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**A Study of $K_S^0 K_S^0$ Pairs in
Multihadronic Z^0 Decays
with the OPAL Detector at LEP**

by

Pierre D. Beaulne B.Sc.

A thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfillment of the requirements
for the degree of
Master of Science

Ottawa-Carleton Institute for Physics
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Ottawa, Ontario, Canada
May, 1998

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the Faculty of Graduate Studies and Research
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submitted by
Pierre D. Beaulne, B.Sc.

in partial fulfillment of the requirements for
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Thesis Supervisor

Chair, Department of Physics

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Date 12th May '98

Abstract

The production of $K_S^0 K_S^0$ pairs in multihadronic Z^0 decays has been investigated using a sample of just under 5 million events recorded with the OPAL detector at LEP. The inclusive production rate of the $f_2'(1525)$ tensor meson has been measured to be

$$\langle n_{f_2'} \rangle = 0.0153 \pm 0.0041(stat.)_{-0.0043}^{+0.0041}(syst.)_{-0.0005}^{+0.0006}(BR)$$

In addition, the effects of Bose-Einstein Correlations (BEC) near the $K_S^0 K_S^0$ threshold have been investigated. The δ function lineshape of the $f_0(980)$ scalar meson generated in JETSET has been replaced by a more realistic one obtained from a simultaneous coupled channel fit of the $f_0 \pi^+ \pi^-$ and $K^+ K^-$ mass spectra. With the improved lineshape, no threshold enhancement of $K_S^0 K_S^0$ pairs is observed, thus no evidence of BEC is found. A search for a resonant enhancement in the $K_S^0 K_S^0$ spectrum near $2.2 \text{ GeV}/c^2$ finds no evidence for production of the $\xi(2230)$ glueball candidate in the OPAL data.

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First I would like to thank all members of the OPAL collaboration, since without their efforts in detector operation, event reconstruction algorithms, previous data analyses, etc., the study presented in this thesis would not have been possible. The list of OPAL authors at the time of writing, is included in Appendix A. Previous members who have left the collaboration are not on this list, but they also deserve recognition for their work while with OPAL. I would also like to thank the physicists, engineers, and various support staff who built and operate the LEP collider, which has performed admirably despite sometimes less than perfect operating conditions.

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Chapter 1

Motivation and Theoretical Framework

1.1 Introduction

In high energy particle physics, the fundamental constituents of matter and the forces that govern the interactions between them are treated within the mathematical confines of the Standard Model. It has been widely successful in explaining and predicting a wide variety of physical phenomena. Among the most notable successes has been the prediction of the existence of the Z^0 and $W^\pm$ particles, which were observed in the early 1980's by collaborations [1, 2] at the CERN laboratories outside Geneva, Switzerland. The Large Electron-Positron (LEP) collider, which became operational in 1989, was built at CERN in order that precision testing of the Standard Model could be done. The four LEP experiments ALEPH, DELPHI, L3 and OPAL have carried out such tests over the years and found that experimental results by and large are in excellent agreement with the theoretical predictions.

However, it has been found that certain aspects of Z^0 decay cannot be fully explained within the context of the Standard Model. One of these is the process by which

quarks from the decay become bound inside the particles observed in the detector, a process known as quark fragmentation or hadronization. The main strength of the Standard Model lies in the fact that the coupling constants used to parameterize it are small enough to justify the use of perturbative methods: powerful tools without which calculations can be inordinately complex or even impossible to carry out. However, the hadronization phase occurs on an energy scale at which the coupling constant is too large for the use of perturbation theory to be justified. As such, there is as of yet no theory which can fully describe hadronization from first principles. This fact has led to the introduction of a number of models in an attempt to describe this hadronization phase.

One of the best ways of testing these models is by measuring the inclusive production rate of particles originating from the initial quark hadronization. The main focus of this thesis is to measure the production rate of such a particle, the $f_2'(1525)$ tensor meson. Since it is neutral, it must be observed through its decay products. A good way to see it is to look for its decay to a $K_S^0 K_S^0$ pair. The K_S^0 meson, which is also neutral, is easily reconstructed from its decay to charged pions and large, highly pure samples can be obtained.

Since the K_S^0 are bosons, the correlated production of neutral kaons, in particular the Bose-Einstein Correlations (BEC) between them is also investigated in this study. BEC effects are expected to manifest themselves near the $K_S^0 K_S^0$ production threshold ($\approx 995 \text{ MeV}/c^2$). However, another meson, the $f_0(980)$, which is just below threshold, can produce a BEC-like signature, and must therefore be treated carefully in order to avoid confusion.

The f_2' is a state that seems to be well described in terms of the quark model. Not all mesons, however, fit neatly within this picture. This has led to the proposal of more

exotic states¹ in order to explain some of the observed mesons. One such state is the $\xi(2230)$, which can also decay to $K_S^0 K_S^0$. This analysis will look for a possible signal for this state as well.

This chapter discusses the necessary background and theoretical principles needed for the analysis. It starts with a discussion of the motivation for carrying out the analysis, and a general description of the Standard Model. The theoretical aspects begin with a look at the mechanisms for production and multihadronic decay of the Z^0 . The hadronization model used in the study is described. Finally, different aspects of the $K_S^0 K_S^0$ system are discussed, including BEC as well as properties of the $f_0(980)$, $f'_2(1525)$ and $\xi(2230)$.

The second chapter focuses on the LEP collider and the OPAL detector. A description of both is provided, along with a review of the generation of the Monte Carlo samples used. A full description of the OPAL Monte Carlo and data sets is also provided.

The next two chapters describe the analysis itself. The reconstruction of events is covered in the third chapter. It includes various corrections and selection cuts used to isolate events of interest and suppress background noise as much as possible, as well as a description of a geometric and kinematic fitting procedure used to improve the mass resolution. The fourth chapter discusses the results of the analysis and considers various sources of systematic uncertainty. Finally, in the last chapter, the results of the analysis are discussed and compared to other available measurements.

¹see Section 1.6.3

1.2 Motivation for Studying the $K_s^0 K_s^0$ System

The production of hadrons in decays of the Z^0 involves a hadronization phase, where the partons from the $Z^0 \rightarrow q\bar{q}(g)$ decay transform into the observed colourless hadrons. Unfortunately this transition is poorly understood as its main phase occurs on a low energy scale of the order of ~ 1 GeV, where the use of perturbative calculation methods is not justified. Consequently, models are relied on to provide a description of this stage. The measurement of particular event properties (such as the f_2' inclusive production rate, studied in this analysis) therefore serve as powerful tests of the models currently in use. Electron-positron annihilations at the Z^0 peak are an ideal environment to carry out such tests. They provide high event rates and since the electrons are thought to be elementary, there are no parton remnants in the beam (as would be the case in pp or $p\bar{p}$ collisions) to further confuse the interpretation of experimental results.

In addition to the testing of fragmentation models, there are other interesting issues in multihadronic decays of the Z^0 , particularly in meson decays and more particularly in those decaying to a $K_s^0 K_s^0$ pair. Experimentally, production rates for the $L=1$ supermultiplet² mesons (particularly the tensors such as the f_2') are not well measured. The DELPHI collaboration has measured the inclusive f_2' production rate in the $K^+ K^-$ channel [3]. This study will attempt a measurement of its inclusive production rate in the $K_s^0 K_s^0$ channel. OPAL has looked at this channel in the past, but saw no clear f_2' signal. Now it is hoped that with much higher statistics and improvements in the analysis, a signal can be seen.

Another interesting feature of the $K_s^0 K_s^0$ system is that it is a system of identical bosons ($J^P=0^-$). Effects due to Bose-Einstein Correlations (BEC), if present, would occur near the $K_s^0 K_s^0$ production threshold and an enhancement in this region could be compared to the results of other studies of BEC in $K\bar{K}$ pairs from e^+e^- annihilation at

²L is the orbital angular momentum of the $q\bar{q}$ pair.

LEP [4, 5, 6, 7]. The $f_0(980)$ meson lies just below the $K_S^0 K_S^0$ threshold, but because of its finite width, it can be observed in the $K_S^0 K_S^0$ channel. It will therefore be necessary to correctly account for its contribution to the $K_S^0 K_S^0$ mass spectrum in order to attribute any excess of events in the data near threshold to BEC effects.

Finally, there has been much work done recently in the $K\bar{K}$ system on the $\xi(2230)$ resonance. The interest in this structure is that it may not be an ordinary $q\bar{q}$ state. On the basis of observations by various groups³, it has been postulated that this might be a glueball (gg bound state) candidate. Most recently, the L3 collaboration at LEP has reported preliminary evidence for this resonance [8] in the $K_S^0 K_S^0$ channel, predominantly in 3-jet events. Therefore, this inclusive analysis may be sensitive to the $\xi(2230)$, helping to improve the interpretation of this state.

1.3 The Standard Model

The fundamental particles can be classified in various ways according to their common properties. The most basic of classifications is based on the spin statistics obeyed by the particle. The basic constituents of matter, the quarks and leptons, all have spin 1/2 and obey Fermi-Dirac statistics: they are called fermions. This means that their wave function must be antisymmetric under identical particle exchange: fermions obey the Pauli exclusion principle. The particles mediating the interactions between fundamental fermions are called bosons. They are integral spin particles which obey Bose-Einstein statistics, meaning that their wave function is symmetric under identical particle exchange: they need not obey the exclusion principle.

The fundamental particles interact through four basic forces. The most well known, and also by far the weakest, is gravity. Any massive particle will experience gravity, but it is so much weaker than the other forces that it is irrelevant in processes with

³see Section 1.6.3

which particle physics is concerned. The interactions with which particle physicists are concerned are electromagnetism and the strong and weak nuclear forces. Electromagnetism is well known to the layman, while the other forces may be less so. The strong force keeps quarks confined inside particles while the effects of the weak force are clearly seen in radioactive decays. More recently, the electromagnetic and nuclear forces have been found to be separate manifestations of one interaction, dubbed the electroweak force.

The Standard Model is the name given to the mathematical treatment of these interactions. It relies on the use of symmetry groups with well defined properties [9], and these must be gauge invariant. That is, the choice of a particular mathematical treatment, or gauge, should not affect any physical results predicted by the theory. The electroweak sector is described by the $SU(2)_{weak}$ and $U(1)_{EM}$ gauge groups, while the strong force relies on the use of the $SU(3)$ group. The Standard Model has been very successful in describing experimental results and making theoretical predictions (of new particles, for example). The electroweak sector describing electromagnetism is known as quantum electrodynamics (QED). Similarly, the treatment of the strong, or colour, force is known as quantum chromodynamics (QCD). It should be noted that there are expectations that these different forces may represent manifestations of a single underlying unified force, but this has not yet been verified experimentally.

The fermions can additionally be classified according to which of the forces they experience. The leptons, such as electrons and neutrinos, interact only electroweakly. Quarks can interact electroweakly or through the strong force, which is sensitive to an intrinsic property (or "charge") called colour. Each quark can have one of three colour charges, corresponding to the three degrees of freedom of the $SU(3)$ gauge group. The nature and strength of this colour charge are such that quarks are not directly observed as free particles, but are instead confined in colourless bound states known as hadrons.

Table 1.1: The fundamental particles: leptons, quarks, and the gauge bosons mediating the interactions between them. The neutrinos may be massless: these numbers represent 95 % confidence level upper limits. Quark masses are not well defined since they are not seen as free particles.

particle	symbol	electric charge (e)	spin ($\hbar$)	mass
electron	e	-1	1/2	0.511 MeV/c ²
muon	μ	-1	1/2	105.6 MeV/c ²
tau	τ	-1	1/2	1777 MeV/c ²
electron neutrino	ν_e	0	1/2	< 5 eV/c ²
muon neutrino	ν_μ	0	1/2	< 0.27 MeV/c ²
tau neutrino	ν_τ	0	1/2	< 24 MeV/c ²
down	d	-1/3	1/2	≈ 10 MeV/c ²
up	u	+2/3	1/2	≈ 5 MeV/c ²
strange	s	-1/3	1/2	≈ 200 MeV/c ²
charm	c	+2/3	1/2	≈ 1.3 GeV/c ²
bottom	b	-1/3	1/2	≈ 4.3 GeV/c ²
top	t	+2/3	1/2	≈ 175 GeV/c ²
photon	γ	0	1	0
gluon	g	0	1	0
Z boson	Z^0	0	1	91.2 GeV/c ²
W boson	$W^\pm$	± 1	1	80.3 GeV/c ²

Mesons⁴ like the pion and the K^0 are quark-antiquark ($q\bar{q}$) states. Baryons such as the proton and neutron are colourless bound states of three quarks.

The up and down quarks, along with the electron and its neutrino, are classified as one family (or generation) of particles. However, there are two other generations of fundamental particles, which seem identical in terms of their interactions, and differ only in mass. The reason for this redundancy is not known⁵. There are therefore 12 fundamental fermions, each of which has a distinct antiparticle with identical mass and spin but opposite charge. The interactions between the fermions are described in

⁴Mesons, composed of 2 spin 1/2 objects, have zero or integral spin and thus are bosons.

⁵Current thinking and experimental evidence suggest that there are only three generations of fundamental fermions, although this is not certain.

terms of the exchange of gauge bosons. The photon (γ) mediates the electromagnetic interaction, which acts on all charged particles. The Z^0 and $W^\pm$ mediate the weak force between the quarks and leptons. Finally, the strong force, which leptons do not experience, is mediated by the exchange of gluons (g). These fundamental fermions and the gauge bosons are listed in Table 1.1

1.4 Production and Multihadronic Decays of the Z^0

As mentioned previously, e^+e^- colliders provide an excellent tool for the study of multihadronic Z^0 decays. The cross section for the annihilation of electrons and positrons into final state hadrons is shown in Figure 1.1 for a range of center of mass energies around the Z^0 peak. A resonant enhancement is seen in the cross section at a center of mass energy $\sqrt{s} = M_Z = 91.2$ GeV. LEP operated around the Z^0 peak from 1989 to 1995, accumulating a very large statistical sample of multihadronic Z^0 decays: just under 5 million multihadronic events were recorded in that period, corresponding to an integrated luminosity $\int \mathcal{L} dt \sim 168 \text{ pb}^{-1}$. Cross section measurements at different center of mass energies near M_Z made it possible to precisely determine various electroweak parameters, such as the Z^0 mass (M_Z) and Z^0 width (Γ_Z^0).

The coupling of the Z^0 to $f\bar{f}$ is also very important in the Standard electroweak Model. The strength and nature of this coupling differs for left and right handed fermions⁶, and can be characterized by the neutral current vector and axial vector coupling constants v_f and a_f . These couplings relate to the charge Q_f and third component of weak isospin⁷ T_f^3 of the fermions as follows:

$$v_f = \frac{T_f^3 - 2Q_f \sin^2 \theta_w}{2 \sin \theta_w \cos \theta_w} \quad (1.1)$$

⁶Left handed fermions have their spins aligned antiparallel to their momentum vector, and right handed ones, vice versa

⁷ T_f^3 has a value of $+\frac{1}{2}$ for up-type quarks and neutrinos and $-\frac{1}{2}$ for down-type quarks and leptons.

$$a_f = \frac{T_f^3}{2 \sin \theta_w \cos \theta_w} \quad (1.2)$$

where θ_w is the Weinberg angle which describes the extent of the mixing between the $SU(2)_{weak}$ and $U(1)_{EM}$ symmetry groups in the standard electroweak model. It can be written in terms of the masses of the W and Z as

$$\sin^2 \theta_w = \left(1 - \frac{M_W^2}{M_Z^2}\right) \quad (1.3)$$

In terms of the above coupling constants, expressions for the $e^+e^- \rightarrow q\bar{q}$ differential cross section, $\frac{d\sigma}{d\Omega_{cm}}$, and the $Z^0 \rightarrow f\bar{f}$ partial decay widths, $\Gamma_{f\bar{f}}$, can be written down [10]. They are listed below to lowest order and neglecting the final state quark masses. The differential cross section is

$$\frac{d\sigma}{d\Omega_{cm}}(e^+e^- \rightarrow q\bar{q}) = N_c \frac{\alpha^2}{4s} \times \left((1 + \cos^2 \theta^*)G_1(s) + 2 \cos \theta^* G_3(s)\right) \quad (1.4)$$

Here $\alpha \approx \frac{1}{137}$ is the QED fine structure constant, s is the square of the center of mass energy, θ^* is the angle between the incoming electron and the outgoing fermion in the center of mass, and $N_c=3$ to account for the three quark colour charges ($N_c=1$ for leptons and neutrinos). The vector and axial coupling constants, along with the Breit-Wigner propagator

$$\chi_0(s) = \frac{s}{(s - M_Z^2) + iM_Z\Gamma_Z^0} \quad (1.5)$$

define the functions $G_1(s)$ and $G_3(s)$ as follows (subscripts e and q refer to electron and quark, respectively):

$$G_1(s) = Q_q^2 - 2v_e v_q Q_q \text{Re}\chi_0(s) + (v_e^2 + a_e^2)(v_q^2 + a_q^2)|\chi_0(s)|^2 \quad (1.6)$$

$$G_3(s) = -2a_e a_q Q_q \text{Re}\chi_0(s) + 4v_e a_e v_q a_q |\chi_0(s)|^2 \quad (1.7)$$

Integrating the differential cross section over the center of mass solid angle $d\Omega_{cm}$, and summing over the allowed quark flavours (excluding the top quark since its production threshold is at $\sqrt{s} = 2m_t \approx 350$ GeV), the total cross section σ_{had} is obtained as a function of the center of mass energy. It is plotted in Figure 1.1, along with some experimental measurements at various center of mass energies. One can see excellent agreement between theory and experiment.

Figure 1.1: The cross section σ_{had} for $e^+e^- \rightarrow$ hadrons plotted against the center of mass energy $\sqrt{s}$. The annihilation can proceed through a virtual photon or a Z^0 , but at energies studied in this analysis, the Z^0 exchange dominates by several orders of magnitude.

Similarly, the partial Z^0 decay widths can be written as

$$\Gamma_{ff} = \frac{N_c G_F M_Z^3}{6\sqrt{2}\pi} (v_f^2 + a_f^2) \quad (1.8)$$

where G_F is the Fermi coupling constant. Table 1.2 shows the results of the above calculations, after accounting for higher order radiative corrections and finite final state

Table 1.2: A comparison of some Standard Model predictions with recent LEP experimental measurements. The errors on the Standard Model predictions are negligible compared to the experimental uncertainties. The Z^0 mass is used as input in the calculation of other quantities.

Quantity	Measured Value	SM Prediction
M_{Z^0} (GeV/ c^2)	91.1867 ± 0.0020	input
σ_{had} (nb)	41.486 ± 0.053	41.45
Γ_Z (MeV/ c^2)	2494.8 ± 2.5	2497
Γ_{had} (MeV/ c^2)	1743.2 ± 2.3	1743.8
Γ_{ll} (MeV/ c^2)	83.91 ± 0.10	83.97
Γ_{nu} (MeV/ c^2)	500.1 ± 1.8	501.6
$\sin^2 \theta_w$	0.2325 ± 0.0008	0.2237

particle masses, as compared to world averages of recent LEP experimental measurements [11]. Excellent agreement is seen between the Standard Model predictions and the experimental measurements. Γ_{had} is the partial Z^0 width for decay to hadrons (all $q\bar{q}$ pairs). Γ_{ll} is the partial width for decay to one lepton generation ($l = e, \mu, \text{ or } \tau$). Γ_{nu} is the partial width for decay to undetected particles: it represents the sum over all neutrino species.

1.5 Quark Fragmentation to Hadrons

The multihadronic decays of Z^0 bosons produced in e^+e^- annihilations all have their origin in a rather simple quark-antiquark state (and possible radiated gluon(s)). The formalism that describes the production of the Z^0 and its subsequent decay to $q\bar{q}$ final states has been described in the previous section. The process by which these quarks then transform into the hadrons observed in the detector, however, is less well understood. Within QCD, the actual calculations involved are so complex that it has not yet been possible to derive a theory describing this transformation from first principles. Therefore, the qualitative understanding of QCD has been used to guide

the development of different models which quantitatively represent the hadronization process [12], with varying degrees of success.

In all hadronization models the description of the event begins with the specification of the primary partons ($q\bar{q}(g)$), whose distribution is dictated by the decay matrix element of the Z^0 . The transition from these primary partons to the final state hadrons is then carried out in conceptually distinct stages [13]. This is illustrated in Figure 1.2

Figure 1.2: An illustration of the $e^+e^- \rightarrow \text{hadrons}$ process. The shaded box represents the second stage described below: hadronization. This is where the string model is used. The decay of the Z^0 and the evolution of the parton shower according to QCD is shown to the left. To the right of the box, the hadronized string fragments decay and are seen in the detector.

Since the kinematically accessible quark masses are much smaller than that of the Z^0 , they are produced at relatively high energies and initiate a cascade of partons. The evolution of this first stage is described by perturbative QCD, since the strong coupling constant ($\alpha_s \approx 0.12$) is still small enough at this scale to justify its use. The cascade evolves the primary partons from the $Q \approx M_Z$ scale^s through a series of successive $q \rightarrow qg$, $g \rightarrow gg$ and $g \rightarrow q\bar{q}$ fragmentations. The evolution continues until $Q \leq Q_0$, when there is no longer enough energy available to create further partons. Typically Q_0 is on the order of 1 GeV. The result of this evolution is a treelike parton “shower”. Global event properties such as momentum spectra, sphericity, thrust and charged particle multiplicity are determined in this calculable stage.

The next stage involves the use of a hadronization model to convert the secondary partons into hadrons. This is carried out at the $Q_0 \approx 1$ GeV (or lower) scale, and thus is less well defined, since perturbative QCD cannot be used on this scale. This stage is assumed to occur locally in space-time, involving only partons which are near each other. This has led to the use of a number of different models in an attempt to describe this transition. Models such as independent, cluster and string fragmentation have been used with varying degrees of success. Only the string models will be discussed here, since they are among the most successful in predicting event properties. In particular, the LUND [14] scheme is described below, as it is the one used to generate the Monte Carlo samples used in this analysis.

In the final stage, unstable primary hadrons decay into stable ones using decay tables for their rates. These are the hadrons which are directly or indirectly observable in the detector. The description of these distinct phases is only conceptual; in reality, the boundaries between them are not very well defined.

^s Q is the 4-momentum transfer, or energy available for the creation of secondary partons

The LUND String Model

String models are based on a simple principle: at large distances, the binding between partons appears to increase linearly (neglecting a short range Coulomb term) with parton separation. When the quarks move apart, the energy stored in the gluon field between them increases as well. The assumption is that the colour field collapses into a long, narrow tube-like structure, or string. The linear dependence of energy on separation means that this string can be characterized by a uniform tension (or spring constant) estimated to be $\kappa \approx 1 \text{ GeV/fm}$. The dynamics are modeled by a massless, relativistic string with no transverse oscillations, meaning that the quarks at each end simply oscillate back and forth along the string [15]. Hard gluon emission is identified with kinks in the string [16].

As the quarks move apart, a point is reached when the string has enough stored energy to pull a quark pair ($q\bar{q}$) or diquark pair ($qq'\bar{q}\bar{q}'$) out of the vacuum, causing it to break into fragments. In the LUND scheme, these fragments are associated with discrete mass hadrons⁹, and as such, iterative breaks will occur until one of these discrete mass values is reached. The probability $\mathcal{P}$ of such a break is given by Wilson's exponential area decay law [17] as follows:

$$\frac{d\mathcal{P}}{dA} = P_0 e^{-P_0 A} \quad (1.1)$$

where the probability per unit area, P_0 , of pair creation is constant. The area A is an area in space-time near the pair production point and is expressed in terms of the fragment mass as $m_{frag}^2 = 2\kappa^2 A$. As such, the area decay law becomes

$$\frac{d\mathcal{P}}{dm_{frag}^2} = b e^{-bm^2} \quad \text{with} \quad b = \frac{P_0}{2\kappa^2} \quad (1.2)$$

The fraction x of the string's original momentum carried off by each segment is

⁹As opposed to continuous mass fragments, or clusters, used in other fragmentation models

described by some fragmentation function $f(x)$. The string fragments and subfragments continue to pull partons out of the vacuum and break until the energy stored in the fragments is comparable to hadronic masses, at which point they are transformed into primary hadrons. In the last stage described above, these primary hadrons subsequently decay into observable particles according to known decay tables.

1.6 The $K_S^0 K_S^0$ System

In all decay processes to specified final states, there are selection rules which limit the allowed quantum numbers of the parent particle. These rules are based on conservation or symmetry principles. The selection rules important to this analysis are based on angular momentum and isospin and CP conservation. CP refers to the product of the charge conjugation (particle-antiparticle interchange) and the parity (space reversal) operators, which is an invariant¹⁰. Isospin is conserved in strong interactions, and angular momentum is always conserved. Selection rules based on these principles limit the number of decay modes possible for any particle, and conversely limit the number of particles that can decay to a specified final state.

The mesons of interest to this analysis do not decay directly to $K_S^0 K_S^0$, even though they are seen in that channel. The actual decay, which the selection rules allow, is to $K^+ K^-$ or $K^0 \bar{K}^0$, and possible BEC effects originate with these bosons. The neutral kaons have spin-parity $J^P=0^-$, and as such, mesons which decay to this state must have $J^P = (even)^+$ or $J^P = (odd)^-$. And because these objects studied are very short lived and decay via the strong interaction, isospin must also be conserved. The neutral kaons are isospin $\frac{1}{2}$ objects, so their parents must have isospin 0 or 1.

Each neutral kaon is then observed through its weak eigenstates K_S^0 and K_L^0 . Therefore, each member of the observed $K_S^0 K_S^0$ pairs can originate from a K^0 or a $\bar{K}^0$. The

¹⁰CP violation effects are ignored in this analysis.

fact that the primary neutral kaons from these meson decays are observed through their weak eigenstates further limits the number of possible mesons for which the $K_S^0 K_S^0$ channel is allowed. The K_S^0 meson has spin-parity $J^P=0^-$ and since small CP violation effects are neglected in this analysis, it is considered to be a CP eigenstate with eigenvalue $CP=+1$. As such, mesons observed in the $K_S^0 K_S^0$ channel are required to have spin-parity $J^{PC} = (even)^{++}$ only. Objects with any other quantum number combinations are forbidden to decay to $K_S^0 K_S^0$.

1.6.1 The $f_0(980)$ and Bose-Einstein Correlations

The presence of BEC effects in this analysis will be seen as an excess of data events near threshold, in comparison to the Monte Carlo expectation with no BEC. This is most easily visible by looking at the distribution of the Lorentz variable $(Q^2)^{11}$. For objects decaying to $K_S^0 K_S^0$, Q^2 can be written as

$$Q^2 = M^2 - 4m^2 \quad (1.1)$$

where M is the invariant mass of the $K_S^0 K_S^0$ pair and m is the mass of the K_S^0 .

As $Q \rightarrow 0$, the probability of observing a pair in a $C=+1$ charge conjugation state is maximal, while it goes to 0 for $C=-1$ states [7, 18]. Neglecting CP violation, the K_S^0 each have $CP=+1$ and negative parity. So the $K_S^0 K_S^0$ system is in a $C=+1$ state and the presence of BEC should be readily observable as an excess of data events over Monte Carlo (with no BEC) near $Q=0$ (threshold). To investigate the strength of the BEC, a normalized correlation function $C(Q)$ is defined via

$$C(Q) = \frac{\rho(Q)}{\rho_0(Q)} \quad (1.2)$$

where $\rho(Q)$ is the measured Q distribution for the data, and $\rho_0(Q)$ is the Monte Carlo distribution in the absence of BEC effects. At $Q=0$, the correlation function attains the

¹¹ Q^2 is the four momentum difference of two 4-vectors, defined as $Q^2 = -t = -(p_1 - p_2)^2$.

value $C(Q)=1$ if no BEC effects are present, while in the presence of BEC, it attains $C(Q)=2$ [19]. However, not all $K_S^0 K_S^0$ pairs are identical bosons ¹², and in practice, the experimental value of $C(Q)$ will be less than 2, even in the presence of BEC.

Interpretation of an excess of events over expectations near the $K_S^0 K_S^0$ threshold is complicated by the decay of the f_0 meson. As previously mentioned, its mass of 980 MeV/ c^2 puts it below the $K_S^0 K_S^0$ threshold, but it can still decay to $K_S^0 K_S^0$ due to its width of 40-100 MeV/ c^2 . As such, an excess of observed events near threshold might be attributed to BEC when it is simply due to the contribution of the f_0 . The treatment of the f_0 to avoid the BEC ambiguity is discussed below and later in Section 4.1.1.

The $f_0(980)$ decays primarily to $\pi^+ \pi^-$, but its finite width makes it possible for a coupling between the $\pi\pi$ and $K\bar{K}$ channels to occur. The coupled channel amplitudes for f_0 decay are written as follows [20, 21]

$$A_{f_0}(\pi\pi) = \frac{m_0 \sqrt{\Gamma_{\pi\pi}}}{m_0^2 - m_{\pi\pi}^2 - im_0(\Gamma_{\pi\pi} + \Gamma_{K\bar{K}})} \quad (1.3)$$

$$A_{f_0}(K\bar{K}) = \frac{m_0 \sqrt{\Gamma_{K\bar{K}}}}{m_0^2 - m_{K\bar{K}}^2 - im_0(\Gamma_{\pi\pi} + \Gamma_{K\bar{K}})} \quad (1.4)$$

where $m_0=0.957$ GeV/ c^2 is the resonance mass, and the partial widths are related to the coupling constants $g_\pi=0.111$ and $g_K=0.423$ by

$$\Gamma_{\pi\pi} = g_\pi \sqrt{\frac{m_{\pi\pi}^2}{4} - m_\pi^2} \quad (1.5)$$

$$\Gamma_{K\bar{K}} = g_K \sqrt{\frac{m_{K\bar{K}}^2}{4} - m_K^2} \quad (1.6)$$

Therefore, a more accurate $K_S^0 K_S^0$ spectrum can be generated to replace the one generated by JETSET, where the f_0 has a mass of 1 GeV/ c^2 and zero width. This will be very useful in making conclusions about BEC in the $K_S^0 K_S^0$ system.

¹² K_S^0 can originate either from a K^0 or from a $\bar{K}^0$.

1.6.2 The Tensor Meson f'_2

The quark model assignments for some meson states, in particular for members of the $L=1$ supermultiplet, are incomplete and in some cases, controversial. The f'_2 tensor meson ($J^{PC} = 2^{++}$) fits within the quark model: it is very likely that it is one of the 3P_2 $q\bar{q}$ states. If this assignment is correct, then the Monte Carlo should predict the f'_2 fragmentation function $\frac{1}{\sigma_{had}} \frac{d\sigma}{dx_0}$ and its total inclusive production rate $\langle n_{f'_2} \rangle = \int \frac{1}{\sigma_{had}} \frac{d\sigma}{dx_p} dx_p$.

An experimental measurement of the inclusive f'_2 production rate would serve as a consistency check of its quark model assignment within JETSET. It would also serve as a test of string hadronization models, such as the LUND scheme used by JETSET to generate the Monte Carlo samples used in this analysis. The value of the f'_2 production rate predicted by JETSET is $\langle n_{f'_2} \rangle = 0.014156$.

1.6.3 The Glueball Candidate $\xi(2230)$

Some observed mesons do not fall neatly into the quark model picture. Because of the self coupling of gluons that exists within QCD, more exotic states such as glueballs (gg), hybrids ($q\bar{q}g$) and multiquark meson states have been proposed to explain some of these states. Possible signatures [22] for a glueball would include enhanced production in gluon rich environments (like radiative J/ψ decays), reduced coupling to photons, a narrow width and flavour independent decays. The $\xi(2230)$ has been observed to have many of these properties [23, 24, 25], and as such, it has been postulated that it may be a glueball.

Recently, the L3 collaboration at LEP has reported observation of the $\xi(2230)$ in the $K_S^0 K_S^0$ channel, predominantly in three jet events, and predominantly in the least energetic of the three jets [8], most of which are due to gluon fragmentation. Experimental observation of a $\xi(2230)$ signal by this analysis would lend support to the L3

claim. and could provide more evidence to help understand how this state should be interpreted.

Chapter 2

LEP and the OPAL Detector

The Large Electron Positron (LEP) Collider is the largest accelerator at the CERN Laboratory, located 100m underground and straddling the French/Swiss border outside Geneva, Switzerland. Electrons and positrons are accelerated in counter-rotating bunches to energies of around 46 GeV¹ and brought into collision at four interaction points (IPs), where the LEP collaborations ALEPH, DELPHI, L3 and OPAL have detectors set up. A general description of the LEP storage ring and a more detailed description of the OPAL detector will be given in this chapter.

2.1 The LEP Ring

Within the LEP beam pipe, the counter-rotating bunches of $\approx 10^{11}$ electrons are kept in near circular orbits by a series of carefully arranged dipole, quadrupole and sextupole magnets. They are accelerated by a series of radio frequency (RF) cavities providing an accelerating voltage $V_{acc} \approx 2.5$ MV/m to boost the electrons from injection

¹LEP operated in this mode until late 1995. The beam energy has gradually been increased since then and LEP now operates with beams of around 92 GeV. The higher energy data is not discussed in this analysis.

to collision energy, and to compensate for energy lost due to synchrotron radiation².

Clearly, LEP must be operated in a mode which can deliver high luminosities to the four experiments, and which can keep backgrounds from synchrotron radiation and off-momentum electrons³ at tolerable levels. This complicated task involves careful adjustment and tuning of parameters related to the operation of the LEP machine.

The amount of luminosity delivered to the experiments can be expressed in terms of measured quantities. The general expression for the luminosity is

$$\mathcal{L} = f_0 k_b \frac{N_b^2}{A} \quad (2.1)$$

where f_0 is the revolution frequency around the ring, k_b the number of bunches, N_b the number of particles per bunch and A the cross sectional area of each bunch. The bunches have charge distributions which are approximately Gaussian, and spatial widths $\sigma_x^* \approx 150\mu\text{m}$, $\sigma_y^* \approx 15\mu\text{m}$ and $\sigma_z^* \approx 15\text{mm}$ at the interaction point. These can be used to express the beam area at the IP as $A \approx 4\pi\sigma_x^*\sigma_y^*$. By using the bunch currents instead of N_b ($I_b = N_b e f_0$), the luminosity is expressed more conveniently as

$$\mathcal{L} = \frac{k_b I_b^2}{4\pi e^2 f_0 \sigma_x^* \sigma_y^*} \quad (2.2)$$

From this expression, it appears that the luminosity can be arbitrarily raised by increasing the number of bunches and/or their current or by minimizing the bunch sizes σ_x and σ_y . However, a number of limiting factors makes this impossible.

The orbits followed by the electron bunches are not purely circular, but undergo transverse oscillations in the horizontal and vertical planes [26]. These so called betatron

²The amount of energy lost by each electron through synchrotron radiation is roughly given by $U_{\text{loss}}(\text{MeV/rev.}) = 0.0885 \frac{E_e^4(\text{GeV})}{\rho(\text{m})}$; or $\approx 85 \text{ MeV/rev.}$

³The term off-momentum electron refers to particles scattered out of the beam's line of flight.

oscillations have amplitudes related to the beta functions at the IP β_x^* and β_y^* . These are related to the emittances as follows:

$$\sigma_x^* = \sqrt{\beta_x^* \epsilon_x} \quad (2.3)$$

$$\sigma_y^* = \sqrt{\beta_y^* \epsilon_y} \quad (2.4)$$

The emittances are a measure of the phase space enclosed by the electron bunches and, by Liouville's theorem [27], must remain constant along the beam path. Hence, the beam dimensions are dependant on the accelerator beta functions, which are design parameters.

The main factor limiting luminosity is a beam-beam effect at bunch crossing, where bunches become defocussed by the interaction of their charge fields. The effect is worsened by reducing beam dimensions, since this also increases their space charge density. This beam-beam tune shift (change in the number of betatron oscillations) is characterized by the beam rigidity [28] $\bar{\xi}$

$$\bar{\xi} = \frac{r_e I_b}{2\pi \epsilon \gamma f_0} \frac{\beta_y^*}{\sigma_x^* \sigma_y^*} \quad (2.5)$$

where $\gamma = \left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}}$ is the Lorentz factor and $r_e = e^2/mc^2$ is the classical electron radius and the * denote values at the IP. If the beam-beam limiting value is reached, the luminosity can be rewritten as

$$\mathcal{L}_{max} = \frac{k_b \gamma}{2\epsilon r_e} \frac{I_b \bar{\xi}}{\beta_y^*} \quad (2.6)$$

Greater luminosity is possible by raising the number of bunches k_b , although proper separation between bunches must be provided (by electrostatic separators) to prevent collisions outside the IPs. LEP has achieved peak luminosities of $\mathcal{L} \approx 1.3 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ while running in the vicinity of the Z^0 peak [29].

2.2 The OPAL Detector

Figure 2.1: The OPAL Detector

2.2.1 General Description

The OPAL (Omni Purpose Apparatus at LEP) detector [30] became operational in 1989. It was designed as a general purpose detector in order to detect a wide variety of the high energy e^+e^- interactions provided by LEP. The major part of the detector is cylindrical and built around the beam pipe at one of the IPs, giving it a solid angle

coverage of nearly 4π . The various subdetector systems are designed to detect all types of processes which occur in e^+e^- collisions, and to accurately reconstruct and classify these processes. A diagram of the OPAL detector, showing the scale and layout of its various components, is shown in Figure 2.1

As shown in Figure 2.1, the region immediately around the beam pipe consists of a set of vertex and tracking detectors sitting in a solenoidal magnetic field of 0.435 Tesla. Their primary function is to track charged particles within their volume by measuring momenta and reconstructing trajectories and secondary vertices. Measurements made of ionization energy loss, dE/dx , are useful in particle identification. Just outside the tracking detectors lie the time of flight (TOF) counters, which measure the time of flight of particles from the interaction point. They are used to send trigger signals, veto cosmic rays, and help in low momentum particle identification. The electromagnetic and hadronic calorimeters lie outside the TOF counters. The EM calorimeter provides measurements of the position and energy of electrons and photons by total absorption of their energy in lead glass blocks. The hadron calorimeter measures the energy of hadrons emerging from the EM calorimeter. Finally, a set of muon chambers are located outside the calorimeters to identify muons by measuring their position and energy. The calorimetry and muon detectors are repeated in the endcap regions. The forward detector (FD) acts as a luminosity monitor by detecting small angle Bhabha ($e^+e^- \rightarrow e^+e^-$) events down to angles of $\theta \approx 25$ mrad. The central (vertex and tracking) detector (CT) will be covered in more detail in this chapter, since this information was crucial in this analysis.

OPAL Coordinate System and Track Parameters

The interaction point is the origin of a Cartesian coordinate system (OPAL MRS) with its z axis in the direction of the electron beam (counter-clockwise around LEP when seen from above), x axis horizontal and directed toward the center of LEP, and

y axis normal to the x - z plane. One can then define the polar and azimuthal angles θ and ϕ in the standard manner: measured from the positive z and x axes, respectively.

In OPAL, as in many other collider experiments, a particle's helical trajectory through the central magnetic field can be fully specified by 5 track parameters [31]. These parameters are chosen such that they are well defined for all tracks reconstructed in the detector volume. They also must be chosen so that the trajectory equations have finite, well behaved derivatives: an important requirement for reconstructing secondary vertices, quark and gluon jets, and other quantities where a fitting procedure is used. Figure 2.2 shows how the parameters are defined.

Figure 2.2: The geometry used in the definition of the OPAL track parameters. The projection in the xy plane is shown in (a), and the $s - z$ projection in (b). The label p.c.a. refers to the point of closest approach to the origin.

By default, OPAL specifies its track parameters at the point on the helical track which is closest to the origin (ie. the IP). This point (x_0, y_0, z_0) is known as the point of closest approach (p.c.a.). They can, however, be transformed to other reference points

on the same trajectory (eg. secondary vertices), if need be. The standard OPAL track parameters are as follows:

- κ is the curvature and is defined by $|\kappa| = \frac{1}{2\rho}$ where ρ is the radius of curvature of the track and κ is signed such that $+\kappa$ implies that the azimuthal angle increases as the particle moves along its trajectory and $-\kappa$ means that ϕ decreases along the trajectory. In OPAL, since the magnetic field is axial with B_z in the $+z$ direction, a particle with a negative charge will have a positive value of κ and vice versa.
- ϕ_0 is the track's azimuthal angle at the p.c.a.
- $d_0 = -x_0 \sin \phi_0 + y_0 \cos \phi_0$ is the impact parameter, the distance from the origin to the p.c.a.
- $\tan \lambda = \cot \theta$, where θ is the polar angle. $\lambda = (\frac{\pi}{2} - \theta)$ is called the "dip angle"
- z_0 is the z coordinate of the track at the p.c.a.

These parameters are related to the momentum components of the particle at the point of closest approach by the following relations:

$$p_t = a \frac{B_z}{\kappa} \quad (2.1)$$

where $a = \frac{e}{2} \times 10^{-14} \approx 1.5 \times 10^{-14}$ for p_t in GeV/c, B_z in kG and κ in cm^{-1} . The momentum components can then be written

$$p_x = p_t \cos \phi_0 \quad (2.2)$$

$$p_y = p_t \sin \phi_0 \quad (2.3)$$

$$p_z = p_t \tan \lambda \quad (2.4)$$

$$p = p_t \sqrt{1 + \tan^2 \lambda} \quad (2.5)$$

$$q = -(\text{sign}(\frac{B_z}{\kappa})) \quad (2.6)$$

2.2.2 The Central Tracking Detectors

The Vertex Detectors

As shown in Figure 2.1 above, the beam pipe at the interaction point is surrounded by two vertex detectors which permit the reconstruction of secondary vertices from the decay of short lived particles. The central vertex (CV) detector is a precision cylindrical drift chamber located inside the inner radius of the jet chamber. It has a length of 100 cm, a diameter of 470 mm and consists of two layers of 36 drift cells. The inner 36 cells each contain 12 axial wires (parallel to the z axis) while the outer 36 contain 6 stereo wires each, inclined at 4° to the z axis. The axial wires provide a measurement of the $r - \phi$ position with a spatial resolution of $\langle \sigma_{r-\phi} \rangle \approx 50 - 55 \mu\text{m}$. The stereo system allows a z measurement with a resolution of $\langle \sigma_z \rangle \approx 700 \mu\text{m}$.

A Silicon Microvertex (SI) Detector was installed in late 1991 around a reduced diameter beam pipe and inside the CV detector, in order to make high precision spatial measurements very near the interaction point. It consists of two layers of silicon wafer ladders chained end-to-end. It originally provided only $r - \phi$ information, but in 1993 it was upgraded with back-to-back $r - \phi$ and $r - z$ wafers to make z measurements of hits and to extend the solid angle coverage. With this upgrade, measurements with spatial resolutions of $\langle \sigma_{r-\phi} \rangle \approx 5 \mu\text{m}$ and $\langle \sigma_z \rangle \approx 13 \mu\text{m}$ are possible. As K_S^0 particles typically decay several to tens of cm from the interaction point, SI information is not needed in this analysis.

The Central Jet Chamber

Located outside the vertex detector is the Central Jet (CJ) chamber, which provides OPAL with the majority of its tracking information. This drift chamber is approximately 4m in length, with inner and outer radii of 25 and 185 cm, respectively. It is comprised of 24 identical sectors each containing a plane of 159 anode wires parallel to the beam direction. The cathode wire planes form the boundaries between the various

sectors. The anode wires determine the $r - \phi$ position of a hit from the wire position and the drift time in the gas. The intrinsic single hit spatial resolution in $r - \phi$ is $\langle \sigma_{r-\phi} \rangle \approx 135 \mu\text{m}$. From a charge division technique measuring the integrated charge at each end of the wire, the z hit coordinate and the particle's energy loss can be calculated. The ratio of charges from opposite wire ends provides a means of making a z hit measurement with a resolution of $\langle \sigma_z \rangle \approx 5 - 6 \text{ cm}$. The sum of these charges is used to calculate the energy loss dE/dx of the particle, with a resolution $(\sigma_{dE/dx})/(dE/dx)$ of 3.1 % in $e^+e^- \rightarrow \mu^+\mu^-$ events and 3.8 % for minimum ionizing pions in hadronic jets.

The transverse momentum of a particle in the central jet chamber is measured from its radius of curvature in the $r - \phi$ plane. The momentum resolution is influenced by multiple scattering and by the magnetic field strength, in addition to the spatial resolution $\sigma_{r-\phi}$ with which the track is measured. The overall accuracy of CJ transverse momentum measurements is given by [32]

$$\frac{\Delta p_t}{p_t} = \sqrt{(0.0015 \cdot p_t)^2 + (0.028^2)} \quad (2.7)$$

with p_t in GeV/c. The first term in 2.7 arises from the single hit spatial resolution $\sigma_{r-\phi}$ and the second term accounts for multiple Coulomb scattering effects.

The Z Chambers

Since the spatial resolution in z is important in determinations of track polar angles θ and invariant mass resolutions and since charge division in CJ can only resolve z hits to $\sigma_z \approx 5\text{-}6 \text{ cm}$, a set of drift chambers are located outside CJ to improve z coordinate measurements. These Z chambers (CZ) consist of 24 drift chambers 4 m long, 50 cm wide and 59 mm thick, sectioned in ϕ such that the drift direction is parallel to the z axis. Each chamber is comprised of 8 drift cells containing 6 anode wires. They collectively cover 94 % of the azimuthal angle and a range of polar angles from 44° to

Table 2.1: Summary of the spatial resolutions of various components of the central tracking system of the OPAL detector

Subdetector	Radial Limits (cm)	Maximum Hits	$\sigma_{r-\phi}$	σ_z
SI	6-7.5	2	5 μm	13 μm
CV axial	10.3-16.2	12	50-55 μm	—
CV stereo	18.8-21.3	6	—	700 μm
CJ	25-185	159	135 μm	5-6 cm
CZ	185-190.9	6	1.5 cm	300 μm

136° ($|\cos \theta| < 0.72$). They provide up to 6 hits allowing an overall average resolution $\langle \sigma_z \rangle \approx 300 \mu\text{m}$. Charge division also provides a crude ϕ measurement, with $\sigma_{r-\phi} \approx 1.5$ cm.

Combined Performance of the Central Detector

Outside the polar angle coverage of the Z chambers, the measurement of θ can however still be improved for particles which leave the jet chamber through the forward and rear endplates. For these tracks, the radius of the last wire with a hit from the exiting particle provides a means of determining the polar angle fairly accurately, as the z coordinate of the jet chamber edge is known. The combination of information from various subdetectors improves the overall precision with which particle momenta and trajectories can be measured. In studies with $e^+e^- \rightarrow \mu^+\mu^-$ events the resolution on the impact parameter d_0 was found to be 75 μm in $r-\phi$ and 2 mm in $r-z$ with CV stereo information (and without SI information). Table 2.1 summarizes the resolution of the CT components.

Table 2.2: Summary of the OPAL MC sets used in this analysis. All samples were generated using JETSET 7.4. Two entries in the $\sqrt{s}$ column indicate the maximum and minimum center of mass energies used in the event generation.

Year	$\sqrt{s}$ (GeV)	number of events
1990	91.2	300000
1991	89.2 93.2	525000
1992	91.2	750000
1993	89.2 93.2	1475000
1994	91.2	4000000
1995	91.2 93.2	1300000
total	-	8350000

2.3 OPAL Monte Carlo simulations

2.3.1 Generation of Multihadronic Z^0 Decays

In order to estimate backgrounds and calculate efficiencies and acceptances for this analysis, it is necessary to have a sample of generated multihadronic Z^0 decays similar to those being looked at in the data. The Monte Carlo samples used in this analysis are summarized in Table 2.2. The package used to generate these events is version 7.4 of the JETSET [33] program. The program begins by specifying a set of primary partons (quarks and gluons) from the Z^0 decay and cascading them using perturbative QCD. The cascade is subsequently fragmented into primary hadrons according to the LUND string model described in the previous chapter. The initial hadrons which are unstable are then allowed to decay into stable baryons, mesons and leptons using tables of known branching ratios [34]. It is important to note that various parameters used by JETSET have been tuned so that global event properties like momentum spectra, multiplicities and event shapes (sphericity, acoplanarity, etc.) resemble those seen in the OPAL data [35]. In general, JETSET is very successful in predicting event properties and thus very useful in calculating efficiencies for the processes studied in this analysis.

2.3.2 The GOPAL Detector Simulation

In order to analyze the generated multihadronic Z^0 decays in the same manner as the OPAL data, it is essential to have a package which simulates the OPAL detector. The generated particles are interfaced with the GOPAL [36] package through files containing particle types and four-vectors. Inside GOPAL, a detailed description of the detector material and geometry is provided to the GEANT [37] package. Then, using Monte Carlo methods, GEANT tracks the generated particles through the virtual detector, taking into account the physics processes that govern particles travelling through matter. These effects include multiple Coulomb scattering of charged particles, all electromagnetic and hadronic interactions, and particle decays. At each step of each particle's passage through the detector, hits and energy deposits in sensitive detector volumes can be calculated. It can also be decided to stop certain particles, or to have them decay. Each subsequent decay particle then goes through the same chain of steps. From these results, the expected response of the detector is simulated and the output stored in data structures identical to those filled by the readout electronics of the OPAL detector. These structures are then processed by the ROPE [38] event reconstruction package in the same way as the real data. The output from ROPE contains information on all reconstructed tracks, EM clusters and other quantities. However, these simulated data structures contain extra information relating reconstructed quantities to the underlying generated particles and properties.

2.4 The OPAL Z^0 Data Sample

The OPAL detector began taking data in 1989. However, since LEP was not fully commissioned until 1990, the low statistics sample from 1989 is not used in this study. Until late 1995, LEP operated at energies around the Z^0 peak, at beam energies ranging from 88 GeV to 95 GeV. This was done in order to get measurements of the Z^0 lineshape near the peak at $\sqrt{s} = M_Z$. During that period, OPAL recorded just under 5 million

multihadronic Z^0 decays. The signature of such decays in the detector is the observation of “jets” of hadrons, collimated roughly in the direction of the original quark(s) (or gluon(s)). Since then, the beam energy has been steadily increased, passing the W^+W^- production threshold ($\sqrt{s} \approx 161$ GeV) to its current value of around 92 GeV per beam. Table 2.3 shows the progression of the beam energy and the luminosity delivered to OPAL over the years. Figure 2.3 shows the weekly luminosity progression for the years of data collection.

Figure 2.3: A year by year summary of the OPAL data taking statistics.

Table 2.3: Summary of the OPAL data. The last row shows the totals for those events used in this analysis. The two entries in the $\sqrt{s}$ column correspond to the minimum and maximum center of mass energies achieved in that period.

year	$\sqrt{s}$ (GeV)	$\int \mathcal{L} dt$ (pb $^{-1}$)	multihadronic events
1989	88.3 95.0	1.2	25801
1990	88.2 94.2	6.6	171141
1991	88.5 93.7	12.9	405393
1992	91.3	23.9	851216
1993	89.4 93.0	33.3	833453
1994	91.1	58.0	1890842
1995a	89.3 92.9	33.6	831614
1995b	130.0 140.0	5.8	5325
1996	161.0 172.0	22.0	41202
1997	130.0 184.0	65.2	75403
90-95 tot	88.2 94.2	168.3	4983659

2.4.1 Selection of Multihadronic Z^0 decays

The types of events studied in this analysis are all produced at center of mass energies $\sqrt{s} \approx M_Z = 91.2$ GeV. Since both beams have the same energy, the interaction will produce Z^0 's which are essentially at rest in the detector. Consequently, its multihadronic decay ($Z^0 \rightarrow q\bar{q}(g)$) will produce quarks in a back to back configuration. When hadronization occurs, many particles are produced, but tend to remain collimated in back to back jets (more hadronic jets can be created through gluon bremsstrahlung). Therefore energy collected in opposite hemispheres of the detector should be roughly equal. Furthermore, the average charge multiplicity in these events is high ($\bar{n}_{ch} \approx 21$ at $\sqrt{s} = M_Z$). These features lead to OPAL's choice of the following selection criteria for Z^0 multihadronic decays [39, 31]

$$N_{chg} \geq 5$$

$$N_{clus} \geq 7$$

$$R_{vis} \geq 0.1$$

$$|R_{bai}| \leq 0.65$$

where N_{chg} and N_{clus} are the number of good charged tracks in the central detector, and the number of EM energy clusters reconstructed in the EM calorimeter. The ratios R_{vis} and R_{bai} are defined as

$$R_{vis} = \frac{\sum E_{raw}}{2E_{beam}} \quad (2.1)$$

$$R_{bai} = \frac{\sum E_{raw} \cos \theta}{\sum E_{raw}} \quad (2.2)$$

Here E_{raw} is the raw energy of a cluster, θ its polar angle, and with the sums being over the N_{clus} good clusters.

Good tracks and clusters must be fairly well reconstructed. To this end, tracks classified as good must satisfy certain cuts on the number of wire hits, impact parameters in $r - \phi$ and z , minimal transverse momentum, and the χ^2 value of track fits through the hit points. Good clusters are simpler to define. They only need energy deposits greater than 100 (200) MeV in at least 1 (2) lead glass block(s) in the barrel (endcap) region.

The main contamination of the multihadronic sample comes from τ pair decays to hadrons and neutrinos. Multiperipheral two photon processes, beam wall events and cosmic rays also contribute to the contamination. Their properties, however, are such that they are efficiently rejected by the above selection criteria. This multihadronic selection procedure has been evaluated to be 98.4 % efficient [39], while the remaining contamination from $\tau^+\tau^-$ and multiperipheral 2γ events is about 0.5 %

Chapter 3

Methods of Event Reconstruction

This analysis begins with a sample of just under 5 million multihadronic events ($\approx 168 \text{ pb}^{-1}$) collected between 1990-1995 at energies on or near the Z^0 peak ($\sqrt{s} \approx M_{Z^0} \approx 91 \text{ GeV}$). In addition to the default multihadronic selection criteria described in Section 2.4.1, only events recorded with the vertex, jet and z chambers fully operational are accepted. Furthermore, the event must contain at least 2 neutral secondary vertices, as described below

3.1 Reconstruction of $K_S^0 \rightarrow \pi^+ \pi^-$ Vertices

Section 2.2.2 describes how the central tracking detectors record wire hit positions, which are then used to reconstruct charged particle trajectories inside the detector volume. Neutral primary particles like the K_S^0 , however, do not produce ionization and therefore leave no tracks. They must therefore be reconstructed via their decay to charged particles, which form a secondary vertex (a V^0) a certain distance from the primary vertex of the event. This section describes how these secondary vertices are reconstructed and how the K_S^0 are identified.

3.1.1 The Neutral Vertex Finder

The K_S^0 mesons used in this analysis are reconstructed through the $K_S^0 \rightarrow \pi^+\pi^-$ decay mode. Since the K_S^0 is relatively long lived ($\tau(K_S^0) \approx 89.3\text{ps}$), it will produce a V^0 displaced from the primary vertex by a few to several centimeters, and its momentum vector will point back to the primary vertex. The characteristic topology of such K_S^0 decays makes it possible to obtain large high purity samples without having to make a lot of inefficient cuts.

The algorithm [40] searches for K_S^0 candidates by forming pairs of oppositely charged tracks within the central detector volume. Those pairs which intersect in the ro plane are taken as possible candidates. The following quantities are then calculated for each candidate:

- The K_S^0 track parameters $(\kappa, d_0, o_0, \tan \lambda, z_0)$.¹
- The ro opening angle of the charged tracks, $\cos \alpha_{ro}$.
- The invariant mass, M_{V^0} , of the V^0 , assuming the charged tracks to be pions.
- The radial decay length, r_d , from the primary vertex to the candidate vertex.
- The angle ζ , between the K_S^0 momentum vector and the flight path vector from the primary vertex (in the ro plane).
- The difference, Δz , between the z coordinates of the tracks at the ro intersection point.

The K_S^0 candidates found in this manner are entangled in a large combinatorial background, so the latter four quantities listed above are used to impose a loose set of cuts in order to improve the signal to noise ratio. First, the z difference is required to satisfy $|\Delta z| < 80\text{cm}$. A tighter cut could bias results because of discrepancies between

¹For neutral tracks, $\kappa = 0$ identically

the Δz distributions seen in data and those generated in the Monte Carlo simulation. To reject random $\pi^+\pi^-$ combinations at the primary vertex, the transverse impact parameter, d_0 , must exceed 3 mm. This provides the largest portion of the background suppression. To further reduce this background, the radial decay length must satisfy $1 < r_d < 150$ cm. Finally, to select those K_S^0 which are consistent with a primary vertex origin, the angle ζ must be less than 2° . All candidates found in this manner are subjected to a geometric fit in the $s - z$ plane, in which the two tracks are constrained to originate from the z coordinate of the V^0 . Secondary vertices whose tracks are totally inconsistent with originating from a common point are rejected by requiring that the value of χ^2 (2 d.o.f) from the $s - z$ fit be less than 50. Finally, only those V^0 's whose $\pi^+\pi^-$ invariant mass is between 400 and 600 MeV/ c^2 are kept for further analysis.

The invariant mass distribution of the candidates passing these cuts, assuming that both tracks are pions, is shown in Figure 3.1 for both Monte Carlo and data events. The K_S^0 peak can clearly be seen sitting on top of the background, much of which consists of random track intersections having nothing to do with the decay of a neutral parent. There is also some contamination due to misidentified photon conversions ($\gamma \rightarrow e^+e^-$) and lambda decays ($\Lambda^0 \rightarrow p\pi$).²

3.1.2 Corrections for Energy Loss and Magnetic Field Variations

The K_S^0 mass fitted to the peaks in Figure 3.1(b) is systematically lower than the Particle Data Group world average K_S^0 mass ($M_{K_S^0}^{PDG} = 497.672 \pm 0.031$ MeV). This is attributed to two different phenomena. First, the pions lose a portion of their energy in traversing the material from the beam pipe vacuum at the interaction point to the central jet chamber, where the momentum measurements are made. The rate of energy loss is given by the Bethe-Bloch equation [41]

²In Λ^0 decays, charge conjugation is implied.

Figure 3.1: The $\pi^+\pi^-$ invariant mass for all V^0 's passing the K_S^0 selection criteria. The Monte Carlo distributions, showing the contributions from different parent particles, is shown in (a), while (b) shows the same distribution for a 1994 data period, fitted with a double Gaussian and a linear background.

$$\frac{dE}{dx} = -\frac{\Lambda_1 q^2}{\beta^2} \left(\Lambda_2 - 2 \log(\gamma \beta) - \beta^2 - \frac{\delta}{2} \right) \quad (3.1)$$

where $\beta = \frac{v}{c}$ and q are the pion velocity and charge, respectively, $\gamma = (1 - \beta^2)^{-\frac{1}{2}}$ and Λ_1, Λ_2 and δ are constants specific to the properties of the medium being traversed. Secondly, the value of the central magnetic field in the jet chamber can vary depending on the current passing through the magnet solenoid, potentially biasing the momentum measurements.

The pion energy loss results in a steady dropoff in the K_S^0 mass at lower momentum values, since the low velocity tracks lose a greater fraction of their energy than do the higher velocity ones. The energy lost by the pions is parametrized by [42]

$$E_{loss} = \frac{ELOSS}{\beta^2} \times \sqrt{1 + \tan^2 \lambda} \quad (3.2)$$

where ELOSS is the calculated mean energy loss due to detector material for a relativistic particle at normal incidence. The β^{-2} term ensures that the low momentum tracks are more strongly corrected since they lose more energy, as can be seen from equation 3.1. This corrects for the energy loss in Monte Carlo events: in the data, however, E_{loss} must be increased by 23 % [43] to fully correct the mass dropoff. Reasons for this discrepancy are not fully understood, and it would seem that there is more material in the detector than is coded in the Monte Carlo.

Variations in the central magnetic field are characterized by shifts in the K_S^0 mass over different data taking periods. Corrections to the magnetic field value are calculated from the shift in mass necessary to bring the K_S^0 mass into agreement with the PDG value. The shifts are small (-0.10 % for '90-'92, -0.33 % for '93-'95) [43] but needed to obtain the correct mass for the K_S^0 . The magnetic field correction is only necessary in the data, since $B_z=0.435$ Tesla is fixed for MC events.

After these corrections have been performed, the K_S^0 mass peaks are perfectly consistent with the PDG K_S^0 mass. The corrected $\pi^+\pi^-$ invariant mass distributions are shown in Figure 3.2(a) for both Monte Carlo and data.

3.1.3 Background Suppression Cuts

The $\pi^+\pi^-$ invariant mass distribution shown in Figure 3.1(a) shows a large background under the K_S^0 peak, as well as contamination from misidentified photons and Λ^0 's. The sample can however be cleaned up by imposing further selection cuts.

Figure 3.2: Invariant mass of the surviving $\pi^+\pi^-$ pairs. The effect of the energy loss and magnetic field corrections is seen in (a) for both data and MC, while (b) shows the distribution for the pairs passing all K_s^0 selection cuts.

The first of these cuts will remove a large portion of the misidentified particles in the sample. This can be done in several ways. One could look at the ionization energy loss dE/dx of the charged tracks. Since dE/dx depends only on the particle velocity $\beta = \frac{v}{c}$, and since the momentum is known, particles of different masses can be separated. The difference between measured energy loss and that calculated with equation 3.1 can then be used to calculate chisquare probability distributions to test various particle hypotheses. Cuts made on these probabilities, or weights, are used to select the desired mass particles. However, the majority of the tracks within the central detector volume are pions, most of which have nothing to do with K_s^0 decays, making it

difficult to specifically pick out pions from K_S^0 decays with a simple cut on their dE/dx weight. For this reason, it is easier and more efficient to make cuts on the V^0 invariant mass, assuming the correct daughter particle mass assignments. This is the method that has been used for this analysis.

Lambdas are easily rejected by forming the $p\pi$ invariant mass distribution for candidate V^0 's. Figure 3.3 shows this distribution for the same vertices shown in the $M_{\pi^+\pi^-}$ distribution. Photons are usually rejected by looking at the e^+e^- invariant mass, but as seen in the $M_{p\pi}$ distribution, the photon conversions have a very small $p\pi$ mass. The Λ^0 peak is clearly visible, and the K_S^0 form the bulk of the background, mostly concentrated at higher masses. Therefore, photons and lambdas are rejected simultaneously by requiring that the $p\pi$ invariant mass be greater than 1125 MeV.

Candidate K_S^0 are required to pass two additional cuts. The first is to suppress a large part of the background due to random track intersections. This is easily done by only accepting candidate K_S^0 vertices whose $\pi^+\pi^-$ invariant mass is within 25 MeV/ c^2 of the mean fitted mass. The second is to improve the mass resolution. Both tracks from the candidate vertex are required to have at least 3 z chamber hits or a well reconstructed endpoint in the jet chamber. The resulting improvement in the intrinsic z hit resolution of the tracks permits a better measurement of the polar angle θ to be made, which in turn results in a better mass resolution on the K_S^0 .

After having made the corrections and cuts described above, a relatively pure sample of K_S^0 is obtained. Figure 3.2(b) shows a Monte Carlo sample which is $(88.5 \pm 0.3) \%$ pure within 25 MeV/ c^2 of the PDG mass.

Figure 3.3: Invariant mass of the candidate V^0 's assuming a decay to $p\pi$. The open histogram represents all accepted V^0 's while the shaded portions represent contributions from the listed particles. Candidates whose $p\pi$ mass falls to the right of the line are accepted.

3.2 Reconstruction of $K_S^0 K_S^0$ Meson Decays

Having obtained a high purity sample of kaons, events with at least 2 surviving K_S^0 candidates are selected. Within each of these events $K_S^0 K_S^0$ pairs are formed. The bulk of the resulting $K_S^0 K_S^0$ invariant mass distribution is combinatorial background resulting from the pairing of unrelated K_S^0 . Because mesons of the form $X \rightarrow K_S^0 K_S^0$ will be visible as small peaks in this background, it will be beneficial to optimize the $K_S^0 K_S^0$ mass resolution, so that signal events have greater prominence above the background. To this end, each $\pi^+ \pi^-$ pair is refit subject to geometric and kinematic constraints

appropriate to the $X \rightarrow K_S^0 K_S^0 \rightarrow 2(\pi^+ \pi^-)$ decay topology. This is described below.

3.2.1 Geometric and Kinematic Fitting

General Procedure

The fit method used in this analysis is a constrained minimization using Lagrange multipliers. The code used was developed by Matthew Jones [44]. Each K_S^0 in a pair is subject to the fit separately, subject to constraints which correspond to the desired $X \rightarrow K_S^0 K_S^0 \rightarrow 2(\pi^+ \pi^-)$ topology. The problem can be stated as follows [45].

Let $\vec{x} = (\kappa^{\pi}, d_0^{\pi}, o_0^{\pi}, \tan \lambda^{\pi}, z_0^{\pi})$ be a vector representing the measured pion track parameters, with covariance matrix V , and $\vec{\alpha}$ be the current estimate of $\vec{x}$. Also let $\vec{p} = (p_x^{K_S^0}, p_y^{K_S^0}, p_z^{K_S^0}, L_d^{K_S^0})$ be a vector containing the three momentum and decay length of the K_S^0 . Finally, let $g(\vec{\alpha}, \vec{p}) = 0$ be a system of constraint equations. Introduce a vector $\vec{\mu}$ of Lagrange multipliers such that $\vec{\alpha}$ minimizes the function:

$$L \equiv (\vec{x} - \vec{\alpha})^T V^{-1} (\vec{x} - \vec{\alpha}) + 2\vec{\mu}^T g(\vec{\alpha}, \vec{p}) \quad (3.1)$$

The details of the minimization procedure are described elsewhere and are not important to this analysis, hence, only the specific parameters fitted and the constraints to which they are subjected are discussed here.

For each K_S^0 , the pion track parameters $\vec{x}$ and the K_S^0 3 momentum and decay length $\vec{p}$ are input. The constraints imposed on the system during minimization are as follows:

$$g_1 = \left(\sum_{i=1}^2 p_x^{\pi_i} \right) - p_x^{K_S^0} \quad (3.2)$$

$$g_2 = \left(\sum_{i=1}^2 p_y^{\pi_i} \right) - p_y^{K_S^0} \quad (3.3)$$

$$g_3 = \left(\sum_{i=1}^2 p_z^{\pi_i} \right) - p_z^{K^0} \quad (3.4)$$

$$g_4 = \left(\sum_{i=1}^2 E^{\pi_i} \right) - \sqrt{(p^{K^0})^2 + m_{K^0}^2} \quad (3.5)$$

$$\begin{aligned} g_{5.6} &= d_0^{\pi_i} - d_0^{\pi_i}{}_{\text{calculated}} \\ &= d_0^{\pi_i} + x_v \sin \phi_0^{\pi_i} + y_v \cos \phi_0^{\pi_i} \end{aligned} \quad (3.6)$$

$$\begin{aligned} g_{7.8} &= z_0^{\pi_i} - z_0^{\pi_i}{}_{\text{calculated}} \\ &= z_0^{\pi_i} - z_v + s_0^{\pi_i} \tan \lambda^{\pi_i} \end{aligned} \quad (3.7)$$

where $s_0 = x_v \cos \phi_0 + y_v \sin \phi_0$ is the arc length in the ro plane from the point of closest approach to the origin (p.c.a.) to the vertex (x_v, y_v, z_v) . The calculation of the last 4 constraints and of s_0 is done in the approximation that the pion tracks are straight lines. Of course, this is not the case, as the pion tracks curve in the central magnetic field, and this curvature cannot be ignored. While travelling along its trajectory, the pion momentum vector will rotate by an angle

$$\sin \Delta\phi = 2\kappa s_0 \quad (3.8)$$

This angular change, along with the track radius of curvature $\rho = \frac{1}{2|\kappa|}$, give its true arc length

$$\begin{aligned} s &= \rho \cdot \Delta\phi \\ &= \frac{\sin^{-1}(2\kappa s_0)}{2\kappa} \end{aligned} \quad (3.9)$$

The last 4 constraints are then corrected for the finite curvature of the tracks as follows:

$$g_{5.6} = d_0^{\pi_i} + x_v \sin \phi_0^{\pi_i} + y_v \cos \phi_0^{\pi_i} + \frac{1}{2\kappa^{\pi_i}} (1 - \sqrt{1 - 4\kappa^{\pi_i 2} s_0^{\pi_i 2}}) \quad (3.10)$$

$$g_{7.8} = z_0^{\pi_i} - z_v + s^{\pi_i} \tan \lambda^{\pi_i} \quad (3.11)$$

The first three constraints just express conservation of momentum: the main kinematic constraint being the fourth one, which ensures that the K_S^0 is on-shell. The next 4 express geometric constraints to ensure that the pions originate from the vertex (x_v, y_v, z_v) , and that the K_S^0 originates from the primary vertex. This is done by expressing the secondary vertex coordinates (x_v, y_v, z_v) in terms of the primary vertex coordinates (x_p, y_p, z_p) as follows:

$$x_v = x_p + L_d p_x^{K_S^0} / p^{K_S^0} \quad (3.12)$$

$$y_v = y_p + L_d p_y^{K_S^0} / p^{K_S^0} \quad (3.13)$$

$$z_v = z_p + L_d p_z^{K_S^0} / p^{K_S^0} \quad (3.14)$$

where the ratio of momenta represent the K_S^0 direction cosines. Once the function is iteratively minimized, the updated parameters are used to calculate the quantities relevant to the analysis, and a final chisquared value (4 d.o.f.) is calculated for the fit according to:

$$\chi^2 = (\vec{r} - \vec{\alpha})^T \mathbf{V}^{-1} (\vec{r} - \vec{\alpha}) \quad (3.15)$$

Fit Results

The procedure was applied to the K_S^0 reconstructed from a Monte Carlo sample of 25000 events. To check the reliability of the method, the input track parameters were smeared about their central values with a Gaussian random number generated using their covariance matrices, $\mathbf{V}$. This was done to ensure that the parameters input to the fit algorithm were unbiased and had an exact Gaussian distribution. For each K_S^0 fit, the probability $\mathcal{P}(\chi^2)$ of obtaining a χ^2 value at least as large as the one seen was calculated: the resulting distribution is shown in Figure 3.4 . It shows a peak near 0, indicating large χ^2 values for those events, but it is seen that the entries in the peak are overwhelmingly due to background. The real K_S^0 vertices are uniformly distributed

and show no evidence of bias, indicating that the procedure is sound given good quality track parameters.

Figure 3.4: The chisquared probability (4 d.o.f.) for fits that converge. The fits were performed on a sample of roughly 25000 Monte Carlo events whose input track parameters were normally distributed.

It is well known, however, that the track parameters reconstructed in the Monte Carlo and the data do contain biases and have non-Gaussian tails. Furthermore, the errors in the covariance matrices tend to be underestimated. This can be seen in Figure 3.5 (a) , where there is a prominent peak near 0 for both Monte Carlo and data events. The peak is larger in the data than in the Monte Carlo, as the understanding of the tracking measurements (especially in z) by OPAL has been difficult, and in its modeling, the hit resolutions have been overly optimistic. Here, it is remedied by smearing the Monte Carlo track parameters by a constant scale factor as follows [46]:

Figure 3.5: The chisquared probability (4 d.o.f.) for fits that converge. The histograms show fits done on the same MC sample as in Figure 3.4, while the points represent fits to a sample of 30000 data events. The MC is normalized such that it contains the same number of fit V^0 's as the data. In (a), no MC parameter smearing is applied, while in (b), the input parameters are smeared by 30 %

$$tpar_{reconstructed}^{(i)} = tpar_{generated}^{(i)} + SF \times (tpar_{reconstructed}^{(i)} - tpar_{generated}^{(i)}) \quad (3.16)$$

The suggested value of $SF = +10\%$ [47] was found to be insufficient to bring the Monte Carlo $\mathcal{P}(\chi^2)$ distribution into agreement with the data and a scale factor of $+30\%$ was used for this analysis. The effect of the 30 % scaling is seen in Figure 3.5(b), where the data and Monte Carlo show very good agreement. The peak at 0 due to non-Gaussian tails in the input parameter distributions and the underestimated errors

is quite large, but is less pronounced for real K_S^0 . A cut on the chisquared probability to eliminate vertices in this peak would not be wise, since the large value of the associated χ^2 is not necessarily due to poorly fit parameters, but to poorly measured input parameters and errors. In addition, a large loss of statistics would result.

$K_S^0 K_S^0$ Resolution

Figure 3.6: The $K_S^0 K_S^0$ mass resolution, shown as a function of the $K_S^0 K_S^0$ invariant mass, obtained from a sample of one million Monte Carlo events.

Despite less than perfect reconstructed track parameters and the problem of underestimated covariance matrices, the fit procedure described above does, in fact, greatly improve the $K_S^0 K_S^0$ mass resolution. To demonstrate this, a distribution of $M_{KK}^{reconstructed} - M_{KK}^{generated}$ was obtained for various mass regions, from a sample of 1

million Monte Carlo multihadronic events. For each mass region, a Gaussian function was fitted to the distribution, both before and after the geometric and kinematic fitting was applied. The width of the fitted Gaussian was taken to be the mass resolution. The results are shown in Figure 3.6. The fitting has clearly improved the $K_S^0 K_S^0$ mass resolution, by about 50 %, over the entire mass range of interest.

3.3 Final $K_S^0 K_S^0$ Sample

Figure 3.7: $K_S^0 K_S^0$ invariant mass from threshold to 3 GeV/c^2 . The entire range of interest to this analysis is shown for both Monte Carlo and data. The Monte Carlo histogram shows the contributions from the various objects of interest.

After having made all the selection cuts described in this chapter, the invariant mass spectrum obtained, shown in Figure 3.7 for Monte Carlo and data, is found to be 84.4 ± 0.2 % pure $K_S^0 \bar{K}_S^0$. The Monte Carlo distribution shows the contributions to the total from $K_S^0 \bar{K}_S^0$ pairs, f_0 , and f'_2 . The three different areas of this distribution relevant to this analysis, namely the $K_S^0 \bar{K}_S^0$ threshold, f'_2 and ξ regions, will be investigated in the next chapter.

Chapter 4

Results and Systematics

Having obtained the $M_{K_S^0 K_S^0}$ spectrum shown in Figure 3.7, the three regions of interest described in chapter one are now examined separately.

4.1 Threshold Region: BEC and the f_0

As stated in Section 1.6.1, Bose-Einstein Correlations (BEC) in the $K_S^0 K_S^0$ system, if present, would be seen as an enhancement in the number of data events near threshold, as compared to the Monte Carlo expectation with no BEC effects. The effect of BEC in the $K_S^0 K_S^0$ system has already been investigated using 1990-1992 OPAL data [4, 7]. The contribution of the $f_0(980)$ meson was not considered in the previous analysis, and will therefore be discussed in more detail in the next section.

4.1.1 The effect of the $f_0(980)$

The f_0 decays primarily to $\pi\pi$, since its mass of $980 \text{ MeV}/c^2$ is below the $K_S^0 K_S^0$ production threshold. However, because it has a finite width, $\Gamma_{f_0}=40\text{-}100 \text{ MeV}$, it can “spill over” into the $K_S^0 K_S^0$ channel, populating mass bins near the $K_S^0 K_S^0$ threshold. Because the f_0 was not included in the previous OPAL analysis, it is necessary to verify

whether the BEC-like enhancement reported in that analysis was real or due to the presence of f_0 . The newest versions of the JETSET program include f_0 production, and this is discussed below.

The f_0 mesons are generated in JETSET with zero width and a mass of 1 GeV to put them above the $K\bar{K}$ threshold. Figures 4.1(a) and 4.1(b) show the reconstructed mass and Q distributions for the generated f_0 's. This is not really useful in the investigation of possible BEC effects, since the delta function at $Q_{f_0} \approx 10$ MeV would confuse the interpretation of the correlation function. Hence, in order to make any viable conclusion on BEC in this system, the exact shape of the $K_S^0 K_S^0$ spectrum due to the f_0 must be known.

In order to obtain a more realistic $K_S^0 K_S^0$ line shape for the f_0 , the entries shown in Figures 4.1(a) and 4.1(b) were replaced with entries distributed as shown in Figures 4.1(c) and 4.1(d). Since the f_0 peak is below the $K_S^0 K_S^0$ threshold and because the $\pi^+ \pi^-$ and $K\bar{K}$ decay channels are coupled, the f_0 spectrum will deviate from a pure Breit-Wigner shape. The total f_0 production rate has been measured by OPAL [48], by simultaneously fitting the $f_0 \pi^+ \pi^-$ and $K^+ K^-$ spectra. The resulting $K\bar{K}$ amplitude has been used to generate the $f_0 K_S^0 K_S^0$ mass spectrum shown in Figure 4.1(c). From this spectrum, the $f_0 Q$ distribution has been obtained and is shown in Figure 4.1(d). Before replacing the revised f_0 mass and Q distributions in the total Monte Carlo, both distributions were scaled by a factor of 1.44 to account for the higher f_0 production rate measured by OPAL ($\langle n_{f_0} \rangle(\text{OPAL}) = 0.141 \pm 0.007 \pm 0.011$) as compared to that used by JETSET ($\langle n_{f_0} \rangle(\text{JETSET}) = 0.09786 \pm 0.0044$).

Figure 4.2 shows the $K_S^0 K_S^0$ mass and Q distributions with the f_0 contribution included. In Figure 4.2(b), it is clear that the BEC effect is not present. It seems that the addition of the corrected f_0 contribution removes any excess the data might have over the Monte Carlo near threshold.

Figure 4.1: $K_S^0 K_S^0$ mass and Q distributions for MC f_0 's. The values generated in JETSET are shown in (a) and (b), while the values obtained from the coupled channel fit are shown in (c) and (d).

As a consistency check, the f_0 Monte Carlo contribution to Q was not included and the correlation function $C(Q)$ was recalculated. In this manner, the results of the 1992 OPAL study of $K_S^0 K_S^0$ BEC could be compared to the present analysis. The Q and $C(Q)$ distributions, without the f_0 contribution, are shown in Figure 4.3. Also shown in the figure is the data from the previous OPAL analysis. Clearly, the two analyses yield similar results: a BEC like effect is present only when the f_0 contribution is ignored.

Figure 4.2: (a) The momentum transfer, Q , and (b) the correlation function $C(Q)$ for $K_S^0 K_S^0$ pairs near threshold. Here, the coupled channel $f_0 K_S^0 K_S^0$ lineshape contribution is included. The line in (b) shows the average value of $C(Q)$, and is consistent with a value of 1.

4.2 Region of the $f'_2(1525)$ Resonance

4.2.1 f'_2 Reconstruction Efficiency

In order to calculate the production rate of the f'_2 it is necessary to know what fraction of the mesons survive the selection cuts described in the previous chapter. This is accomplished using the Monte Carlo simulation of $K_S^0 K_S^0$ decays in the OPAL detector. The f'_2 's are reconstructed via their $K_S^0 K_S^0 \rightarrow 2(\pi^+ \pi^-)$ decays, and the number, N_{recon} , passing the selection cuts is known from the Monte Carlo. The number, N_{gen} ,

Figure 4.3: The momentum transfer, Q (a), and correlation function, $C(Q)$ (b), for $K_S^0 K_S^0$ pairs near threshold. The f_0 is not included. The results of the 1992 OPAL analysis showing a BEC effect are also shown, normalized to the number of events observed in this analysis.

of generated f_2' passing through this decay chain is also known from the Monte Carlo. Therefore, the efficiency for reconstruction of such decays is written $\epsilon_r = N_{recon}/N_{gen}$, and the uncertainty in this efficiency is evaluated by $\sigma_{\epsilon_r} = \sqrt{\epsilon_r(1 - \epsilon_r)/N_{gen}}$.

The Monte Carlo contains 54123 reconstructed $K_S^0 K_S^0$ pairs, of which only 434 originate from a parent f_2' . A total number of 113594 generated f_2' are contained in the Monte Carlo, of which 8961 decay to $K_S^0 K_S^0 \rightarrow 2(\pi^+ \pi^-)$. Using $N_{recon}=434$ and $N_{gen}=8961$, the efficiency of the selection procedure described in the previous chapter is evaluated to be:

$$\epsilon_r = 4.843 \pm 0.226\%.$$

4.2.2 Fitting the f'_2 Signal

To perform a fit to the f'_2 signal, functional forms are needed to describe both background and signal. In this analysis, the background was parameterized by a cubic polynomial of the form:

$$BK^G(M) = a_0 + a_1 M + a_2 M^2 + a_3 M^3 \quad (4.1)$$

where M is the $K_S^0 K_S^0$ invariant mass and a_i the fitted coefficients. The f'_2 signal, on the other hand, was described by a normalized Breit-Wigner of the form

$$BW_{f'_2}(M) = \frac{n_{f'_2}}{\pi} \cdot \frac{(\frac{\Gamma_{f'_2}}{2})}{(M - M_{f'_2})^2 + (\frac{\Gamma_{f'_2}}{2})^2} \quad (4.2)$$

where $n_{f'_2}$ is the number of f'_2 fitted, and $M_{f'_2} = 1525 \pm 5 \text{ MeV}/c^2$ and $\Gamma_{f'_2} = 77 \pm 10 \text{ MeV}^{-1}$ are the PDG mass and width [22] of the f'_2 . Therefore, the $K_S^0 K_S^0$ invariant mass spectrum was fitted with the function:

$$f(M) = BK^G(M) + BW_{f'_2}(M) \quad (4.3)$$

The fitting procedure was first carried out on the Monte Carlo sample, shown in Figure 4.4, such that values of fitted quantities could be checked against their generated values. To that end, the BW function was fitted to the $K_S^0 K_S^0$ mass spectrum of the 434 f'_2 's passing all selection cuts, shown in Figure 4.4(a). With the mass, width and number of events in the peak left free, the values obtained from the fit were $M_{f'_2} = 1529 \pm 3$

¹ $\Gamma_{f'_2} = \sqrt{\Gamma_{natural}^2 + \sigma_{resolution}^2} = \sqrt{76^2 + 10^2} \approx 77 \text{ MeV}$. Strictly speaking, the BW function should be convoluted with a Gaussian detector resolution function, but the small resolution here makes this unnecessary.

MeV/c^2 . $\Gamma_{f_2'}=80\pm6 \text{ MeV}$ and $n_{f_2'}=466\pm23$ ($\chi^2/d.o.f.=17.1/14$). With the mass and width fixed at their PDG values, the fit yielded $n_{f_2'}=461\pm23$ ($\chi^2/d.o.f.=19.6/16$). In the first instance, the fitted mass and width were in excellent agreement with their generated values, and in both cases, the fitted number of f_2' was consistent with the actual number of events in Figure 4.4(a).

Figure 4.4: $K_S^0 K_S^0$ invariant mass in the region of the f_2' . The real f_2' are shown in (a), while (b) shows a fit to the entire MC spectrum.

A fit to the data spectrum necessarily incorporates the background, since there is no way to separate the two. Therefore, the full Monte Carlo spectrum was fitted with $f(M)$ above to verify the consistency of the fitted value of $n_{f_2'}$. The mass and width were fixed at their PDG values. The fit result, shown in Figure 4.4(b), was $n_{f_2'}=553\pm144$

($\chi^2/d.o.f.=4.14/9$), somewhat high, albeit with a large error, but still consistent with the 434 generated f'_2 passing all selection cuts. This large uncertainty is a result of the dominant background around the signal.

Having checked the reliability of the fit results, the data spectrum was next fitted as above. The BW amplitude was set to 0 to first fit for the background a_1 's and then the amplitude was left free. The mass was varied, with the width fixed, and the fit was redone until a minimum in the value of χ^2 was found, along with the $\chi^2_{min} + 1$ uncertainty. The procedure was then repeated varying the width at fixed mass. In this way, the measured values for the mass and width of the data peak were found to be $M_{f'_2} = 1512 \pm 11 \text{ MeV}/c^2$ and $\Gamma_{f'_2} = 45 \pm 35 \text{ MeV}$. Both values are consistent with the PDG f'_2 mass and width. Having verified the consistency of the measured mass and width with their PDG values, the latter were used to fit for the BW amplitude.

Figure 4.5: $K_S^0 K_S^0$ invariant mass in the region of the f'_2

With the mass and width fixed at their PDG values, the data spectrum was fitted as above with $f(M)$, to obtain the number of f'_2 in the peak. The result of the fit to the data is shown in Figure 4.5. The range of the fit was from 1310 to 1730 MeV/ c^2 (see section 4.4), the same as was used in Figure 4.4. The fit yielded good results ($\chi^2/\text{d.o.f.}=10.1/9$), and the fitted number of f'_2 was found to be:

$$n_{f'_2} = 366 \pm 100$$

4.2.3 Extraction of the f'_2 Production Rate

In order to obtain the total f'_2 production rate, the number $n_{f'_2}$ obtained from the fit must be corrected for the inefficiency of the selection procedure used and for other decay modes not seen in this analysis. The production rate is defined simply as the ratio of the total, corrected number of f'_2 to the number of Z^0 multihadronic decays analyzed. It can be written as follows:

$$\langle n_{f'_2} \rangle = \frac{n_{f'_2}}{\epsilon_r \cdot [BR] \cdot N_{MH}} \quad (4.4)$$

where $n_{f'_2}$ is the result of the fit above, ϵ_r is the reconstruction efficiency from Section 4.2.1, $N_{MH}=4738697$ is the number of multihadronic Z^0 decays analyzed and $[BR]$ is a product of branching ratios, used to correct for unseen decay modes.

The branching ratio factor is given by the product of the following:

$$[BR] = \frac{1}{4} \cdot [BR(f'_2 \rightarrow K\bar{K})] \cdot [BR(K_s^0 \rightarrow \pi^+\pi^-)]^2 \quad (4.5)$$

Here $BR(K_s^0 \rightarrow \pi^+\pi^-) = (68.61 \pm 0.28) \%$ [22] corrects for unseen K_s^0 decays to $\pi^0\pi^0$. Correction for non $K\bar{K}$ f'_2 [22] decays is made with $BR(f'_2 \rightarrow K\bar{K}) = (88.8 \pm 3.1) \%$. Finally, the factor of $\frac{1}{4}$ accounts for the fact that only 25 % of $K\bar{K}$ pairs end up as $K_s^0\bar{K}_s^0$. Half of them first decay to $K^0\bar{K}^0$ (the other half decay to K^+K^-), and half

of these remaining neutral pairs end up as $K_S^0 K_S^0$ (the $K_S^0 K_L^0$ decay is forbidden for $J^{PC} = (even)^{++}$ mesons). Using the above numbers in equation 4.4, yields the result:

$$\langle n_{f_2'} \rangle = 0.01527 \pm 0.00414$$

where the quoted error is purely statistical. Systematic uncertainties are discussed in Section 4.4.

4.3 Higher Mass Resonance: the $\xi(2230)$

The third $K_S^0 K_S^0$ mass region of concern to this analysis is that shown in Figure 4.6. Recently, the L3 Collaboration at LEP reported indications of $\xi(2230)$ production in multihadronic Z^0 decays, observed through the $K_S^0 K_S^0 \rightarrow 2(\pi^+ \pi^-)$ decay mode [citegfl3:98]. The signal seen by L3 is present predominantly in three jet events. This analysis was not concerned with the number of jets in the events; however, the ≈ 20 MeV $K_S^0 K_S^0$ mass resolution in the region of the ξ (see Figure 3.6) is about 4 times better than that reported by L3, and the OPAL data sample contains roughly a million more multihadronic Z^0 decays. Therefore, a signal, if present, should be visible in the $K_S^0 K_S^0$ invariant mass distribution in the region of the arrow in Figure 4.6.

Evidence for a ξ signal in the region of 2.2 GeV is not seen in the distribution of Figure 4.6. The smooth line through the data points represents a cubic fit to the background, of the same form used to parameterize the background in the f_2' region. The region of the ξ shows evidence of nothing beyond statistical fluctuations. Hence, no evidence of $\xi(2230)$ production in the OPAL data is found by this analysis.

4.4 Systematic Effects on the f_2' Rate

The error quoted on the f_2' production rate in section 4.2.3 was statistical only. However, there are additional sources of uncertainty in this rate due to a variety of

Figure 4.6: $K_S^0 K_S^0$ invariant mass above 2 GeV. The arrow shows where the $\xi(2230)$ should be seen.

contributions, from the selection criteria used to statistical uncertainties in quantities like branching ratios. Whatever the source, the effect of these systematic uncertainties on the measured rate must be investigated.

4.4.1 Monte Carlo Statistics

The efficiency, ϵ_r , for reconstructing $f_2' \rightarrow K_S^0 K_S^0 \rightarrow 2(\pi^+ \pi^-)$ decays was calculated using a sample of generated events. In principle, this efficiency could be calculated to an arbitrary degree of precision but in practice the size of the Monte Carlo samples is limited, and thus errors of a statistical nature are introduced on the calculated efficiency. This error could be reduced by generating more events from which to estimate the efficiency, and is therefore treated separately from the statistical error due to the finite size of the data sample. The efficiency calculated for this analysis was found in Section 4.2.1 to be $\epsilon_r = 4.843 \pm 0.226\%$. The effect of varying ϵ_r by $\pm 1\sigma$ on the measured f_2'

production rate is shown in Table 4.1

4.4.2 Selection and Fit Procedures

The effect of procedures used to reduce background and to fit the f_2' signal on the measured production rate was also investigated. First, the range over which the fit was performed was varied from the default 420 MeV/ c^2 around the peak, down to 300 and up to 510 MeV/ c^2 . The number of f_2' fitted is shown in Figure 4.7(a) for each fit range used. There is no evidence of a systematic variation in the fitted values and the average value, shown by the line in Figure 4.7(a), is consistent with that measured in Section 4.2.2. Nevertheless, the calculated r.m.s. of the values of 50 was taken to be the error associated with variation of the fit range. Table 4.1 shows the variation in the production rate from the fit range uncertainty.

Next, the size of the $M(K_S^0 K_S^0)$ bins was varied about the default value of 30 MeV/ c^2 . The variation in $n_{f_2'}$ with bin size is shown in Figure 4.7(b). Again, no evidence of a systematic variation is seen, and the average value fitted is consistent with that in Section 4.2.2. As was the case with the fit range, the r.m.s. for the values, calculated to be 42, was taken to be the uncertainty associated with the choice of bin size. The variation in the production rate from this bin size variation is also shown in Table 4.1.

In obtaining the sample from which $K_S^0 K_S^0$ pairs were formed, candidate K_S^0 were accepted only if their $\pi^+ \pi^-$ invariant mass was within 25 MeV/ c^2 of the mass fitted to the K_S^0 peak. The size of this mass window was varied from 20 MeV/ c^2 to 30 MeV/ c^2 to investigate how this cut affects the measured production rate. With the size of this mass window changed, a new reconstruction efficiency was calculated and used to determine the new production rate. The variation of $\langle n_{f_2'} \rangle$ from the change in this mass window is shown with the other sources in Table 4.1.

Figure 4.7: Variation of $n_{f'_2}$ with (a) the range used in the signal fit, and (b) the $K_S^0 K_S^0$ mass bin size. The lines show the average value of $n_{f'_2}$.

4.4.3 f'_2 Resonance Parameters

In doing the fits to the f'_2 peak, the mass and width of the resonance were fixed at their Particle Data Group values, $M_{f'_2}^{PDG} = 1525 \pm 5$ MeV/c² and $\Gamma_{f'_2}^{PDG} = 77 \pm 10$ MeV. The measured values of mass and width, found by minimizing the χ^2 value for the fit, were found to differ, but still agreed with the PDG values. In order to evaluate the uncertainties associated with the value of the resonance parameters, the mass and width were varied in turn, with the other remaining fixed, by 1σ about their PDG values. The resulting variation in the production rate is summarized in Table 4.1.

Table 4.1: Summary of the sources of systematic error on the f_2' production rate.

Error Source	Variation in $\langle n_{f_2'} \rangle$ (%)
Monte Carlo Statistics	+4.90 -4.46
Fit Range Variation	± 13.70
Bin Size Variation	± 11.53
Mass Window Variation	+0.28 -15.28
$M_{f_2'}^{PDG} \pm 1\sigma$	+9.34 -11.72
$\Gamma_{f_2'}^{PDG} \pm 1\sigma$	+17.10 -9.42
total systematic uncertainty	+26.91 -28.28

4.4.4 Branching Ratio Uncertainties

In the calculation of the f_2' production rate, the Particle Data Group branching ratios were used to correct the measured rate for decays to modes unseen by this analysis, via

$$BR(f_2' \rightarrow K\bar{K}) = (88.8 \pm 3.1)\%$$

$$BR(K_s^0 \rightarrow \pi^+\pi^-) = (68.61 \pm 0.28)\%$$

These branching ratios are averages of many measurements, and they have an associated uncertainty which is irreducible without making more measurements. For this reason, the error in the production rate due to experimental uncertainties in branching ratios is treated separately from the other sources of systematic error, which can in principle be reduced. The production rate was therefore recalculated, in turn varying each branching ratio by $\pm 1\sigma$ about their measured values. Table 4.2 summarizes the resulting variation of the production rate.

Table 4.2: Summary of the uncertainties in the f'_2 production rate due to branching ratios

BR Source	Variation in $\langle n_{f'_2} \rangle$ (%)
$BR(f'_2 \rightarrow K\bar{K}) \pm 1\sigma$	$+3.62$ -3.37
$BR(K_s^0 \rightarrow \pi^+\pi^-) \pm 1\sigma$	$+0.82$ -0.81
total BR uncertainty	$+3.71$ -3.47

4.4.5 Final Value of the f'_2 Production Rate

The total percentage variations from systematic sources, calculated by adding the separate contributions in quadrature, are listed in Tables 4.1 and 4.2. These can now be used to quote the final result for the measurement of the f'_2 production rate. From Section 4.2.3, the value found was:

$$\langle n_{f'_2} \rangle = 0.01527 \pm 0.00414(stat.)$$

The errors calculated in Tables 4.1 and 4.2 can now be added to the above number. As a result, the measured production rate for f'_2 mesons in multihadronic Z^0 decays is found to be

$$\langle n_{f'_2} \rangle = 0.0153 \pm 0.0041(stat.)^{+0.0041}_{-0.0043}(syst.)^{+0.0006}_{-0.0005}(BR)$$

Chapter 5

Discussion of Results and Conclusions

This analysis has investigated several aspects of the $K_S^0 K_S^0$ system. It has been carried out on the almost 5 million multihadronic Z^0 decays collected by OPAL from 1990 to 1995.

First, the f_0 lineshape in the $K_S^0 K_S^0$ channel has been investigated. The f_0 δ function used in JETSET has been replaced by a more realistic representation, obtained from a coupled channel analysis of the $K\bar{K}$ and $\pi^+\pi^-$ decay channels. With this new lineshape, the excess of data events over Monte Carlo near the $K_S^0 K_S^0$ threshold, which had previously been attributed to the effect of Bose-Einstein Correlations, is not seen. The BEC like effect previously quoted seems to have been due to the fact that the f_0 contribution to the $K_S^0 K_S^0$ mass spectrum had been ignored. No evidence of BEC was seen in this analysis.

Secondly, the total inclusive production rate for the f_2' tensor meson has been measured to be

$$\langle n_{f_2'} \rangle = 0.0153 \pm 0.0041(stat.)_{-0.0043}^{+0.0041}(syst.)_{-0.0005}^{+0.0006}(BR)$$

in good agreement with the rate of

$$\langle n_{f'_2} \rangle = 0.020 \pm 0.005(stat.) \pm 0.006(syst.)$$

obtained by the DELPHI collaboration in an analysis of the $f'_2 K^+ K^-$ decay channel. It also strongly supports the JETSET prediction of

$$\langle n_{f'_2} \rangle = 0.014156$$

This provides OPAL with its first measurement of the f'_2 production rate and is the first LEP measurement using the $K_S^0 K_S^0$ channel. The agreement between the measured rate and that predicted by JETSET, as well as the absence of major inconsistencies between data and Monte Carlo indicates that the use of string hadronization models continues to be justified. This agreement is also consistent with the f'_2 being a 3P_2 $q\bar{q}$ state, as it is generated within JETSET.

Lastly, a signal for the $\xi(2230)$, recently reported by the L3 collaboration, has not been found in the OPAL data by this analysis. The $K_S^0 K_S^0$ mass spectrum in the region of $2.2 \text{ GeV}/c^2$ shows evidence of nothing beyond statistical fluctuations about the background. The OPAL Z^0 sample shows no evidence of $\xi(2230)$ production in the $K_S^0 K_S^0$ channel.

Appendix A

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