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SEARCH FOR THE B_c
MESON IN HADRONIC Z^0 DECAYS
USING THE OPAL DETECTOR AT LEP

by

Matthew Fairbanks Herndon

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Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
1999

Advisory Committee:

Professor Abolhassan Jawahery , Chairman/Advisor
Professor Nick Hadley
Professor Sarah Eno
Professor Rabindra Mohapatra
Professor Alice Mignerey

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ABSTRACT

Title of Dissertation: SEARCH FOR THE B_c
MESON IN HADRONIC Z^0 DECAYS
USING THE OPAL DETECTOR AT LEP

Matthew Fairbanks Herndon, Doctor of Philosophy, 1999

Dissertation directed by: Professor Abolhassan Jawahery
Department of Physics

A search for decays of the B_c meson was performed using data collected from 1990–1995 with the OPAL detector on or near the Z^0 peak at LEP. The decay channels $B_c^+ \rightarrow J/\psi\pi^+$, $B_c^+ \rightarrow J/\psi a_1^+$ and $B_c^+ \rightarrow J/\psi\ell^+\nu$ were investigated, where ℓ denotes an electron or a muon. Two candidates are observed in the mode $B_c^+ \rightarrow J/\psi\pi^+$, with an estimated background of (0.63 ± 0.20) events. The weighted mean of the masses of the two candidates is $(6.32 \pm 0.06) \text{ GeV}/c^2$, which is consistent with the predicted mass of the B_c meson. One candidate event is observed in the mode $B_c^+ \rightarrow J/\psi\ell^+\nu$, with an estimated background of (0.82 ± 0.19) events. No candidate events are observed in the $B_c^+ \rightarrow J/\psi a_1^+$ decay mode, with an estimated background of (1.10 ± 0.22) events. Upper bounds at the 90% confidence level are set on the production rates for these processes.

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DEDICATION

To my parents William and Nancy Herndon

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The research performed in this thesis was completed with the help of hundreds of people. Thanks are due to the people who designed, built and operated the LEP collider. Thanks are due to all of the members of the OPAL detector collaboration who worked to design, build and operate the OPAL experiment.

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Chapter 1

Introduction

The LEP programs involving the collision of electron and positron beams at center of mass energy at or near the Z^0 resonant peak produced data for seven years from 1989 to 1995. The data was recorded and analyzed by four detector collaborations; ALEPH, DELPHI, L3 and OPAL. In total approximately sixteen million hadronic Z^0 decays were recorded by the four experiments combined. This allowed the detailed study of the electroweak force through the production and decay of Z^0 bosons. One important area of physics study possible at LEP was the study of the b quark. Approximately 15.16% of Z^0 decays or 21.69% of hadronic Z^0 decays are to $b\bar{b}$ [1]. The large number of b quarks produced, along with the high boost of the b quarks and the clean environment provided by an e^+e^- collider made LEP an ideal place to study b physics.

The properties of b flavored hadrons have been studied at many experiments. Properties studied in detail include the production mechanisms, spectroscopy, decays and lifetimes. In particular the study of the spectroscopy of the ground-state pseudoscalar mesons containing a b quark is almost complete with all the predicted states having been observed, by experiments at CESR, DORIS, LEP and the TEVATRON, except for the beauty-charm meson $B_c(\bar{b}c)$. The B_c meson can be produced at LEP in hadronic Z^0 decays. Though few B_c are expected to be produced at LEP if they are found this will allow the B_c mass and production rate to be measured.

This work reports on a search for B_c decays in a data sample of 4.2×10^6 hadronic Z^0 decays collected with the OPAL detector at LEP. The analysis of the B_c decays includes searches for the decay modes $B_c^+ \rightarrow J/\psi \pi^+$, $B_c^+ \rightarrow J/\psi a_1^+$ and $B_c^+ \rightarrow J/\psi \ell^+ \nu$, where ℓ denotes an electron or a muon.

A summary of the relevant theoretical background is given in chapter 2. This includes a brief introduction to the Standard Model which focuses on the topics of the weak interaction, the CKM matrix and QCD. Also specific models of b flavored hadron production, spectroscopy and decay are discussed.

A description of the LEP collider and the OPAL detector is given in chapter 3. Also simulation and processing procedures for data are discussed.

The analysis is presented in chapter 4. The event selection procedure is described. The efficiencies and backgrounds for each decay mode are presented. The candidate events are discussed and the results presented in the form of production rate limits for each decay mode.

In chapter 5 the results are summarized and compared to the results of other relevant experiments.

Appendix A describes the results of a research and development study. The project involved the design of a Time-of-Flight system for the Babar detector at Stanford Linear Accelerator.

Chapter 2

Theory

2.1 The Standard Model

The Standard Model is the most successful theory for describing the interactions between the known fundamental particles of nature. The fundamental particles in this model are known as quarks and leptons. They are pointlike, spin $\frac{1}{2}$ objects. There are six flavors of quarks and leptons and a left and right-handed helicity version of each flavor of particle (See table 2.1). The left-handed particles are grouped into three families of weak isospin doublets according to how they interact. The right handed particles are grouped in weak isospin singlets.

Leptons		Quarks	
Left-handed	Right-handed	Left-handed	Right-handed
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	e_R, ν_{eR}	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	u_R, d_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\mu_R, \nu_{\mu R}$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	c_R, s_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\tau_R, \nu_{\tau R}$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	t_R, b_R

Table 2.1: The fermions

The letters u, d, c, s, t and b represent the six quark flavors; up, down, charm, strange, top and bottom respectively. The letters e, μ , τ , ν_e , ν_μ and ν_τ represent

the electron, muon and tau leptons and their associated neutrinos respectively.

There are four known fundamental interactions between the particles. They are known as the electromagnetic, weak, strong and gravitational interactions. The first three interactions are known to be mediated by force carriers called intermediate gauge bosons. These bosons are spin one objects. Some theories postulate that the gravitational force is carried by a spin two boson known as a graviton. The forces and associated gauge bosons are listed in table 2.2. The gravitational force acts on all the particles, including the neutrinos. However, it is too weak to affect interactions at particle accelerators. The strong force acts on the quarks, the weak force acts on all the quarks and leptons and the electromagnetic force acts on all of the quarks and leptons except the neutrinos. The particles that each force acts on are said to carry the charge of that force. These charges are electric charge, flavor and color for the electromagnetic, weak and strong forces respectively. An additional boson, the Higgs, is postulated which gives mass to the other fundamental particles through its interactions with them.

Boson Name	Associated Force
photon (γ)	Electromagnetic
$W^{\pm}, Z^0$	Weak
gluon (g)	Strong
graviton	Gravitational

Table 2.2: The bosons

The fundamental particles and the interactions between them, with the ex-

ception of gravity, can be understood in terms of Yang-Mills gauge theories. A complete unified theoretical description of the electromagnetic and weak forces is given by the group $SU(2)_L \otimes U(1)_Y$ in a model known as the Electroweak Model. Quantum Chromodynamics(QCD) gives a description of the strong force in terms of the group $SU(3)_C$. Work in understanding the implications and measuring the parameters of these theories is ongoing. Relevant features of each of these theories will be discussed in the following sections.

2.2 The Electroweak Model

2.2.1 The Electromagnetic Interaction

The electromagnetic force is familiar as providing the binding energy in atoms and is classically described by the Maxwell's equations. The electromagnetic interaction can be described in terms of quantum field theory and gauge theory. In this formalism the particles of nature are described by fields and the interactions arise from a local gauge symmetry. The Standard Model holds that the electromagnetic, weak and strong interactions all arise from local gauge symmetries of which the electromagnetic interaction is the simplest example. In addition each symmetry has an associated conserved quantity. The interactions of these fields is described by a Lagrangian and the equations of motion and conserved quantities can be found by computing the Euler-Lagrange equations.

The electromagnetic force is known to be invariant under internal local phase transformation of the fields under the $U(1)$ group. It can be shown that a valid Lagrangian and equations of motion for the electromagnetic interaction must include a vector boson field, $A_\mu(x)$, to remain invariant under this type of

transformation. The resulting Lagrangian is

$$\mathcal{L} = \bar{\psi}i\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi + e\bar{\psi}\gamma^\mu\psi A_\mu$$

where $\psi(x)$ are complex fields that represent the interacting spin $\frac{1}{2}$ particles (spinors) of nature. The vector field A_μ that was introduced can be identified as the photon field. The term $m\bar{\psi}\psi$ gives mass to the particle field ψ . The term $e\bar{\psi}\gamma^\mu\psi A_\mu$ defines the form and strength of the interaction between the particle fields and the photon field. By computing the Euler-Lagrange equations for this Lagrangian we find that the charge $Q = \int d^3x j^0$ is conserved, where $j^0 = e\bar{\psi}\gamma^0\psi$. The theory outlined above is known as Quantum Electrodynamics (QED).

2.2.2 The Weak Interaction

The weak interaction was first observed in the β decay of nucleons. Both hadrons and leptons can decay via the weak interaction. Examples of decays via the weak interaction for leptons and hadrons respectively are μ decay, $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ ¹, and π^+ decay, $\pi^+ \rightarrow \mu^+ \bar{\nu}_\mu$. At typical energies for particle decay the weak interaction is several orders of magnitude weaker than the strong and electromagnetic interactions. This relative weakness leads to the long lifetime of particles that decay exclusively via the weak interaction. At the energy scales of typical high energy colliders, about or above 100 GeV, the magnitude of the weak interaction becomes comparable to that of the electromagnetic interaction.

One of the first successful models of the weak interaction was developed by

¹Throughout this thesis charge conjugate modes are implied.

Enrico Fermi[2]. He described the weak interaction as involving two weak “currents” in a vector-vector interaction analogous to the electromagnetic interaction with a magnitude parameterized by the Fermi constant, G_f . The Fermi constant can be accurately measured in experiments such as the measurement of the muon lifetime and has a value of $G_f = (1.16639 \pm 0.00001) \times 10^{-5} \text{ GeV}^{-2}$ [3].

Further experimentation revealed that Fermi’s model of the weak interaction was incomplete and needed to be modified. For instance in 1950 in an experiment performed by Wu *et al.* it was shown that the weak β decay of ^{60}Co violated parity conservation in the weak interaction [4]. Parity violation could be included in the weak interaction by modifying the vector current to a vector and axial vector form [5]. Further experiments revealed that the strength of the weak interaction in muon decay was 2.6% more than that in nuclear β decay. Also the observation of decays such as $K^+ \rightarrow \mu^+ \nu_\mu$ demonstrated the weak interactions could couple two different quark families together [6]. These results were explained by Cabibbo as being caused by quark mixing [7]. A complete theoretical explanation for quark mixing had to wait for a unified gauge model of the Electroweak interaction to be developed.

2.2.3 Electroweak Unification

The weak interaction can be fully described as a gauge interaction. In this format it can be unified with the electromagnetic interaction into one composite interaction. A full or historical derivation of the Standard Electroweak Model [8] [9] can be found elsewhere [10]. The combined electroweak interaction is invariant under local gauge transformations of $SU(2)_L \otimes U(1)_Y$ group. The full electroweak lagrangian is

$$\mathcal{L}_{EW} = L_1 + L_2$$

where

$$\mathcal{L}_1 = \bar{\chi}_{Li} \gamma_\mu (i\partial_\mu - g\mathbf{T} \cdot \mathbf{W}_\mu + \frac{1}{2}g'Y B_\mu) \chi_{Li} + \bar{\psi}_{Rj} \gamma^\mu (i\partial_\mu - \frac{1}{2}g'Y B_\mu) \psi_{Rj}$$

and

$$\mathcal{L}_2 = -\frac{1}{4} \mathbf{W}_{\mu\nu} \cdot \mathbf{W}^{\mu\nu} - \frac{1}{4} B_{\mu\nu} \cdot B^{\mu\nu}$$

where $\mathbf{T}$ and Y are the generators of the $SU(2)_L$ and $U(1)_R$ gauge groups respectively. $\mathbf{T}$ represents three generators T_i which satisfy a non-abelian algebra, $[T_i, T_j] = if_{ijk}T_k$. Y is defined by $Q = T^3 + \frac{Y}{2}$ where T^3 is the third, diagonal, matrix of the 3 $\mathbf{T}$ generators. χ_{Li} and ψ_{Rj} are the left-handed isospin doublets and right-handed isospin singlets respectively for both the quarks and leptons. A sum over the three generations, $i, j = 1, 2, 3$, is implied. The constants g and g' quantify the strengths of the different components of the electroweak interaction, and $\mathbf{W}_\mu$ and B_μ represent three plus one vector bosons and must be introduced to construct a gauge invariant lagrangian. They can be identified with the physical vector bosons of the electroweak interaction, Z^0 , W^+ , W^- and A (photon), using the conversions

$$\begin{pmatrix} W_3 \\ B \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} Z \\ A \end{pmatrix}$$

and

$$W^\pm = (W_1 \pm W_2)/\sqrt{2}$$

where θ_W is known as the Weinberg weak mixing angle and relates the coupling strengths of the electromagnetic and weak interactions, $g = e/\sin \theta_W$.

The term L_1 gives the lepton and quark kinetic energies and their interactions with the electroweak vector bosons. The weak interaction term has a V-A structure and divides the weakly interacting particles into right-handed singlets and left-handed doublets with a $SU(2)$ group structure. Only the left handed fermions and neutrinos (or right handed antifermions and antineutrinos) within the same $SU(2)_L$ doublet or “family” couple via the weak current. The term L_2 gives the kinetic energies and self interactions of the electroweak vector bosons. The electroweak vector bosons can interact with each other due to the non-abelian nature of the gauge group. The term L_3 gives the self couplings of the vector bosons.

2.2.4 Symmetry breaking, mass and the CKM matrix

The theory outlined above preserves the local $SU(2)_L \otimes U(1)_Y$ electroweak gauge symmetry and predicts that all the quarks and leptons and the four gauge bosons of the electroweak interaction are massless. However, experiments have shown that almost all of the fermions, possibly excepting some of the neutrinos, and three of the electroweak gauge bosons, excepting the photon, are massive. Also the only observed symmetry of the electroweak interaction is $U(1)_{EM}$. The simplest method of breaking the local gauge symmetry the electroweak interac-

tion and providing mass to the leptons, quarks and three of the gauge bosons is to introduce a new doublet of scalar bosons known as Higgs bosons. The modified Lagrangian includes the two extra terms below.

$$\mathcal{L}_3 = |(i\partial_\mu - g\mathbf{T} \cdot \mathbf{W}_\mu - \frac{1}{2}g'YB_\mu)\phi|^2 - V(\phi)$$

and

$$\mathcal{L}_4 = (iG_{ij}\bar{\chi}_{Li}\phi\psi_{Rj} + \text{hermitian conjugate})$$

where ϕ represents the Higgs field and $V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$ is the Higgs potential [11]. The terms G_{ij} represent a matrix of coupling strengths of the Higgs to the quarks and leptons.

The term $\mathcal{L}_3$ gives the masses and couplings of the Higgs and vector bosons and $\mathcal{L}_4$ gives the masses and couplings to the Higgs for each fermion. One feature of this lagrangian is that it is invariant under transformations of the $U(1)_{EM}$, so that charge is conserved. The masses come from the Higgs-Yukawa couplings of the Higgs boson to the other quarks, leptons and bosons. The masses of the gauge bosons are predicted by this mode. The masses of the fermions and Higgs are not predicted, since the parameters G_{ij} and the parameters of the Higgs doublet, μ and λ , are all free parameters not predicted by the model. The coupling constant matrix G_{ij} can contain off diagonal terms. The presence of these terms means that the quark eigenstates of the weak interaction are not the eigenstates of the Hamiltonian(or mass). The Hamiltonian can be diagonalized to find the mass eigenstates. The diagonalized eigenstates of the Hamiltonian can be converted to other Hamiltonian eigenstates or "mixed" by interactions

involving the charged weak gauge bosons. The mixing can be expressed in terms of a 3×3 unitary matrix. For the full observed three generations of quarks the matrix has 3 real parameters and one complex phase. One parameterization proposed by Kobayashi and Maskawa is as follows [12].

$$U = \begin{pmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} = \begin{pmatrix} c_1 & -s_1 c_3 & -s_1 s_3 \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + s_2 c_3 e^{i\delta} \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta} & c_1 s_2 s_3 - c_2 c_3 e^{i\delta} \end{pmatrix}$$

where $s_i = \sin \theta_i$ and $c_i = \cos \theta_i$. The mixing angles have been measured, or constrained, by experiment. The 90% confidence limits are [3]:

$$U = \begin{pmatrix} 0.9745 - 0.9760 & 0.217 - 0.224 & 0.0018 - 0.0045 \\ 0.217 - 0.224 & 0.9737 - 0.9753 & 0.036 - 0.042 \\ 0.004 - 0.013 & 0.035 - 0.042 & 0.9991 - 0.9994 \end{pmatrix}$$

2.3 The Strong Interaction

2.3.1 Quarks and Gluons

The quark model has had great success. Six quarks have been found as expected. All of the observed hadrons can be constructed from the lightest five quarks. The top quark decays too quickly to form bound states. Using a $SU(3)_{Flavor}$ symmetry for the lightest (up, down and strange) quarks the spectroscopy of the lighter hadrons could be explained in terms of the quantum number isospin and strangeness. However, to consistently explain the spectroscopy of all the hadrons an additional quantum number was needed. The color degree of freedom with three possible states, red, blue and green was proposed [13]. In the terms of

quantum field theory if we have a new conserved quantity, color, we should have a new symmetry and a new interaction vector bosons. These bosons which carry the strong force are known as gluons and have been experimentally observed [14].

2.3.2 Quantum Chromodynamics

The symmetry group of Quantum Chromodynamics is $SU(3)_{Color}$. The Lagrangian is

$$\mathcal{L} = \bar{q}(i\gamma^\mu\partial_\mu - m)q + -g(\bar{q}\gamma^\mu T_a q)G_\mu^a - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu}$$

where q_i denotes the three possible color fields. G_μ^a are 8 massless gauge bosons and can be identified with the gluons. The coupling strength is g and T_a are 8 traceless 3×3 matrices that are the generators of the $SU(3)_{Color}$ symmetry group that the strong interaction is invariant under. The $SU(3)_{Color}$ group is non-Abelian and the generators T_a satisfy the algebra

$$[T_a, T_b] = if_{abc}T_c$$

where f_{abc} represent real constants and a sum over c is implied.

Note that the gluons are massless, carry color charge and can interact with themselves. This self-interaction has no analog in QED. The self interaction of the gluons leads to several important features of QCD. First additional gluon pairs are created in the vacuum surrounding a quark. There are some theoretical calculations which indicate that this may lead to a color potential that increases with radius. A potential of this type would explain the observed phenomena of

confinement in which pair or triplets of quarks are confined to stay near each other in color neutral combinations. Close to a quark the potential of the color field decreases with radius. This effect, which has been rigorously proven, makes it possible to calculate QCD problems perturbatively for situations involving short distances or high momentum transfers. To calculate the coupling in strong interactions a running coupling constant which decreases with increasing momentum transfer, or decreasing distance scale, is used. One form of running coupling constant is

$$\alpha_s(q^2) = \frac{\alpha_s(q_0^2)}{1 + B\alpha_s(q_0^2)\ln(q^2/q_0^2)} = \frac{1}{1 + \ln(q^2/\Lambda^2)}$$

where $B = (33 - 2n_f)/12\pi$ and $\Lambda = q_0^2 e^{-1/B\alpha_s(q_0^2)}$ [15]. The constant n_f is the number of quark flavors and the strong coupling constant must be defined at some reference momentum scale q_0 .

In bound state problems a phenomenological potential that reproduces the observed features of the strong force is often used. An example of a phenomenological potential [16] is

$$V(r) = -\frac{\kappa}{r} + \frac{r}{a^2}$$

where $\kappa = -4\alpha_s/3$ is related to α_s , which can be calculated for any momentum scale and a is determined from experiment.

2.4 B Physics

The study of hadrons which include the bottom or b quark is an important tool for investigating both the electroweak interaction and QCD. In Electroweak

physics we can study the CKM matrix elements V_{cb} and V_{ub} , which quantify the weak coupling of the b quark to the charm, c, and up, u, quarks. It is possible that these matrix elements contain a complex phase which would lead to (CP) violation in the b sector. Also related to b physics is the CKM matrix element V_{tb} , which quantifies the coupling of the b quark to the top, t, quark. V_{tb} is expected to be near unity. Because of the small magnitudes of V_{cb} and V_{ub} the b flavored hadrons are expected to be long lived. The study of the weak decays and lifetimes of these hadrons will allow the precise measurement of V_{cb} and V_{ub} .

In strong interaction physics we can study the spectroscopy of strong bound state systems involving the b quark. QCD calculations are simpler to perform for hadrons involving a heavy quark. If the system involves one heavy quark, $Q\bar{q}$ or Qqq , such as the $B^+(u\bar{b})$, the relative heaviness of one of the quarks can be used to simplify the calculation of solutions. If the hadron includes two heavy quarks, $Q\bar{Q}$, such as the $B_c^+(c\bar{b})$, the system can be approximated as nonrelativistic which also simplifies calculations. Below is described, in brief, the status of the spectroscopy and decay models of the b hadrons. Special emphasis is given to the B_c^+ , which completes the spectrum of pseudoscalar b flavored mesons and is the focus of the work presented here.

2.4.1 Spectroscopy of b hadrons

There is a wide spectrum of light b hadrons produced in the high energy environment. The ground state pseudoscalar mesons are the $B^+(u\bar{b})$, $B^0(d\bar{b})$ and $B_s^0(s\bar{b})$ mesons. The observed ground state baryons are the $\Lambda_b^0(udb)$, $\Xi_b^0(usb)$ and $\Xi_b^-(dsb)$ baryons. Some of the predicted ground state baryons with higher angular momentum are the $\Sigma_b^+(udb)$ and $\Omega_b(ssb)$. Some observed excited state

mesons are the $B^* (u\bar{b})$ and $B^{**} (u\bar{b})$ mesons.

Light b hadrons

The mass of the b hadrons have been predicted by many methods. First consider systems involving one heavy quark and one light quark, $Q\bar{q}$. Each method uses an effective potential. All of the methods incorporate relativity, since one of the two quarks is light the system is inherently relativistic. Effects such as Spin-spin and spin-orbit effects are calculated in perturbation theory. These methods use the nonrelativistic quarkonium model (NRQM) [17] with relativistic corrections introduced by hand [18]; using a semirelativistic equation (SRT), such as the solution used by Fermi and Yang to study the pion as a bound state of the nucleon [19] [20]; or using a fully relativistic treatment, such as those developed by Bethe-Salpeter(BSE) [21] [22] or Blankenbecler-Sugar-Logunov-Tavkhelidze(BSLT) [23] [24].

With the discovery of most of the ground state pseudoscalar b mesons their experimentally measured masses can be used to improve the predictions of the excited state masses. One useful tool to perform these predictions is Heavy Quark Effective Theory(HQET) [25]. HQET proceeds from the observation that the energy levels and spin effects of the b meson bound states are mostly decoupled from the properties of the quark. This can be understood as follows. Inside a meson the momentum transfer between quarks are on the order of $\Lambda \approx m_p/3 \approx 300 \text{ MeV}/c$, where m_p is the mass of the proton. If the mass of the heavy quark is much larger than Λ then the change in velocity of the heavy quark in any momentum transfer will be very low. Therefore the heavy quark can be treated as a stationary source of color or gluons independent of its

mass and spin. This gives the lagrangian a new $SU(2)_S \otimes SU(3)_F$ spin-flavor symmetry simplifying calculations. The properties of bound states are then calculated using an effective potential in the limit where the heavy quark is very massive or infinitely massive [26]. Spin-spin and spin-orbit effects are calculated in perturbation theory.

Table 2.3 gives mass predictions for the ground state b meson masses and some of the lowest lying excited states. The predictions listed are those of semirelativistic theory (SRT) [20], relativistic theory (BSLT) [28] and Heavy Quark Effective Theory (HQET) [26]. Also given are the experimentally measured masses [3].

Meson	Experimental Mass	SRT	BSLT	HQET
B^+	5.2789 ± 0.0018	5.269	5.302	NA
B^{+*}	5.3249 ± 0.0018	5.321	5.360	5.3258
B^0	5.2798 ± 0.0016	NA	5.302	NA
B^{0*}	5.3256 ± 0.0016	NA	5.360	5.3258
B_s^0	5.3696 ± 0.0024	5.354	5.371	NA
B_s^{0*}	5.4163 ± 0.0033	5.416	5.434	5.4341

Table 2.3: Mass predictions for the ground state b meson masses and some of the lowest lying excited states. The predictions listed are those of semirelativistic theory (SRT), relativistic theory (BSLT) and Heavy Quark Effective Theory (HQET). Also given are the experimentally measured masses. All masses in GeV/c^2 NA stands for not available.

The presence of an additional quark makes the b baryon masses more difficult

to predict than those of the b mesons. However, predictions have been made by exploiting the regularities in the mass spectra of the known hadrons to construct sum rules which give the masses of the b baryons [27]. This method is an application [29] of the Feynman-Hellmann theorem [30]. The predictions from sum rules are compared with experimental data in table 2.4.

Hadron	Experimental Mass	Sum Rules
Λ_b	5.624 ± 0.009	5.627
Σ_b	not found	5.818
Ξ_b	not found	5.955
Ω_b	not found	6.075

Table 2.4: Mass predictions from sum rules compared with experimental data for the light B baryons. All masses in GeV/c^2

Heavy hadrons

Several mesons involving two heavy quarks have been observed. Unflavored mesons containing only the c quark are the angular momentum $J = 0$, $\eta_c (c\bar{c})$ and the $J = 1$, $J/\psi (c\bar{c})$ mesons. Also observed are many excited states such as the ψ' . Unflavored mesons containing only b quarks are the $J = 1$, $\Upsilon (b\bar{b})$ and excited states. The $J = 0$, $\eta_b (b\bar{b})$ has not been observed. There is one expected stable flavored bound state of $(b\bar{c})$, the B_c^+ . The B_c^+ should also have excited states such as the B_c^{+*} . The B_c^+ is the last unfound pseudoscalar ground state b meson and completes the b spectroscopy picture.

The mass of heavy quark mesons can be accurately predicted. Since the two

quarks are both heavy the mass of the bound state can be approximated using Nonrelativistic Quark Models(NRQM). This method uses a QCD effective potential with the nonrelativistic Schrodinger equation. The total mass is calculated as the constituent quark masses plus the energy of the potential. Excited state masses can be found by including spin-spin or spin-orbit terms perturbatively.

The effective potential must reproduce the qualitative features of QCD. These are asymptotic freedom for small separations of the particles and confinement at larger separations. The effective interquark potential is known well in the region around the J/ψ and Υ families. Some example potentials are the QCD motivated Buchmuller and Tye (QCD) [31]

$$V(r) = \int \frac{d^3q}{(2\pi)^3} e^{i\mathbf{r}\cdot\mathbf{q}} \frac{4}{3} \frac{12\pi}{27} \frac{1}{q^2(1 + q^2/\Lambda^2)}$$

(This QCD potential was also used in reference [32] where they modified it by using a value of $\Lambda = 0.300 \text{ GeV}/c^2$ (QCDM).),

A power law potential (PL) [33]

$$V(r) = -8.064\text{GeV} + (6.898\text{GeV})(r \times 1\text{GeV})^{0.1}$$

a logarithmic potential (Log) [34]

$$V(r) = -0.6635\text{GeV} + (0.733\text{GeV})\ln(r \times 1\text{GeV})$$

and a Coulomb-plus-linear, "Cornell potential" (Cor) [16]

$$V(r) = -\frac{\kappa}{r} + \frac{r}{a^2}$$

where $\kappa = 0.52$ and $a = 5.18\text{GeV}^{-1}$. (The Coulomb-plus-linear potential can also be augmented with a constant term (CorC) [35].)

To predict the mass of various particles one solves the Schrodinger equation for the potential to find the 1S wave function at the origin, $\psi(0)$, and then uses the the mass difference between the ground state and one excited state to fix the strong coupling constant.

$$M(^3S_1) - M(^1S_0) = \frac{32\pi\alpha_s |\psi(0)|^2}{9m_i m_j}$$

The constituent quark masses can be taken from theory or found by fitting the ψ or Υ spectra. An example of the results of this technique, using the charmonium family to predict the Υ and B_c^+ masses, is given in table 2.5 using the potentials above (QCD, QCDM, PL, Log and Cor [36]).

The mass of the B_c^+ has also been predicted in the framework of HQET which gives a value of $6.2478 \text{ GeV}/c^2$ [37]. The predicted masses for the B_c^+ , calculated using various potentials, range from $6.24-6.31 \text{ GeV}/c^2$ [36]. The good agreement between all of these values gives confidence to the idea of searching for the B_c^+ in a narrow mass range around these predicted values.

2.4.2 Decays

The weak decays of the b flavored hadrons are relatively well understood. The decays are due to the weak interaction with corrections from short distance QCD effects. The decay widths can be calculated using the electroweak model and perturbative QCD. In calculating weak decays it is necessary to understand the initial wave function of the hadron, the weak decay current and the wave func-

Hadron	Experimental Mass	QCD	QCDM	PL	Log	Cor
$\eta_c(1S)$	2.9798 ± 0.0021	2.980				
$J/\psi(1S)$	3.09688 ± 0.00004	3.097				
$\psi'(2S)$	3.68600 ± 0.00010	3.686				
$\Upsilon(1S)$	9.46037 ± 0.00021	9.464	NA	9.462	9.460	9.476
B_c^+	6.40 ± 0.52	6.264	6.314	6.248	6.266	6.254
B_c^{+*}	not found	6.337	6.355	6.319	6.334	6.343

Table 2.5: The mass predictions of five QCD potentials for the Υ and the B_c^+ . The parameters of the potentials were tuned using experimental data from the charmonium family. Experimentally measured masses are shown for comparison. All masses in GeV/c^2 .

tions of the final decay products, the three of which enter into the matrix element which gives the amplitude of the decay. Calculations of the decay widths of the light b flavored hadrons have been performed and can be compared to experimental measurements. Similar techniques can be used to predict the decays of the heavy b flavored meson, the B_c^+ .

Light b hadron decays

The decays of the light b flavored mesons have been calculated using semirelativistic theories(SRT) and HQET. In calculating b decays the spectator model is used in which it is assumed that only the b quark decays and then the decay products hadronize with the lighter quark. Both semileptonic and hadronic decays of the b quark are possible. Often only two body decays are calculated

since they involve simpler kinematics than decays to more than two daughters. As an example, the predictions of a semirelativistic model developed by Bauer, Stech and Wirbel [38] and HQET [25] [39] [40] for are shown in table 2.6 with the experimentally measured branching ratios [3] for comparison. Decays involving B^0 decay to two bodies including a J/ψ are chosen for presentation in order to demonstrate the accuracy of decay width predictions for modes similar to the modes in which decays of the B_c^+ are expected to be observed. The branching fraction predictions agree with experiment at the 1 to 2 σ level.

Decay Mode	Exp	HQET	Semi
$J/\psi K^0$	$8.9 \pm 1.2 \times 10^{-4}$	7.7×10^{-4}	5.7×10^{-4}
$J/\psi K^{0*}$	$1.35 \pm 0.18 \times 10^{-3}$	1.6×10^{-3}	2.0×10^{-3}

Table 2.6: Branching fractions predictions of a semirelativistic model developed by Bauer, Stech and Wirbel and HQET compared with experimentally measured branching fractions.

Heavy b meson decays

Decays of heavy quark systems such as the B_c^+ are described using nonrelativistic quark model(NRQM). Several methods have been used to calculate B_c^+ decay branching fractions and the lifetime. Each method assumes the spectator model for the decay of the quark. Some of the methods use relativistic corrections since the decay products can be moving at relativistic speeds in decays involving a large recoil. One method uses the NRQM to describe the wave function of the initial meson [41]. The wave function is then converted into a covariant relativistic

form(BSE) [21] for calculation of the decay matrix elements. A second method uses a nonrelativistic wave function developed by Isgur, Grinstein, Scora and Wise (IGSW) [42] [43]. This method was improved by Bauer, Stech and Wirbel (BSW) [44] by correcting the wavefunction using form factors at large recoil momenta.

The decay of the B_c meson is governed by the weak interaction; the lowest energy strong decay, popping a $u\bar{u}$ quark pair out of the vacuum to form a lower mass beauty meson and a charmed hadron (see figure 2.1) is forbidden by energy conservation ($m_{B_c^+} = 6.28 < 1.864 + 5.279 = m_{B^+} + m_{D^0}$). Assuming the spectator model for the decays, information about the lifetime and inclusive decay rates can be obtained by considering the possible decays and comparing them to similar decays of D and B mesons. The allowed decays are as follows.

Figure 2.1: Strong decay of the B_c^+ : $B_c^+ \rightarrow D^0 B^+$. This decay is forbidden by energy conservation ($m_{B_c^+} = 6.28 < 1.864 + 5.279 = m_{B^+} + m_{D^0}$).

- a. c spectator ($\bar{b} \rightarrow \bar{c} W^+$) decay. The partial width of the c spectator decay can be estimated from the analogous light b meson decay width $\frac{1}{\tau_B}$.

- b. b spectator ($c \rightarrow sW^+$) decay. The partial width of the c spectator decay can be estimated from the analogous light c meson decay width $\frac{1}{\tau_{D^0}}$. However since the mass of the spectator b quark and resulting B meson is large compared to the c quark mass the kinematic phase space that the c quark can decay to is limited as compared to that of the decay of the c quark in the D meson. This effect can be shown to suppress the decay width by a factor of 0.6 [43].
- c. The annihilation decays that are not Cabibbo suppressed or helicity suppressed. Annihilation to $c + \bar{s}$ ($c\bar{b} \rightarrow W^+ \rightarrow c + \bar{s}$) and annihilation to $\tau + \nu_\tau$ ($c\bar{b} \rightarrow W^+ \rightarrow \tau + \nu_\tau$). These annihilation decays are expected to contribute approximately 5% and 2% to the total width respectively [41].

The total width can then be taken as

$$\frac{1}{\tau_{B_c^+}} = \frac{1}{\tau_{B^+}} + \frac{0.6}{\tau_{D^0}} + \frac{1}{\Gamma_{\text{anni}}}$$

from the measured decay rate of the lighter B and D mesons.

$$\frac{1}{\tau_{B_c^+}} = 4.45 \times 10^{-13} \text{ sec}$$

Predictions for the B_c^+ range from half to one forth of the lifetime of the B mesons [41] [43] [44].

Since the b quark will decay predominantly into a c quark it is expected that there will be a significant branching ratio into modes involving the J/ψ meson. Some important decay modes involving J/ψ are shown in figures 2.2, 2.3, 2.4 and 2.5 and the predicted branching ratios from references BSE [41], IGSW [43] and

BSW [44] are given in table 2.7. The most likely decay modes to be seen at LEP are $B_c^+ \rightarrow \psi\pi^+$, $B_c^+ \rightarrow \psi a_1^+$ and $B_c^+ \rightarrow \psi \ell^+ \nu$. Among the other decay modes with large branching fractions is the decay $B_c^+ \rightarrow \psi \rho^+$. However this decay is difficult to detect because the $\rho^+ \rightarrow \pi^+ \pi^0$ decay involves a neutral pion. The decay $B_c^+ \rightarrow B_s^0 \pi^+$ also has a large branching ratio but the B_s^0 is difficult to exclusively reconstruct. The three models predict differing branching fractions.

Figure 2.2: Exclusive decay of the B_c^+ meson: $B_c^+ \rightarrow \psi\pi^+$.

Figure 2.3: Exclusive decay of the B_c^+ meson: $B_c^+ \rightarrow \psi a_1^+$.

Figure 2.4: Semileptonic decay of the B_c^+ meson: $B_c^+ \rightarrow \psi \ell^+ \nu$

Figure 2.5: Exclusive decay of the B_c^+ meson: $B_c^+ \rightarrow B_s^0 \pi^+$

2.4.3 Production of b hadrons

Light b hadron production

B hadrons can be produced at LEP in hadronic Z^0 decays. Light B hadrons are produced by soft fragmentation process, involving spontaneous creation of $q\bar{q}$ (see figure 2.6). The relative rates for production of mesons via soft fragmentation are 1:1:0.3 for $B_u:B_d:B_s$ production respectively [45]. The fraction of the b quark momentum that is carried by the final B hadron was first parameterized by

Decay Mode	BSE	IGSW	BSW
$J/\psi\pi^+$	2.1×10^{-3}	1.9×10^{-3}	NA
$J/\psi a_1^+$	NA	NA	NA
$J/\psi\ell^+\nu$	4.6×10^{-2}	5.1×10^{-2}	2.9×10^{-2}
$J/\psi\rho^+$	6.4×10^{-3}	4.7×10^{-3}	NA
$B_s\pi^+$	4.9×10^{-2}	3.7×10^{-2}	2.6×10^{-2}

Table 2.7: Predicted branching fractions of the B_c^+ meson for exclusive and semileptonic decay modes for three theoretical models.

Peterson *et al.* [46],

$$\frac{dN}{dx_p} = \frac{1}{x_p[1 - 1/x_p - \epsilon_p/(1 - x_p)]^2}$$

where $x_p = p/p_{\max}$ and ϵ_p is a free parameter. The momentum distribution of B hadrons at LEP is shown in figure 2.8. The parameter of the distribution, ϵ_p , has been tuned to produce the measured mean energy fraction ($\langle x_E \rangle = E_B/E_{\text{beam}}$), measured at OPAL. The measured mean energy fraction ($\langle x_E \rangle$) for the light b hadrons is $\langle x_E \rangle = 0.695 \pm 0.006 \pm 0.008$ [47].

Heavy hadron production

The production mechanism for the $\bar{b}c$ bound states differs from that of the B_d , B_u and B_s mesons, since the soft fragmentation process, involving spontaneous creation of $b\bar{b}$ or $c\bar{c}$, is severely suppressed. For c quark production the rate is expected to be $10^{-10} - 10^{-11}$ [45]. The predicted dominant production mechanism, shown in figure 2.7, involves the emission and splitting to $c\bar{c}$ of a hard gluon

Figure 2.6: Production of light B mesons via the soft fragmentation mechanism: $Z^0 \rightarrow (b\bar{b})(q\bar{q})$.

in the process $Z^0 \rightarrow b\bar{b}$. This process can be calculated in perturbative QCD because the momentum transfer of the gluon, q , satisfies, $q^2 > 4m_c^2 \gg \Lambda_{\text{QCD}}$. Perturbative QCD calculations predict a production rate of 10^{-5} to 10^{-4} B_c per hadronic Z^0 decay, with a momentum spectrum that is considerably softer than that of the lighter B hadrons [48] (see figure 2.8). The predicted mean energy fraction ($\langle x_E \rangle$) for the B_c meson is $\langle x_E \rangle = 0.55$. The hard gluon radiation method is also the production method for prompt charmonium and Υ both of which have been observed at OPAL [49] [50] at levels too large to be accounted for by the soft fragmentation process.

2.5 Search for the B_c^+ meson

The accurate prediction for the mass of the B_c^+ should allow a search to be performed in an e^+e^- environment where the mass can be fully reconstructed. In addition the high relative mass of the B_c^+ should make it easily distinguishable

Figure 2.7: Feynman Diagram for the predicted B_c^+ production process $Z^0 \rightarrow b\bar{b} \rightarrow B_c^+ X$

from the lighter B mesons. The large branching ratio to states involving J/ψ indicates that decay channels such as $B_c^+ \rightarrow \psi\pi^+$, $B_c^+ \rightarrow \psi a_1^+$ and $B_c^+ \rightarrow \psi\ell^+\nu$ would be relevant modes to search for B_c^+ meson decays. The B_c^+ is important to search for since it is the last predicted pseudoscalar ground state meson unfound in the B sector. It is also the only predicted explicitly flavored ground state meson involving two heavy quarks. For these reasons both its discovery and the study of its bound state properties, decays and lifetime are important.

Figure 2.8: Momentum spectrum of B_c mesons from the process $Z^0 \rightarrow b\bar{b} \rightarrow B_c X$ generated using JETSET 7.4 (histogram). Overlaid is the prediction of the theoretical model (solid line). Also shown is the momentum distribution of light B mesons for the OPAL tune of JETSET 7.4 in which the mean energy of b hadrons agrees with the experimental value (dashed line).

Chapter 3

Experimental Apparatus, Data Processing and Simulation

3.1 The LEP Accelerator

The Large Electron Positron (LEP) accelerator is an electron positron collider. It has four collision points instrumented with particle detectors where electron positron annihilation can be studied in the center of mass energy range $90 \text{ GeV}/c^2$ to $200 \text{ GeV}/c^2$. This allows the detailed study of the electroweak force through the production and decay of Z^0 and W^+ bosons. The production of large numbers of Z^0 bosons allows the study of physics involving b quarks as well as the lighter quarks and leptons through Z^0 boson decay. In addition, searches for new particles such as the Higgs boson or various predicted Supersymmetric (SUSY) particles can be performed. The operation of the LEP accelerator is divided into two phases. In phase I (1989-1995) the electron and positron beams were accelerated to energies near 45.6 GeV with a center of mass energy at or near the Z^0 production resonance. In phase two (1996-) the beams are operated at energies above 80 GeV which provides center of mass energies sufficient to produce W^+W^- pairs. The maximum center of mass energy achieved through 1998 is 94.5 GeV per beam.

The LEP accelerator is located at the European Laboratory for Particle

Physics (CERN), which is a research complex including many accelerators located on the border between France and Switzerland near the city of Geneva. The layout of CERN is shown in figure 3.1. A detailed description of the LEP accelerator can be found in ref. [51]. The LEP ring is 26.66 km in circumference. The shape is roughly circular with straight portions at each of four interaction points and four access points which alternate at regular intervals. The four interaction points (numbered 2, 4, 6 and 8) are instrumented with particle detectors (L3, ALEPH, OPAL and DELPHI). Some relevant machine parameters are given in table 3.1 [52].

Parameter	Value	
Phase	Phase I (Z^0) (1995)	Phase II (1998)
Beam Energy	45.6 GeV	(94.3 – 94.5) GeV
Energy Spread ($\delta E/E$)	1.0×10^{-3}	
Peak Luminosity	$2.4 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$	$5.0 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$
Time Between Collisions	$22 \mu\text{s}$	
Transverse Beam Dimensions	Horizontal: $200 \mu\text{m}$ Vertical: $8 \mu\text{m}$	
Bunch Length	1.8 cm	1.0 cm

Table 3.1: LEP machine parameters during 1995 and 1998. Values were taken from refs. [2]. Note that the beam energy in 1996 at the start of LEP II operation was 80.5 GeV and has been increased gradually since then. Also note that the $22 \mu\text{s}$ time between collisions is for single bunch operation.

During Phase I the beam electron and positrons were accelerated using 128

CERN Accelerators

LEP: Large Electron Positron collider
 SPS: Super Proton Synchrotron
 AAC: Antiproton Accumulator Complex
 ISOLDE: Isotope Separator OnLine DEvice
 PSB: Proton Synchrotron Booster
 PS: Proton Synchrotron

LPI: Lep Pre-Injector
 EPA: Electron Positron Accumulator
 LIL: Lep Injector Linac
 LINAC: LINear ACcelerator
 LEAR: Low Energy Antiproton Ring

Rudolf LEY, PS Division, CERN, 02.09.90

Figure 3.1: CERN accelerator complex

copper cavities powered by 16, 1 MW klystrons [53]. In preparation for phase II the cavities were replaced by superconducting cavities in order to achieve higher beam energies. The cavities are located in two diametrically opposed sections of the ring near interaction points 2 and 6. The cavities are run at 321.21 Mhz which is 31320 times the LEP revolution frequency. The beam is steered by 3304 dipole, 808 quadrupole, 8 superconducting quadrupole and 504 sextupole magnets. Most of the magnets are grouped in cells with 12 dipole magnets used to bend the beam, two quadrupoles for focusing and two sextupoles used to compensate the beam energy dependence of the focusing action of the quadrupoles. The 8 superconducting quadrupoles are located in sets of two at the ends of each detector in order to focus the beams at the interaction points. In addition to the magnets listed above there are orbit correctors, wigglers and others dipole magnets usually used near the interaction or injection points for fine tuning the beams. Electrostatic separators are used to prevent the beams from interacting except at the interaction points.

During Phase I and Phase II the beams have been operated in several different modes. From 1990 – 1992 LEP operated with four bunches of both electrons and positrons. In 1993 and 1994 eight bunches were used in a “pretzel” scheme [54]. In 1995 LEP used bunch train scheme, with four bunch trains containing either two or four bunches each [55]. Currently in LEP Phase II a bunch train scheme with two bunches per train is used. Each new scheme resulted in improved average luminosity.

The electron and positrons which collide in LEP are produced and accelerated using several different CERN facilities. An electron gun produces the electrons which are accelerated to 600 MeV by one of the two of the LEP Injector Linacs

(LILs). Electrons are then injected into the Electron Positron Accumulation ring (EPA). Positrons are produced by inserting a tungsten target at the end of the first LIL. They are then accelerated by the second LIL and injected into the EPA storage ring. Electron and positrons are accumulated in the EPA. Then either the accumulated electrons or positrons are injected into the Proton Synchrotron where they are accelerated to 3.5 GeV. Then they are injected into the Super Proton Synchrotron where they are accelerated to 20 GeV. Finally they are injected into LEP. Electron and positron bunches are injected into LEP separately and several bunches are needed to achieve large enough currents. The LEP beam pipe is kept at a pressure on order of 10^{-11} Torr, 10^{-9} Torr while the beams are in circulation, which is low enough to prevent unacceptable beam losses and backgrounds due to beam gas interactions.

One cycle of LEP operation is as follows. First 20 GeV electrons and positrons are injected into the LEP ring. Typical currents are about 3000 μA per beam for during phase I and 4000 μA in phase II. Then the beams are accelerated to an energy of 45.6 GeV. The beams are then focused and collimated in the interaction regions in order to reduce beam related background and increase collision luminosity. In phase I the beams are then brought into collision at the interaction regions. In phase II running the beams are usually further accelerated and focused. Often some current is lost during these processes. Final phase II currents are usually about 2500 μA before they are brought into collision. In both phases data is taken for periods of up to 8 hours after the beams are brought into collision. The data taking time period varies based on parameters such as the initial current. The data taking period is terminated after luminosity becomes sufficiently low and the remaining beam current is directed to a stationary target.

In phase I(1989-1990) several thousand runs were completed and approximately 4 million hadronic Z^0 decays were recorded by each of the four LEP detectors.

3.2 The OPAL Detector

The Omni Purpose Apparatus for LEP (OPAL) is one of the four particle detectors operating at LEP. It is a multipurpose apparatus with acceptance for particle decays over nearly the entire 4π solid angle. It was built to detect all expected interactions occurring in e^+e^- interactions at or above the Z^0 resonance. A detailed description of the OPAL detector can be found in [56].

The main features of OPAL are as follows: high precision reconstruction of primary and secondary vertices close to the interaction point; tracking of charged particles in order to measure their momentum; identification of charged particle via energy loss (dE/dx) due to specific ionization; identification of electrons and photons via measurement of their energy; measurement of Hadronic energy, identification of muons and measurement of absolute luminosity via measurement of Bhabha scattering events.

The OPAL detector is shown in figures 3.2 and 3.3. The OPAL coordinate system is defined with the z -axis following the electron beam direction, the x -axis pointing towards the center of the LEP ring and the y -axis pointing upwards, normal to the beam plane, forming a right-handed coordinate system. The polar angle θ is defined relative to the z -axis, and r and ϕ are the standard cylindrical polar coordinates. Charged particle tracking is performed by the central detector system that is located in a solenoidal magnetic field of 0.435 T. The central tracking system consists of a two layer silicon microvertex detector,

installed in 1991 [57] [58], a high precision vertex drift chamber, a large volume jet chamber and a set of planar drift chambers measuring track coordinates along the z axis. Particle identification is provided by measurement of specific ionization (dE/dx) in the jet chamber. The central detector is surrounded by a lead glass electromagnetic calorimeter with a pre-sampler. The magnet yoke is instrumented with layers of streamer tubes that serve as a hadron calorimeter and provide additional information for muon identification. Four layers of planar drift chambers surrounding the detector provide tracking for muons. In the forward region are a forward calorimeter and tracking detector and a silicon-tungsten luminometer to measure luminosity.

3.2.1 Beam Pipe

The inner radius of OPAL is bounded by the beam pipe. The OPAL beam pipe was designed to minimize coulomb scattering and other interactions with the beam pipe material while being able to support the 4 bar gas pressure of the central detector and the $\sim 10^{-11}$ Torr vacuum inside the beam pipe. In addition the beam pipe had to provide RF shielding. A carbon fiber composite together with a 0.1 mm thick aluminum liner was chosen. The inner radius was 78 mm. The beam pipe was constructed in three sections ~ 1150 mm long. The carbon fiber central section was 1.3 mm thick and included two 5.0 mm thick stiffening rings while the other two sections were 2.0 mm thick. For particles crossing the beam pipe at a normal angle, the beam pipe forms 0.66% of a radiation length. In 1991 a silicon microvertex detector was installed and the original beam pipe was replaced with a 1.1 mm thick beryllium beam pipe at an inner radius of 53 mm [57].

Figure 3.2: The OPAL detector. 3D view.

3.2.2 Silicon Microvertex Detector

A silicon microvertex detector (SI) was installed in the OPAL detector in 1991 [57]. The 1991 detector consisted of two layers which formed concentric cylinders parallel to the z axis. Each layer was made up of 25 "ladders" which were 180 mm long and 33 mm wide divided into 3, 60 mm long silicon wafers placed end to end. The wafers were glued onto a 0.5 mm epoxy-kevlar composite plate. Read out was performed by strips. The 1991 configuration provided improved track

Figure 3.3: The OPAL detector. 2D views. a) $x - y$ view perpendicular to the beam line. b) $x - z$ view with beam parallel to the z axis.

reconstruction efficiency and resolution of vertices in the $r - \phi$ coordinates. In 1993 the detector was upgraded by gluing $r - z$ wafers back to back with the original $r - \phi$ wafers [58]. In 1995 the detector was upgraded by tilting the ladders to close gaps in ϕ and the outer layer was changed from three to five wafers per ladder [59]. The SI provides precision measurements of secondary vertices of short lived particles and of the primary vertex. The intrinsic single hit resolution of the detector is $\sim 7 \mu\text{m}$. Alignment uncertainties add an additional uncertainty of $\sim 20 \mu\text{m}$. Performance for tracking and vertex reconstruction is discussed below.

3.2.3 Central Tracking Detectors

The central tracking detectors are the central vertex detector (CV), the central jet chamber (CJ) and the z -chambers (CZ). All three chambers are contained inside a pressure vessel that contains a mixture of ($\sim 88\%$) argon, ($\sim 10\%$) methane and ($\sim 2\%$) isobutane at a pressure of 4 bar. Outside of the pressure vessel is a 0.435 T solenoidal magnet which provides a highly uniform field within the volume of the tracking detectors. The CV provides precision vertex measurements for short lived particles and provides an accurate point to fix the curves used in measuring the momentum of charged tracks close to the vertex. The CJ is a large volume jet chamber and provides position and energy loss measurements for charged particles at up to 159 points allowing measurements of momentum and the measurement of specific ionization (dE/dx) for particle identification. The CZ is a set of planar drift chambers measuring track coordinates along the z axis.

Central Vertex Detector

The central vertex chamber (CV) is a precision drift chamber. It is a cylindrical chamber 1 m long with inner and outer radii of 88 mm and 235 mm providing $\sim 95\%$ solid angle coverage. The wires are divided into 18 layers with an inner set of 12 axial wires layers and an outer set of 12 stereo wires layers rotated at 4° with respect to the axial wires. Each layer is divided into 36 azimuthal cells of wires. The axial cells contain 12 staggered anode wires with spacing of 5.3 mm. The stereo cells contain 6 staggered anode wires spaced 5.0 mm apart. The anode wires alternate with potential wires. The anode-potential planes that make up the cells alternate with cathode planes which divide the cells. $r - \phi$ measurements are provided by drift time measurements in the axial cells. Measurements of the z coordinate are provided by the stereo cells. A coarse z measurement is performed by measuring the time difference of the signals from either end of a wire. The resolution of the detector is $\sim 50 \mu\text{m}$ in the $r - \phi$ plane and $\sim 700 \mu\text{m}$ in z .

Jet Chamber

The central jet chamber (CJ) is a large volume drift chamber. It is a cylindrical chamber 4 m long with an inner and outer radii of 0.25 m and 1.85 m. The chamber is divided into 24 radial sectors. Each sector contains 159 staggered sense wires spaced 10 mm apart parallel to the z axis. The sense wire alternate with potential wires. The sectors are divided by cathode wire planes. Measurements of r , ϕ and z are provided by wire position, drift time and charge division measurements respectively. Energy loss measurements for charged particles at up to 159 points provided measurements of specific ionization, dE/dx . The

maximum drift distance is 3 cm at the innermost wires and 25 cm at the outermost wires. A maximum of 159 points are measured for particles that pass through the chamber in the range $43^\circ < \theta < 137^\circ$ and 98% of the total solid angle is covered by regions of the chamber where at least 8 points are measured. The single hit resolution of the detector is $\sim 135 \mu\text{m}$ in the $r - \phi$ plane and $\sim 6 \text{ cm}$ in z . The dE/dx resolution is 2.8% for μ -pairs and 3.2% for minimum ionizing hadrons. The dE/dx measurements for various leptons and hadrons is shown in figure 3.4.

z-chambers

The central z-chambers (CZ) are planar drift chambers located outside the CJ detector. The detector is 4 m long, 59 mm thick cylinder and is divided into 24, 50 cm wide chambers. The chambers are divided into 8, 50 cm cells in the z direction. Each cell has 6 staggered anode wires spaced 4 mm apart in the center of the cell perpendicular to the z direction. The z coordinate is measured by drift time and the ϕ coordinate is found by charge division. The detector covers 67% of the solid angle and 94% of the ϕ coordinate. The resolution of the detector is $\sim 300 \mu\text{m}$ in z and $\sim 6 \text{ cm}$ in the $r - \phi$ plane.

Magnet

The OPAL solenoidal magnet is located outside of the central detectors and their pressure vessel and inside of the electromagnetic calorimeter. For this reason it was designed for transparency to particles as well as uniform field. The magnet is a 0.435 T water cooled solenoid. The coil is 6.3 m long, 151 mm thick (96 mm of aluminum and 54 mm of glass epoxy) and has a radius of 2.16 m. There are

Figure 3.4: Measured dE/dx for hadronic tracks, electrons and muons vs. momentum.

0.4 radiation lengths of material before the magnet. The magnet is 1.7 radiation lengths thick which includes the pressure vessel wall from which it is mechanically supported. The power consumption is 5 MW at a maximum current of 7000 A. The uniformity of the field is $\pm 0.5\%$.

The return yoke of the magnet is located outside of the electromagnetic calorimeter. The return yoke is made of soft steel plates 0.8 – 1.0 m in thickness. The yoke is split into 5 parts; two “C”s, two poletips and one central section. The gaps between the steel plates have been instrumented with streamer tubes to form barrel, endcap and poletip hadronic calorimeter.

Combined Central Detector Performance

The central tracking and SI detectors are used to determine the vertex information for short lived particles and the interaction vertex. The central tracking and SI detectors are also used to determine the momentum of particles with the CV and SI fixing the innermost points of the tracks. The combined transverse impact parameter resolution, d_0 ($\Sigma d_0 = (d_{0\mu^+} + d_{0\mu^-})/\sqrt{2}$), is shown in figure 3.5, for muon pair tracks. The two impact parameters are signed with respect their position along the y axis with respect to the primary vertex. The primary vertex is found using charged tracks with a technique that follows any significant shifts in the beam spot during a LEP physics cycle [60]. The d_0 resolution is $\sigma_{d_0} = 20.2 \mu\text{m}$. Without the SI detector the resolution is $\sigma_{d_0} = 40.6 \mu\text{m}$. The resolution of the projection of the impact parameter vector on the z axis, z_0 , including SI, is $\sigma_{z_0} = 85 \mu\text{m}$. z_0 is signed as above with respect to the primary vertex. The momentum resolution expressed as $1/p$ for μ -pair events is shown in figure 3.6. The resolution for 45.6 GeV/ c μ -pair tracks is 5.8%. The

transverse resolution for tracks can be more generally given by the expression $(\delta p_{xy}/p_{xy})^2 = (2\%)^2 + (0.15\% \cdot p_{xy})^2$, where p_{xy} is in GeV/c. The first term is from multiple scattering. The second is due to intrinsic resolution of the central detectors.

3.2.4 Time of Flight Counters

The time-of-flight counters (TOF) measure the flight time of particles from the interaction region to the TOF counters. This information is used in the trigger and to distinguish bunchlets in the same bunch train. The TOF system consists of 160 scintillating counters arranged in a cylinder outside the solenoid at a radius of ~ 2.36 m. Each counter is a 6.840 m long, 91 mm wide and 45 mm thick. Light is collected at the ends and detected by phototubes. The signals from the photomultipliers are split and read out by an 11 bit(50 ps/count) TDCs and a 12 bit charge integrating ADCs. Timing measurements are taken from the mean time of the TDCs and a coarse measurement of the z coordinate is found from the ADCs via light division. The resolution of the z measurement is $\sigma_z = 5.5$ cm. The timing resolution is found to be $\sigma_t = 460$ ps for muon pair events. The timing information is used primarily to reject cosmic ray backgrounds and in the trigger system.

3.2.5 Calorimeters

The calorimeter includes three separate detectors. The electromagnetic presampler samples showers started in the ~ 2.1 radiation lengths of material between the calorimeter and the interaction points. The electromagnetic calorimeter measures the energy of photons and electrons. The hadronic calorimeter detects the

Figure 3.5: The d_0 distribution for tracks from μ -pair events in the barrel region ($\cos \theta > 0.7$), where at least one silicon vertex detector hit is required.

Figure 3.6: the $1/p$ distribution of negatively and positively charge tracks in μ -pair events that went into the barrel region ($\cos \theta > 0.7$).
 q is the charge of the muon.

passage of hadrons and other particles not absorbed by the inner detectors and samples the energy deposited by that passage.

Electromagnetic Presampler

The electromagnetic presampler is divided into two parts. There is the barrel electromagnetic presampler (PB) located between the TOF and the barrel electromagnetic calorimeter and the endcap electromagnetic presampler (PE) located between the pressure vessel and the endcap electromagnetic calorimeter at both ends of the experiment.

The purpose of the PB is to sample and determine the position of electromagnetic showers that initiated in the ~ 2.1 radiation lengths of material between the barrel electromagnetic calorimeter and the interaction point. The PB consists of 16 chambers arranged in a cylinder around the beam line at a radius of 2.4 m. Each chamber contains two layers of 24 limited steamer mode tubes with wires running in the axial direction. The tubes are 9.6 mm square with 1 mm thick PVC walls. The two layers are offset by one cell halfwidth in order to reduce inefficiencies. The anode is formed by wires running the length of each tube axially and the cathode by 1 cm strips located on both sides of the tube layers running at 45° to the wires, with the two sets orthogonal to each other. The cathodes are resistive and operated at high voltage. The gas mixture is 32% n-pentane and 68% CO_2 . Position is determined and energy sampled by measurements from the two sets of cathode strips. The z coordinate is independently determined by charge division on the wire. The PB covers the region $|\cos \theta| > 0.81$. The resolution of the PB for the position of electromagnetic showers is 6 to 4 mm for showers ranging from 6 to 50 GeV. The resolution of

the z measurements from charge division on the wires is 10 cm.

The PE consists of two layers of 16 multiwire chambers each in an umbrella like arrangement. One layer consists of 16 large trapezoidal chambers inclined at 18° to the beam line. The other layer consists of 16 small trapezoidal chambers perpendicular and close to the beam line. The two layers and adjacent chambers in each layer overlap each other to insure full coverage. Each chamber has four anode wires, cathode strips on one side and conductive pads on the other. The strips fan out radially from the beam line and the wires are perpendicular to the strips. The wires are operated at high voltage. Position is determined by the strips and charge division on the wires. Energy measurements are performed by reading out the pads. The gas mixture used in the PE is 55% CO_2 and 45% n-pentane. The PE covers the region $0.83 < \cos \theta < 0.93$. The intrinsic resolution for a minimum ionizing particle is 2-4 mm.

Electromagnetic Calorimeter

The electromagnetic calorimeter (ECAL) is divided into two parts. There is the barrel electromagnetic calorimeter (EB) located between the PB and the return yoke of the magnet and the endcap electromagnetic calorimeter (EE) located between the PE and the endcap return yoke of the magnet.

The EB acts as a full absorbtion calorimeter with good energy resolution for particles from tens of MeV to 100 GeV. The EB consists of 9440 lead glass blocks arranged in a cylindrical array with an inner radius of 2.455 m. Each lead glass block is 10 cm by 10 cm and 37 cm in depth. The blocks point toward the interaction region with a slight offset to avoid gaps. The lead blocks present 24.6 radiation lengths of material. Cherenkov radiation produced by showers

in the EB is detected by 4-inch magnetically-shielded phototubes coupled to the back of the blocks. The EB covers the region $|\cos\theta| > 0.82$. The energy resolution is degraded by as much as a factor of two by the ~ 2.08 radiation lengths of material in front of the EB. However, 50% of this degradation can be recovered by the presampler. The energy resolution with the presampler is $\sigma_E/E \simeq 0.2\% + 6.3\%/\sqrt{E}$, where the constant term is the intrinsic resolution of the calorimeter.

The EE consists of two groups of 1132 lead glass blocks arranged in half dome shaped arrays following the curve of the pressure vessel. The lead glass blocks are 9.2 cm by 9.2 cm by with three different lengths (38.0 cm, 42.0 cm and 52.0 cm) which correspond to approximately 22 radiation lengths with the minimum length corresponding to 20.5 radiation lengths. The blocks are aligned axially or parallel to the beam line. Cherenkov radiation produced by showers in the EE is detected by vacuum phototriodes which can function in the axial magnetic field. The EE covers the region $0.81 < \cos\theta < 0.98$. The energy resolution is $\sigma_E/E \simeq 5.0\%/\sqrt{E}$ for particles at low energy.

Hadronic Calorimeter

The hadronic calorimeter (HCAL) is divided into 5 segments; two poletips, two endcaps and the barrel calorimeter. The 5 segments are located between the electromagnetic calorimeter and the muon chambers and instrument the return yoke of the magnet.

The barrel hadronic calorimeter (HB) acts as a sampling calorimeter for hadronic showers. It can also be used in detecting muons. The HB consists of 24, 9 layer wedges instrumented with limited streamer tubes alternating with 8

slabs of iron in a cylinder around the beam line. The wedges point toward the interaction point and are 10 m long with inner and out radii of 3.39 m and 4.39 m. Each slab is 10 cm thick with 25 mm gaps for instrumentation. The chambers consist of 8 axial tubes with inner dimensions of 9 mm by 9 mm and 1 mm thick walls made of extruded PVC. One side of the tube is open and the tube is covered with a gas tight jacket. The anode is provided by a wire running the length of the chamber. The inner walls of each tube are covered with graphite and a stabilizer and act as a cathode, except for the wall at the inner radius which is left open. The wires are operated at high voltage. Signals are read out on 4 mm strips below the chambers (inner radius) centered below the wires. The strips provide digital signals which can track particles in the $r - \phi$ plane. In addition total integrated charge is read out on 50 cm by 50 cm pads positioned above the chamber (outer radius). The pads are summed radially into towers to determine the total charge. The gas mixture used in the HB is 75% isobutane and 25 % argon. The material in front of the HB represents ~ 2.2 interaction lengths. The HB provides 4 or more interaction lengths. The HB covers the region $|\cos \theta| > 0.81$. The energy resolution of the HB is $\sigma_E \simeq 120\%/\sqrt{E}$.

The HE consists of 24 8 layer wedges instrumented with limited streamer tubes alternating with 7 slabs of iron in a cylinder around the beam line at either end of the detector. The wedges are 1 m long and have inner and outer radii of 1.9 m and 3.3 m. Each slab is 10 cm thick with 35 mm gaps for instrumentation. The HE covers the region $0.81 < \cos \theta < 0.91$. The chambers, readout and function are identical to those of the HB except in that the chambers are oriented with the wires parallel to the x coordinate.

The HP consists of 16, 10 layer wedges instrumented with limited streamer

tubes alternating with 9 slabs of iron in an cylindrical array around the beam line at either end of the detector. The wedges are 0.81 m long and have inner and out radii of 0.6 m and 1.8 m. Each slab is 7.2 cm thick with 10 mm gaps for instrumentation. The HP covers the region $0.91 < \cos \theta < 0.99$. The chambers and readout are identical to those of the PE. The resolution of the HP for energy is also $\sigma_E \simeq 120\%/\sqrt{E}$.

3.2.6 Muon Detector

The MB is used to detect and discriminate muons from hadrons. The barrel muon detector (MB) consists of 110 large area drift chambers arranged in four layers that form cylinders outside of the HB. The chambers are 1.2 m wide, 10.4 m long and 90 mm deep. Some shorter chambers are used to make room for magnet support legs. The layers are staggered by 50 mm in ϕ direction. Each chamber contains two anode wires strung axially. The cathode is formed by diamond shaped cathode pads. There are four sets of diamond shaped cathode pads; 171 mm pads on the outer and inner sides of the chamber and 1710 mm pads beyond the smaller pads. Both the cathode pads and the anode wires are operated at high voltage with a voltage difference of 1.85 kV between them. The gas mixture is 90% argon 10% ethane. Signals are read out at either end of the wires and pads with the wires and large pads used to resolve the ambiguity in the measurements in the small pads. The z coordinate is determined by pad location, ϕ by drift time and r by layer location. The MB covers the angular region $|\cos \theta| > 0.72$. Track segments in the muon detector are matched to tracks in the central tracking system. The maximum drift distance is 297 mm. The intrinsic resolution is 1.5 mm in the $r - \phi$ plane and 1 mm for the z coordinate.

The endcap muon detector (ME) consists of two sets of 8 quadrant chambers and 4 patch chambers on the forward and backward ends of the detector outside of the HE. The quadrant chambers are arranged in two sets of four located at $|z| = 5.50$ m and $|z| = 6.15$ m. The quadrant chambers overlap vertically and have a gap horizontally for the beam line, mechanical supports and wiring. The patch chambers cover the horizontal gap close to the beam line and overlap horizontally with the quadrant chambers. Each quadrant chamber is 6 m square. The patch chambers are 3 m horizontally and 2 m vertical. All chambers contain two layers of 9 mm square streamer tubes with 1 mm thick walls. One side of the tube is open and the tube is covered with a gas tight jacket. The two layers are spaced 19 mm apart and arranged with streamer tubes horizontal and vertical to the ground. Each tube contains one anode wire. The walls of the chamber are covered with a water based carbon suspension which acts as the cathode. The anode is operated at high voltage. Two sets of 8 mm strips are located on either side of the tubes perpendicular and parallel to the wires. The gas mixture used in the ME is 75% isobutane and 25 % argon. Signals are read out on the strips. The ME covers the region $\sim 0.67 < \cos \theta < 0.985$. Track segments in the muon detector are matched to tracks in the central tracking system. The intrinsic resolution is 1 mm for perpendicular strips and 3 mm for parallel strips.

3.2.7 The Forward Detectors

Several detectors are located in the forward and backward regions close to the beam line 2 m to 3 m from the interaction region. The main detectors are the forward detector (FD) and the silicon tungsten luminometer (SW). They both measure the luminosity from Bhabha scattering and act as luminometers. They

have clean acceptance between 47 and 120 mrad, only obstructed by the beam pipe and the central tracker pressure vessel.

Forward Detector

The forward detector (FD) consists of a calorimeter, tube chambers, drift chambers, a fine luminosity monitor, a gamma catcher and a far forward luminosity monitor. The forward calorimeter consists of 35 layers of lead-scintillator attached to wavelength shifters and read out by vacuum phototetridodes. Each layer is divided into 16 azimuthal segments. The calorimeter presents 24 radiation lengths. The front 4 radiation lengths act as a presampler. The energy resolution is $\sigma_E \simeq 17\%/\sqrt{E}$ and the ϕ resolution of 1.5° . The tube chambers consists of three planes of proportional tubes between the presampler and the main calorimeter. They have a position resolution of 3 mm. The drift chambers consist of 2 layers with two gaps and two wires per gap located in front of the calorimeter. The resolution is 300 μm in the radial drift direction and 1 mm parallel to the wire (using charge division). The fine luminosity monitor consists of four pairs of scintillators between the two layers of the drift chambers. The scintillators are 6 mm thick and are placed at 45° angles. They record timing and charge information for each event with a timing resolution of 300 ps. The gamma catcher which consists of a ring of lead-scintillator is located in front of the fine luminosity monitor and farther from the beam line to make room for beam pipe supports. The gamma catcher is 7 radiation lengths and detects electrons or photons. The far forward monitor consists of lead-scintillators located at 7.85 m from the interaction region. The far forward monitor is 20 radiation lengths thick and detects electron showers. The forward detector, excepting the

gamma catcher, has acceptance between 39 and 140 mrad. However, the acceptance below 47 mrad is obstructed by the beam pipe support structure and the acceptance beyond 120 mrad is obstructed by the tubes for the central jet chamber laser calibration system. The gamma catcher, which is located in front of the central jet laser calibration system, covers the region between 142 and 200 mrad. The total experimental systematic uncertainty in the luminosity measurement by the FD is $\sim 0.5\%$.

Silicon Tungsten Luminometer

The silicon tungsten luminometer (SW) was installed in 1993. It was designed to function as the primary luminometer reducing the experimental systematic error by a factor of 5 to under 0.1%. The SW consists of two interlocking C-shaped modules with 19 layers each [61]. Each layer consists of a tungsten halfdisk and 8 silicon wedges which contain 64 pads each. The half disks are also include a printed circuit board with readout electronics and a 2 mm aluminum support plate. The 19 layers present 22 radiation lengths and are located 2.4 m from the interaction points with inner and outer radii of 62 mm and 142 mm. The SW has acceptance between 30 and 55 mrad. This degrades the acceptance in part of the region covered by the forward detector. The SW acceptance between 34 and 47 mrad is degraded by the support material for the beam pipe. The total experimental systematic uncertainty in the luminosity measurement by the SW is $\sim 0.08\%$ [62].

3.2.8 Data Acquisition and Control Systems

Each subdetector has a dedicated data acquisition (DAQ) system [63]. Triggering is performed centrally using information from several subdetector DAQ systems. Online computers provide centralized control of the subdetectors and trigger as well as reconstruction and storage of data events. A separate system monitors safety information. The OPAL data flow is shown in figure 3.7

Subdetector Data Acquisition

Each OPAL subdetector has a dedicated data acquisition (DAQ) system. The DAQ computers are called "local system crates" (LSC) and implemented in VME. The LSC computers typically use 68020 or 68030 microprocessors and the OS9 operating system. Several DAQ systems are HP RISC microprocessors using the Unix operating system. These computers collect, process and export subdetector data. In addition each system is able to receive trigger signals, some systems can provide fast trigger information, and many system functions can be controlled by central online computers.

Trigger System

The trigger system is designed to provide high efficiency for physics events, rejection of backgrounds, such as cosmic rays and beam gas interactions and low dead time. The original trigger was single state, since the 45 kHz bunch crossing rate allowed more time between beam crossings than the electronics reset time [64]. This trigger used 120 digital trigger signals sent from 11 subdetectors. The detectors used were the CV and CJ (combined to form a track trigger TT), TOF, EE, EB, HS HT, MB, ME, FD and SW (after installation). The individual

Figure 3.7: Typical flow of data in OPAL. Each element is described in the sections on online computing or offline computing.

trigger signals are of two types. High threshold direct signals such as total energy sums or track counts and low threshold $\theta - \phi$ hits (in 6 – 24 overlapping bins). The triggers are combined to form overall trigger decisions according to as many as 60 programmable conditions. The original trigger has almost 100% efficiency for Z^0 decay modes.

The bunch crossing rate was upgraded to 90 kHz in 1992 [65]. Since the time between bunch crossing was smaller than the subdetector reset time a two level trigger was implemented using a fast pretrigger to reduce the number of signals to process in the main trigger. The pretrigger used digital trigger signals sent from 7 subdetectors. The detectors used were the CV, CJ, TOF, EE, EB, ME and SW. The design of the pretrigger was similar in design to the main trigger except in that only 12 overlapping bins of ϕ are used. The main trigger was left unchanged. The new trigger has a dead time of 1.5% and almost 100% efficiency for Z^0 decay modes.

Central Online Computers

The central online computers reconstruct and store the data as well as providing centralized monitoring and control of many subdetector functions. The control system was originally implemented in the PROLOG language on VAX workstations and was later upgraded to the C++ programming language on HP unix workstations.

Data processing and storage is as follows. Data is collected from the DAQ LSC computers and sent to an event builder which merges the data. The event builder is buffered and can receive data from different subdetector LSCs out of sequence. The event data is then passed through an event filter which acts as

a software trigger [66]. In addition the filter partially reconstructs and classifies events. Events that pass the filter selection are classified as physics (FYZ1) events. A second important classification is the Gold Plated Multihadron Selection (GPMH). The GPMH selection is also used in a refined form for offline analysis. The details of the GPMH selection are discussed in the analysis section. After filtering the event is then fully reconstructed by the online event reconstruction system. Events are then stored to tape (later upgraded to optical disk) and directly to the offline systems where they can be accessed for analysis. Table 3.2 lists the number of OPAL DST data events collected for FYZ1 and GPMH events.

Year	Number of FYZ1 Events	Number of GPMH Events
1990	1358156	147633
1991	2623793	345426
1992	4790862	766857
1993	11542512	703923
1994	19686963	1710553
1995	18878506	727006

Table 3.2: FYZ1 and GPMH events stored on SHIFT

The online computers provide monitoring of subdetector performance in both the event filter and the online event reconstruction system. The trigger system is also monitored by the online computer system. The online computers also provide centralized access to the subdetector which allows the performance of procedures such as restarts or monitoring of histograms generated in the LSCs.

Slow Control Systems

Monitoring of safety information is provided by a separate slow control system. The system consists of several VME crates connected to a dedicated monitoring VME crate in the main control room. In addition there is a separate gas safety system (GSS) to monitor gas conditions. These systems monitor analog and digital information from each subdetector. Values are compared to nominal ranges at periodic times and warnings and alarms can be given or automatic actions taken if certain preprogrammed conditions are met. Control of many safety functions is possible from the central slow control VME crate.

3.3 Computing and Data Processing

The analysis presented in this work uses data collected with the OPAL detector. OPAL data is processed in several steps before being used for physics analysis. The data is processed using several online and offline computing systems described below. In addition this work uses simulated data to estimate backgrounds and efficiencies as described below.

Online and Offline Computing

The first steps of data processing: event building, filtering and event reconstruction are performed on the online computing systems described above. After reconstruction events are transferred to the SHIFT (Scalable Heterogeneous Integrated Facility) analysis computers, which currently consists of several Silicon Graphics computers. SHIFT is a system for batch processing and tape handling. On SHIFT events can be analyzed using programs that read the reconstructed

data. The data is also stored in a raw compacted form which contains all the original information provided by the subdetectors. The raw data can be analyzed in its raw form or reconstructed again. SHIFT also acts as the primary storage and access system for simulated data. Simulated data can be stored in reconstructed or raw form and analyzed using identical methods to those used on the real data. Simulated Monte Carlo events are generated using several simulation programs which are run on offline clusters of HP, DEC or DEC Alpha workstations. The event reconstruction and analysis software is also available for use on each offline cluster so that simulated events or small amounts of data can be tested on local computers.

Event Reconstruction

The event reconstruction program is known as ROPE (Reconstruction of OPAL Events). It includes subprograms for reconstructing raw subdetector data into events. There are also routines for steering, data access and utility programs for various data processing and analysis tasks. ROPE can process real data or Monte Carlo simulated data in either raw or reconstructed form.

Modules exist to reconstruct data from all subdetector or related subdetector groups. Charged track information is reconstructed for the central tracking and silicon microvertex detectors including vertex or impact parameter information where possible. Electromagnetic clusters are reconstructed from electromagnetic calorimeter and presampler information. Hadronic clusters are reconstructed in each of the hadronic calorimeter segments. Similarly clusters are reconstructed in the forward and silicon tungsten detectors. Where possible energy clusters are matched to tracks from the central detectors and to energy clusters in other

detectors. Track segments in the muon detectors are reconstructed and matched with central detector tracks. Reconstructed data is stored in a form known as Data Summary Tapes (DSTs). The raw data is also stored in a compressed form known as Dense Data Summary Tapes (DDSTs).

3.4 Simulation

A Monte Carlo simulation is used to determine the reconstruction and selection efficiencies for the various processes and for estimating the background levels. Monte Carlo production takes place in three steps. First the physics processes are simulated and final state particle four vectors are produced by a generator program. Next the detector response is modeled by a full detector simulation. The output detector response to the simulated events is then processed and reconstructed as described above in an identical manner to the real data events.

Event Generators

Several simulated event generators are used to produce Monte Carlo events for OPAL analysis. For analysis of LEP I data involving the production and decay of Z^0 bosons the general purpose generators JETSET 7.4 [67], HERWIG 5.9 [68] and YFS3FF [69] are used. Each generator has features useful for studying physics events. JETSET 7.4, which is used in this analysis and will be described in more detail below, provides many routines for different treatments of parton distributions, fragmentation and decay. HERWIG (Emission Reactions With Interfering Gluons) explicitly tracks gluons and color and simulates effects such as interference and color coherence. YFS3FF (Fermion Pair Production Initial

and Final State Exponentiation) provides routines for detailed treatments of the QED matrix elements for initial state radiation (ISR) and final state radiation (FSR). Other generators, such as SUSYGEN [70] and or KORALZ [71], are used to simulate specific processes such as SUSY production and $Z^0 \rightarrow \tau^+\tau^-$ respectively. The output of SUSYGEN can be used by a generator such as JETSET 7.4 to simulate the decays. At LEP II energies two of the main generators used are PYTHIA [67], an updated version of JETSET, or KORALW [72], a generator that produces all of the four fermion diagrams including W pair production.

The JETSET 7.4 program [67] was used to generate e^+e^- annihilation events and the decay of the Z^0 boson in this analysis. JETSET 7.4 simulates e^+e^- annihilation using a parton-shower or matrix element approach. It also provides routines for jet fragmentation, multiple interaction, particle decays and both initial and final-state parton showers using various theoretical models of hard and soft physics interactions. The parameters used in JETSET 7.4 can be tuned to provide agreement with experimental data [73]. The output is in the form of momentum 4-vectors and particle ID codes for each parton, primary hadron and decay product in the interaction.

Detector Simulation

The next step in event simulation is to model the detector response. The output four vectors of JETSET 7.4 are used as input in the GOPAL [74] (GEANT and OPAL) full detector simulation. GOPAL uses routines from GEANT [75] which is a set of generic routines designed to simulate the passage of particles through matter. The trajectories, scattering, decays of long lived particles and other physical interactions are all simulated by GEANT. GEANT also provides

routines used to define the detector geometry and composition. GOPAL uses the simulated response provided by the GEANT routines to determine the specific response of each subdetector to the passage of particles. The simulated digitization of the response is also performed. The distributions in GOPAL are produced using functions which are parameterized by fitting to the data. Wherever possible parameters used in GOPAL are measured in data. The output of GOPAL is identical to the output of the online OPAL data acquisition computers except in that it includes Monte Carlo information including the generated four vectors, the particle IDs and a tree structure relating each particle to its parent or daughter particles.

The reliability of the GOPAL detector simulation has been tested extensively by comparison with data. In general the quality of the simulation is good and the remaining problems do not effect this analysis. The following is an itemized discussion of the simulation of subdetectors or groups of subdetectors relevant to this analysis.

- Central Tracking Detectors: The problems with the central detector simulation include discrepancies in the distribution of pulse heights of individual hits for large signals in the silicon(SI) detector. This is understood as being due to the anomalously high pulse heights that occur in the data that are not simulated by the Landau distribution of pulse heights in the Monte Carlo. In addition the number of tracks with no central vertex(CV) information matched to them is slightly overestimated. Also the distribution of the number of hits per track in the z chambers (CZ) has discrepancies. However, the quantities that are commonly used in analysis, the hit rate in the SI, the number of hits per track in the central jet (CJ) and whether

a track has any hits in the CZ, are well simulated. In addition the dE/dx deposition in the CJ is well simulated (see figure 3.8). Also the combined $r - \phi$ tracking resolution is good (see figure 3.9). However, the z tracking resolution in the Monte-Carlo is slightly too narrow.

- Calorimeters: The resolution of the electromagnetic calorimeters, including the presampler, and the hadronic calorimeters is slightly too good in the simulation. However, the shape of the energy distributions is in good agreement with the data.
- Muon Chambers: The resolution of the muon chambers is slightly too good in the simulation. This is understood as being due to systematic errors made in the survey of the muon chamber positions that are not included in the simulation. However, the muon finding efficiency is well simulated.

In general the data important for this analysis, which includes quantities such as: vertex resolution, momentum resolution, energy deposited in the electromagnetic calorimeter and tracking of muons in the hadronic calorimeter and muon chambers, are well simulated.

Figure 3.8: Comparison of real data (solid line) and Monte Carlo (points with error bars) for the jet chamber. The Monte Carlo is normalized to the number of events in the data. (a) Distribution of the number of hits per track in multihadronic events useable for the calculation of the dE/dx for tracks in the barrel region ($\cos \theta > 0.7$). (b) The relative dE/dx resolution as a function of the number of hits in multihadronic events for tracks in the barrel region. (c,d) The measured dE/dx for tracks in multihadronic events in the momentum ranges (c) 0.4 – 0.8 GeV/c and (d) 2.5 – 4.0 GeV/c.

Figure 3.9: Comparison between data (solid line) and Monte Carlo (points with error bars) for multihadronic events (a-c) and muon pair events (d) for the central tracking detectors. The Monte Carlo is normalized to the number of events in the data. (a) The impact parameter in the $r-\phi$ plane. (b) The impact parameter in the $r-\phi$ plane (larger scale). (c) The impact parameter in z . (d) the distribution of $1/p$ (signed by charge) for muon pair events.

Chapter 4

Analysis

4.1 Introduction

This chapter details the methods and results of a search for B_c decays in a data sample of 4.2×10^6 hadronic Z^0 decays collected with the OPAL detector at LEP.

This analysis of the B_c decays includes searches for the decay modes:

- $B_c^+ \rightarrow J/\psi \pi^+$
- $B_c^+ \rightarrow J/\psi a_1^+$, where $a_1^+ \rightarrow \rho^0 \pi^+$ and $\rho^0 \rightarrow \pi^+ \pi^-$
- $B_c^+ \rightarrow J/\psi \ell^+ \nu$.

The analysis involves the reconstruction of J/ψ candidates in the leptonic mode $J/\psi \rightarrow \ell^+ \ell^-$, which are then combined with other tracks to form $J/\psi \pi^+$, $J/\psi \pi^+ \pi^- \pi^+$, and $J/\psi \ell^+$ combinations. The $J/\psi \ell^+$ combination is a partial reconstruction of the semileptonic decay mode $B_c^+ \rightarrow J/\psi \ell^+ \nu$. The desirable features of such a search are: high efficiency and low background reconstruction of J/ψ in its leptonic decay modes, high efficiency reconstruction of B_c in modes involving a minimum number of extra particles aside from the J/ψ , precise mass reconstruction in exclusive modes and the high branching ratio of the semileptonic decay mode. Precise mass reconstruction in the exclusive modes is important because it, along with the narrowness of the theoretical predictions for the B_c mass, allows the search to be performed in a small mass window.

Three candidates B_c^+ decays are observed, two in the $B_c^+ \rightarrow J/\psi\pi^+$ mode and one in the $B_c^+ \rightarrow J/\psi\ell^+\nu$ mode. The invariant mass of the $B_c^+ \rightarrow J/\psi\pi^+$ candidates are $(6.29 \pm 0.17) \text{ GeV}/c^2$ and $(6.33 \pm 0.063) \text{ GeV}/c^2$, which are consistent with the predicted mass of the B_c meson. The $B_c^+ \rightarrow J/\psi\pi^+$ candidates are the only pair of fully reconstructed B_c^+ events observed experimentally.

At the time this search was performed the B_c mesons was the last unfound psuodoscaler ground state b-flavored meson. The B_c^+ is of particular interest since it is the only possible flavored meson involving two heavy quarks. Several collaborations at both Tevatron and LEP had conducted searches for the B_c meson. The previous search performed by the OPAL Collaboration found one candidate in the mode $B_c^+ \rightarrow J/\psi\pi^+$ with an expected background of 0.3 [76]. The CDF Collaboration performed a search for the B_c in the mode $B_c^+ \rightarrow J/\psi\pi^+$. For several different cuts on candidate lifetime the number of candidates was found to be consistent with the number of background events [77]. The DELPHI Collaboration found one candidate in the $B_c^+ \rightarrow J/\psi\pi^+$ decay mode and one candidate in the $B_c^+ \rightarrow J/\psi\pi^+\pi^-\pi^+$ decay mode with the expected backgrounds of 1.7 and 2.3 in each mode respectively [78]. The reconstructed masses of DELPHI B_c^+ candidates are significantly different. The ALEPH Collaboration found two candidates in the $B_c^+ \rightarrow J/\psi\ell^+\nu$ consistent with an expected background of 0.81 events [79]. In addition they present invariant mass and vertexing evidence that casts doubt on whether the two candidates are true B_c^+ . They also present the results of a separate analysis in which a B_c candidate is found by scanning all $J/\psi X^+$ candidates with a mass above the B^+ mass. Each collaboration sets confidence limits on the production rates for each process except CDF which set a limit on the ratio of the production rates of the processes $B_c^+ \rightarrow J/\psi\pi^+$

over $B^+ \rightarrow J/\psi\pi^+$. These results are presented in the conclusion chapter for comparison to the results of this analysis.

Given the fact that at best only a few events are expected in each channel, it is crucial that the combinatorial background be minimized. Theoretical predictions for the production [80] and branching fractions [81] give an expectation of approximately 0.07 to 0.3 $B_c^+ \rightarrow J/\psi\pi^+$ events and 1 to 6 $B_c^+ \rightarrow J/\psi\ell^+\nu$ events in the OPAL data set. None of the papers in the literature predict the branching fraction to the $B_c^+ \rightarrow J/\psi a_1^+$ mode. The dominant background to the sample of B_c candidates is from random combinations of J/ψ 's produced in b hadron decays with other tracks from b hadron decays or from the fragmentation process. Other backgrounds include random combinations of prompt J/ψ or fake J/ψ candidates with other tracks in the event. The selection criteria were developed by studying Monte Carlo simulated events containing the signal and background processes.

4.2 Data Sample and Hadronic Event Selection

The data used in this study were collected between 1990 and 1995 using the OPAL detector at LEP. The sample corresponds to approximately 4.2×10^6 hadronic Z^0 decays. Data taken in 1990 includes no silicon microvertex information. Data taken between 1991 and 1992 includes $r - \phi$ hits from two silicon microvertex layers. Data taken from 1993 on includes both $r - \phi$ and $r - z$ hits from three silicon microvertex layers. The number of hadronic events recorded in each year is given in table 3.2 in chapter 3. The selection criteria for hadronic events was taken from [82] and is as follows. The criteria used were based on

energy clusters in the electromagnetic calorimeter and the charged track multiplicity. Clusters in the barrel region were required to have an energy of at least 100 MeV, and clusters in the end cap detectors were required to contain at least two adjacent lead glass blocks and have an energy of at least 200 MeV. Tracks were required to have at least 20 measured hits and a distance of closest approach to the interaction point of less than 2 cm in the direction perpendicular to the beam axis and less than 40 cm along the beam axis. Tracks were also required to have a minimum momentum component transverse to the beam direction of 50 MeV.

The following four requirements defined a multihadron candidate:

- at least 7 clusters;
- at least 5 tracks;
- a total energy deposited in the lead glass of at least 10% of the center-of-mass energy: $R_{vis} \equiv \Sigma E_{clus} / \sqrt{s} > 0.1$, where E_{clus} is the energy of each cluster;
- an energy imbalance along the beam direction which satisfied $R_{bal} \equiv | \Sigma(E_{clus} \cdot \cos \theta) | / \Sigma E_{clus} < 0.65$.

The cut on the number of clusters and the number of tracks efficiently eliminated Z^0 decays into charged lepton pairs. The vertex requirements on tracks served to eliminate events caused by cosmic rays. The R_{vis} cut discarded two-photon and beam-gas events. The cut in R_{bal} rejected beam-wall, beam-gas and beam-halo events, as well as cosmic rays in the end caps. Alternative selection criteria which used only charged tracks, as well as the selection criteria based on the

electromagnetic calorimeter and the time-of-flight counters, as described in the previous publications [83, 84], were used to check the selection described above. The main contamination in the hadronic data sample comes from $\tau^+\tau^-$ events and two-photon multihadronic events. For $\tau^+\tau^-$ events, a background fraction was estimated by using Monte Carlo events generated with the KORALZ program [85]. The background from two-photon processes was estimated from the data by measuring the ratio of the numbers of events with high and low R_{vis} and the ratio of the numbers of events with high and low R_{bal} as functions of the beam energy. The selection efficiency for the multihadronic events is $(98.1 \pm 0.5)\%$, with a background of less than 0.1%.

4.3 Track Identification

This analysis requires the identification of tracks as pion, kaon, electron or muon candidates. In addition to the track selection criteria described above we impose the following requirements on all charged tracks:

- The number of hits in the central detector used for the reconstruction of a track must be greater than 40 (this restricts the acceptance to $|\cos \theta| < 0.94$);
- The distance of closest approach to the beam axis in the x - y plane must be less than 0.5 cm;
- The transverse momentum with respect to the beam direction must exceed 0.25 GeV/ c ;
- The total momentum of the track must exceed 0.5 GeV/ c ;

- To obtain accurate polar angle measurements, a barrel ($|\cos \theta| < 0.72$) track is required to match with a z -chamber track segment containing at least 3 hits; forward going tracks are constrained to the point where they leave the chamber;
- The tracks are constrained in z to the primary vertex. The primary vertex is found using charged tracks with a technique that follows any significant shifts in the beam spot during a LEP physics cycle [86].

These criteria ensure high quality tracks, which are necessary to obtain good mass resolution and particle separation in this analysis.

4.3.1 Hadron Identification

A track is identified as a pion if the dE/dx probability for the pion hypothesis, that is the probability that the specific ionization energy loss in the jet chamber (dE/dx) is compatible with that expected for a pion, exceeds 2.5% if the measured dE/dx is lower than the expected dE/dx for a pion, and 0.1% if it is higher. For the purpose of background rejection, tracks are identified as kaons if the dE/dx probability for the kaon hypothesis is greater than 5%.

4.3.2 Electron Identification

Leptons are identified by imposing the following selection criteria. We require the track momentum $p > 2.0$ GeV/ c , and $|\cos \theta| < 0.9$. For electron identification we use a neural network algorithm [87]. The electron neural network is based on a set of twelve physical quantities measured for each track in the central tracking chambers, the presampler and the lead-glass electromagnetic calorimeter:

- p , the track momentum;
- $\cos \theta$, the cosine of the polar angle of the track;
- dE/dx , the specific ionization energy loss of the track in the central tracking chamber;
- $\sigma(dE/dx)$, the estimated error on dE/dx ;
- E/p , the energy in the electromagnetic calorimeter cluster associated to the track divided by the track momentum;
- the total number of lead-glass blocks in the electromagnetic cluster;
- E_{cone}/p , where E_{cone} is the sum of the energy deposited in the lead-glass blocks whose center is contained within a cone of half angle 30 mrad around the track direction;
- the number of lead glass blocks in the cone;
- $E_{\text{cone}}/(E_{\text{cone}} + \Delta E)$, where ΔE is the energy contained in all blocks adjacent to the blocks used to calculate E_{cone} ;
- $\theta_{\text{track}} - \theta_{\text{cluster}}$, the difference in θ between the track position extrapolated to the electromagnetic calorimeter and the center of the electromagnetic cluster;
- $\phi_{\text{track}} - \phi_{\text{cluster}}$, the difference in ϕ between the track position extrapolated to the electromagnetic calorimeter and the center of the electromagnetic cluster;
- the multiplicity of the presampler cluster associated to the track.

The high level of complementarity and redundancy between these variables, provided by several independent subdetectors, ensures a good efficiency and rejection over the whole detector. A powerful multidimensional algorithm is needed in order to make optimal use of all the available information. These quantities are therefore used as input to a neural network [88] which provides the final classification. The chosen set of inputs has been selected from a much larger set of potentially discriminating or meaningful variables. While most of those retained have intrinsic separating power between hadrons and electrons (such as dE/dx , E/p , ...), some variables which are not discriminating in themselves (e.g., the momentum p and the polar angle $\cos \theta$ of the track) are nevertheless useful in that they contain important information about existing correlations between all inputs. The network used is of the feed-forward type with one hidden layer made of 15 nodes. It was trained on simulated data to discriminate between electrons and hadrons, in the momentum range $p > 2 \text{ GeV}/c$. At the end of this learning phase, the network's output can be computed for any track in real data events. This output is a real function of the inputs whose value, ranging from 0 to 1, is a measure of the probability that the track being considered is an electron. The overall efficiency for the identification of electrons from B hadron decays is $(77 \pm 5)\%$ with a cut of greater than 0.9 on the neural network output. The efficiency was determined from Monte Carlo. The error in the electron identification efficiency was determined by comparing the efficiencies in Monte Carlo and data for a pure sample of electrons from photon conversions. A test sample of pions obtained by kinematical identification of $K^0 \rightarrow \pi^+\pi^-$ decays also allowed a direct comparison of misidentification probabilities between data and Monte Carlo. The contamination from hadronic background is estimated to

be $5 \pm 1\%$.

4.3.3 Muon Identification

For muon identification, two sets of selection criteria are used. For muon candidates combined to form J/ψ candidates in the $B_c^+ \rightarrow J/\psi\pi^+$ and $B_c^+ \rightarrow J/\psi a_1^+$ modes we employ a “normal” muon selection. In this selection we require a ϕ - θ match between the extrapolated muon candidate track and a track segment reconstructed in the muon chamber [89]. In addition, we require that the candidate muon track be the best match to the muon segment. When no match to a muon segment is found, we search for a match with a track segment in the hadron calorimeter [90]. The efficiency for this “normal” muon identification is $(85 \pm 4)\%$. The efficiency was determined from Monte Carlo. The errors for the muon identification were determined by comparing the efficiency between Monte Carlo and data for a pure sample of muons from muon pair events. For muon candidates combined to form B_c candidates in the decay $B_c^+ \rightarrow J/\psi\ell^+\nu$, where $J/\psi \rightarrow \ell^+\ell^-$, we employ a “strong” muon identification [91]. In this selection we use only tracks matched with track segments in the muon detector, reject tracks identified as kaons using dE/dx information, and apply an isolation cut by requiring that there be less than 20 track segments in the muon detector within 0.3 radians of the track. The efficiency for this “strong” muon identification used in the $B_c \rightarrow J/\psi\ell\nu$ mode is $(76 \pm 4)\%$. The fake rates for the muon identifications are expected to be less than 1%.

4.4 Search for B_c decays

Events are organised into jets of particles which are constructed using charged tracks and neutral clusters that are not associated to any charged track. To form jets we use the scaled invariant mass jet-finding algorithm of JADE with a jet resolution parameter $y_{\text{cut}} = 0.04$ [92]. Candidates are formed from appropriate combinations of charged tracks which are assigned to the same jet.

4.4.1 Reconstruction of J/ψ Decays

The J/ψ meson decays are reconstructed in the leptonic modes $J/\psi \rightarrow \mu^+\mu^-$ and $J/\psi \rightarrow e^+e^-$. A pair of opposite sign electron or muon candidates in the same jet, with an invariant mass consistent with the J/ψ mass, is considered a J/ψ candidate. Muon candidates combined to form J/ψ candidates in the $B_c^+ \rightarrow J/\psi\pi^+$ and $B_c^+ \rightarrow J/\psi a_1^+$ modes must satisfy the “normal” muon identification. Muon candidates combined to form J/ψ candidates in the $B_c^+ \rightarrow J/\psi\ell^+\nu$ mode must satisfy the criteria of the “strong” muon identification. J/ψ candidates are required to have an invariant mass within the range 2.9 to 3.3 GeV/c^2 for the $\mu^+\mu^-$ channel, and within the range 2.8 to 3.3 GeV/c^2 for the e^+e^- channel. The $J/\psi \rightarrow e^+e^-$ candidate range is extended to lower masses in order to include the tail in the $J/\psi \rightarrow e^+e^-$ invariant mass distribution due to electron bremsstrahlung radiation in the detector and J/ψ radiative decays. Figure 4.1 shows the lepton pair invariant mass distributions for leptons selected with the “normal” lepton selection in the range 2.5 to 3.5 GeV/c^2 , where the J/ψ peak is clearly visible in both e^+e^- and $\mu^+\mu^-$ modes. The peak position and width are consistent with the J/ψ mass and the expected resolution of the OPAL detector.

We find a total of 354 $J/\psi \rightarrow e^+e^-$ candidates and 551 $J/\psi \rightarrow \mu^+\mu^-$ candidates using the normal muon selection. We find 391 $J/\psi \rightarrow \mu^+\mu^-$ candidates using the "strong" muon selection.

4.4.2 Selection of B_c Candidates

The dominant background to the sample of B_c candidates is from random combinations of J/ψ 's produced in b hadron decays with other tracks from b hadron decays or from fragmentation. Given the fact that at best a few events are expected in each channel, it is crucial that the combinatorial background be reduced to below the level of the expected signals. The selection criteria were developed by studying Monte Carlo simulated events containing the signal processes and a simulated sample of five-flavor Z^0 events (described below). In general, significant background suppression can be achieved by taking advantage of the hard momentum spectrum and the long lifetime of the b hadrons. However, the soft momentum spectrum of the B_c weakens the discrimination power of any momentum cut. Furthermore, since there is large uncertainty in the predictions of the B_c lifetime, no decay length cut is used. The criteria are summarized below:

- a. In all decay modes J/ψ candidates are kinematically constrained to the nominal J/ψ mass in order to improve the B_c mass resolution. Events that do not converge in the kinematic constraint algorithm are discarded. Monte Carlo studies show that less than 0.2% of J/ψ candidates from B_c^+ fail the kinematic constraint.

Figure 4.1: Invariant mass spectrum of selected (a) e^+e^- , and (b) $\mu^+\mu^-$ pairs. Also shown are the mass regions where the J/ψ candidates are defined.

- b. For the exclusive modes, $J/\psi\pi^+$ and $J/\psi a_1^+$, we require that the dE/dx measurement for each pion candidate be "consistent" with the expected value for a pion (as described in section 3).
- c. In the semileptonic mode, $B_c^+ \rightarrow J/\psi \ell^+ \nu$, there is a large background at lower masses involving fake J/ψ or J/ψ combined with fake leptons or leptons from cascade decays. This background is reduced by using the "strong" muon identification for all muon candidates and requiring the ℓ^+ lepton track momentum $p > 4.0 \text{ GeV}/c$.
- d. For $J/\psi\pi^+\pi^-\pi^+$ combinations, we require that the three-pion combination be consistent with resulting from the decay $a_1^+ \rightarrow \rho^0\pi^+$, where $\rho^0 \rightarrow \pi^+\pi^-$. The invariant mass of the three pion combination must be consistent with the a_1 mass, $(1.0 < M(\pi^+\pi^-\pi^+) < 1.6) \text{ GeV}/c^2$, and the invariant mass of at least one of the two $\pi^+\pi^-$ pairs must be in the ρ^0 mass range, $(0.65 < M(\pi^+\pi^-) < 0.90) \text{ GeV}/c^2$.
- e. All tracks from the B_c must be consistent with originating from the same decay vertex. For each B_c candidate we determine the decay vertex from the intersection of the tracks, including the tracks forming the J/ψ candidate, in the x - y plane. We require the χ^2 probability of the vertex fit to exceed 1%.
- f. Since the combinatorial backgrounds are largest at low momenta, we impose a minimum momentum cut on the B_c candidates. For the $J/\psi\ell^+\nu$ mode, where the full momentum of the candidate is not reconstructed, we require the momentum of the $J/\psi\ell^+$ combination to exceed 30% of the beam energy. For $J/\psi\pi^+$ combinations we require the momentum of the

B_c candidate to exceed 55% of the beam energy. For the $B_c^+ \rightarrow J/\psi a_1^+$ candidates, where the combinatorial background is more severe, the candidate momentum is required to exceed 70% of the beam energy.

- g. For the exclusive modes, we take advantage of the fact that the decay products of a pseudoscalar meson are isotropically distributed in its rest frame. We define θ^* as the angle between the B_c candidate direction and the direction of the J/ψ in the B_c rest frame. Since the combinatorial background mainly peaks near the backward direction ($\cos \theta^* = -1.0$), we require $\cos \theta^* > -0.8$.
- h. For the exclusive modes, the invariant mass of the B_c candidates must be in the mass interval 6.0 to 6.5 GeV/c^2 (hereafter referred to as the signal region) which is centered around the predicted B_c mass, with a width which is about three times the B_c mass resolution ($\simeq 80 \text{ MeV}/c^2$) on each side. The mass window includes the entire range of predictions for the B_c mass. For the semileptonic mode, where the full invariant mass cannot be calculated, the invariant mass of the $J/\psi \ell^+$ combination is used to define the signal region. The rarity of random combinations of three leptons in hadronic Z^0 decays combined with the high mass of the B_c produces a natural separation point between the signal and the background combinations. Figure 4.4 shows the invariant mass distribution for $J/\psi \ell^+$ combinations from a sample of simulated $B_c^+ \rightarrow J/\psi \ell^+ \nu$ decays, along with the distribution of the combinatorial background from simulated samples of the $B \rightarrow J/\psi X$ and prompt J/ψ events (see the following section for detail). The signal distribution peaks above 4.0 GeV/c^2 and the background com-

binations are mostly at lower masses. Hence we restrict the signal region to the mass interval 4.0 to 6.5 GeV/ c^2 .

- i. $B^+ \rightarrow J/\psi K^+$ decays can fake $B_c^+ \rightarrow J/\psi \ell^+ \nu$ decays if the kaon is misidentified as a lepton. For the semileptonic mode we reject candidates that have a reconstructed mass within 3σ in mass resolution ($\sigma \simeq 60 \text{ MeV}/c^2$) of the measured B^+ mass when the third lepton candidate is assigned the kaon mass.

4.5 Reconstruction Efficiencies and Background Levels

A Monte Carlo simulation is used to determine the reconstruction and selection efficiencies for the various decay modes and for estimating the background level. Signal and background processes are generated using the JETSET 7.4 program [93]. The GOPAL detector Monte Carlo program is used to simulate the detector response [94] [95]. Excepting the FSR correction for Monte Carlo simulated events, described below, data and Monte Carlo simulated samples are analysed using the same reconstruction program.

4.5.1 B_c Reconstruction Efficiencies

The process $Z^0 \rightarrow b\bar{b} \rightarrow B_c X$ and subsequent B_c meson decays are simulated using the JETSET 7.4 program. Figure 2.8 in chapter 2 shows the prediction of reference [96] for the B_c momentum spectrum along with the JETSET 7.4 simulation of the B_c spectrum. In addition to simulating B_c production as described in

reference [96], JETSET 7.4 includes contributions from the production of excited states of $\bar{b}c$ bound states. The two momentum distributions are similar. Also shown is the distribution for light b hadrons given by the Peterson et al. fragmentation function [97], with its parameter tuned to produce the measured mean energy fraction ($\langle x_E \rangle = E_B/E_{\text{beam}}$), indicating that the B_c spectrum is predicted to be considerably softer than that for the light b hadrons. The measured mean energy fraction ($\langle x_E \rangle$) for the light b hadrons is $\langle x_E \rangle = 0.695 \pm 0.006 \pm 0.008$ [98], while for the generated B_c meson we find $\langle x_E \rangle = 0.54$. JETSET does not include radiative decay of J/ψ into lepton pairs. The presence of unreconstructed final state radiation (FSR) in the decay $J/\psi \rightarrow \ell^+(\ell^-\gamma)$ produces a tail toward lower masses in the invariant mass distribution. The effect of FSR on the J/ψ mass distribution is included in Monte Carlo events at reconstruction level. The photon energy is calculated using first order perturbative QED [99]. An error is calculated to account for the higher order terms [100].

Samples of 2000 events were simulated for each of the following decay modes: $B_c^+ \rightarrow J/\psi\pi^+$, $B_c^+ \rightarrow J/\psi a_1^+$, where $a_1^+ \rightarrow \rho^0\pi^+$ and $\rho^0 \rightarrow \pi^+\pi^-$, and the semileptonic mode $B_c^+ \rightarrow J/\psi\ell^+\nu$, where ℓ denotes an electron or a muon. In each event the J/ψ decays to $\ell^+\ell^-$. The reconstruction efficiencies are calculated with the B_c meson simulated at a mass of $6.25 \text{ GeV}/c^2$. In the $J/\psi\pi^+$ mode the leptons from the J/ψ decay are expected to have a $\sin^2\theta$ angular distribution with respect to the J/ψ direction in the B_c rest-frame. In order to simulate this distribution, which was not included in the Monte Carlo generator, the selected events in the $J/\psi\pi^+$ mode were reweighted. For the decay $B_c^+ \rightarrow J/\psi a_1^+$ we conservatively assume an a_1^+ width of 400 MeV. Each sample is composed of events with the appropriate B_c decay and subsequent $J/\psi \rightarrow \ell^+\ell^-$ decay. The mass

resolution is found to be about $80 \text{ MeV}/c^2$ in the mode $J/\psi\pi^+$ and $100 \text{ MeV}/c^2$ in the mode $J/\psi a_1^+$ [101]. The reconstruction efficiencies for these modes are $(10.0 \pm 0.7)\%$ and $(1.8 \pm 0.3)\%$, respectively, and $(5.5 \pm 0.5)\%$ for the semileptonic mode $B_c^+ \rightarrow J/\psi \ell^+ \nu$, where the errors are due to Monte Carlo statistics. Figures 4.2, 4.3 and 4.4 show the mass distributions of the $J/\psi\pi^+$, $J/\psi a_1^+$ and $J/\psi \ell^+$ combinations respectively from the Monte Carlo simulated B_c^+ event samples. The reconstruction efficiency is sensitive to the B_c momentum distribution. An estimate of this sensitivity is found by comparing the efficiencies obtained using the distribution predicted by JETSET 7.4 with those obtained assuming the theoretical calculations of reference [96]. Values of $m_b = (4.9 \pm 0.2) \text{ GeV}/c^2$ and $m_c = (1.5 \pm 0.2) \text{ GeV}/c^2$ were used for the input quark masses [102]. In the $J/\psi\pi^+$ mode the difference is 16.3%. For the $J/\psi a_1^+$ mode, where a harder cut of $x_E > 0.7$ is applied, a difference of 37.9% is found. In the semileptonic mode the difference is 5.7%. We take the systematic errors on the efficiencies to be one half of the difference for each mode.

4.5.2 Background Levels

The JETSET 7.4 parton shower Monte Carlo generator is used for the simulation of the hadronic Z^0 decays. For the fragmentation of heavy quarks into charmed and light b-flavored hadrons, we use the Peterson fragmentation function. JETSET 7.4 parameters and branching ratios were tuned to match OPAL experimental results [103] [104]. The effect of FSR on the J/ψ mass distribution is included as discussed above.

The following simulated data sets were used to estimate the background levels:

Figure 4.2: Invariant mass distribution of reconstructed $J/\psi\pi^+$ combinations that pass all analysis cuts from a simulated sample of $B_c^+ \rightarrow J/\psi\pi^+$ decays.

Figure 4.3: Invariant mass distribution of reconstructed $J/\psi a_1^+$ combinations that pass all analysis cuts from a simulated sample of $B_c^+ \rightarrow J/\psi a_1^+$ decays.

Figure 4.4: Invariant mass distribution of reconstructed $J/\psi\ell^+$ combinations that pass all analysis cuts from a simulated sample of $B_c^+ \rightarrow J/\psi\ell^+\nu$ decays (dashed open histogram), and combinatorial background from enriched samples of Monte Carlo simulated $B \rightarrow J/\psi X$ (solid open histogram) and prompt J/ψ (hatched histogram) events. The backgrounds are normalized to the number of events expected in the data sample. The normalization of the signal is arbitrary. Also shown is the mass region where the B_c candidates are defined.

- A simulated event sample of 4×10^6 five-flavor hadronic Z^0 decays, nearly equal in size to the data sample, was used for studying the hadronic background processes. This simulated event set gives an estimate of the background from fake J/ψ and hadronic Z^0 decays containing the process $B \rightarrow J/\psi X$, where a $J/\psi \rightarrow \ell^+ \ell^-$. In total, the simulated hadronic event sample contains 2800 events containing a leptonic J/ψ decay.
- Since the dominant source of background is from J/ψ 's in B decay, a sample of 80,000 hadronic Z^0 decays containing the process $B \rightarrow J/\psi X$, where a $J/\psi \rightarrow \ell^+ \ell^-$ decay is present in each event, was used to increase the statistical significance of the background study. This Monte Carlo sample is equivalent to 30 times the size of the data sample.
- Two samples of 4000 events containing the processes $Z^0 \rightarrow J/\psi q\bar{q}$ and $Z^0 \rightarrow J/\psi c\bar{c}$ were produced in order to study background due to prompt J/ψ production from gluon fragmentation and c quark fragmentation, respectively, which are the predicted dominant production mechanisms for prompt J/ψ [105]. The predicted branching ratios for these processes are $\text{Br}(Z^0 \rightarrow J/\psi q\bar{q}) = 1.9 \times 10^{-4}$ and $\text{Br}(Z^0 \rightarrow J/\psi c\bar{c}) = 0.8 \times 10^{-4}$. These Monte Carlo sets are equivalent to 40 and 100 times the size of the data sample, respectively.

The expected background level in each channel is determined by searching for B_c decays in the simulated hadronic Z^0 event samples. According to Monte Carlo simulations the background combinations at masses below the signal region are dominated by the combinations of a real J/ψ with random tracks from b hadron decays or from the fragmentation processes. The J/ψ mesons originate

dominantly from the decays of b hadrons, with a small fraction, $(4.8 \pm 1.7 \pm 1.7)\%$ [106], of prompt J/ψ , J/ψ resulting from the fragmentation processes.

The resulting invariant mass distributions for the B_c candidates in the three modes are shown in figure 4.5. From these distributions we estimate the background level (see table 4.1) by counting the number of candidates in the signal region and normalizing to the number of events expected in the data sample. The contribution to the background from $B \rightarrow J/\psi X$ events is normalized using the measured rate $\text{Br}(Z^0 \rightarrow J/\psi X) = (3.9 \pm 0.2 \pm 0.3) \times 10^{-3}$ [76]. The contribution from prompt J/ψ is normalized using the measured rate of prompt J/ψ production $\text{Br}(Z^0 \rightarrow \text{prompt } J/\psi X) = (1.9 \pm 0.7 \pm 0.7) \times 10^{-4}$ [106], with the two components of the prompt J/ψ signal each assigned a fraction of the total branching rate according to the ratio of their theoretical production rates. The measured rate of prompt J/ψ production is in agreement with the theoretical rates. The uncertainty in the normalization factors is used as a systematic error for each background estimate.

4.6 Results

Figure 4.6 shows the invariant mass distributions of the $J/\psi\pi^+$, $J/\psi a_1^+$, and $J/\psi\ell^+\nu$ candidates in the data sample. The shapes and overall levels of the distributions below the signal regions are consistent with the distributions obtained from the simulated background samples. In the mode $J/\psi\pi^+$ we find two events in the signal range 6.0 to 6.5 GeV/c^2 . The invariant masses of the two B_c candidates are $(6.29 \pm 0.17) \text{ GeV}/c^2$ and $(6.33 \pm 0.063) \text{ GeV}/c^2$. The errors are calculated from the errors on the track parameters. The reconstructed decay

Figure 4.5: Invariant mass distribution of (a) $J/\psi\pi^+$ combinations, (b) $J/\psi a_1^+$ combinations and (c) $J/\psi l^+$ combinations in the simulated background samples. Background events from the process $B \rightarrow J/\psi X$ are represented by the open histogram. Background events from prompt J/ψ processes are represented by the hatched histogram. Background events involving fake J/ψ are represented by the shaded histogram. Also shown are the mass regions where the B_c candidates are defined.

Background	Decay Mode		
	$B_c^+ \rightarrow J/\psi \pi^+$	$B_c^+ \rightarrow J/\psi a_1^+$	$B_c^+ \rightarrow J/\psi \ell^+ \nu$
$B \rightarrow J/\psi X$	$0.22 \pm 0.09 \pm 0.02$	$1.01 \pm 0.19 \pm 0.09$	$0.61 \pm 0.15 \pm 0.06$
$J/\psi(\text{c}q\bar{f})$	$0.24 \pm 0.05 \pm 0.13$	$0.07 \pm 0.03 \pm 0.04$	$0.13 \pm 0.04 \pm 0.07$
$J/\psi(\text{g}f)$	$0.17 \pm 0.06 \pm 0.09$	$0.02 \pm 0.02 \pm 0.01$	$0.07 \pm 0.04 \pm 0.04$
Total	$0.63 \pm 0.12 \pm 0.16$	$1.10 \pm 0.19 \pm 0.10$	$0.82 \pm 0.16 \pm 0.10$

Table 4.1: Background estimates from samples of 80,000 $B \rightarrow J/\psi X$ enriched events, 4000 prompt J/ψ from the gluon fragmentation (gf) process, $Z^0 \rightarrow J/\psi q\bar{q}$, and 4000 prompt J/ψ from the c quark fragmentation (cqf) process, $Z^0 \rightarrow J/\psi c\bar{c}$. The first error is statistical and the second is systematic.

times of the two candidates are $\tau = (-0.06 \pm 0.19)$ ps and $\tau = (0.09 \pm 0.10)$ ps, respectively. The estimated background in this mode is (0.63 ± 0.20) events. The probability for a background of 0.63 events to fluctuate to 2 or more is 13.2%. In the mode $J/\psi \ell^+ \nu$ we find one event in the signal region. The mass of the candidate $J/\psi \ell^+$ combination is $5.76 \text{ GeV}/c^2$. The momentum is $15.4 \text{ GeV}/c$. The reconstructed decay length is (0.14 ± 0.14) cm. The estimated background in this mode is (0.82 ± 0.19) events. In the signal region above the mass of the candidate event, 5.76 to $6.5 \text{ GeV}/c^2$, the probability to observe one or more events from background is 8.9%, while the efficiency is reduced to $(0.6 \pm 0.2)\%$. There are no candidate events in the $J/\psi a_1^+$ mode in the signal region compared with an estimated background of (1.10 ± 0.22) events. The mass and lifetimes of the candidates are summarized in table 4.2. Event displays of the candidates are shown in figures 4.7, 4.8 and 4.9.

Figure 4.6: Invariant mass distribution of (a) $J/\psi\pi^+$ combinations, (b) $J/\psi a_1^+$ combinations and (c) $J/\psi l^+$ combinations in the data sample. Also shown are the mass regions where the B_c candidates are defined.

Run event 3577: 2:560 Date 921109 Time 40129 Ctrk(N= 36 Surp= 60.3) Ecal(N= 35 SurE= 53.9) Hcal (N=11 SurE= 11.6)
 Beam 45.645 Evis 88.4 Emiss 2.9 Vtx (0.02, 0.05, 0.03) Muon(N= 3) Sec Vtx(N= 7) Post(N= 0 SurE= 0.0)
 Bz=4.850 Bunchlet 111 Thrust=0.9298 Aplan=0.9034 Obstat=0.0794 Sph=0.0445

Figure 4.7: $J/\psi\pi$ candidate 1

Run event 5281:157445 Date 940723 Time 183041 Ctx:Ne 21 SumE= 87.21 Ecal(N= 26 SumE= 23.1) Fcal(N=10 SumE= 27.5)
 Ebeam 45.810 Evis 120.0 Emiss -28.8 Vtx (-0.01, -0.04, -0.08) Muon(N= 3) Sec Vtx(N= 0) Pdet(N= 0 SumE= 0.0)
 Bz=4.350 Bunchlet 1/1 Thrust=0.9642 Aplan=0.0016 Ob st=0.1166 Sph=0.0205

Figure 4.8: $J/\psi\pi$ candidate 2

Run/event 3563:175598 Date 941014 Time 134629 ChkNo 25 Surpa***** Ecal(N= 31 SurEs= 44.2) Hcal (N=14 SurEs= 17.3)
 Ebeam 45.612 Evis2229.8 Emiss***** Vtx (0.00, 0.02, -0.64) Muon(N= 2) Sec Vtx(N= 4) Foot(N= 0 SurEs= 0.0)
 Bz=4.350 Bunchler 11 Thrust=0.9978 Aplan=0.0000 Ot alfa=0.0034 Sphar=0.0000

Figure 4.9: $J/\psi\ell$ candidate 1

Decay Mode	Mass(GeV/c ²)	Lifetime(ps)
$B_c^+ \rightarrow J/\psi \pi^+$	6.29 ± 0.17	-0.06 ± 0.19
	6.33 ± 0.06	0.09 ± 0.10
Decay Mode	Mass(GeV/c ²)	Decay Length(cm)
$B_c^+ \rightarrow J/\psi \ell^+ \nu$	5.76	0.14 ± 0.14

Table 4.2: Masses and lifetimes of the candidate events. The mass of the $B_c^+ \rightarrow J/\psi \ell^+ \nu$ candidate is the estimated mass of the three lepton combination. Since the full mass can not be reconstructed, the lifetime can not be calculated and the decay length of the three lepton vertex is given instead.

4.7 Upper Bounds on the Production Rates

We determine an upper bound at 90% confidence level on the number of events in each channel by applying Poisson statistics to the number of events observed in the signal region, without background subtraction. This is used to calculate an upper limit on the production rate from:

$$\begin{aligned}
 & \frac{\text{Br}(Z^0 \rightarrow B_c^+ X)}{\text{Br}(Z^0 \rightarrow q\bar{q})} \times \text{Br}(B_c^+ \rightarrow \text{final state}) \\
 &= N(\text{at } 90\% \text{ C.L.}) \times \frac{\epsilon_{had}}{(N(Z^0) \times \epsilon \times \text{Br}(J/\psi \rightarrow \ell^+ \ell^-))},
 \end{aligned} \tag{4.1}$$

where $N(Z^0)$ is the total number of hadronic Z^0 events in the data sample; ϵ_{had} is the hadronic event selection efficiency, 0.981 ± 0.005 ; ϵ is the reconstruction efficiency for each mode; and $\text{Br}(J/\psi \rightarrow \ell^+ \ell^-)$ is the branching ratio for the leptonic decays of J/ψ , $J/\psi \rightarrow e^+ e^-$ and $J/\psi \rightarrow \mu^+ \mu^-$, 0.1203 ± 0.0028 [107].

Error Source	Decay Mode		
	$B_c^+ \rightarrow J/\psi\pi^+$	$B_c^+ \rightarrow J/\psi a_1^+$	$B_c^+ \rightarrow J/\psi\ell^+\nu$
MC statistics	7.2%	16.6%	9.1%
B_c fragmentation	8.2%	19.0%	2.9%
Lepton eff.	6.5%	6.5%	7.5%
$\text{Br}(J/\psi)$	2.3%	2.3%	2.3%
hadronic eff.	0.5%	0.5%	0.5%
final state radiation	0.6%	0.6%	0.6%
Total error	12.8%	26.2%	12.4%

Table 4.3: Summary of systematic errors on the product branching ratio upper limits.

For the mode $B_c^+ \rightarrow J/\psi a_1^+$, we also account for the branching ratio $\text{Br}(a_1^+ \rightarrow \rho^0\pi^+) = 0.5$. The total systematic uncertainties on the branching ratio upper limits for each mode are shown in table 4.3. These systematic uncertainties are included in the following 90% confidence level upper limits using the technique of ref. [108]:

$$\frac{\text{Br}(Z^0 \rightarrow B_c^+ X)}{\text{Br}(Z^0 \rightarrow q\bar{q})} \times \text{Br}(B_c^+ \rightarrow J/\psi\pi^+) < 1.06 \times 10^{-4},$$

$$\frac{\text{Br}(Z^0 \rightarrow B_c^+ X)}{\text{Br}(Z^0 \rightarrow q\bar{q})} \times \text{Br}(B_c^+ \rightarrow J/\psi a_1^+) < 5.29 \times 10^{-4},$$

$$\frac{\text{Br}(Z^0 \rightarrow B_c^+ X)}{\text{Br}(Z^0 \rightarrow q\bar{q})} \times \text{Br}(B_c^+ \rightarrow J/\psi\ell^+\nu) < 6.96 \times 10^{-5},$$

where the branching ratio for the mode $B_c^+ \rightarrow J/\psi \ell^+ \nu$ is for decay to either $J/\psi e^+ \nu$ or $J/\psi \mu^+ \nu$.

If we interpret the two candidate events in the $B_c^+ \rightarrow J/\psi \pi^+$ mode as signal we find a branching ratio of,

$$\frac{\text{Br}(Z^0 \rightarrow B_c^+ X)}{\text{Br}(Z^0 \rightarrow q\bar{q})} \times \text{Br}(B_c^+ \rightarrow J/\psi \pi^+) = (3.8_{-2.4}^{+5.0} \pm 0.5) \times 10^{-5},$$

where the first error is statistical and the second systematic.

Chapter 5

Conclusion

I have performed a search for B_c meson decays in data collected with the OPAL detector at LEP. Two candidate $B_c \rightarrow J/\psi\pi^+$ decays are observed in a mass window around the theoretical prediction of the B_c mass, compared with an estimated background of (0.63 ± 0.20) events in this mode. The weighted average mass of the two candidates is $(6.32 \pm 0.06) \text{ GeV}/c^2$, which is consistent with the predicted mass of the B_c meson. One candidate is observed in the mode $B_c^+ \rightarrow J/\psi\ell^+\nu$, with a $J/\psi\ell^+$ mass of $5.76 \text{ GeV}/c^2$. The estimated background in this mode is (0.82 ± 0.19) events. I have also searched for the decay $B_c^+ \rightarrow J/\psi a_1^+$, but no candidate events were observed. The estimated background in this mode is (1.10 ± 0.22) events. Upper limits at the 90% confidence level are calculated for the production rates of these processes,

$$\frac{\text{Br}(Z^0 \rightarrow B_c^+ X)}{\text{Br}(Z^0 \rightarrow q\bar{q})} \times \text{Br}(B_c^+ \rightarrow J/\psi\pi^+) < 1.06 \times 10^{-4},$$

$$\frac{\text{Br}(Z^0 \rightarrow B_c^+ X)}{\text{Br}(Z^0 \rightarrow q\bar{q})} \times \text{Br}(B_c^+ \rightarrow J/\psi a_1^+) < 5.29 \times 10^{-4},$$

$$\frac{\text{Br}(Z^0 \rightarrow B_c^+ X)}{\text{Br}(Z^0 \rightarrow q\bar{q})} \times \text{Br}(B_c^+ \rightarrow J/\psi\ell^+\nu) < 6.96 \times 10^{-5}.$$

The branching ratio limits for the $B_c^+ \rightarrow J/\psi\pi^+$ and $B_c^+ \rightarrow J/\psi\ell^+\nu$ mode are comparable with the limits reported by the ALEPH, DELPHI and CDF collaborations [109][110][111]. The highest predicted product branching ratios from theory are 7.0×10^{-7} and 8.5×10^{-6} for the $B_c^+ \rightarrow J/\psi\pi^+$ and $B_c^+ \rightarrow J/\psi\ell^+\nu$ decay modes respectively [112] [113]. The branching fraction for the decay $B_c^+ \rightarrow J/\psi a_1^+$ has not been predicted. Also the masses of the OPAL candidates can be compared with the measured mass of the B_c^+ from CDF, $(6.40 \pm 0.52) \text{ GeV}/c^2$ [114]. The initial CDF search was for the B_c decay mode $B_c^+ \rightarrow J/\psi\pi^+$ [111]. The number of candidates was found consistent with the estimated background and they reported a 95% confidence level limit on the ratio of the branching ratios times production rates of $B_c^+ \rightarrow J/\psi\pi^+$ over $B^+ \rightarrow J/\psi\pi^+$. The limit is given as a function of lifetime. For a lifetime of 0.33 ps the ratio is 0.10. For a lifetime of 0.50 ps the ratio is 0.07. A subsequent search for the decay mode $B_c^+ \rightarrow J/\psi\mu^+\nu$, where $J/\psi \rightarrow \mu^+\mu^-$, found a significant number of candidate events over the expected background [114]. The candidates are not fully reconstructed and the mass is found from the shape of the three lepton invariant mass distribution. The measured mass is $(6.40 \pm 0.52) \text{ GeV}/c^2$ which is consistent with the theoretical mass and the mass of the fully reconstructed OPAL $B_c^+ \rightarrow J/\psi\pi^+$ candidates. The measured lifetime of the CDF candidates is $0.46_{-0.16}^{+0.18} \pm 0.03 \text{ ps}$. The measured ratio of the branching ratios times production rates of $B_c^+ \rightarrow J/\psi\mu^+\nu$ over $B^+ \rightarrow J/\psi\pi^+$ is $0.132_{-0.037}^{+0.041} \pm 0.031_{-0.020}^{+0.032}$, where the first error is statistical, the second error is systematic and the third error is due to the measured error on the lifetime of the B_c^+ . Table 5.1 compares the production rate limits for searches at ALEPH, DELPHI and OPAL. Note that the more restrictive limits of ALEPH and DELPHI in the $B_c^+ \rightarrow J/\psi\pi^+$

are largely due to lack of any signal in their data. Also in the $B_c^+ \rightarrow J/\psi \ell^+$ and $B_c^+ \rightarrow J/\psi a_1^+$ ALEPH and DELPHI perform a background subtraction before calculating the limits. All OPAL candidate events are included in the limits without background subtraction. In addition DELPHI limits assume a B_c^+ lifetime of 0.4 ps, which is consistent with the lifetime measured at CDF $0.46_{-0.16}^{+0.18} \pm 0.03$ ps [114], where the first error is statistical and the second is systematic, and a hadronic branching fraction of 0.699 for the Z^0 decays [115]. Also the DELPHI search for the $J/\psi a_1^+$ mode, where $a_1^+ \rightarrow \pi^+ \pi^+ \pi^-$, did not assume a resonant decay.

Decay Mode	ALEPH	DELPHI	OPAL
$J/\psi \pi^+$	$< 3.6 \times 10^{-5}$	$< 1.5 \times 10^{-4}$	$< 1.06 \times 10^{-4}$
$J/\psi a_1^+$	Na	$< 2.50 \times 10^{-4}$	$< 5.29 \times 10^{-4}$
$J/\psi \ell^+ \nu$	$< 5.2 \times 10^{-5}$	$< 8.3 \times 10^{-5}$	$< 6.96 \times 10^{-5}$

Table 5.1: 90% confidence level limits on the production rates.

Note that the more restrictive limits of ALEPH and DELPHI in the $B_c^+ \rightarrow J/\psi \pi^+$ are largely due to lack of any signal in their data. Also in the $B_c^+ \rightarrow J/\psi \ell^+$ and $B_c^+ \rightarrow J/\psi a_1^+$ ALEPH and DELPHI perform a background subtraction before calculating the limits. All OPAL candidates event are included in the limits without background subtraction.

Appendix A

A Prototype Time-Of-Flight Detector

A.1 Introduction

In this appendix I report on a study of the precision of Time-Of-Flight measurements using plastic scintillator counters with Fine Mesh Photomultiplier Tubes (FM PMT). This work was part of an investigation of several techniques considered for hadron identification in the B factory detector (*BABAR*) at SLAC. In cosmic ray tests of prototype counters we achieved a time resolution of 91 ps with a 3.0 m long counter and 70 ps with a 1.0 m long counter.

With the approval of the B factories at SLAC and KEK laboratories [116, 117], where the physics objectives of the experiments require the identification of hadrons for particles of momenta up to nearly 5.0 GeV/c, an extensive study has been underway to identify a reliable technique for hadron identification. One of the approaches to this problem has been the use of Time-Of-Flight (TOF) measurements with plastic scintillator counters. The overall design of the detectors however, allows for only modest particle flight paths (about 1 m) over which TOF measurements can be performed. Thus, to cover a significant part of the momentum region of interest, high precision TOF measurements are required. At the nominal energies of the SLAC B factory, a TOF system with a resolution of 100 ps at a radial flight path of 1.0 m, provides greater than three sigma

separation for kaons from pions for momenta up to 1.1 – 1.3 GeV/c, which corresponds to about 80% of the so-called tagging kaons, kaons from the decay sequence $b \rightarrow c \rightarrow s$.

This work was part of a study of several techniques considered for hadron identification in the *BABAR* detector at the SLAC B factory. It was aimed at determining the achievable precision in time measurements using plastic scintillator counters with fine-mesh photomultiplier tube (FM PMT) read out. A TOF system with similar constraints to those in this study is operating in the CLEO II detector at the Cornell Electron Storage Ring (CESR) [118, 119]. In the CLEO II system, each counter consists of a 2.8 m long scintillator bar with a PMT readout at each end, which is located outside the solenoidal magnetic field of the detector [120]. A long (1.9 m) Lucite light guide provides the optical coupling between the PMT and the scintillator bar. The reported time resolution for this system is 154 ps. One possible improvement over this design is the elimination of the light guide, which has a significant contribution to the time spread of the photons at the photodetector. This can be achieved by using a photodetector that functions in the 1.5 Tesla magnetic field of the *BABAR* detector, such as fine-mesh photomultiplier tubes [121], hence allowing for direct coupling of the PMT and the scintillator. Some of the other major factors that affect the time resolution are the photoelectron statistics, the scintillation decay time, light propagation in the scintillator, transit time spread and the risetime of the PMT signal. Availability of fast plastic scintillators and fast photomultiplier tubes that operate in a magnetic field allow for the design of counters with improved parameters over those in previous experiments.

Our approach is similar to that reported by Kichimi et al [122, 123]. The

prototype counters differ from the CLEO II design by essentially removing the light guide between the scintillator bar and the PMT, and the use of the Fine Mesh Photomultiplier Tube R2490-05 from the Hamamatsu Corporation. The scintillator is Bicron BC-408 with the principal light component at a wavelength of 425 nm, a decay time of 2.1 ns and bulk attenuation length of 3.8 m. The FM PMT R2490-05 has an active photocathode diameter of 37 mm and a gain of about 5×10^6 at an operating voltage of -2500 V. The timing characteristics of R2490-05, namely its fast risetime (2.1 ns), short transit time (8.5 ns) and small transit time spread (0.4 ns (FWHM) for a single photoelectron), are well suited for application in timing measurements.

A.2 Experimental Setup

We tested two prototype counters, the first, a 3.0 m long scintillator bar with FM PMT readout at the bar ends (see Figure A.1a), hereafter referred to as counter-A. The second prototype, counter-B, was a 1.0 m long scintillator bar with the FM PMT's placed on the top of the counter each viewing the mirrored end of the bar which is at an angle of 45° with respect to the FM PMT (see Figure A.1b.) These correspond to the possible designs for the barrel and endcap region of the *BaBar* detector, respectively. A 5 cm tapered Lucite light cone provided the coupling between the FM PMT and the scintillator bar for counter-A. The FM PMT's and light cones were mounted with Bicron BC-630 optical grease [124]. The mirrored end of counter-B was produced by mounting a front surface mirror to the 45° end with optical grease. The FM PMT's were operated at -2200 V using Hamamatsu voltage distribution assembly E4233-01 [125].

Figure A.1: Schematic drawing of (a) prototype counter-A and (b) prototype counter-B.

Figure A.2 shows a schematic diagram of the cosmic ray setup. The prototype counter is sandwiched between two scintillator bars, R1-R2 and R3-R4, which provide a reference time. The reference counters are (50 cm long) $\times$ (5 cm $\times$ 6 cm) scintillator bars (Bicron BC-408) coupled to a fast PMT (Hamamatsu assembly H2431 with PMT R2083 and voltage distribution included) at each end. The reference PMT's R1, R2, R3, and R4 were operated at -2500 V. In addition two scintillator counters $T1$ and $T2$ are used to define the cosmic ray trigger. In order to harden the cosmic ray momentum spectrum to above 0.6 GeV/c, a stack of lead bricks (41 cm thick) is placed between the lower reference counter(R1-R2) and the $T1$ trigger counter.

The signal from each PMT is split and fed into a leading edge discriminator (Lecroy 623B) with a threshold of -30 mV and a charge integrating Analog-to-Digital Converter (ADC, Lecroy 2249A 0.25 pC/count). A cosmic ray trigger is defined as the coincidence of all eight discriminator outputs. The trigger signal from the coincidence circuit serves as the start signal for a Time-to-Digital Converter (TDC, Lecroy 2228A 50 ps/count) and the gate for the ADC. An output from each discriminator channel is delayed and fed into a stop input of the TDC module. The TDC digitizes and records the interval between the arrival of the start signal and the discriminator signal. This provides a "raw time" for each PMT. However, since the crossing time of the discriminator varies with the pulse height of the input signal, the measured time of the PMT is determined by applying a pulse height dependent correction to the "raw time", as described in the following section. The ADC gate was 60 ns wide.

A pulsed nitrogen laser was used to monitor the performance of the system and to determine the overall time jitter of the read out electronics. The laser

Figure A.2: Schematic drawing of the cosmic ray test setup.

light was coupled to the counters by three optical fibers mounted to the center of the scintillator bars. The laser pulses are 1 ns wide at a wave length of 337 nm and a repetition rate of about 1 Hz. In the monitoring state a pin diode, which was simultaneously illuminated by the laser pulse, was used to produce the start pulse for the TDC and the gate for the ADC.

A.3 Analysis Method

For each PMT the measured time, T_{PMT} , is determined from the TDC and the ADC read out as follows:

$$T_{PMT} = TDC(PMT) - \frac{\alpha_{PMT}}{\sqrt{ADC(PMT)}},$$

where the second term accounts for the time slewing in the discriminator caused by the varying pulse height of the input signal. The $TDC(PMT)$ is the TDC "raw time" in picoseconds and the $ADC(PMT)$ is the pedestal subtracted ADC counts for this PMT. The constant α_{PMT} is determined from the data as described below.

The mean time of the two FM PMT's on the prototype counter,

$$T_M = \frac{T_{M1} + T_{M2}}{2}$$

provides a measurement of the time at which the particle traverses the counter, plus an offset which is related to the length of the bar, the effective speed of light in the scintillator bar, the transit time of the electrons in the FM PMT and the amount of time delay in the cabling. We determine the resolution in T_M , by comparing it with a reference time as defined below.

Since the prototype counter is at the mid-point between the reference counters R1-R2 and R3-R4, the mean of the measured times of the four PMT's on the reference counters,

$$T_{ref} = \frac{T_{R1} + T_{R2} + T_{R3} + T_{R4}}{4},$$

corresponds to the time at which the particle traverses the prototype counter. The resolution in T_M is determined from the rms spread of the difference $T_{dif} = T_{ref} - T_M$ after subtracting in quadrature the spread of the reference time, T_{ref} .

The resolution of the reference time, $\sigma(T_{ref})$, can be extracted from the spread of the quantity $T_R = (T_{R1} + T_{R2})/2 - (T_{R3} + T_{R4})/2$, which corresponds to the time-of-flight of the particles from the reference counter R3-R4 to reference counter R1-R2. A simple error analysis yields,

$$\sigma(T_{ref}) = \frac{\sigma(T_R)}{2}$$

The spread in T_R is primarily due to measurement uncertainties. A small spread of a few picoseconds is expected from the angular distribution of cosmic rays.

A.4 Results

The data consisted of several samples of cosmic ray events, each typically recorded over a period of about a week and containing several hundred events. During the runs, the fluctuations in the operating conditions of the experiment, including the temperature, the PMT high voltages, and TDC and ADC calibrations were routinely monitored.

The time jitter of the read out electronics was determined by measuring the response of the system for laser pulses. In the laser monitoring stage, the FM

PMT's were run at a lower voltage (-1500 V) to avoid saturation effects. The light intensity at the FM PMT from the laser pulses was typically a factor of 50 larger than that from minimum ionizing particles. Figure A.3 shows the distribution of $(TDC(M1) - TDC(M2))/2$ for laser pulses, which has an rms spread of 29 ps. This corresponds to an upper limit on the time jitter of the read out electronics.

A typical output signal from a cosmic ray for counter-A is shown in Figure A.4. The risetime of the signal varies from 3 - 6 ns depending on the distance of the FM PMT to the point where the cosmic ray passes through the counter.

The constants α_{PMT} for the reference counters are determined by minimizing the width of the T_R distribution. Figure A.5 shows the final distribution of T_R for one typical data sample. The distribution after minimization is fit to a Gaussian of width 83 ps. This corresponds to a resolution of 41 ps for the reference time (T_{ref}).

The pulse height corrections for the FM PMT's M_1 and M_2 are determined by minimizing the rms width of the distribution in $T_{ref} - T_M$, where the correction constants for the reference counters are fixed to the values obtained above. Figure A.6 shows the final distribution of $T_{ref} - T_M$. Accounting for the resolution of the reference time in quadrature, we find a resolution of $\sigma(T_M) = 91 \pm 6$ ps for counter-A at the center. The uncertainty is based on a 3.7 ps statistical error and an estimated systematic error of 5 ps added in quadrature. The systematic error is determined from the variation in the results due to changes in the cuts applied to the data. The distribution of $T_{ref} - T_M$ for the prototype counter-B is shown in Figure A.7. For the center of the bar we find a resolution of 70 ± 7 ps. The uncertainty is based on a 4.2 ps statistical error and an estimated

Figure A.3: Distribution of time difference for the the two FM PMT's on prototype counter-A for laser pulses.

Figure A.4: Typical output signal for a FM PMT on counter-A. The vertical scale is 1.5 V per division and the horizontal scale is 5 ns per division.

systematic error of 5 ps.

The position dependence of the resolution was studied by moving the prototype counter with respect to the reference and trigger counters. For the off-center positions, in order to account for the difference in the resolutions of the two FM PMT's, the time resolution was determined separately for each FM PMT in the following manner. First the spread in the quantities

$$T_{right} = T_{M1} - \frac{T_{R1} + T_{R3}}{2}$$

and

$$T_{left} = T_{M2} - \frac{T_{R2} + T_{R4}}{2}$$

were determined. The individual resolutions of each counter $\sigma(M1)$ and $\sigma(M2)$ were determined by subtracting in quadrature the appropriate contribution from the reference counters. The expected overall time resolution was determined

Figure A.5: Distribution of T_R for a typical run.

Figure A.6: Distribution of $T_{ref} - T_M$ for a run at the center of counter-A. (Note that to determine the final resolution of T_M the resolution of the reference counters must be subtracted in quadrature from the resolution of $T_{ref} - T_M$.)

Figure A.7: Distribution of $T_{ref} - T_M$ for a run at the center of counter-B.
 (Note that to determine the final resolution of T_M the resolution of the reference counters must be subtracted in quadrature from the resolution of $T_{ref} - T_M$.)

from the weighted resolution of the two FM PMT's. For the center position this method gave a result consistent with that obtained from the simple averaging method described above. Figure A.8, shows the time resolution as a function of the position along the prototype counter-A. As expected the resolution away from the center improves because the measurement is dominated by the FM PMT that is closer to the particle trajectory. The dependence of the resolution on the position along counter-B is shown in Figure A.9.

We estimate the mean number of photoelectrons in each FM PMT from the spread of the ratio of pulse heights in the two FM PMT's on the prototype counters. Figure A.10 shows the distribution of $\text{ADC}(\text{M1})/\text{ADC}(\text{M2})$ for a run at the center of counter-A. The spread in this distribution is partly due to photoelectron statistics and partly due to additional noise in the multiplication process in the PMT's [126]. Treating the spread as purely due to statistical fluctuation in the number of photoelectrons, we estimate an average of 500 photoelectrons in each FM PMT for counter-A. The same analysis for counter-B yields 370 photoelectrons, for each FM PMT.

A.5 Summary and Conclusions

We studied the precision of time-of-flight measurements using scintillator counters with fine-mesh photomultiplier tube readout as part of an investigation of particle identification techniques for the *BABAR* detector at the SLAC B factory. Two prototype counters with parameters close to possible designs for the barrel and endcap region of the *BABAR* detector were tested in cosmic rays. A resolution of 91 ps was obtained for a 3.0 m long counter and 70 ps for a 1.0 m long counter

Figure A.8: The resolution of test counter-A versus position. The origin is at the center of the counter.

Figure A.9: The resolution of test counter-B versus position. The origin is at the center of the counter.

Figure A.10: The ratio of $\text{ADC}(\text{M1})/\text{ADC}(\text{M2})$ for cosmic rays traversing counter-A at the center.

with FM PMT read out on the side of the scintillator bar. These results are consistent with those reported by Kichimi et al. for similar counters, and constitute a significant improvement over the CLEO II design which uses conventional photomultipliers and long light guides to couple the scintillator bar to the PMT. Simulation studies indicate that the absence of light guides in our design, which reduces the spread in arrival times of the photons at the photocathode, is the dominant factor responsible for the improved resolution.

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