECL outputs</td>
</tr>
<tr>
<td>MODE</td>
<td>Change TTL to ECL data format to memory data</td>
</tr>
<tr>
<td>A/B</td>
<td>Select A or B RAM on the A/D board</td>
</tr>
<tr>
<td>TEST</td>
<td>System self test</td>
</tr>
<tr>
<td>REMOTE</td>
<td>Select remote or local control</td>
</tr>
<tr>
<td>MRST</td>
<td>Master reset</td>
</tr>
<tr>
<td>DS</td>
<td>Data strobe to PSF-DIP</td>
</tr>
<tr>
<td>EOR</td>
<td>End of record to PSF-DIP</td>
</tr>
<tr>
<td>WA</td>
<td>Write abort to PSF-DIP</td>
</tr>
<tr>
<td>PRDY</td>
<td>PSF ready</td>
</tr>
<tr>
<td>DRDY</td>
<td>PSF-DIP ready</td>
</tr>
<tr>
<td>PBC</td>
<td>Pre-beam crossover from PSF-DIP</td>
</tr>
<tr>
<td>WAO</td>
<td>Write abort from PSF-DIP</td>
</tr>
<tr>
<td>TL1YES</td>
<td>Alternate start signal</td>
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<tr>
<td>TL0</td>
<td>level-0 trigger</td>
</tr>
<tr>
<td>TL1ABORT</td>
<td>LEVEL-1 abort</td>
</tr>
<tr>
<td>FAST CLEAR</td>
<td>Start PSF-100 sampling the event sequence</td>
</tr>
<tr>
<td>A7</td>
<td>Abort sequencer data output</td>
</tr>
<tr>
<td>PED</td>
<td>Enable pedestal data to the ALU</td>
</tr>
<tr>
<td>CAL</td>
<td>Calibrate test pulse signal</td>
</tr>
<tr>
<td>SIN</td>
<td>Start data output from PSF-100</td>
</tr>
<tr>
<td>S1</td>
<td>Store pedestal</td>
</tr>
<tr>
<td>S2</td>
<td>Store pedestal plus signal</td>
</tr>
</tbody>
</table>

Table C.1: A list of the signal names and their functions

116
<table>
<thead>
<tr>
<th>Control board jumpers</th>
<th>Test point</th>
</tr>
</thead>
<tbody>
<tr>
<td>1....RESET SELECT</td>
<td>1..CAL1</td>
</tr>
<tr>
<td>2....SELECT SAMPLE SOURCE</td>
<td>2..SAMPLE'</td>
</tr>
<tr>
<td>3....S1-S2 REVERSAL</td>
<td>3../S1R</td>
</tr>
<tr>
<td>4....S1-S2 REVERSAL</td>
<td>4../S2R</td>
</tr>
<tr>
<td>5....SELECT START SOURCE</td>
<td>5../RESET</td>
</tr>
<tr>
<td>6....SELECT ABORT SOURCE</td>
<td>6..START</td>
</tr>
<tr>
<td>7....DISABLE CRATE 2</td>
<td>7../RST</td>
</tr>
<tr>
<td>8....DISABLE CRATE 1</td>
<td>8..EOR</td>
</tr>
<tr>
<td>9....LOCAL PSF-100 TESTING</td>
<td>9..SAMPLE</td>
</tr>
<tr>
<td>10..DISABLE EXT A/D ADDRESSING</td>
<td></td>
</tr>
<tr>
<td>11..LOACL PSF-100 TESTING FOR S1.S2.RST</td>
<td></td>
</tr>
<tr>
<td>12..SELECT CLOCK SOURCE</td>
<td></td>
</tr>
<tr>
<td>13..MAN/AUTO INC A/D CARD ADDRESS SELECT</td>
<td></td>
</tr>
<tr>
<td>14..INTERNAL OSC POWER</td>
<td></td>
</tr>
<tr>
<td>15..DISABLE A/D CARD SELECT COUNTER</td>
<td></td>
</tr>
<tr>
<td>16..DISABLE SELF TEST CLOCK</td>
<td></td>
</tr>
<tr>
<td>17..DISABLE BNC TEST OUTPUTS</td>
<td></td>
</tr>
</tbody>
</table>

Table C.2: Control board jumpers

Pedestal store mode (Local or Remote)

Disable PRDY, STRB and abort communication to the DRP's;
Issue a read command to obtain pedestals;
Select ALU function F(F:A+B. A:A/D, B:threshold);
Select memory write;
Select PED;
Start digitizing;
Send SIN,01,02 to PSF-100's;
Enable ARM CONV;
Look for Q7 to end data transfer.

Table C.3: PSF logics: Pedestal and store mode
Run mode
hline Select threshold
Enable PRDY, STRB, abort to DRP's
Clear counters
Select ALU function F(F:A+B, A:A/D, B:threshold);
Select run
Start on BC0
Wait for BGO OK signal
Issue SIN.01,02 to PSF-100's
ARM CONV Enable
01', 02' Clocking (240ns delay)
Strobe data to DRP's
Generate EOB from Q7, drop PRDY to DRP's

Table C.4: PSF logics: Run mode 1

<table>
<thead>
<tr>
<th>Run mode: to read the memory into the DRP's</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fake PRDY and STRBS to the DRP's</td>
</tr>
<tr>
<td>Disable abort from DRP's</td>
</tr>
<tr>
<td>Clear all counters</td>
</tr>
<tr>
<td>Select A/D board address (1-24)</td>
</tr>
<tr>
<td>Select ALU function</td>
</tr>
<tr>
<td>Select read mode</td>
</tr>
<tr>
<td>Set run</td>
</tr>
<tr>
<td>Select raw mode</td>
</tr>
<tr>
<td>Generate start</td>
</tr>
<tr>
<td>Strobe data to DRP's</td>
</tr>
<tr>
<td>Generate EOB from Q7, drop PRDY</td>
</tr>
</tbody>
</table>

Table C.5: PSF logics: Run mode 2
Bibliography


[12] L3 software, CERN.

[13] The L3 Collaboration, B. Adeva et al.,
    The construction of L3
    NIM A 289 (1990) 35.

[14] S. W. Herb et al.,

[15] "Large Electron Positron storage ring", tech. notebook; CERN publication
    (november 1989).

[16] F. Dydak, Results from LEP and the SLC,
    Raporteur talk, 25th international conference on HEP
    Singapore (august 1990).
    CERN preprint PPE/91-14.

[17] The L3 Collaboration, B. Adeva et al.,
    Measurement of the Electroweak Parameters from Hadronic and Leptonic decays
    of the Z⁰

[18] M. Fukushima,
    The trigger and data acquisition system of the L3 experiment,
    L3 Internal note 957

[19] F. Bruyant
    The L3 event reconstruction. Concepts and data structures
    L3 internal note 743, March 26, 1990.


[22] F. A. Berends, Z⁰ Line Shape,
    Z⁰ Physics at LEP1 (volume 1), CERN Yellow repport 89-08,
    Edited by G. Altarelli, R. Kleiss, C. Verzegnassi.

[23] J.D. Bjorken
    Proceedings of the 1976 SLAC Summer Institute on Particule physics
[24] $Z^0$ Physics at LEP 1,
Edited by G. Altarelli, R. Kleiss, C. Verzegnassi.
CERN Yellow Report 89-08 volume 2.

[25] Particle Data Group

[26] KORALZ, S. Jadach et al.
$Z^0$ physics at LEP 1,
Edited by G. Altarelli, R. Kleiss, C. Verzegnassi.
CERN Yellow Report 89-08 Vol. 3.

[27] The L3 Collaboration, B. Adeva et al.
Decay properties of tau leptons measured at the $Z^0$ resonance. L3 preprint #31,
submitted to Phys. Lett. B.


[49] ITT Technical Data Sheet F4149. ITT Technology Co., Fort Wayne, IN, USA.


VITA

Jianzhong Bao was born in 1961. He entered Nankai University at Tianjin, China in 1979 and obtained a B.S. degree in 1983 and a M.S. degree in physics in 1986. In September of 1986 he began studying in the Physics Department at Johns Hopkins. After completing the course requirements and one year's involvement in the development of the readout electronics for the Plastic Scintillating Fiber system for the L3 detector, he moved to CERN in November of 1989 to continue his research. At CERN he worked on the calibration of the z-coordinates for the vertex chamber, and later the identification of various tau decay modes. In the spring of 1991 he began studying the leptonic decays and polarization of the tau lepton in its electron decay mode, which eventually became the topic of this thesis.