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Λ Production in 91 GeV e^+e^- Collisions

by

Paul Routenburg

**A thesis submitted to the Faculty of Graduate Studies and Research in partial
fulfilment of the requirements for the degree of Doctor of Philosophy**

**Department of Physics
Carleton University
Ottawa-Carleton Institute for Physics
Ottawa, Ontario
September 1992**

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Abstract

An analysis of $\Lambda + \bar{\Lambda}$ production in the data collected with the OPAL detector during 1990 is presented. A total inclusive rate is determined and checked through detailed systematic studies. This rate is found to be 0.356 ± 0.011 (stat.) ± 0.028 (syst.) per multihadron event.

The inclusive cross sections as a function of the fractional Λ energy (x_E) and ξ ($\xi = \ln(1/x_p)$, where x_p is the fractional Λ momentum) are determined and compared to the predictions of the HERWIG 5.0 and JETSET 7.2 Monte Carlos as tuned to agree with global event shapes at an average centre-of-mass energy of 91 GeV. The overall Λ rate is in agreement with the JETSET prediction but less than that predicted by HERWIG. The fragmentation function observed is softer than predicted by either Monte Carlo. Scaling violations are observed in the x_E distribution compared to the observations between 29 and 35 GeV. This is attributed to increased gluon radiation.

A study is then made of the Λ decay length distribution, and of the production and decay angles. Reasonable agreement is found between the data and the expectations. There is some indication that the Λ rate increases faster with event sphericity than does the charged multiplicity. This effect is thought to be due to increased baryon production in gluon fragmentation. Finally, an investigation into $\Lambda - \bar{\Lambda}$, $\Lambda - \Lambda$ and $\bar{\Lambda} - \bar{\Lambda}$ production in the same event is presented. The results support local baryon number conservation and agree with the JETSET prediction. It is also shown that an additional meson is produced between the baryon and the antibaryon a significant fraction of the time.

Acknowledgements

This thesis would not have been possible without the help of many people along the way. The data collection required the hard work and dedication of the many physicists, engineers, technicians and students who have worked on the OPAL project over the years.

Once the processed data was in hand the analysis specific to this thesis could begin. Throughout the analysis my advisor, Richard Hemingway, provided a great deal of insight and advice into Monte Carlos and data analysis. Other members of the OPAL group at Carleton also provided advice at various stages along the way, particularly Bob Carnegie and Penny Estabrooks. Thanks also go to the other graduate students on the project, especially Ali Pouladdej who worked on the K^0 analysis at the same time that the Λ analysis was underway. Many of the problems encountered at various points along the way were common to both analyses and through cooperation they were overcome.

Thanks also go to the regular crowd at Mike's Place for the many hours of darts, baseball, bridge and other activities that helped to keep me relatively sane through my graduate student career. A very special thanks must go to Elisabet who pushed me to go on and do a Phd. Without her urging me on, I would have never reached the point where this thesis could have been started. Patricia, the friendship and interesting times that you've given to me over the past two years will never be forgotten.

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Chapter 1

INTRODUCTION

During the past four decades our understanding of the basic structure of matter has grown in leaps and bounds. In the 1940's it was thought that atoms consisted of a nucleus made up of protons and neutrons surrounded by electrons and these were thought to be the basic building blocks of all matter.

With the subsequent discovery of many different particles it was thought that the protons, neutrons and other, supposed “fundamental”, particles were made up of just a few even smaller entities which were called quarks. Electrons on the other hand are thought to be fundamental objects themselves and are part of a group of particles known as leptons. Together the quarks and leptons are known as fermions. Over the years a theory has been developed which nicely explains how quarks are combined to form all the particles that have been discovered. This theory, known as the Standard Model [1], also explains the interactions between all pairs of the fundamental fermions.

While the Standard Model has done an excellent job in explaining particle physics observations so far, it lacks several key elements. It does not explain why

there appears to be only a specific number of quarks and leptons, nor does it predict the masses of these particles. Not all of the quarks that are predicted to exist within the Standard Model have yet been found. All of the particles that act as carriers of the forces found in nature should be massless but two of them, however, are quite massive. The mechanism by which these particles acquire their mass requires that another, as yet undiscovered, particle exist. This object, known as the Higgs boson, has eluded all searches thus far. The Standard Model does not even make a prediction for the mass of this object. Despite these shortcomings there is, as yet, no definitive experimental evidence in contradiction with it.

In the remainder of this Chapter an introduction to the Standard Model will be given. One method of probing the Standard Model is to study collisions between the various particles. A particularly powerful experiment involves the study of collisions between high energy electrons and positrons. The result of such a collision is the creation of a number of different types of particle. Measuring the properties of these particles provides many invaluable tests of Standard Model predictions. The basics of these e^+e^- collisions will also be reviewed in this chapter.

1.1 The Standard Model

The standard model is currently accepted as the basic theory of the fundamental particles and their interactions. All matter is thought to be made up of a small number of spin $1/2$ objects collectively known as fermions. Forces between these fermions are carried by objects of integral spin, known as bosons. There are four known forces: electromagnetism, the weak force, the strong force and gravity.

The fermions are grouped into three families, or generations, as shown in Ta-

Generation	Particle		Charge	Mass
1	Quarks	up (u)	+2/3	325 MeV
		down (d)	-1/3	325 MeV
	Leptons	electron (e)	-1	511 keV
		ν_e	0	< 17 eV
2	Quarks	charm (c)	+2/3	1.6 GeV
		strange (s)	-1/3	500 MeV
	Leptons	muon (μ)	-1	106 MeV
		ν_μ	0	< 0.27 MeV
3	Quarks	top (t)	+2/3	> 91 GeV (see text)
		bottom (b)	-1/3	5 GeV
	Leptons	tau (τ)	-1	1784 MeV
		ν_τ	0	< 35 MeV

Table 1.1: The fundamental fermions in the Standard Model.

ble 1.1. Each family contains two quarks, one charged lepton and one neutral lepton (a neutrino, denoted by the symbol ν). There is no reason within the Standard Model as to why there are only three generations. A measurement using the combined 1989 and 1990 data from the four LEP experiments gives the number of light neutrino species as 3.00 ± 0.05 [2]. For each particle there is a corresponding antiparticle which has the same mass but opposite charge and other quantum numbers. A particle can annihilate with its antiparticle to form a neutral boson.

Since quarks do not exist as free objects it is impossible to measure their masses directly. The values listed in Table 1.1 for the u, d, s, c and b quarks are the constituent masses as used in the JETSET Monte Carlo program [3] which is used extensively in the analysis throughout this thesis. The top quark, as yet undiscovered, is believed to exist, but with a very heavy mass. The lower limit is 91 GeV at the 95 % confidence limit, assuming that it decays weakly to a bottom quark [4]. If non-standard decays are allowed the lower mass limit is 55 GeV. From

the combined LEP data the top quark mass is predicted to be 132^{+27+18}_{-31-19} GeV [2].

The two heavier generations are unstable and decay via the weak force to the lightest generation. Particles containing a b quark decay to those with a c quark and then to those containing an s quark. These particles then decay to stable particles containing only u and d quarks. The protons and neutrons that form atomic nuclei consist of combinations of u and d quarks. Quarks cannot decay directly to another quark of the same charge in a lower generation; b quarks therefore are not observed to decay directly to s quarks for example. These "flavour changing neutral currents" are very strongly suppressed in the basic Standard Model and this suppression was one of the many predictions in the development of the theory [5]. It was because of this that the existence of a fourth quark, called charm, was predicted.

An interaction between a pair of fermions can be thought of as the exchange of field quanta (bosons) between the two particles. In the case of the electromagnetic force, the theory of quantum electrodynamics (QED) describes the electromagnetic interactions between fermions. At the quantum level the electromagnetic force between two electrons consists of the emission and absorption of photons, the quantum of the electromagnetic field.

The strength of the force depends on the strength of the coupling of the relevant boson to the fermion. The coupling constant in the electromagnetic case is the fine structure constant, $\alpha = 1/137.036$. The range of the force depends on the boson mass, with the potential given by the Yukawa form

$$V(r) = \frac{1}{r} \exp(-mcr/\hbar)$$

Since the photon is massless the range of the electromagnetic force is infinite.

Boson	Force	Mass	Range	Spin
photon (γ)	electromagnetism	0	infinite	1
$W^\pm$	weak (charged current)	80 GeV	10^{-18} m	1
Z^0	weak (neutral current)	91 GeV	10^{-18} m	1
gluon (g)	strong	0 (assumed)	10^{-16} m	1
graviton	gravity	0 (assumed)	infinite	2

Table 1.2: The four known forces and some properties of the exchanged bosons.

The W and Z bosons are very massive objects, therefore the weak force acts only over very short distances. In Table 1.2 the four forces are listed along with their range and the exchanged boson.

Gluons, like quarks, cannot be observed freely in nature. Theoretically the gluon is believed to be massless. Since gluons are required to be confined inside hadrons as discussed below, the range of the strong force is assumed to be of typical hadronic size (10^{-16} m). Gravity has not yet been included in the Standard Model and the graviton remains to be detected. The other three forces have been unified within the Standard Model, and this unified group of forces is often referred to by its group theory notation: $SU(3)_{\text{colour}} \times SU(2)_{\text{weak}} \times U(1)_{\text{em}}$. The weak and electromagnetic forces are unified into a single electroweak field theory. At very high energies the two forces are the same. At even higher energies the strong, weak and electromagnetic forces would all act as though they were the same force.

Not every force acts on all fermions. The electromagnetic and weak forces act between quarks and between the charged leptons. Neutrinos, being neutral, are subject only to the weak force. The strong force acts only between quarks.

The theory of the strong force, quantum chromodynamics (QCD) [6], predicts that quarks cannot exist freely as single objects. In addition to their electric

charge quarks carry a "colour charge" which can be one of three colours: red, blue or green. Their antiparticles, antiquarks, have the corresponding anticolour. Gluons couple to this colour charge in the same way that photons couple to the electric charge. Only colourless combinations of quarks and antiquarks can be observed and there are three possible ways to form these combinations: quark plus antiquark, a combination of three quarks of three different colours or a combination of the three anticolours. Particles made up of a quark and an antiquark are called mesons. Colourless combinations of quarks or antiquarks are referred to as baryons and antibaryons respectively. Collectively these particles are grouped into a class of particles called hadrons. Protons and neutrons, the lightest baryons, consist of the quark combinations uud and udd respectively.

Since gluons carry the colour charge they can couple to themselves. It is because of this self-coupling that quarks cannot exist as free particles. As the distance between a pair of quarks increases the force between them increases to such an extent that they cannot escape. Production of additional quark pairs becomes energetically more preferred and these quarks combine into hadrons. This leads to the concept of hadronization, the subject of Chapter 2. It is necessary to study the hadrons in order to infer information about how the quarks actually materialize into the particles that we can observe in our experiments.

1.2 e^+e^- Collisions

The Standard Model has been developed as a result of many years of experimental and theoretical work. One of the experimental techniques that has been used is to collide electrons and positrons at high energies. The electrons and positrons circulate in opposite directions in a storage ring. When they collide they annihilate

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Figure 1.1: Feynman diagrams showing the process $e^+e^- \rightarrow f\bar{f}$ via production of a γ or Z^0 boson.

and form a boson (either a γ or Z^0) with an energy equal to the sum of the electron and positron energy. This boson immediately decays to a fermion-antifermion pair as shown in Figure 1.1. Studies of e^+e^- collisions have produced many of the most important results in particle physics.

Figure 1.2 shows the Standard Model predictions of the cross sections for the processes $e^+e^- \rightarrow \text{hadrons}$, $e^+e^- \rightarrow \mu^+\mu^-$ and $e^+e^- \rightarrow \gamma\gamma$, and the results of experiments with centre-of-mass collision energies between 10 and 92 GeV. Excellent agreement is seen between the data and the predictions over the entire energy range.

In Figure 1.2 a very prominent feature is seen at about 90 GeV in the case of the $e^+e^- \rightarrow \text{hadrons}$ and $e^+e^- \rightarrow \mu^+\mu^-$ reactions. This is due to the preferential annihilation of the e^+ and e^- into a Z^0 as the centre-of-mass energy approaches the Z^0 mass. The shape of the resonance is given by a Breit-Wigner form centered at M_Z with width Γ_Z . Very precise measurements of these two quantities are extremely important in testing Standard Model predictions. From the analysis of the combined LEP data [2] these values are 91.175 ± 0.021 GeV and 2.487 ± 0.010 GeV respectively.

The differential cross section for the process $e^+e^- \rightarrow f\bar{f}$, shown in Figure 1.1, contains contributions from three sources: the pure QED contribution from the photon diagram, the pure weak contribution from the Z^0 diagram and a contribu-

Figure 1.2: Cross sections for various processes in e^+e^- events compared to Standard Model predictions.

tion from the interference between the two diagrams. The pure QED term is

$$\frac{d\sigma_f}{d(\cos \theta)} = \frac{\alpha^2 e_f^2}{4s} (1 + \cos^2 \theta)$$

where α is the electromagnetic fine structure constant, e_f the charge of the fermion, θ the angle between the fermion and electron directions and $\sqrt{s}$ the centre-of-mass energy. The angular distribution of the produced fermion-antifermion pair is symmetric in $\cos \theta$. When the weak and interference terms are added the cross section becomes [7]:

$$\frac{d\sigma_f}{d(\cos \theta)} = \frac{\alpha^2 e_f^2}{4s} (C_0(1 + \cos^2 \theta) + C_1 \cos \theta)$$

where

$$C_0 = e_f^2 - 2e_f v_e v_f \Re(\chi) + (v_e^2 + a_e^2)(v_f^2 + a_f^2)|\chi|^2$$

$$C_1 = -4e_f a_e a_f \Re(\chi) + 8v_e v_f a_e a_f |\chi|^2$$

and

$$\chi = \frac{G_F M_Z^2}{8\pi\alpha\sqrt{2}} \frac{s}{(s - M_Z^2 + iM_Z\Gamma_Z)}$$

v_e and v_f are the polar vector and a_e and a_f are the axial vector coupling constants of the electron and fermion respectively to the Z^0 . G_F is the Fermi coupling constant and M_Z and Γ_Z are the mass and width of the Z^0 resonance.

Due to the $\cos \theta$ term in the complete cross section a forward-backward asymmetry occurs in the angular production of the fermion-antifermion pair. This asymmetry is given by

$$A_{FH} = \frac{\int_0^1 \frac{d\sigma_f}{d(\cos \theta)} - \int_{-1}^0 \frac{d\sigma_f}{d(\cos \theta)}}{\int_{-1}^1 \frac{d\sigma_f}{d(\cos \theta)}}$$

Precise measurements of the forward-backward asymmetries of the various fermions are also a very important test of the Standard Model. In Figure 1.3 the measured forward-backward asymmetries are shown for $\mu^+\mu^-$ and $b\bar{b}$ pairs as a function of the centre-of-mass energy and compared to the Standard Model prediction. In both cases the agreement is excellent.

1.3 The Λ^0 Baryon

The Λ^0 baryon consists of the quarks s, d and u arranged in an isospin singlet with spin 1/2. It is the lightest strange baryon with a mass of 1115.63 ± 0.05 MeV [8]. Its relatively long lifetime $((2.63 \pm 0.020) \times 10^{-10}$ seconds [8]) allows it to travel a significant distance away from its production point. It decays to a proton and negatively charged pion 64.1 ± 0.5 % [8] of the time. This allows for the isolation of a relatively clean sample of Λ^0 over a wide range of momentum. The antiparticle, $\bar{\Lambda}^0$ is made up of the corresponding antiquarks. Its mass and lifetime are identical to that of the Λ^0 and it decays to an antiproton and a positively charged pion. Throughout this thesis the notation Λ^0 will be used to refer to both particle and antiparticle unless it is specifically stated otherwise.

Since the Λ^0 is a baryon and contains a strange quark the measurement of its production rate and properties is an important test of hadronization models.

Figure 1.3: Forward-backward asymmetries of $\mu^+\mu^-$ and $b\bar{b}$ pairs as a function of centre-of-mass energy.

The highest energy e^+e^- collisions currently available are at energies of about 90 GeV, around the Z^0 mass. The production of hadrons in high energy collisions is not directly calculable within QCD or the Standard Model. The quarks that are initially produced undergo a process known as hadronization and appear as a shower of particles in the experimental detectors. To deduce the properties of the underlying quark and gluon interactions requires the use of a hadronization model. The observations of the properties of the particles that are produced can be compared to the model predictions and the models improved or rejected based on those observations.

In Chapter 2 the interactions between quarks and how they appear to us in our experiments will be covered in more detail. Several hadronization models will be reviewed. Chapter 3 describes the LEP storage ring, the OPAL detector and the collection of the data that is analyzed in this thesis. Chapters 4 and 5 provide details of the isolation of the Λ signal and the results of the analysis. In Chapter 6 the results are summarized and given in context with relevant observations from other analyses.

Chapter 2

THEORY

As discussed in the previous Chapter the Z^0 decays predominantly into multi-hadronic final states. This process is shown schematically in Figure 2.1. The process $e^+e^- \rightarrow q\bar{q}$ (region (a) in Figure 2.1) in which a γ or Z^0 boson decays into a quark-antiquark pair was covered in Chapter 1. In this Chapter the transformation of this fermion-antifermion pair into the particles that we observe experimentally is explained.

In region (b) of Figure 2.1 the initial $q\bar{q}$ pair may radiate gluons. These gluons may then branch into a $q\bar{q}$ pair or a pair of gluons. At this stage perturbative QCD is used to describe the underlying physics process.

Since quarks and gluons are coloured objects they cannot be observed as single free particles. It is at this point, in part (c) of Figure 2.1, that the partons¹ from stage (b) materialize into colourless hadrons. This process, known as hadronization or fragmentation cannot be directly calculated using QCD. At this stage various phenomenological models are used and the discussion of these models is the major focus of this Chapter.

¹Quarks, antiquarks and gluons are referred to generically as partons.

Figure 2.1: Schematic illustration of an e^+e^- annihilation event.

In the final stage of Figure 2.1, unstable, short-lived hadrons decay into the particles that are actually observed. The structure of the events that are seen has a direct relationship to the partons created in stage (b). Observation of the production rates and momentum spectra of the various final state particles provides information about the fragmentation process. These observations are then compared to the model predictions. As more information is collected the models are either improved or become obsolete.

Baryon production is a particularly interesting aspect of the fragmentation process. By studying baryon production it is hoped that additional information can be obtained about how the initial partons hadronize. Baryons can provide information about the fragmentation process that is not available by observing only mesons.

2.1 Perturbative QCD

Perturbative QCD is used to describe the production of multijet events. Each parton may produce a jet, which is just a distinct group of particles. A $q\bar{q}$ event produces two jets, while an event in which either the q or $\bar{q}$ radiates a hard gluon appears as a three jet event if the gluon is emitted at a large angle relative to the initial quark direction. A hard gluon is one that takes away a significant fraction of the momentum of the originating quark. If the gluon branches into a $q\bar{q}$ pair or a pair of gluons before hadronization, a four jet event is possible. The relative frequency of 2, 3 and 4-jet events is dependent on the value of the strong coupling constant α_s .

Experimentally the association of an observed jet with an initial parton is not

clear cut. A jet is a set of particles grouped together based upon some resolution criteria. Several different schemes exist and the number of jets defined in each scheme depends on the values of the jet resolution parameters chosen. By measuring the relative frequencies of 2, 3 and 4-jet events a value of α_s can be determined and the observed jet rates compared to perturbative QCD calculations using the matrix element approach.

Unlike the electromagnetic fine structure constant α , α_s decreases with increasing momentum transfer (Q^2). This is because of the self-interactions of the gluons which is due to the colour charge that they carry. For short range, high Q^2 reactions, the quarks and gluons interact weakly with a strength decreasing logarithmically with increasing Q^2 . The high Q^2 region (part (b) of Figure 2.1) should be calculable by perturbation theory.

There are two approaches to perturbative QCD: the matrix element method and the parton shower approach. The matrix element method calculations are done in complete second order ($\mathcal{O}(\alpha_s^2)$) perturbation theory. In this method the final state can have no more than four partons. In the parton shower approach the leading and next-to-leading logarithmic terms from all orders in perturbation theory are summed and used to generate a shower of partons. At some cutoff value, Q_0 , the shower is stopped. Typically, for energies around the Z^0 mass, ten final state partons are created for a Q_0 value of 1 GeV [9].

In the matrix element method, which in principle is the correct approach, Feynman diagrams are calculated order by order. The diagrams for 3-jet production (the first order QCD process $e^+e^- \rightarrow q\bar{q}g$) are shown in Figure 2.2(a) where either the q or $\bar{q}$ radiates a gluon. Second order corrections to this process come from vertex and propagator diagrams shown in Figure 2.2(b). A full second order

Figure 2.2: Feynman diagrams for 3 and 4-jet production.

($\mathcal{O}(\alpha_s^2)$) calculation of the 3-jet rate thus includes the diagrams in Figure 2.2(a) and a contribution from the diagrams of Figure 2.2(b).

The diagrams for 4-jet production in second order QCD (the processes $e^+e^- \rightarrow q\bar{q}gg$ and $e^+e^- \rightarrow q\bar{q}q\bar{q}$) are shown in Figure 2.2(c). Not all the possible diagrams are given. The ones omitted can be obtained by symmetry from those shown. As the order increases the calculations become increasingly difficult and have, as yet, only been done completely to second order.

In the parton shower approach successive $q \rightarrow qg$, $g \rightarrow gg$ and $g \rightarrow q\bar{q}$ branch-

Figure 2.3: Schematic illustration of the evolution of a parton shower.

ings occur according to probabilities given by the Altarelli-Parisi equations [10]. The process is shown schematically in Figure 2.3.

At each branching the partons become less virtual until some chosen point is reached and the process ended. For each branching the “leading logarithm” approximation is used in which only the leading terms in the perturbative expansion are kept. Most shower algorithms are of the coherent branching type. This means that the parton branchings are required to take place with decreasing emission angles as the shower evolves. At the end of the process the partons are grouped together to give a description of multijet events. One of the best known

parton shower algorithms is that of Marchesini and Webber [11]. The JETSET Monte Carlo [3] also uses a parton shower approach. While the shower models are expected to give a good description of the substructure of jets, they do not, in principle, predict the rates for well-separated jets.

As the centre-of-mass energy of an event increases the number of gluons emitted increases. This increased gluon emission can be accommodated in the parton shower approach, but this method does not explicitly predict the relative rates of 2, 3 and 4-jets events. The number of hard gluons radiated is important in determining the jet structure of an event. Determining a value of α_s from the 3-jet rate therefore requires the use of matrix element calculations which become increasingly difficult as the number of emitted gluons increases. However, due to the probabilistic nature of the parton shower branchings, this method can easily be implemented into a Monte Carlo event generator. It has been found that overall event shapes are better represented by QCD shower Monte Carlos. Since each method has its advantages, some combination of the two approaches is used in perturbative QCD studies.

A number of quantities related to the observed event shapes can be used to determine α_s . The relative production rates of 3-jet events can be used to calculate a value of α_s . Furthermore, energy and angular correlations between the observed hadrons are also sensitive to the value of α_s . A number of α_s values have been determined from studies of event shapes, jet rates and energy correlations by the four LEP experiments. The current weighted average of these values to $\mathcal{O}(\alpha_s^2)$ is [9]

$$\alpha_s(M_{Z^0}) = 0.120 \pm 0.006.$$

Two other methods of determining α_s have also been used. Firstly, from a measurement of the hadronic partial width of the Z^0 a value of α_s can be calculated. This value is, to $\mathcal{O}(\alpha_s^3)$ [9]

$$\alpha_s(M_{Z^0}) = 0.138 \pm 0.015.$$

Secondly, α_s can also be determined from studying the ratio of hadronic to electronic τ branching ratios. This gives a value of α_s at the τ mass which is then extrapolated to the Z^0 mass. The average value obtained from this method to $\mathcal{O}(\alpha_s^3)$ is [9]

$$\alpha_s(M_\tau) = 0.347^{+0.029}_{-0.031}$$

$$\alpha_s(M_{Z^0}) = 0.120^{+0.005}_{-0.006}$$

The results obtained from all three methods are in excellent agreement and the result from the τ measurement very nicely demonstrates the Q^2 dependence, or “running” of α_s as shown in Figure 2.4.

2.2 Fragmentation

As the initial $q\bar{q}$ pair and any additional radiative partons move apart the distance scale of the interaction increases, Q^2 decreases, α_s becomes large ($\alpha_s \sim 1$) and perturbative QCD is no longer applicable. It is at this point that phenomenological models must be used to describe how the coloured partons transform into colourless hadrons. This is region (c) in Figure 2.1 where typical energy scales are around 1 GeV.

Figure 2.4: Measurements of α_s in the energy range between the τ and Z'' mass.

Fragmentation schemes may be divided into three main classes: independent fragmentation, string fragmentation and cluster fragmentation. These different methods are not necessarily exclusive and models exist which contain both string and cluster aspects. The models are all iterative in that the fragmentation process is a series of processes like jet $\rightarrow$ meson + remainder jet, string $\rightarrow$ hadron + remainder string, cluster $\rightarrow$ cluster + cluster or cluster $\rightarrow$ hadron + hadron. In the remainder of this Section the three different fragmentation schemes are discussed.

Figure 2.5: Independent fragmentation of a $q\bar{q}$ pair.

2.2.1 Independent Fragmentation (IF)

In the IF model each parton is assumed to fragment independently based on the Field-Feynman mechanism [12]. This process is illustrated in Figure 2.5. Each of the initial partons q and $\bar{q}$ fragments into a jet of hadrons according to an iterative procedure.

In the field behind the original quark q a new quark pair $q_1\bar{q}_1$ is produced and a hadron can then be formed from q and $\bar{q}_1$, leaving q_1 free. Production of another pair $q_2\bar{q}_2$ will give another hadron $q_1\bar{q}_2$ and so on. The fragmentation of

the original $\bar{q}$ is done separately, in an analogous way. In the very last step the q and $\bar{q}$ jets are merged to conserve energy, momentum and flavour. The available field energy between the original $q\bar{q}$ pair has thus been transformed into hadrons which come out essentially aligned along the original $q\bar{q}$ axis.

The initial hadron $q\bar{q}_1$ will take a fraction z of the available quark energy-momentum

$$z = \frac{(E + p_{||})_{\text{hadron}}}{(E + p_{||})_{\text{quark}}}$$

where E is the energy and $p_{||}$ is the momentum component along the initial quark direction. The reason z is defined in this way is that it is Lorentz invariant under a boost along the original quark direction. Conservation of energy and momentum implies that the remainder jet (assuming the process to be $\text{jet} \rightarrow \text{hadron} + \text{remainder jet}$) carries the remaining fraction $1 - z$. The particle $q_1\bar{q}_2$ can then take a fraction $z_1 = (1 - z)z'$ with $0 < z' \leq 1$, and so on. The remainder jet is thus assumed to fragment as a scaled down version of the original jet, except that the leading flavour is now q_1 rather than q .

Monte Carlo methods are used to determine the resulting particle spectra with a "fragmentation function" $f(z)$ used to give the z distribution of the produced hadrons. Random numbers are used at each step to assign values to variables according to a given probability distribution. The original Field-Feynman parametrization was

$$f(z) = 1 - a + 3a(1 - z)^2$$

with $a = 0.77$ determined from experimental e^+e^- , electron-proton and neutrino-nucleon interactions [12]. Since the above form appeared to be too strongly peaked

as $z \rightarrow 0$, several other forms have been suggested for $f(z)$ and these are available as options within the JETSET Monte Carlo.

Studies of charm and bottom quark fragmentation have shown that a harder fragmentation is needed for these quarks. A harder fragmentation simply means that the hadron takes a large fraction of the available energy. In this case the "Petersen" formula [13] is often used

$$f(z) = \frac{1}{z(1 - \frac{1}{z} - \frac{\epsilon}{1-z})^2}$$

where $\epsilon = (m_0/m_q)^2$ with m_0 a reference mass and m_q the heavy quark mass. Another popular form for $f(z)$ developed within the context of string fragmentation will be given in the next Section.

Transverse momentum to the jet axis for the $q\bar{q}$ pairs produced in the energy field is introduced according to a Gaussian distribution with $\langle p_T \rangle = \sigma = 0.35$ GeV and local p_T compensation within each pair. A primary hadron's p_T is then the vectorial sum of the component quark p_T values.

In the IF model gluons also fragment independently. Several possibilities have been considered: (i) the gluon is allowed to fragment just like a quark, (ii) a separate gluon fragmentation function is used, or, (iii) the gluon jet is split into parallel q and $\bar{q}$ jets which then fragment.

Areas of concern with the IF scheme are related to the conservation of energy, momentum and flavour and Lorentz invariance issues. Energy, momentum and flavour are not exactly conserved at the end of the fragmentation process and must be patched up as a final step. An important question, which can be used to differentiate between models, is whether the observed hadrons originate from

sources which are Lorentz boosted relative to the overall event centre-of-mass. Three jet events provide an area in which to search for such effects. It is not the jets themselves, but the areas between the jets which are most sensitive to reference frame effects. This effect is known as the "string effect" and will be discussed further in the next Section.

2.2.2 String Fragmentation (SF)

The string fragmentation idea was first introduced by Artru and Mennessier [14]. The Lund group subsequently developed an elaborate model of string fragmentation [15] which has become known as the Lund model. A Monte Carlo implementation of SF developed by the Lund group, JETSET [3], is used extensively in e^+e^- event analysis. Several of the concepts of IF such as the iterative nature of the process and the Gaussian p_T spectrum are also used in string fragmentation.

The initial $q\bar{q}$ pair produced in an e^+e^- annihilation moves apart back-to-back in the overall event centre-of-mass frame. The colour flux lines will be constrained to a thin tubelike region with a diameter typical of hadron sizes, roughly 1 fermi.

To solve the fragmentation problem the concept of a massless string with no transverse degrees of freedom was introduced. There is then only a problem in one space and one time dimension. The string can be thought of as representing the position of the axis of the cylindrically symmetric colour flux tube.

The string constant κ , the amount of energy per unit length, is phenomenologically known to be ~ 1 GeV/fermi. The tube-like field between the q and $\bar{q}$ contains a constant amount of field energy per unit length, i.e., the potential between them increases linearly with separation (a confining potential).

Figure 2.6: String fragmentation of a $q\bar{q}$ pair.

As the distance between the q and $\bar{q}$ increases, additional $q\bar{q}$ pairs are produced in the field between them. When this occurs the process can be thought of as the breaking of the string which continues iteratively through the process $\text{string} \rightarrow \text{hadron} + \text{remainder string}$ until the string energy is used up in creating hadrons. This iterative concept is identical to that used in the IF model.

The SF process is shown schematically in Figure 2.6. The $q\bar{q}$ pairs from successive string breaks materialize as hadrons, aligned roughly along the initial $q\bar{q}$ direction. The momentum of the initial $q\bar{q}$ pair pull the produced hadrons along, producing a jet of particles associated with each of the initial partons.

The fragmentation functions given in Section 2.2.1 can be used in the SF model as well. The fragmentation function developed by the Lund group, and the default

option in the JETSET Monte Carlo, is

$$f(z) = \frac{1}{z} z^{a_\alpha} \left(\frac{1-z}{z} \right)^{a_\beta} \exp\left(-\frac{bm_T^2}{z}\right)$$

where the indices α and β correspond to the flavours produced at the “old” and “new” $q\bar{q}$ vertices that together define the hadron. m_T is the transverse mass: $m_T^2 = m^2 + p_T^2$. In principle there is a different a_α for each flavour and a common b parameter. However, it is assumed that all the a 's are the same so that $f(z)$ becomes

$$f(z) = z^{-1}(1-z)^a \exp(-bm_T^2/z).$$

The explicit mass dependence in $f(z)$ implies a harder fragmentation for the heavier hadrons containing b and c quarks.

Production of the various $q\bar{q}$ pairs in the colour field, or analogously the breaking of the string, is governed by an exponential production probability. A pair can be created classically at one point in the colour field, assuming that the q or $\bar{q}$ have no mass or transverse momentum. However, if the quarks have mass or p_T they must be produced a certain distance apart so that the field energy between them can be transformed into the transverse mass, m_T . Quantum mechanically, the quarks may be created at a point and then tunnel out to the allowed region. The production probability, P , for this process will be proportional to

$$P \propto \exp(-\pi m_T^2/\kappa) = \exp(-\pi m^2/\kappa) \exp(-\pi p_T^2/\kappa).$$

This factorization leads to a flavour independent Gaussian p_T spectrum for the $q\bar{q}$ pair. Since the string is assumed to have no transverse degrees of freedom, this p_T must be compensated between the q and $\bar{q}$ of the pair as in the IF model.

Because of the tunnelling effect heavier quarks will have to travel further and so their production rates will be suppressed. Production rates of quarks in the colour field are given by the ratio $u : d : s : c = 1 : 1 : 0.3 : 10^{-11}$ if quark masses are assumed to be $m_u = m_d = 125 \text{ MeV}$, $m_s = 300 \text{ MeV}$, and $m_c = 1.4 \text{ GeV}$. Thus, charm and heavier quarks are not expected to be produced in the fragmentation process. The suppression of $s\bar{s}$ production is actually a free parameter in the model. The value determined experimentally from the ratio of nonstrange to strange mesons is in the neighbourhood of the value of 0.3 given above.

Momentum and flavour are naturally conserved in the SF model, contrary to the IF case. A significant difference appears between the two models due to the treatment of gluon fragmentation. In SF gluons are thought of as "kinks" in the string. The "kink" gives the centre of the string a transverse momentum while the opposite ends of the string have opposite momenta along the original $q\bar{q}$ direction. As a result of the fragmentation of the $q\bar{q}g$ system in SF, hadrons are expected to frequent the regions between the quark and gluon and the $\bar{q}$ and the gluon. The region between the q and $\bar{q}$ is comparatively depleted. The IF model predicts equal particle densities between all the partons since the only way of giving transverse momentum to the particles is via the Gaussian p_T distribution. In SF the entire system is being pulled by the gluon.

Figure 2.7 illustrates the difference between IF and SF in the 3-jet case. In IF each of the three partons fragment separately while in the SF case strings are stretched from the quark to the gluon and from the $\bar{q}$ to the gluon. Each string hadronizes in its rest frame and the hadrons are then boosted to the e^+e^- centre-of-mass frame. A distribution of the normalized charged particle flow from the 1990 OPAL data [16] is shown in Figure 2.8 along with the predictions from sev-

Figure 2.7: Illustration of $q\bar{q}g$ fragmentation in the IF and SF models.

models. The angle ψ is measured in the event plane from the highest energy jet towards the intermediate energy jet. The JETSET and ARIADNE [17] models use SF while the COJETS [18] model uses IF. The experimental observations are clearly better reproduced by the SF model than by the IF model.

2.2.3 Cluster Fragmentation (CF)

In the QCD cluster models the initial quarks undergo successive gluon emissions according to perturbative QCD as shown in Figure 2.3. The best known shower

Figure 2.8: Charged particle flow in 3-jet events compared to IF and SF models.

algorithm is by Marchesini and Webber [11]. The shower evolves until the gluons approach a cutoff value. This can be thought of as a fictitious gluon mass - as the shower proceeds the resulting gluons are less virtual and as they approach mass shell the shower terminates. The gluons are then split into $q\bar{q}$ pairs, and colourless clusters formed through a process called preconfinement.

The flavour composition of each cluster is known from the q and $\bar{q}$ that created it. Heavy clusters may then decay further to 2 clusters. The clusters then break up into hadrons, with a cluster either associated directly to a hadron, or via a two-body decay into a pair of hadrons. A cluster is broken by randomly choosing a $q\bar{q}$ pair or a diquark-antidiquark pair that join together with the original $q\bar{q}$ pair in the cluster. The hadron species are determined purely from phase-space considerations, with charge and flavour conserved in the decay. Higher mass and spin objects are then suppressed due to the limited phase-space available.

Cluster fragmentation offers the possibility of a simple description of hadronization rather than the complicated fragmentation chains of the IF and SF models. A cluster is specified only by its flavour content and mass. In the CF scheme the parton shower and cluster phase-space decays give a complete momentum distribution. The separate longitudinal and transverse momentum descriptions present in the IF and SF models are not needed.

The CF scheme is implemented in a Monte Carlo program known as HERWIG [19]. The predictions of this program and of JETSET are most often compared to the experimental data. Since SF and CF are only models of what is really happening in the fragmentation process neither can claim to be correct. The models are judged on their ability to reproduce existing experimental observations and predict quantities not yet measured. Both JETSET and HERWIG do equally well at

predicting global event properties.

Measurements of individual particle production rates and momentum spectra may help to differentiate between models. In particular, observations of baryon production provides a significant test of the models. In the next Section the specifics of baryon production in the SF and CF models are discussed.

2.3 Baryon Production

Initial ideas about fragmentation assumed that only mesons were produced in e^+e^- collisions. However it was soon noticed that baryons were produced quite frequently. Between centre-of-mass energies of 3.6 and 5.2 GeV it was observed that the proton production fraction was between 5 and 8 % [20]. TASSO estimated, at experiments between 12 and 30 GeV centre-of-mass energy, that at least 40 % of all events at the highest energy contained baryons [21]. Several different production mechanisms have since been suggested: quark recombination [22], leading diquarks [23], colour fluctuations [24], diquarks within the fragmentation chain [25], and cluster decays [11].

The two models most widely used at present are the diquark model, as implemented in the SF scheme of JETSET, and the cluster decay model. The other production mechanisms, while possible at a very small level, have been ruled out as a significant source of baryon production based on previous experimental observations. For details refer to a recent review article by Saxon [26]. Baryon production also occurs in the decay of B mesons (mesons containing a b quark) at a level of a few percent [27].

2.3.1 Diquark model

The initial proposal for baryon production in the Lund SF model was via the production of diquark-antidiquark pairs in the colour field. A quark (colour triplet) would then combine with a diquark (a colour antitriplet) to produce a colourless baryon. The diquarks are assumed to be point-like objects and produced just like $q\bar{q}$ pairs, with the production ratio given by the tunneling suppression formula of Section 2.2.2. Since a diquark is more massive than a quark, baryon production is naturally suppressed relative to meson production.

The baryon and antibaryon produced in this way will be neighbours in rank and thus close in rapidity. Rank simply refers to the order in which particles are produced in the fragmentation. The first particle produced is first in rank, the second particle produced is second in rank and so on. There is a relationship between the rank of a particle and its rapidity. On average, higher rank particles have the highest rapidities while those produced near the end of the fragmentation chain will have a lower rapidity. Rapidity is defined as

$$y = \frac{1}{2} \ln \frac{E + p_{||}}{E - p_{||}}$$

where E is the particle energy and $p_{||}$ is its momentum parallel to some axis used to define the momentum flow in an event. For a back-to-back two jet event this axis corresponds closely with the original $q\bar{q}$ direction. This is discussed further in Chapter 5.

Quarks are spin 1/2 objects so a diquark is then either spin 0 or spin 1. Adding another quark gives either a spin 1/2 or spin 3/2 baryon. The spin 1 diquark is expected to be suppressed relative to the spin 0 diquark. Since strange diquarks

are heavier than nonstrange ones, they will be additionally suppressed. The Lund model contains several user-tuneable parameters related to the production of diquarks which be given later in this Chapter.

Baryons containing u , d and s quarks may be grouped into a spin $1/2$ octet and a spin $3/2$ decuplet as shown in Figure 2.9. The quark content of each of the members is shown. Measurements of the relative production rates of the baryons as a function of strangeness and spin provides valuable information in the study of baryon production models. For example, the rate of Ξ^- (quark content dss) relative to the Λ (quark content uds) gives an indication of the strange diquark suppression. A comparison of the Ξ^{*-} versus the Ξ^- rate gives information about the relative rate of spin 1 diquark production.

2.3.2 “Popcorn” Model

A more general framework for baryon production is the so-called popcorn model [28] developed to replace the model in which diquarks were produced as point-like objects in the colour field. In the popcorn model diquarks as such are not produced. Instead, $q\bar{q}$ pairs pop out of the colour field one at a time, hence the name “popcorn”. The popcorn model can be considered as an “effective diquark” model, where given the right conditions, successively produced quark pairs may produce what is effectively a diquark. In the model, the baryon and antibaryon may not necessarily be neighbours in rank. Often, additional $q\bar{q}$ pairs can be produced, leading to the production of a meson between the baryon (B) and antibaryon ($\bar{B}$).

Baryon production is shown schematically in Figure 2.10. In Figure 2.10(a) baryon production is via a diquark pair which can be either a point-like object or an “effective diquark” made from two separate quarks. Figure 2.10(b) illustrates

Figure 2.9: The baryon octet and decuplet.

the “popcorn” mechanism where a meson is produced between the $B\bar{B}$ pair by the creation of another $q\bar{q}$ pair. It is assumed that no more than one meson can be produced between the $B\bar{B}$ pair.

The basic idea of the popcorn model is that fluctuations of $q\bar{q}$ pairs with the wrong colour may occur. For example, say that the original $q\bar{q}$ pair is red-antired. A red colour field is then stretched between the $q\bar{q}$. If a red-antired pair is now produced, the string will break and a meson will be formed. However, if a blue-antiblue or green-antigreen pair is produced in the red field, the string will not break. If a blue-antiblue pair is created it will feel no net force towards either

Figure 2.10: Schematic diagram of baryon production in the diquark and “popcorn” models.

the red q or the antired $\bar{q}$ and it will just float around in the field. If, before the pair annihilate a green-antigreen pair is produced, the blue quark and green quark will form an antired colour antitriplet (an effective diquark) and be pulled towards the initial red quark (a red colour triplet). These 3 quarks then form a baryon. Similarly the antiblue and antigreen antiquarks will form an antibaryon with the antired $\bar{q}$.

In the case of the $B\bar{B}$ configuration the point diquark and popcorn models are essentially the same. In the $BM\bar{B}$ popcorn configuration the effective diquark and

Parameter	Default Value	Description
PARJ(1)	0.10	diquark production fraction
PARJ(2)	0.30	strange quark fraction relative to u and d quarks
PARJ(3)	0.40	extra strange diquark suppression
PARJ(4)	0.05	suppression of spin 1 diquarks
PARJ(5)	0.50	relative occurrence of $B\bar{B}$ and $B\bar{B}$ production
PARJ(6)	0.50	extra suppression for $s\bar{s}$ pair shared in $B\bar{B}$ configuration
PARJ(7)	0.50	extra suppression for a strange meson in $B\bar{B}$ configuration

Table 2.1: Parameters in the JETSET Monte Carlo related specifically to baryon production.

antidiquark share only one quark pair, so it is possible to have a strange baryon produced with a nonstrange baryon or to have an octet baryon produced with a decuplet baryon. A study of baryon correlations within an event can thus give further information into whether diquarks are produced as point-like objects or whether they are combinations of individual quarks.

In JETSET several parameters are related specifically to baryon production. The default values of these parameters are given in Table 2.1 along with a brief description of the parameter and its designation within the Monte Carlo program [3].

These parameters, with the exception of PARJ(1) and PARJ(2) are based on "educated guesses". The first two parameters have been adjusted based on experimental observations. The parameter values given in the Table have done a reasonable job of describing baryon rates observed thus far. Within the available statistics large changes in some of the parameters can still reproduce the observed rates. More data on as many baryon species as is possible, and on baryon correla-

tions with an event are required in order to constrain the parameters.

2.3.3 Baryons From Cluster Decay

As discussed in Section 2.2.3 the final stage of the CF scheme is the formation of colourless clusters. These clusters then decay into hadrons. Assume that the $q\bar{q}$ pair forming a cluster is given by flavour $q_1\bar{q}_2$. The cluster can decay directly to a single hadron or undergo a two-body decay. This is done by creating a new pair $Q_3\bar{Q}_3$ where the Q_3 can be either a quark or a diquark, selected randomly and with equal probability from the flavours $u, d, s, c, b, t, uu, ud, us, ds, dd$, and ss . The cluster then decays into two hadrons of composition $q_1\bar{Q}_3$ and $\bar{q}_2Q_3$. If various mass relations are satisfied then the production of the octet and decuplet baryons of Figure 2.9, as well as heavier charm and bottom baryons occurs. Note that there is no additional suppression of strange quarks, diquarks, strange diquarks or spin 1 diquarks beyond simple phase-space considerations.

Baryon production in HERWIG is sensitive to only one parameter, CLMAX, the cluster mass. In fact, there are only 3 major user controlled parameters in HERWIG that are adjusted to give predictions for both global event characteristics and individual particle properties. This is in contrast to JETSET which has several parameters which can be tuned for global event characteristics and many more which affect predictions of individual particle properties such as those in Table 2.1 that affect baryon production. The parameters of both models used to obtain agreement with global event shapes will be given in the next Chapter.

2.4 Summary

The process $e^+e^- \rightarrow \gamma/Z^0 \rightarrow q\bar{q} \rightarrow \text{hadrons}$ has been outlined. The initial stage of the process $q\bar{q} \rightarrow \text{hadrons}$ can be described using perturbative QCD, either via matrix element calculations or by a parton shower approach.

The partons generated in this perturbative stage do not appear in nature. Rather, they go through a process known as hadronization or fragmentation which cannot be calculated by QCD. Phenomenological models, implemented through computer programs are used to predict the properties of the events and the individual hadrons that are observed. Three such models have been described and compared.

Baryon production within the string and cluster fragmentation models has been introduced. Observation of the rates of baryons produced and their properties is expected to be a major test of the models. The subject of this thesis is a detailed study of Λ^0 production around the Z^0 resonance at 91 GeV. In Chapter 6 the measurement of Λ^0 production is discussed in conjunction with measurements of other strange baryons and strange mesons at the same energy. The measurements are then compared to the model predictions.

Chapter 3

EXPERIMENTAL APPARATUS

The data analyzed in this thesis were collected with the OPAL (Omni-Purpose Apparatus for LEP) detector, one of four located at the LEP (Large Electron Positron) storage ring. Data were first recorded in the period August - December 1989 ($\sim 30,000$ multihadronic decays). The data collected from April - November 1990 ($\sim 150,000$ multihadronic events) are used in this analysis.

Before the data collected online during the operation of the detector is usable in most physics analyses it must undergo extensive offline processing. Since the detector is very complicated and the underlying physics processes complex, Monte Carlo programs are essential in understanding and analyzing the data that has been collected. In this Chapter the LEP storage ring, the OPAL detector and the offline analysis software and Monte Carlos are described.

3.1 The LEP Storage Ring

In LEP electrons and positrons circulate in opposite directions and can collide at up to eight interaction points located around the 27 kilometre circumference storage ring. Before reaching the main LEP ring the particles are accelerated in stages by three smaller rings. The LEP injection system and layout of the main ring are shown in Figure 3.1.

Electrons and positrons are accumulated in eight bunches in the 600 MeV EPA (Electron-Positron Accumulation) ring. When the bunches are of sufficient intensity they are transferred to the PS (Proton Synchrotron) ring and accelerated to 3.5 GeV. From the PS the bunches are transferred to the SPS (Super Proton Synchrotron) and accelerated to 20 GeV. Finally, the bunches are injected into the main LEP ring where they can be accelerated up to about 50 GeV.

Each beam in LEP has four bunches. The revolution time for a bunch is about 88.9 μs . The bunches can be described by Gaussian profiles in x , y and z with $\sigma_x \sim 200 \mu\text{m}$, $\sigma_y \sim 15 \mu\text{m}$ and $\sigma_z \sim 1.4 \text{ cm}$. The size of the beam overlap region is ellipsoidal with total height of about 20 μm , a total width of about 300 μm and a length of about 2 centimetres in z . The beams can collide at eight points around the ring, however they do so only at the four intersection regions shown in Figure 3.1 where the detectors are located. The OPAL detector is located at point P6. The other LEP detectors, L3, ALEPH and DELPHI are located at points P2, P4 and P8 respectively. Electrostatic separators keep the beams from colliding at the points where no detectors are situated.

The luminosity of an e^+e^- storage ring is given by

Figure 3.1: The LEP injection system and main storage ring.

$$\mathcal{L} = \frac{fnN_1N_2}{4\pi\sigma_x\sigma_y}$$

where f is the bunch circulation frequency, n the number of bunches, N_i the number of particles per bunch and σ_x, σ_y are the horizontal and vertical bunch dimensions. The peak design luminosity of LEP is about $1.6 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$, assuming a current of 3 mA in each beam. During 1990 running maximum beam currents were about 1.8 mA and peak luminosities about $5 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$.

The rate for a particular reaction is given by

$$R = \mathcal{L}\sigma$$

where σ is the cross section for the desired reaction. From Figure 1.1 the peak Z^0 cross section for $e^+e^- \rightarrow \text{hadrons}$ is about 40 nb. At the maximum 1990 luminosity given above one would then expect about 0.2 Z^0 per second.

3.2 The OPAL Detector

The OPAL detector, shown in Figure 3.2, is a large (radius ~ 5 metres, length ~ 12 metres) device designed to give nearly complete acceptance for Z^0 decays over the entire 4π solid angle. The detector is composed of a number of sub-systems designed to provide precise measurements of charged particle trajectories and electromagnetic and hadronic energies in all types of e^+e^- events. The main components are a central tracking system enclosed in a solenoidal magnet, a lead glass electromagnetic calorimeter, a hadron calorimeter and muon detectors. A

forward detector system is used to measure the luminosity and identify particles emitted at small angles with respect to the beam line. Since the central tracking system is crucial to this analysis, it will be described in some detail. The other detector components will be covered only briefly. A more detailed description of the complete detector has been published [29].

The OPAL coordinate system is defined as having the origin located at the nominal interaction point and the z axis in the e^- beam direction. The x axis is horizontal and points towards the centre of the LEP ring and the y axis is normal to the $x - z$ plane. The radial coordinate, r , is in the $x - y$ plane. The polar angle θ is measured from the z axis and the azimuthal angle ϕ from the x axis about the z axis.

In the OPAL detector bunches cross at the interaction point every $22.2 \mu\text{s}$. This corresponds to a rate of about 45,000 per second. It is impossible to record data from the detector for every crossing. Only a very small fraction of the beam crossings will produce an actual Z^0 event (about one every five seconds as shown above). The trigger system is designed to select only interesting physics events with a high efficiency. These events are then recorded by the data acquisition system for further analysis.

The trigger rate for all events during 1990 was at the level of about 1.5 to 2.5 Hz. Besides selecting Z^0 decays to hadrons or leptons, the trigger also accepts other types of events and various sources of background. The trigger rates for various processes will be given in Section 3.2.7, following the description of the detector. Further details of the trigger system may be found in [30].

Figure 3.2: The OPAL detector.

3.2.1 The Central Detector

The central tracking system used during the 1989 and 1990 running consisted of three separate drift chamber devices operating inside a pressure vessel at a pressure of 4 bar. The pressure vessel is closed at each end by a bell-shaped cover. The gas mixture used in all 3 detectors consists of argon (88.2 %), methane (9.8 %) and isobutane (2 %). The pressure of the gas is supported by a beam pipe at a radius of 7.8 cm from the interaction point. This beam pipe consists of a 0.1 mm aluminum tube onto which are attached a series of overlapping layers of carbon fibre with a total thickness of 1.3 mm. The beam pipe represents 0.66 % of a radiation length. The magnet of the OPAL detector consists of a self-supporting, water-cooled aluminum coil and an iron yoke which is segmented for use as a hadron calorimeter. This magnet provides a field of 0.435 Tesla, uniform to about ± 0.5 % within the central tracking volume.

Vertex Detector

The vertex detector (CV) is a 1 metre long, 47 cm diameter high precision cylindrical drift chamber that surrounds the beam pipe. It is used to help locate the decay vertices of short-lived particles and to improve the momentum resolution of charged tracks. The chamber has an inner layer of 36 axial sectors and an outer layer of 36 stereo sectors. Figure 3.3 shows the layout of a section of the vertex detector.

In the inner layer each sector has a plane of 12 anode or sensing wires strung parallel to the beam direction, located between radii of 10.3 and 16.2 cm with a spacing of 5.3 mm. The outer layer of stereo sectors each has 6 anode wires lying

Figure 3.3: Endplate wire layout for a section of the vertex detector.

between radii of 18.8 and 21.3 cm with a spacing of 5 mm. Each anode wire defines a drift cell. Ionization from a charged particle passing through the cell is collected at the anode wire. The anode wires are 20 μm diameter gold plated W-Rh, the potential wires are 200 μm diameter gold plated Cu-Be and the cathode planes use 125 μm diameter Cu-Be wires spaced 1 mm apart. The cathode planes form the boundaries between adjacent sectors.

The stereo angle of the wires in the outer layer is $\sim 4^\circ$. Information from these wires is used to obtain precise information about the z coordinate of the particle trajectory. The fitting method is based on the method of constrained nonlinear least-squares fitting using the Lagrange multipliers method [31]. All of the anode wires are offset from the plane defined by the potential wires by an alternating stagger of $\pm 41 \mu\text{m}$ in order to resolve the ambiguity as to whether a particle passed to the right or left side of the wire plane. In addition, there is an additional bowing of the anode wires by 50 - 100 μm due to electrostatic forces when voltage is applied to the chamber.

The electrostatic field conditions in a cell are determined by the anode wire surface field (which determines the gas gain) and the drift field. These fields are determined by the voltages applied to the cathode planes and potential wires. The anode wires are grounded. The average spatial resolution of the chamber is about 55 μm when the chamber is operated at a drift field of 2.5 kV/cm and an anode surface field of 360 kV/cm

The axial cells provide a precise measurement of position in the $x - y$ plane by precisely measuring the arrival time of the electrons at the anode wire. The maximum drift distance of about 1.5 cm limits the effects due to diffusion. A good multi-hit detection capability is necessary to resolve individual particles within

jets. By reducing the discrimination time between successive pulses to about 40 - 50 ns, a two particle separation of about 2 mm is achieved, assuming an average electron drift velocity of about 40 $\mu\text{m}/\text{ns}$ in a drift cell.

Both ends of each anode wire are connected to preamplifiers and the signals are then fed to constant fraction discriminators. A measurement of the electron drift time is obtained by combining the outputs from each wire end in a mean timer. For each of the 648 cells a measurement of the drift time is given by a TDC (time to digital converter) with a bin width of 0.67 ns. This TDC value is then used offline to calculate where the particle passed through the drift cell. The signals from each wire end are also passed to a unit which measures the difference in their arrival times. A measurement of this difference to 0.1 ns allows the z coordinate to be determined roughly to about 4 cm. This information is used in the trigger and in offline track finding and fitting. A more precise z measurement is obtained by combining axial and stereo cell information in the offline tracking analysis.

Jet Chamber

The jet chamber (CJ), like the vertex detector, is of cylindrical design. It is 4 metres long with an inner radius of 25 cm and an outer radius of 185 cm. This chamber records the tracks of charged particles and measures their momentum. Particle identification is also done by multiple sampling of the energy loss in the gas. The chamber is divided into 24 identical sectors each with 159 anode wires parallel to the beam line. As in the vertex chamber, cathode wire planes form the boundaries between adjacent sectors.

The anode wires are grounded and lie between radii of 25.5 and 183.5 cm, equally spaced by 1 cm, alternating with potential wires. The maximum drift

distance varies from 3 cm for the inner wires to 25 cm for the outermost wires. The stagger of the wires is $\pm 100 \mu\text{m}$. The wires are strung between 2 conical endplates and the z length of the wires depends on the radius according to $|z| = 147 + 0.268R$ cm.

Within the range $43^\circ < \theta < 137^\circ$ up to 159 points can be measured along each track and at least 8 points on a track are obtained over a solid angle of 98 % of 4π . For each drift cell the (r, ϕ) coordinates are determined from the wire position and drift time. The integrated charge is measured at each end of the wire and the ratio determines the z coordinate to within several centimetres. The sum of the charges is used to calculate the energy loss, dE/dx , of the particle.

Preamplifiers are mounted on each of the chamber endplates and the output from each end of every wire recorded with 100 MHz FADCs (flash analog to digital converters). The high speed sampling significantly improves the time measurement and two-particle separation. The digitized data is read out into 20 microprocessors for further online data reduction and track finding, and for use in the trigger.

The chosen operating point of the jet chamber (gas gain $\sim 10^4$ and a drift field of 890 V/cm) is chosen as a trade-off between requirements for good dE/dx information (low gas gain) and good z resolution (high gas gain). From a study of $e^+e^- \rightarrow \mu^+\mu^-$ events the $r - \phi$ resolution was determined to be $135 \mu\text{m}$ at a mean drift distance of 7 cm. The average z resolution is 6 cm. The momentum resolution σ_p/p^2 is $2.2 \times 10^{-3} \text{ GeV}^{-1}$. The dE/dx resolution for the $\mu^+\mu^-$ events was calculated to be 3.8 %. These values are somewhat better than the values that would be obtained from multihadronic events. In particular, significant systematics exist in the determination of the reconstructed z coordinate. This will be discussed further in Chapter 4.

Z-Chambers

The Z-chambers (CZ) are used to obtain a precise measurement of the z coordinate of tracks as they leave the jet chamber. They are arranged to form a barrel layer around the jet chamber covering the polar angle range $|\cos \theta| < 0.72$ and 94 % of the azimuthal acceptance. The precise z measurements from these chambers improves both the polar angle and invariant mass resolutions. This is very important in this study of Λ^0 production as will be shown in the next Chapter.

The Z-chamber system consists of 24 panels, 4 metres long, 50 cm wide and 5.9 cm thick. Each panel is divided into eight 50 x 50 cm cells giving a maximum drift distance of 25 cm in the z direction. The maximum drift voltage is about 20 kV giving a drift field of 800 V/cm. Each cell has 6 anode wires with 4 mm spacing and a stagger of $\pm 250 \mu\text{m}$. The wires are read out at each end using FADCs identical to those used in the jet chamber readout. Charge division is used to obtain the ϕ coordinate, in a method analogous to that used to determine the z coordinate in the jet chamber. The $r - \phi$ resolution is about 1.5 cm and the z resolution about 300 μm .

In the offline data processing stage track reconstruction is done separately for each of the 3 detectors. Track segments from each detector are then merged and a combined track fit is done using the coordinates from each detector. This track merging process and combined performance of all 3 detectors will be discussed in Section 3.3.2.

3.2.2 Time-of-Flight (TOF) System

The time of flight system (TB) generates trigger signals and, by measuring the time of flight of a particle from the interaction point, it also allows charged particle identification in the range 0.6 - 2.5 GeV. It also provides an effective method of rejecting cosmic ray events by vetoing events that are out of time with the beam crossing. The TOF system consists of 160 scintillation counters forming a barrel layer 684 cm long at a radius of 2.36 metres. This layer is positioned just outside the magnet coil and covers the region $|\cos \theta| < 0.82$. Typical timing resolution is between 300 and 400 picoseconds, depending on the z position along the counter.

3.2.3 Electromagnetic Calorimeter

The purpose of the electromagnetic calorimeter is to detect and measure the energies and positions of electrons, positrons and photons. It consists of a total absorption calorimeter divided into three overlapping assemblies of lead glass blocks (a barrel and 2 endcaps) covering 89 % of the solid angle. Lead glass was chosen because of its excellent intrinsic energy resolution ($\sigma_E/E \sim 0.2\% + 6.3/\sqrt{E}$ % where E is the electromagnetic energy in GeV), spatial resolution, granularity and electron-hadron discrimination. The lead glass used is SF57, which is 75 % by weight PbO with a density of 5.54 g cm^{-3} .

Since there are approximately 2 radiation lengths of material in front of the calorimeter (mostly due to the magnet coil and pressure vessel) most electromagnetic showers will start before the lead glass. Presampling devices (wire chambers) are therefore installed in both the barrel and endcap regions immediately in front of the lead glass. These presamplers measure the position and energy of the

preshower and help to improve the overall electromagnetic energy resolution and electron-hadron discrimination. The hit multiplicity in the presamplers is approximately proportional to the energy deposited in front of the presampler and is then used to correct the shower energy measured in the calorimeters.

The barrel calorimeter (EB) consists of a cylindrical array of 9440 lead glass blocks providing 24.6 radiation lengths of material. These blocks should contain all the energy produced in an electromagnetic shower and are located at a radius of 2.46 metres and cover the polar angle range $|\cos \theta| < 0.82$. Each block is approximately 10 cm x 10 cm in cross section and 37 cm in depth. To maximize detection efficiency and minimize the probability of a particle traversing more than one block the longitudinal axis of each block is angled to point at the interaction region. The blocks are tilted slightly from a perfectly pointing geometry to prevent particle losses in the gaps between blocks.

The endcap electromagnetic calorimeter (EE) consists of two domed arrays, each of 1132 blocks, located just outside the pressure bells. The EE covers the polar angle from $0.81 < |\cos \theta| < 0.98$. The axes of the blocks are parallel to the beam line and come in three lengths (38, 42 and 52 cm) and are arranged to follow the contours of the pressure bell. They provide on average about 22 radiation lengths of material.

3.2.4 Hadron Calorimeter

The hadron calorimeter is used to measure the energy of hadrons emerging from the electromagnetic calorimeter and assists in the identification of muons. It is built in 3 sections: the barrel, the endcaps and the poletips. The iron of the magnet return yoke provides at least 4 interaction lengths of absorber over 97 %

of the solid angle. This yoke is segmented into layers, with planes of detectors between each layer. Most hadrons are absorbed in the hadron calorimeter leaving only muons to pass through. Since hadronic interactions may occur in the 2.2 interaction lengths of material preceding the hadron calorimeter, it is necessary to use information from the electromagnetic calorimeters to correctly measure the hadronic energy.

The barrel region (HB) consists of 9 layers of chambers alternating with 8 layers of 10 cm thick iron, between radii of 3.39 and 4.39 metres. The barrel ends are closed off by toroidal endcap regions (HE) consisting of 8 layers of chambers alternating with 7 layers of iron.

The chambers are limited streamer tube devices strung with anode wires 1 cm apart in a mixture of 75 % isobutane and 25 % argon. The signals from the wires are used only for monitoring purposes. Signals are obtained from the induced charge collected on pads located on the outer chamber surface and from aluminum strips located on the inner surface. In the barrel the strips are parallel to the beam line and in the endcaps they are perpendicular.

The layers of pads are grouped together to form towers which divide the solid angle into 48 bins of 7.5° in ϕ and 21 bins in θ . The signals from the pads are summed to provide an estimate of the energy in the shower. The 57,000 strips are used to provide muon tracking information and for shower profile mapping.

The pole-tip region (HP) extends the coverage of the hadron calorimeter from $|\cos \theta| = 0.91$ down to 0.99. In this region the number of sampling layers is increased to 10. The detectors are 0.7 cm thick multiwire proportional chambers containing a gas mixture of 55 % CO_2 and 45 % n-pentane. As in HB and HE, the chambers have pads on one side and strips on the other.

The energy resolution of the combined detector varies from $100\%/\sqrt{E}$ for energies below 15 GeV to $140\%/\sqrt{E}$ at 45 GeV.

3.2.5 Muon Detector

As the outermost part of the OPAL detector, this subdetector is designed to identify muons in the presence of a hadron background. Over most of the solid angle a particle has to traverse the equivalent of 1.3 metres of iron, or about 7 interaction lengths of material for a pion. The probability of a pion not interacting is about 0.001. Muons of momentum less than about 2 GeV are likely to be stopped in the absorber before reaching the muon detectors.

The barrel region detector (MB) consists of 110 drift chambers covering the range $|\cos \theta| < 0.68$ with 4 layers. Each endcap muon detector (ME) consists of an arrangement of limited streamer tubes in 4 layers which are perpendicular to the beam axis. The detector covers the angular region between $0.67 < |\cos \theta| < 0.985$.

3.2.6 The Forward Detector

The forward detector (FD) provides acceptance for particles from the interaction region emitted at small angles to the beam line (between 47 and 120 mrad). The primary purpose of this device is to measure the luminosity of LEP by detecting low angle Bhabha scattering events. It is also used to tag electrons from two-photon events. It consists of a set of calorimeters (lead-scintillator sandwich), proportional tube chambers and drift chambers.

3.2.7 The Trigger and Online System

Although the LEP beams cross at the OPAL interaction point about 45,000 times every second the data acquisition system can only record several events per second. Some way of selecting only those crossings with a possible e^+e^- interaction is thus necessary. Distinctive signatures for physics and background events allow for some discrimination early on in the data acquisition chain. The trigger decides which crossings are of interest for possible analysis later on. Since chamber drift times can be as long as $8\ \mu\text{s}$ and electronics reset times up to $7\ \mu\text{s}$, only about $7\ \mu\text{s}$ is left for the trigger decision.

During 1990 the average trigger rate was about 2 Hz. Table 3.1 gives a breakdown of this rate. The events in the “other” category were due to beam-wall and beam-gas interactions, beam halo muons produced at the various collimators, and synchrotron radiation. Beam-wall and beam-gas interactions occur when a beam particle interacts with a residual gas molecule in the beam line or with the beam pipe itself.

Event Type	Trigger Rate (Hz)
multihadronic Z^0 decays	0.15
leptonic Z^0 decays	0.02
genuine FD Bhabhas	0.2
cosmic rays and noise	0.6
Other	1.0

Table 3.1: Approximate average trigger rates for various categories of events.

Many of the subdetectors discussed above provide information to the trigger system. The trigger decision is based on information from the vertex and jet chambers (combined into a “track trigger”), the TOF, electromagnetic and hadron

calorimeters, and the muon and forward detectors. Signals from each of the subdetectors are divided into 2 categories. Direct signals such as energy sums or track multiplicities use information from a single detector and have relatively high thresholds. To allow lower thresholds and to include spatial correlations between subdetectors, the detector is divided into a matrix of 6 θ and 24 ϕ bins. This layout is shown schematically in Figure 3.4.

The central trigger processor combines the information for all the individual subdetectors and the $\theta - \phi$ matrix and makes a decision to accept or reject the event. Due to a high degree of redundancy in the trigger system, the efficiencies for the physics channels $e^+e^- \rightarrow$ hadrons, leptons, $\gamma\gamma$ and small angle Bhabha scattering are $\geq 99.9\%$. If an event is to be accepted, a signal is sent to all subdetectors to start their readout. Each of the 15 subdetectors is read out separately into its own LSC (local system crate). The trigger and track trigger also have their own associated LSCs. These LSCs perform some data reduction and format and prepare the data for the software filter. The data flow from the LSCs through the data acquisition chain is shown in Figure 3.5.

The subevents from each LSC are assembled by the "event builder" into a single data structure. The event builder also acts as a buffer for the filter processor. In the filter a series of microprocessors performs a fast analysis of each event. Events are classified into various physics categories and events flagged as background can be rejected or passed on at a reduced level. At the filter level typically about 23 % of all triggers could be rejected as obvious "junk". The filter processor also controls many online monitoring histograms and an event display.

Data from the filter were stored on approximately 3000 IBM data storage cartridges as a permanent backup and for further processing using the full offline

Figure 3.4: Overview of trigger generation by the $\theta - \phi$ matrix.

Figure 3.5: Overview of the data acquisition system.

reconstruction program. This processing was done using the CERN IBM 3090 facility. Typical event sizes for a multihadronic event are 200 kBytes of raw data and 25 kBytes after processing to the DST-only stage. Processing time for an event on the IBM 3090 is about 2 to 3 seconds per multihadronic event. Table 3.2 lists the number of triggers and the numbers of events selected at various stages of the data processing. About 2.8 % of all triggers were finally selected as multihadronic Z^0 decays.

Description	Number of events
Total triggers	5.2 M
flagged as "junk" by filter	1.2 M (23 %)
rejected by filter	536 k (10 %)
events recorded to tape	4.7 M
events processed offline	4.0 M (76 %)
events selected for possible physics interest	1.4 M (27 %)
multihadronic Z^0 decays	147 k (2.8 %)
leptonic Z^0 decays	33 k
luminosity Bhabha events	285 k

Table 3.2: Summary of the data collected during 1990.

As improvements are made to the reconstruction software and the calibration constants the data can be reprocessed at a subsequent date. The calibration constants are stored in a database that can be accessed by both online and offline processors. In the next Section the event reconstruction and offline analysis software is described.

3.3 Offline Analysis Software

The event reconstruction program, known as ROPE, processes the raw data from the detector and produces a DST (data summary tape) from which the physics analyses are performed. It also contains a set of routines, called GROPE, used for event display. The ROPE process is also run online in the filter as described above.

In any high energy physics experiment it is necessary to use a Monte Carlo simulation of the detector in order to gain an understanding of detector acceptances and efficiencies. Monte Carlo programs can be divided into two types: event generators and the actual simulation of the detector response. The OPAL simulation program, GOPAL, can be interfaced to several event generators and produces an output identical in format to that obtained from the actual detector. This "fake" data can then be used to study detector acceptance and response for a particular physics study.

3.3.1 Event Reconstruction

The event reconstruction program (ROPE) is a collection of routines used to reconstruct events from digits produced by the detector or by the detector simulation program. Digits consist of data in the form of output from TDCs, ADCs or similar units. With an appropriate set of calibration constants, drift chamber hit coordinates or calorimeter energy can be reconstructed. The hit coordinates are then used to determine the trajectories of charged particles that passed through the detector.

Each subdetector has a set of routines that takes the raw data and processes it

into quantities that can be used in physics studies. Information about track parameters, the event primary vertex and secondary vertices, dE/dx , TOF, calorimeter energies and muons are stored into a DST format. ROPE then provides a set of routines that allows this DST information to be accessed for subsequent analysis. All of the analysis in Chapters 4 and 5 has been done from these DSTs. The selection of the multihadronic event sample that was studied required information from all detectors. This selection will be described further in Chapter 4.

The analysis of the selected multihadronic sample presented in this thesis relied entirely on the central detector charged track information on the DST. Each of the 3 central detectors provides tracking information. The central tracking (CT) processor then takes the information about the track segments in each detector and attempts to merge them together. A track fit is then done using a method that explicitly includes the effect of multiple Coulomb scattering in the detector gas, in the material between the chambers and in the beam pipe [33].

3.3.2 The OPAL Track Parameters

The trajectories of charged tracks in the OPAL central detector are specified using a set of parameters (κ , ϕ_0 , d_0 , $\tan \lambda$, and z_0), defined as follows:

- κ is the curvature, with $\kappa = 1/2\rho$ and ρ the radius of curvature. In OPAL, with the magnetic field along the positive z axis, a positive value of κ corresponds to a particle with negative charge.
- ϕ_0 is the angle made by the track tangent at the point of closest approach (pca) to the origin in the $x - y$ plane.

- d_0 is the track impact parameter. $|d_0|$ is the distance from the origin to the pca in the $x - y$ plane. If $\vec{d}$ is the vector from the origin to the pca, $\hat{\phi}$ the unit vector at the pca and $\hat{z}$ the unit vector along the z axis then $d_0 = \hat{\phi} \times \vec{d} \cdot \hat{z}$ gives the sign of the impact parameter.
- $\tan \lambda$ is the "dip angle" = $\cot \theta$ where θ is the polar angle measured from the z axis.
- z_0 is the value of z at the pca. The $s - z$ projection of the track is a straight line, $z = z_0 + s \tan \lambda$, where s is the $r - \phi$ path length from the pca.

With a magnetic field of B kGauss and κ in units of cm^{-1} the momentum, in GeV, of the particle in the $r - \phi$ plane is given by $p_t = 1.5 \times 10^{-4} B / \kappa$. The three components of the momentum are then given by $p_x = p_t \cos \phi_0$, $p_y = p_t \sin \phi_0$ and $p_z = p_t \tan \lambda$.

At the time of this analysis the momentum resolution in the $r - \phi$ plane for charged particles in the region $|\cos \theta| < 0.7$ was $(\sigma/p_t)^2 = 0.025^2 + (0.0018 p_t)^2$, with p_t in GeV. The d_0 resolution for 45 GeV tracks determined from $Z^0 \rightarrow e^+e^-$ and $Z^0 \rightarrow \mu^+\mu^-$ events was $40 \mu\text{m}$. This resolution degrades to $\sim 65 \mu\text{m}$ at 10 GeV and $\sim 300 \mu\text{m}$ at 1 GeV because of multiple Coulomb scattering. Angular resolutions are estimated at ~ 0.1 mrad in ϕ and 2 mrad in θ for tracks above 20 GeV in the range $|\cos \theta| < 0.7$.

After the track reconstruction process the tracks are used to determine the primary vertex of the event. This is done in a set of routines known as the CX processor. CX also reconstructs secondary vertices that are well separated from the primary vertex. These secondary vertices are formed from the intersection of

oppositely charged pairs of tracks. Decays of K^0 and Λ^0 particles give rise to this secondary vertex topology and they will be discussed in detail in the next Chapter.

3.3.3 Event Display

Event displays are useful in studying reconstruction of events. The detector geometry and raw data can be displayed as well as the reconstructions. This can be very useful in debugging the reconstruction routines. The event display package, GROPE, is based on the GKS [34] graphics package.

An event display of a selected multihadronic event is shown in Figure 3.6. Figure 3.6(a) shows the entire detector geometry with the central tracking and calorimeter information. The 2 jet structure of the event is readily apparent. The size of the calorimeter blocks is proportional to the energy deposited. The arrows in the outer ring of the figure represent reconstructed muon trajectories. In Figure 3.6(b) an expanded view of the central detector region is shown. The tracks numbered 15 and 22 form a well separated vertex about 35 cm from the primary vertex and the invariant mass is consistent with that of a $\Lambda^0 \rightarrow p\pi$ decay.

3.3.4 Monte Carlo Programs

The event generators and detector simulation package used in OPAL will now be described. Event generators are used to generate various types of physics events. These programs produce the particles and initial kinematics that would be expected from a real event. The detector simulation package defines the geometry of the detector and controls the tracking of the particles through this geometry. At the end, a set of simulated "raw data" is produced in the same format as

Figure 3.6: Display of a selected multihadronic event.

that provided by the real detector. This data can then be analyzed by the same reconstruction programs as the real data.

Event Generators

There are many event generators available to produce multihadronic events, leptonic events, two-photon events, Higgs events ¹ and so on. The generators produce the initial particle configuration and kinematics. In this analysis two multihadron generators were used, the Lund Monte Carlo, known as JETSET [3] and the HERWIG Monte Carlo [19].

Generation of a multihadronic event begins with the production of an initial quark-antiquark pair. Initial state radiation is also included. The initial partons then shower and hadronize into particles which can be observed in the detector. Both generators use a parton shower approach although JETSET has the matrix element method as an option. The main hadronization models were covered in Chapter 2. JETSET uses string fragmentation while HERWIG uses cluster fragmentation. HERWIG uses the same particle decay tables as those used in JETSET.

Both Monte Carlos were tuned to provide good agreement with global event characteristics [35]. These tuned Monte Carlos can then be used to investigate the properties of individual particle species. In each case several parameters were optimized. Table 3.3 lists those parameters in JETSET and HERWIG that were changed from the default values. Version 5.0 of the HERWIG program uses the actual OPAL-tuned values in the latest version of the program. Λ_{QCD} is the QCD

¹A Higgs event is one in which the decay of a Higgs boson is simulated.

Generator	Program name	Default value	OPAL value	Units
JETSET Λ_{QCD}	PARJ(81)	0.40	0.29	GeV
JETSET σ_q	PARJ(21)	0.35	0.37	GeV
JETSET a	PARJ(41)	0.50	0.18	GeV ⁻²
JETSET b	PARJ(42)	0.90	0.34	
HERWIG Λ_{QCD}	QCDLAM	0.20	0.20	GeV
HERWIG Q_0	RMASS(13)	0.75	0.75	GeV
HERWIG	CLMAX	3.50	3.50	GeV

Table 3.3: The parameters of the JETSET 7.2 and HERWIG 5.0 Monte Carlo programs which have been tuned to provide agreement with the measured OPAL event shape variables.

scale parameter which appears in both programs. In JETSET the other parameters that were adjusted were σ_q , the width of the Gaussian transverse momentum distribution for the quarks produced in the fragmentation, and a and b , the fragmentation function parameters. In HERWIG, the parameters that were tuned correspond to Q_0 , the shower cutoff parameter (RMASS(13)), and the cluster mass (CLMAX).

Detector Simulation

The OPAL detector simulation program, GOPAL [36], is based on the CERN GEANT package [32]. GEANT provides a set of geometrical shapes (boxes, tubes, polygons, etc.) that can be used to build up a definition of the complete detector geometry. All volumes are described by the appropriate materials or a mixture of materials.

GEANT also controls the tracking of particles through sensitive volumes (e.g. a drift cell in the vertex chamber). When a particle traverses a sensitive volume its

position and momentum (a "hit") are stored. At each tracking step processes such as multiple Coulomb scattering and energy loss are calculated. Secondary processes such as hadronic interactions in the detector material, photon pair production, delta rays, particle decays and so on are also included.

At the end of the tracking stage all of the "hit" information is collected and the detector response simulated. Detector resolution effects and inefficiencies are included at this point. The output of this "digitization" stage is a data structure identical to that provided by the online data acquisition system. This structure is filled with the simulated raw data (digits) and it can then be processed by the ROPE reconstruction code and a DST created. In the case of Monte Carlo data additional information is stored on the DST that allows one to know exactly which particles were generated and their kinematics. In this way it is possible to calculate the detector acceptance for a particular particle decay. Figure 3.7 shows the organization of the analysis code, from the event generator through to the creation of a DST.

3.4 Summary

The experimental apparatus used to obtain the data analyzed in the next two Chapters has been reviewed. The LEP accelerator provides electron and positron beams of up to 50 GeV in energy. These beams are made to collide in the centre of a large detector designed to provide nearly 4π acceptance to charged particles, photons and neutral hadrons.

The OPAL detector and each of its subdetectors, the event reconstruction software, particularly charged particle tracking and the Monte Carlo programs used

Figure 3.7: Overview of the Monte Carlo event simulation process.

in physics analysis have been described. In order to fully understand detector efficiency and the results of one's analysis it is important that the detector simulation agree with the real data as closely as possible. In the next Chapter this question is addressed in relation to the data collected from the central detector that is used in this study.

Chapter 4

DATA SELECTION

Criteria for selecting hadronic Z^0 decays are presented and possible backgrounds to these events are discussed. Once a sample of good multihadronic events has been selected a comparison is made between the data sample and a Monte Carlo sample of JETSET 7.2 events that have been passed through an identical selection procedure. These events are then searched for Λ decays. The search procedure and the cuts used to improve the signal to background ratio are presented. The method of extracting the number of events from the mass peaks is shown to give good agreement with the number of events known to exist in the Monte Carlo.

4.1 Selection of Hadronic Z^0 Decays

The initial data sample consisted of 147,248 events flagged in the filter as “gold plated multihadrons (GPMH)”. The data were recorded during 1990 at seven centre-of-mass energies within ± 3 GeV about the peak of the Z^0 resonance. The energies and the percentage of events at each energy are: 88.3 (1.6 %), 89.3 (3.8 %), 90.3 (5.2 %), 91.3 (74.0 %), 92.3 (7.5 %), 93.3 (4.8 %) and 94.3 GeV (3.1 %). The

event weighted centre of mass energy was 91.314 GeV.

The GPMH classification is done online using only information from the electromagnetic calorimeters and time-of-flight counters. A further classification, known as the "Tokyo"¹ multihadronic selection was done during offline ROPE processing of all filter flagged events. Events are selected as multihadronic decays based on electromagnetic calorimeter information and charged track multiplicity.

For the GPMH selection barrel electromagnetic clusters are required to have one block with at least 100 MeV of energy deposited and at least one nearest neighbour with 50 MeV. In the endcap the initiating block must have at least 200 MeV and the nearest neighbour(s) 100 MeV. GPMH events are required to have

- total energy summed over all clusters ($\Sigma E_{\text{cluster}}$) > 8 GeV
- at least 6 clusters
- $\Sigma E_{\text{cluster}} > 2$ GeV in the hemisphere opposite the highest energy cluster
- passed the halo muon rejection cut

and if the barrel cluster energy sum is greater than 2 GeV in 2 or more clusters then 3 or more time-of-flight counters are required. Halo muons are produced by interactions of beam particles in the collimators upstream from the detector. These muons then travel almost parallel to the beam line and interact in the detector.

In the Tokyo selection process clusters in the barrel region are required to have an energy of at least 100 MeV in one or more blocks while in the endcap at least 2 adjacent blocks with an energy of at least 200 MeV are required. Charged tracks are required to have

¹This selection was developed by the Tokyo group in the OPAL collaboration.

- $p_t \geq 50 \text{ MeV}$, $|\cos \theta| \leq 0.995$, $|d_0| \leq 2 \text{ cm}$, $|z_0| \leq 40 \text{ cm}$
- χ^2 from both the $r - \varphi$ and $s - z$ track fits ≤ 999
- ≥ 20 jet chamber hits, and the radius of the first hit $\leq 60 \text{ cm}$.

An event is selected if it satisfies all the following conditions:

- at least 7 clusters
- at least 5 tracks
- a total energy deposition in the electromagnetic calorimeter of at least 10 % of the centre-of-mass energy: $R_{\text{vis}} \equiv \Sigma E_{\text{cluster}} / \sqrt{s} > 0.1$
- an energy imbalance along the beam direction $R_{\text{bal}} \equiv \Sigma(E_{\text{cluster}} \cdot \cos \theta) / \Sigma E_{\text{cluster}} < 0.65$

The events selected for further study were those GPMH events which passed the Tokyo selection and in which the jet chamber, barrel and endcap electromagnetic calorimeters and the forward detector were known to be at nominal operating voltages. In addition, the electromagnetic calorimeters were required to be active in the trigger. After imposing these requirements 138,638 events remained.

In the determination of the Z^0 lineshape parameters [37] a total of 139,893 events, corresponding to a total integrated luminosity of 6.6 pb^{-1} , from the 1990 run were classified as multihadronic Z^0 decays. The 0.9 % difference between the two data sets is due to the fact that the selection for this analysis was done only from the filter flagged GPMH sample while that in [37] was made from all filter selected events. This small difference is assumed to have no affect on any of the results given in this thesis.

Figure 4.1: Feynman diagrams illustrating two-photon processes in e^+e^- collisions.

The main source of contamination in the hadronic event sample is from $\tau^+\tau^-$ events. Most of these events and Z^0 decays to other charged leptons are of low multiplicity and are removed by the requirement of at least 5 charged tracks. Remaining $\tau^+\tau^-$ events are estimated to represent about 0.1 % of the selected multihadronic decays. This fraction is estimated in [37] by passing a sample of Monte Carlo generated $\tau^+\tau^-$ decays through the same selection procedure as the data.

Other sources of background are due to two photon processes (illustrated in the Feynman diagrams of Figure 4.1), cosmic rays, beam-gas and beam-wall collisions. In the latter two processes a particle from one of the beams collides with a residual gas molecule inside the beam pipe or with the wall of the beam pipe itself.

The cut on the amount of energy deposited in the electromagnetic calorimeter (R_{vis} as defined above) discards most two photon and beam-gas events. These events have a smaller effective centre-of-mass energy than a Z^0 event and also typically have a low multiplicity. Cosmic ray events are removed by the vertex requirements on the tracks and time-of-flight information. Beam-wall events are rejected primarily through the energy imbalance cut (R_{bal}). It is estimated that

all background processes have been reduced to about 0.1 %, with the $\tau^+\tau^-$ events the most common type of background.

4.2 Data to Monte Carlo Comparisons

Before comparing the data to a Monte carlo sample, a further selection of events was made based on track parameters, the number of charged tracks and the angle of the thrust axis.

Thrust is one of several variables used to describe the shape of an event. It is defined as

$$T = \max\left(\frac{\sum |p_{||}|}{\sum |p|}\right)$$

where $p_{||}$ is the particle momentum parallel to the thrust axis, which is chosen such as to maximize $\sum |p_{||}|$. p is the momentum of the particle and the sum is over all particles in an event. Narrow back-to-back 2-jet events have $T \approx 1$ while an isotropic event has a value of $T \approx 0.5$. The direction of the thrust axis is often taken to be the event axis. For 2-jet, high thrust events the thrust axis is closely related to the direction of the original $q\bar{q}$ pair.

A "good" track is one which meets these conditions: $p_t \geq 0.15$ GeV, $|\cos \theta| \leq 0.94$, $|d_0| \leq 5$ cm, $|z_0| \leq 99$ cm, $\chi^2 \leq 999$, and number of CJ hits ≥ 40 . These track cuts are standard in many OPAL physics analyses. An event is retained for further analysis if it contains at least 5 good tracks and $|\cos(\text{thrust})| \leq 0.9$. These 2 requirements ensure a good sample of multihadron events that are well contained within the detector.

The Monte Carlo samples used in this analysis consisted of 164,042 JETSET 7.2 events and 89,926 HERWIG events (19,876 HERWIG 4.3, 18,228 HERWIG 4.6 and 51,822 HERWIG 5.0). The HERWIG events were used in determining the detector efficiency function as detailed in the next Chapter.

Not all multihadronic events produced by a generator will pass through the multihadronic event selection process. The acceptance of the Tokyo multihadron selection process is estimated to be $98.4 \pm 0.4 \%$ [38]. The error is the uncertainty estimated due to detector simulation and the modelling of the fragmentation process. After applying the Tokyo selection to the Monte Carlo samples 161,327 (98.35 %) JETSET and 88,277 (98.17 %) HERWIG events remained.

The selection criteria given earlier in this Section were applied to both the data and the Monte Carlo data sets. 131,253 data events, 154,070 JETSET events and 84,228 HERWIG events remained. Several global event characteristics as well as reconstructed track parameters can now be compared between the data and JETSET samples.

Global event characteristics are compared in Figure 4.2. The Monte Carlo distributions are plotted as histograms and the data as points. The number of Monte Carlo events has been normalized to the number of data events. The charged multiplicity, sum of charged track momentum, thrust and sphericity distributions are plotted. In each case the agreement between the Monte Carlo and the data is good.

Sphericity is another of the shape variables often used to describe an event. It is defined as

$$S = \frac{3 \sum p_i^2}{2 \sum p^2}$$

Figure 4.2: A comparison of the number of charged tracks, sum of charged momentum, thrust and sphericity for the JETSET Monte Carlo (histogram) and the data (points).

where p_t is the particle momentum transverse to the sphericity axis. Narrow back-to-back 2-jet events have $S \approx 0$ while isotropic events have $S \approx 1$. Sphericity is related to thrust but because it is quadratic in momentum it is more sensitive to the high momentum particles in an event.

Distributions of individual track p_t , d_0 , z_0 and $\cos \theta$ are given in Figure 4.3. In the p_t distribution the agreement between the data and Monte Carlo is good. In the other distributions there are obvious discrepancies. In the d_0 case, the Monte Carlo distribution is more peaked and slightly narrower than the data distribution. The resolution in d_0 , estimated from a Gaussian fit to the distributions is $320 \mu\text{m}$ for the Monte Carlo and $370 \mu\text{m}$ for the data. There are known to be systematic effects in several aspects of charged track reconstruction that are not well-modelled in the detector simulation program. Some sources of such systematics are due to calibration constants, field distortions in a drift cell, diffusion effects due to long drift distances, tracks that are close to or cross wire planes, multi-hit effects on a wire and so on.

The difference between the data and the detector simulation appear quite prominently when one looks at the z information. The z_0 distribution for the data is shifted, wider and has very significant tails when compared to the Monte Carlo. Major systematic effects in the z reconstruction of tracks in the jet chamber have existed since the beginning of data taking at OPAL. Significant effort has been spent and is still being spent in trying to understand these problems. In the $\cos \theta$ distribution a striking difference is seen at values greater than ± 0.7 . In the Monte Carlo version used in this analysis it was known that a significant amount of material present in the detector was not included in the simulation. This difference affected the region just outside values of $\cos \theta$ of ± 0.7 where the electromagnetic

Figure 4.3: A comparison of the transverse momentum, d_0 , z_0 and $\cos \theta$ distributions for tracks in the JETSET Monte Carlo (histogram) and the data (points).

barrel and endcap calorimeters overlap.

The zed chambers subtend the values of $\cos \theta$ between ± 0.7 and here the agreement between the data and Monte Carlo is reasonable. A good determination of the opening angle (θ difference) between a pair of tracks in the $s - z$ plane is necessary for an accurate determination of the invariant mass. The tracks used in the search for Λ are therefore required to have values of $\cos \theta$ between ± 0.7 and to have zed chamber hits. The benefits of this restriction are discussed further in Section 4.4.

4.3 Λ Search Procedure

After the track quality and event selection cuts discussed in the previous Section the remaining events are searched for " V^0 " candidates. A V^0 is simply a pair of oppositely charged tracks which intersect. If the invariant mass of all V^0 are plotted, then after appropriate cuts to improve signal to background, clear mass peaks for the K^0 and Λ^0 are seen. This analysis is concerned with the Λ^0 search but the procedure applies equally well in a K^0 search.

Figure 4.4 shows the geometry of a Λ (or K^0) decay. The only difference between the two is topological. Since the proton in the Λ decay carries off most of the momentum the pion can be left with quite a low momentum, even for Λ momentum of several GeV. In contrast, the K^0 decay is more symmetric, with the 2 pions sharing the parent momentum more equally. In a Λ decay the track with the higher momentum is always a proton for Λ of momentum greater than 287 MeV.

All neutral pairs of good charged tracks are checked for geometrical intersections

Figure 4.4: The geometry of a Λ decay. α is the cosine of the angle between the reconstructed Λ momentum vector and the radius vector.

in the $x - y$ plane. Each V^0 candidate is required to pass a set of criteria based on the track parameters of the component tracks and the geometric properties of the V^0 itself. A subroutine, called CXV0, exists as part of the standard OPAL offline analysis software. This routine has a set of default cuts that are used in searching for V^0 . The standard default values of the cuts used are stated first, and then new values for the cuts as used in this study are explained.

Each neutral track pair is first required to satisfy the condition that the sum of the absolute values of d_0 ($= \sum |d_0|$) for the two tracks be greater than 0.2 cm.

Figure 4.5: The $|d_0|$ sum for the tracks from known Λ decays (solid histogram) and a sample of background decays (dashed histogram).

This cut is very effective in reducing the combinatorial background as can be seen in Figure 4.5. Real Λ can be tagged in the Monte Carlo and distributions of relevant quantities plotted for known Λ and a sample of background events. The background events were selected from the mass sidebands that were used in the sideband subtraction method of Section 4.5. The background distribution in Figure 4.5 continues to rise sharply at smaller values of $\Sigma|d_0|$ while that for real Λ peaks and then drops off at low values. A cut of $\Sigma|d_0|$ greater than 0.5 cm is used in this analysis.

For each track pair passing the $\Sigma|d_0|$ cut the $x-y$ plane intersections of the two tracks are then calculated. Either of the 2 possible intersections are then required to pass several tests.

Figure 4.6: The z separation at the decay point between the tracks from known Λ decays (solid histogram) and a sample of background decays (dashed histogram).

The separation in z of the two tracks at the intersection point must be less than 20 cm. Because of known differences between the data and Monte Carlo simulation with respect to the z information, this cut was relaxed to 100 cm. As can be seen from Figure 4.6 this cut has no effect in the Monte Carlo. However, since tails are known to exist in the data in distributions involving the z information the cut was effectively removed in order to eliminate the possibility of a systematic effect being introduced into the analysis.

The separation of the V^0 vertex from the primary event vertex in the $x - y$ plane was required to be between 1 and 150 cm. This cut was not changed. The cut at 1 cm removes all the combinations from the many tracks which originate from or very close to the primary vertex.

21 of/de 2

PM-1 3 1/2" x 4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

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If either track had hits further than 6 cm “upstream” (i.e. at a radius less than 6 cm less than the radius of the V^0), the intersection was rejected. This cut was removed due to the possibility of losing events in which, for example a wrong CV track were added to a CJ track.

The cosine of the angle between the vector from the primary event vertex to the V^0 vertex and the V^0 momentum vector ($\alpha = \cos(\vec{r} \cdot \vec{p})$) is required to be greater than 0. This is just a requirement that the two tracks be in the same hemisphere. Since the Λ is neutral and in most cases originates near the primary vertex this angle should be small. In this analysis the value of α was required to be greater than 0.98. In Figure 4.7 very few real Λ have a value of α less than 0.98. This cut could be even tighter, but for reasons that will be discussed below it was decided to use a very loose value for this cut.

A “pseudo- χ^2 ”, defined as $(\Delta z/\sigma_z)^2 + (\sin(\vec{r} \cdot \vec{p})/\sigma_{\sin(\vec{r} \cdot \vec{p})})^2$ is required to be less than 25. The values of σ_z and $\sigma_{\sin(\vec{r} \cdot \vec{p})}$ are fixed at 5 cm and 0.015 rad respectively. According to Figure 4.8 this cut should also be effective in eliminating background since a larger fraction of the background distribution lies above 25. However it was found that because of the fixed value of $\sigma_{\sin(\vec{r} \cdot \vec{p})}$ this cut was systematically removing more of the data than Monte Carlo at low momentum. This is thought to be due to the large multiple Coulomb scattering probability at low momentum causing a degradation in the estimate of the Λ momentum. This will then be reflected in the measurement of the angle between $\vec{r}$ and $\vec{p}$. The second term in the “pseudo- χ^2 ” can become very large because of the small σ value so it was decided that this cut should be removed, again to eliminate the possibility of a systematic error being introduced.

Intersections remaining at this point are then subjected to a constrained fit in

Figure 4.7: α for known Λ decays (solid histogram) and a sample of background decays (dashed histogram).

z . This fit adjusts the slopes of the tracks in the $s - z$ plane so that they appear to originate from the same point. This gives an improved mass resolution for the Λ . The χ^2 from this fit is required to be less than 100. This value was relaxed to 200, again because of known differences in the z information in the data as compared to the Monte Carlo. The distribution for known Λ and background is shown in Figure 4.9.

If, after all of these tests two intersections remain for a track pair the intersection with the smallest "pseudo- χ^2 " is chosen. This in effect chooses the intersection with the smallest z separation. It was found that in the Monte Carlo, for known Λ , the constrained fit in many cases gave a mass consistent with the Λ mass for either intersection. Systematics due to resolution of intersection ambiguities are therefore expected to be small.

Figure 4.8: The “pseudo- χ^2 ” for known Λ decays (solid histogram) and a sample of background decays (dashed histogram).

As well as the geometric cuts discussed above, it was also required that the impact parameter of the V^0 ($d_{0v} = r_v \sin(\vec{r} \cdot \vec{p})$, where r_v is the radius of the V^0) be less than 0.4 cm. This cut and the cut on $\cos(\vec{r} \cdot \vec{p})$ are strongly correlated and after the $\Sigma|d_0|$ cut is the most effective in reducing the background.

In Figure 4.10 it can be seen that most of the real Λ have d_0 values less than about 0.25, while for the background a significant tail exists. For the real Λ , some of those with larger d_0 values come from decays of the long-lived heavy baryons Ξ^- and Ω^- . Based solely on this Figure a tighter cut than the value of 0.4 cm could be used. However, as was pointed out in the discussion of the “pseudo- χ^2 ” the measurement of the angle between $\vec{r}$ and $\vec{p}$ is known to suffer some degradation in the data at low momentum. To avoid any significant systematic due to differences between the data and the Monte Carlo it was decided to use loose values of all the

Figure 4.9: χ^2 for the constrained $s - z$ fit for known Λ decays (solid histogram) and a sample of background decays (dashed histogram).

cuts that use this angular information, i.e., α , the “pseudo- χ^2 ” and d_{0v} .

In addition V^0 candidates having an invariant mass assuming an e^+e^- hypothesis of less than 60 MeV were rejected. No exclusion of candidates with the V^0 consistent with being a K^0 was made.

An additional requirement was placed on the $\cos\theta$ value of each track in the V^0 and on the number of CZ hits on each of the tracks. Both tracks were required to have $|\cos\theta| \leq 0.7$ as well as at least 4 CZ hits. These additional requirements will be discussed in the next Section in conjunction with determining the CJ+CZ matching efficiency.

In summary, a V^0 was kept if these conditions were met:

Figure 4.10: d_0 for the reconstructed V^0 for known Λ decays (solid histogram) and a sample of background decays (dashed histogram).

- $\Sigma|d_0|$ greater than 0.5 cm,
- Δz less than 100 cm,
- $\cos(\vec{r} \cdot \vec{p})$ greater than 0.98,
- χ^2_{n-z} less than 200,
- d_{0v} less than 0.4 cm,
- $m_{e^+e^-}$ greater than 60 MeV,
- each track had at least 40 central detector hits, and,
- $|\cos \theta|$ less than 0.7 and at least 4 CZ hits on each track.

4.4 Determining The CZ Matching Efficiency

In this analysis it was desired that both tracks that make up the V^0 should have at least 4 CZ hits. This requirement was made so that a good measurement of the opening angle, and hence of the reconstructed mass could be obtained. The improvement in the reconstructed mass peaks can be seen in Figure 4.11 (JETSET) and Figure 4.12 (data). Figures 4.11(a) and 4.12(a) are for those V^0 's in which both tracks have 4 or more CZ hits while in Figures 4.11(c) and 4.12(c) one or neither track has any CZ hits. In both the data and the Monte Carlo the peak in which both tracks have a CZ hit requirement is clearly narrower ($\sigma = 1.93 \pm 0.04$ as compared to 3.32 ± 0.32 MeV in the Monte Carlo, and $\sigma = 2.39 \pm 0.08$ as compared to 4.74 ± 0.46 MeV in the data). The peaks are also more clearly defined with respect to the background when the CZ requirement is made. The resolution in the data is not as good as that predicted by the Monte Carlo due to systematic effects in the track reconstruction that are not included in the detector simulation. The fit shown is a Gaussian peak with an exponential background for the region below the Λ mass and a linear background for the region above.

In the Monte Carlo the peak position is located at 1115.80 ± 0.04 MeV and in the data the value is 1115.70 ± 0.06 MeV. These values are in agreement with the latest value of the Λ mass as given by the Particle Data Group, 1115.63 ± 0.05 MeV [8].

Adding an additional requirement that both tracks have CV stereo information gives the mass distributions in Figures 4.11(b) and 4.12(b). This reduces the available statistics due to a lack of CV stereo information on many tracks and also because many of the Λ travel sufficiently far enough from the interaction point

Figure 4.11: Invariant mass distributions from the JETSET sample for track pairs with (a) both tracks having CZ hits, (b) as (a) and both tracks having CV stereo information, and (c) neither or only 1 track having CZ hits.

Figure 4.12: Invariant mass distributions from the data sample for track pairs with (a) both tracks having CZ hits, (b) as (a) and both tracks having CV stereo information, and (c) neither or only 1 track having CZ hits.

to pass the vertex chamber before decaying. In the Monte Carlo the resolution improved to $\sigma = 1.74 \pm 0.08$ compared to the case when both tracks were required to have only good CZ information ($\sigma = 1.93 \pm 0.04$). In the data there was no significant improvement in the resolution ($\sigma = 2.32 \pm 0.16$ compared to 2.39 ± 0.08 MeV). The better resolution is due to the additional z information obtained from the CV stereo system.

After the event selection and track cuts of Section 4.2 are applied, the efficiency of matching CJ+CZ tracks in both the data and the Monte Carlo must be determined. The method uses all tracks that pass the initial track cuts. The matching efficiency is simply the fraction of tracks in a given p_t and $|\cos\theta|$ bin that have 4 or more CZ hits.

It was found that a significant difference exists in the number of CJ hits on tracks of positive and negative charge at low momentum (less than about 500 MeV). This can be seen on Figures 4.13 (Monte Carlo) and 4.14 (data). In the Monte Carlo, positively charged tracks have noticeably fewer hits than negatively charged tracks of the same momentum. The same effect occurs in the data, but to a lesser extent. Much of this difference is due to an error in the treatment of positively charged tracks in the Monte Carlo. It is expected that at low momentum positively charged tracks should have fewer hits than negatively charged tracks. This is due to the magnetic field causing a change in the drift direction in the jet chamber compared to when there is no field present. The angle between the two drift directions is known as the Lorentz angle.

Because the pion in a Λ decay can be of quite low momentum it was decided to calculate separate matching efficiencies for positive and negative charged tracks. Tables 4.1 through 4.4 give the matching efficiency as a function of track p_t for

CJ hits (+ charge)(Monte Carlo)

CJ hits (- charge)(Monte Carlo)

Figure 4.13: Number of CJ hits at low momentum for positively and negatively charged tracks separately in the JETSET sample.

Figure 4.14: Number of CJ hits at low momentum for positively and negatively charged tracks separately in the data sample.

all tracks with $|\cos \theta| \leq 0.7$ for positive and negatively charged tracks separately. Figures 4.15 and 4.16 show the single track matching efficiencies for all of the $\cos \theta$ ranges for both the data and the Monte Carlo. In the Monte Carlo it can be seen that at low momentum the matching efficiency is significantly lower for positively charged tracks. The same trend can be seen in the data but to a lesser degree. Above about 1 GeV the single track matching efficiency reaches a plateau of about 80 % for the data and 90 % for the Monte Carlo.

4.5 Determining the Number of Λ Events

After application of all cuts from Sections 4.1 and 4.2 the mass distributions shown in Figure 4.17 (Monte Carlo) and Figure 4.18 (data) are obtained. Bin widths are 1 MeV, except for the 20 - 30 GeV distribution in which a bin width of 1.5 MeV is used. The number of events in each of the mass peaks is determined using sideband subtraction. The peak and sideband regions are indicated on the figures. From the fits in Figures 4.11(a) and 4.12(a) the σ value is about 2 MeV. Defining the signal region to be $\pm 3\sigma$ gives a total width of the signal region of 12 MeV, centered around the Λ mass. Two sideband regions, each equal to one-half the width of the peak region are chosen. These sidebands are separated from the peak region to try to get away from tails on the peak. The total number of events in the two sidebands is subtracted from the total number of events in the peak region to obtain a net number of events in the peak.

For the Monte Carlo it is possible to determine whether a found Λ was actually a true generated Λ . In Table 4.5 the number of generated Λ that were actually reconstructed are given, along with the number found for various choices of the width of the signal region. The study was not done on the 20 - 30 GeV bin since

p_t (GeV)	$ \cos\theta $						
	0. - 0.1	0.1 - 0.2	0.2 - 0.3	0.3 - 0.4	0.4 - 0.5	0.5 - 0.6	0.6 - 0.7
0.1 - 0.2	0.697 ± 0.008	0.697 ± 0.008	0.701 ± 0.007	0.707 ± 0.007	0.693 ± 0.007	0.639 ± 0.007	0.498 ± 0.007
0.2 - 0.4	0.753 ± 0.003	0.754 ± 0.003	0.751 ± 0.003	0.762 ± 0.003	0.745 ± 0.003	0.734 ± 0.003	0.674 ± 0.003
0.4 - 0.6	0.805 ± 0.003	0.802 ± 0.003	0.808 ± 0.003	0.827 ± 0.003	0.818 ± 0.003	0.797 ± 0.003	0.748 ± 0.003
0.6 - 0.8	0.811 ± 0.004	0.810 ± 0.004	0.817 ± 0.004	0.837 ± 0.003	0.820 ± 0.003	0.801 ± 0.003	0.727 ± 0.004
0.8 - 1.0	0.815 ± 0.004	0.812 ± 0.004	0.802 ± 0.004	0.830 ± 0.004	0.824 ± 0.004	0.794 ± 0.004	0.706 ± 0.004
1.0 - 1.2	0.806 ± 0.005	0.802 ± 0.005	0.818 ± 0.004	0.825 ± 0.004	0.821 ± 0.004	0.792 ± 0.004	0.691 ± 0.005
1.2 - 1.4	0.807 ± 0.005	0.807 ± 0.005	0.815 ± 0.005	0.829 ± 0.005	0.815 ± 0.005	0.792 ± 0.005	0.691 ± 0.005
1.4 - 1.6	0.807 ± 0.005	0.802 ± 0.006	0.813 ± 0.005	0.826 ± 0.005	0.805 ± 0.005	0.784 ± 0.005	0.695 ± 0.006
1.6 - 1.8	0.798 ± 0.006	0.797 ± 0.006	0.810 ± 0.006	0.830 ± 0.005	0.815 ± 0.006	0.796 ± 0.006	0.702 ± 0.006
1.8 - 2.0	0.796 ± 0.007	0.802 ± 0.006	0.811 ± 0.006	0.829 ± 0.006	0.809 ± 0.006	0.793 ± 0.006	0.704 ± 0.007
2 - 3	0.803 ± 0.005	0.800 ± 0.003	0.808 ± 0.003	0.829 ± 0.003	0.824 ± 0.003	0.795 ± 0.003	0.702 ± 0.003
3 - 4	0.793 ± 0.005	0.799 ± 0.004	0.813 ± 0.004	0.822 ± 0.004	0.816 ± 0.004	0.797 ± 0.004	0.716 ± 0.004
4 - 5	0.789 ± 0.006	0.804 ± 0.005	0.815 ± 0.005	0.833 ± 0.005	0.820 ± 0.005	0.810 ± 0.005	0.728 ± 0.005
5 - 7	0.800 ± 0.005	0.806 ± 0.005	0.819 ± 0.005	0.834 ± 0.004	0.826 ± 0.005	0.811 ± 0.005	0.735 ± 0.005
7 - 10	0.809 ± 0.006	0.813 ± 0.006	0.825 ± 0.005	0.840 ± 0.005	0.845 ± 0.005	0.832 ± 0.005	0.757 ± 0.006
10 - 20	0.811 ± 0.006	0.825 ± 0.006	0.826 ± 0.006	0.854 ± 0.005	0.843 ± 0.006	0.842 ± 0.006	0.769 ± 0.007
20 - 45	0.813 ± 0.014	0.829 ± 0.013	0.844 ± 0.013	0.813 ± 0.015	0.845 ± 0.015	0.827 ± 0.016	0.708 ± 0.023

Table 4.1: CJ+CZ single track matching efficiency as a function of track p_t and $|\cos\theta|$ (1990 Data - Positively Charged Tracks).

p_t (GeV)	$ \cos \theta $						
	0. - 0.1	0.1 - 0.2	0.2 - 0.3	0.3 - 0.4	0.4 - 0.5	0.5 - 0.6	0.6 - 0.7
0.1 - 0.2	0.711 ± 0.008	0.700 ± 0.007	0.700 ± 0.007	0.718 ± 0.007	0.682 ± 0.007	0.645 ± 0.007	0.484 ± 0.007
0.2 - 0.4	0.779 ± 0.003	0.773 ± 0.003	0.768 ± 0.003	0.779 ± 0.003	0.769 ± 0.003	0.755 ± 0.003	0.692 ± 0.003
0.4 - 0.6	0.800 ± 0.003	0.807 ± 0.003	0.805 ± 0.003	0.829 ± 0.003	0.811 ± 0.003	0.794 ± 0.003	0.744 ± 0.003
0.6 - 0.8	0.802 ± 0.004	0.805 ± 0.004	0.812 ± 0.004	0.836 ± 0.003	0.818 ± 0.004	0.796 ± 0.004	0.723 ± 0.004
0.8 - 1.0	0.803 ± 0.004	0.804 ± 0.004	0.811 ± 0.004	0.829 ± 0.004	0.816 ± 0.004	0.788 ± 0.004	0.696 ± 0.004
1.0 - 1.2	0.807 ± 0.005	0.799 ± 0.005	0.804 ± 0.005	0.825 ± 0.004	0.818 ± 0.004	0.789 ± 0.004	0.695 ± 0.005
1.2 - 1.4	0.803 ± 0.005	0.795 ± 0.005	0.804 ± 0.005	0.819 ± 0.005	0.810 ± 0.005	0.791 ± 0.005	0.692 ± 0.005
1.4 - 1.6	0.808 ± 0.006	0.803 ± 0.006	0.801 ± 0.006	0.829 ± 0.005	0.807 ± 0.005	0.789 ± 0.005	0.695 ± 0.006
1.6 - 1.8	0.790 ± 0.006	0.802 ± 0.006	0.804 ± 0.006	0.816 ± 0.006	0.806 ± 0.006	0.796 ± 0.006	0.693 ± 0.006
1.8 - 2.0	0.812 ± 0.006	0.799 ± 0.006	0.799 ± 0.006	0.826 ± 0.006	0.822 ± 0.006	0.805 ± 0.006	0.701 ± 0.007
2 - 3	0.802 ± 0.003	0.802 ± 0.003	0.815 ± 0.003	0.828 ± 0.003	0.812 ± 0.003	0.803 ± 0.003	0.711 ± 0.003
3 - 4	0.801 ± 0.004	0.791 ± 0.004	0.812 ± 0.004	0.835 ± 0.004	0.822 ± 0.004	0.800 ± 0.004	0.712 ± 0.005
4 - 5	0.804 ± 0.005	0.798 ± 0.004	0.806 ± 0.005	0.832 ± 0.005	0.819 ± 0.005	0.810 ± 0.005	0.726 ± 0.006
5 - 7	0.800 ± 0.005	0.808 ± 0.005	0.817 ± 0.005	0.829 ± 0.004	0.837 ± 0.004	0.809 ± 0.005	0.734 ± 0.005
7 - 10	0.810 ± 0.006	0.813 ± 0.006	0.827 ± 0.005	0.850 ± 0.005	0.832 ± 0.005	0.824 ± 0.005	0.752 ± 0.006
10 - 20	0.821 ± 0.006	0.816 ± 0.006	0.826 ± 0.006	0.855 ± 0.005	0.857 ± 0.005	0.827 ± 0.006	0.775 ± 0.007
20 - 45	0.815 ± 0.013	0.817 ± 0.014	0.835 ± 0.013	0.860 ± 0.013	0.838 ± 0.014	0.808 ± 0.016	0.767 ± 0.022

Table 4.2: CJ+CZ single track matching efficiency as a function of track p_t and $|\cos \theta|$ (1990 Data - Negatively Charged Tracks).

p_t (GeV)	$ \cos \theta $						
	0. - 0.1	0.1 - 0.2	0.2 - 0.3	0.3 - 0.4	0.4 - 0.5	0.5 - 0.6	0.6 - 0.7
0.1 - 0.2	0.640 ± 0.008	0.688 ± 0.007	0.709 ± 0.007	0.709 ± 0.007	0.712 ± 0.007	0.690 ± 0.007	0.533 ± 0.007
0.2 - 0.4	0.696 ± 0.003	0.733 ± 0.003	0.747 ± 0.003	0.756 ± 0.003	0.748 ± 0.003	0.749 ± 0.003	0.716 ± 0.003
0.4 - 0.6	0.857 ± 0.003	0.876 ± 0.002	0.876 ± 0.002	0.881 ± 0.002	0.878 ± 0.002	0.880 ± 0.002	0.854 ± 0.002
0.6 - 0.8	0.901 ± 0.003	0.902 ± 0.003	0.903 ± 0.002	0.902 ± 0.002	0.893 ± 0.003	0.892 ± 0.002	0.864 ± 0.003
0.8 - 1.0	0.915 ± 0.003	0.915 ± 0.003	0.906 ± 0.003	0.907 ± 0.003	0.899 ± 0.003	0.906 ± 0.003	0.879 ± 0.003
1.0 - 1.2	0.921 ± 0.003	0.912 ± 0.003	0.911 ± 0.003	0.915 ± 0.003	0.900 ± 0.003	0.903 ± 0.003	0.882 ± 0.003
1.2 - 1.4	0.914 ± 0.003	0.919 ± 0.003	0.908 ± 0.003	0.915 ± 0.003	0.905 ± 0.003	0.908 ± 0.003	0.882 ± 0.003
1.4 - 1.6	0.923 ± 0.003	0.919 ± 0.003	0.910 ± 0.004	0.917 ± 0.003	0.900 ± 0.004	0.913 ± 0.003	0.891 ± 0.004
1.6 - 1.8	0.920 ± 0.004	0.925 ± 0.004	0.911 ± 0.004	0.923 ± 0.004	0.902 ± 0.004	0.901 ± 0.004	0.888 ± 0.004
1.8 - 2.0	0.923 ± 0.004	0.922 ± 0.004	0.913 ± 0.004	0.920 ± 0.004	0.905 ± 0.004	0.918 ± 0.004	0.891 ± 0.004
2 - 3	0.926 ± 0.002	0.925 ± 0.002	0.919 ± 0.002	0.920 ± 0.002	0.915 ± 0.002	0.917 ± 0.002	0.896 ± 0.002
3 - 4	0.928 ± 0.003	0.927 ± 0.003	0.919 ± 0.003	0.923 ± 0.003	0.918 ± 0.003	0.923 ± 0.003	0.909 ± 0.003
4 - 5	0.924 ± 0.003	0.922 ± 0.003	0.925 ± 0.003	0.925 ± 0.003	0.922 ± 0.003	0.922 ± 0.003	0.908 ± 0.003
5 - 7	0.930 ± 0.003	0.927 ± 0.003	0.927 ± 0.003	0.925 ± 0.003	0.924 ± 0.003	0.923 ± 0.003	0.909 ± 0.003
7 - 10	0.935 ± 0.003	0.929 ± 0.003	0.931 ± 0.003	0.934 ± 0.003	0.928 ± 0.003	0.929 ± 0.003	0.913 ± 0.004
10 - 20	0.937 ± 0.003	0.934 ± 0.004	0.930 ± 0.004	0.937 ± 0.004	0.929 ± 0.004	0.934 ± 0.004	0.926 ± 0.004
20 - 45	0.938 ± 0.008	0.919 ± 0.009	0.920 ± 0.010	0.922 ± 0.010	0.931 ± 0.009	0.902 ± 0.012	0.881 ± 0.017

Table 4.3: CJ+CZ single track matching efficiency as a function of track p_t and $|\cos \theta|$ (Monte Carlo - Positively Charged Tracks).

p_t (GeV)	$ \cos \theta $						
	0. - 0.1	0.1 - 0.2	0.2 - 0.3	0.3 - 0.4	0.4 - 0.5	0.5 - 0.6	0.6 - 0.7
0.1 - 0.2	0.737 ± 0.006	0.758 ± 0.006	0.755 ± 0.006	0.741 ± 0.006	0.746 ± 0.006	0.713 ± 0.006	0.544 ± 0.006
0.2 - 0.4	0.831 ± 0.003	0.840 ± 0.003	0.827 ± 0.003	0.827 ± 0.003	0.819 ± 0.003	0.812 ± 0.003	0.779 ± 0.003
0.4 - 0.6	0.882 ± 0.003	0.883 ± 0.002	0.878 ± 0.002	0.881 ± 0.002	0.867 ± 0.003	0.872 ± 0.002	0.853 ± 0.002
0.6 - 0.8	0.904 ± 0.003	0.903 ± 0.003	0.893 ± 0.003	0.897 ± 0.003	0.889 ± 0.003	0.887 ± 0.003	0.870 ± 0.003
0.8 - 1.0	0.907 ± 0.003	0.906 ± 0.003	0.900 ± 0.003	0.902 ± 0.003	0.891 ± 0.003	0.894 ± 0.003	0.872 ± 0.003
1.0 - 1.2	0.914 ± 0.003	0.913 ± 0.003	0.902 ± 0.003	0.908 ± 0.003	0.895 ± 0.003	0.901 ± 0.003	0.872 ± 0.003
1.2 - 1.4	0.926 ± 0.003	0.918 ± 0.003	0.906 ± 0.003	0.908 ± 0.003	0.895 ± 0.003	0.900 ± 0.003	0.880 ± 0.004
1.4 - 1.6	0.919 ± 0.004	0.914 ± 0.004	0.906 ± 0.004	0.915 ± 0.003	0.904 ± 0.004	0.903 ± 0.004	0.893 ± 0.004
1.6 - 1.8	0.919 ± 0.004	0.913 ± 0.004	0.910 ± 0.004	0.912 ± 0.004	0.906 ± 0.004	0.913 ± 0.004	0.887 ± 0.004
1.8 - 2.0	0.915 ± 0.004	0.920 ± 0.004	0.915 ± 0.004	0.919 ± 0.004	0.907 ± 0.004	0.903 ± 0.004	0.889 ± 0.004
2 - 3	0.927 ± 0.002	0.922 ± 0.002	0.915 ± 0.002	0.920 ± 0.002	0.911 ± 0.002	0.914 ± 0.002	0.900 ± 0.002
3 - 4	0.923 ± 0.003	0.929 ± 0.003	0.920 ± 0.003	0.919 ± 0.003	0.919 ± 0.003	0.921 ± 0.003	0.900 ± 0.003
4 - 5	0.928 ± 0.003	0.924 ± 0.003	0.924 ± 0.003	0.926 ± 0.003	0.920 ± 0.003	0.922 ± 0.003	0.906 ± 0.004
5 - 7	0.928 ± 0.003	0.925 ± 0.003	0.924 ± 0.003	0.930 ± 0.003	0.921 ± 0.003	0.930 ± 0.003	0.911 ± 0.003
7 - 10	0.927 ± 0.004	0.935 ± 0.003	0.923 ± 0.004	0.928 ± 0.003	0.929 ± 0.003	0.934 ± 0.003	0.911 ± 0.004
10 - 20	0.943 ± 0.003	0.936 ± 0.003	0.928 ± 0.004	0.929 ± 0.004	0.929 ± 0.004	0.938 ± 0.004	0.913 ± 0.004
20 - 45	0.909 ± 0.009	0.919 ± 0.009	0.898 ± 0.010	0.914 ± 0.010	0.912 ± 0.011	0.915 ± 0.012	0.855 ± 0.018

Table 4.4: CJ+CZ single track matching efficiency as a function of track p_t and $|\cos \theta|$ (Monte Carlo - Negatively Charged Tracks).

Figure 4.15: CZ single track matching efficiency in the JETSET sample.

Figure 4.16: CZ single track matching efficiency in the data sample.

Figure 4.17: Invariant mass distributions as a function of momentum for the JETSET sample. The peak and sideband regions used in obtaining the number of events in the peak are indicated.

Figure 4.18: Invariant mass distributions as a function of momentum for the data sample. The peak and sideband regions used in obtaining the number of events in the peak are indicated.

Momentum (GeV)	# Generated Reconstructed	Width of Signal Region				
		10 MeV	12 MeV	14 MeV	16 MeV	18 MeV
0.5 - 1	223	261 $\pm$ 35 +38	265 $\pm$ 37 +42	278 $\pm$ 39 +55	264 $\pm$ 42 +41	278 $\pm$ 44 +55
1 - 2	1047	1051 $\pm$ 62 +4	1064 $\pm$ 66 +17	1073 $\pm$ 70 +26	1057 $\pm$ 74 +10	1084 $\pm$ 77 +36
2 - 3	1146	1116 $\pm$ 59 -30	1115 $\pm$ 63 -31	1155 $\pm$ 67 +9	1199 $\pm$ 70 +53	1213 $\pm$ 73 +97
3 - 4	881	886 $\pm$ 49 +5	939 $\pm$ 52 +58	965 $\pm$ 55 +84	950 $\pm$ 58 +69	964 $\pm$ 60 +83
4 - 5	689	662 $\pm$ 40 -27	677 $\pm$ 43 -12	693 $\pm$ 45 +4	681 $\pm$ 47 -8	684 $\pm$ 50 -5
5 - 7	982	927 $\pm$ 45 -55	961 $\pm$ 74 -21	988 $\pm$ 50 +6	986 $\pm$ 52 +4	1007 $\pm$ 54 +25
Sum of Differences		-65	+53	+184	+169	+291
7 - 10	851	664 $\pm$ 37 -187	691 $\pm$ 39 -160	714 $\pm$ 41 -137	693 $\pm$ 43 -158	706 $\pm$ 45 -145
10 - 15	614	430 $\pm$ 29 -184	463 $\pm$ 30 -151	467 $\pm$ 32 -147	487 $\pm$ 33 -127	493 $\pm$ 35 -121
15 - 20	243	143 $\pm$ 17 -100	165 $\pm$ 18 -78	172 $\pm$ 18 -71	176 $\pm$ 19 -67	181 $\pm$ 20 -59
20 - 30	115	68 $\pm$ 12 -47	68 $\pm$ 12 -47	68 $\pm$ 12 -47	68 $\pm$ 12 -47	68 $\pm$ 12 -47
TOTAL	6791	6208 $\pm$ 131	6408 $\pm$ 139	6573 $\pm$ 147	6561 $\pm$ 154	6710 $\pm$ 161

Table 4.5: Number of Λ found in the JETSET Monte Carlo sample as a function of signal window width.

clearly a wide window is required. The signal window width in this case was left fixed at 16 MeV. A difference between the number found from sideband subtraction and the actual number found is calculated for each bin. If the bins below 7 GeV are summed, it is found that overall the 12 MeV signal region finds 53 Λ too many, while the 10 MeV window finds 65 too few. As the width of the window is increased, the difference between the generated number and the number found from sideband subtraction increases. This would indicate that the 12 MeV signal window is a reasonable choice, at least below 7 GeV.

Above 7 GeV even the wider signal windows are unable to pick up all of the reconstructed Λ . All choices of signal window width find too few. That the sideband subtraction method finds too few events is due to increasing tails on the

Momentum (GeV)	Primary	Secondary Decay	Hadronic Interaction	Total
0.5 - 1	203	19	1	223
1 - 2	939	107	1	1047
2 - 3	1042	103	1	1146
3 - 4	789	91	1	881
4 - 5	606	83	0	689
5 - 7	882	99	1	982
7 - 10	756	94	1	851
10 - 15	549	65	0	614
15 - 20	217	26	0	243
20 - 30	105	10	0	115
TOTAL	6088	697	6	6791

Table 4.6: Origin of Λ reconstructed in the JETSET Monte Carlo sample.

mass peaks. Larger numbers of events have a poorly reconstructed mass as the momentum increases. This effect should occur in both the data and Monte Carlo, and to first order should not affect the final result. A systematic error due to the choice of the signal window will be discussed in the next Chapter. For the 7 to 10 GeV range a width of 14 MeV was chosen while between 10 and 30 GeV a width of 16 MeV was used.

In Table 4.6 the origins of the reconstructed generated Λ are given. Primary refers to those produced directly in the fragmentation or from decays of short-lived particles such as the Σ^0 or Λ_c^+ . Secondary decays are from long-lived parents such as Ξ^- or Ω^- . About 90 % of the Λ reconstructed are primary with 10 % from secondary decays. The number of Λ created in hadronic interactions in the detector that are found by the analysis procedure is negligible.

As a further check of the number of events extracted from each of the mass distributions, a fit with a Gaussian peak plus a linear background was done on

Momentum (GeV)	MONTE CARLO		1990 DATA	
	Mass (MeV)	σ (MeV)	Mass (MeV)	σ (MeV)
0.5 - 1	1115.3 ± 0.39	2.13 ± 0.29	1115.7 ± 0.41	2.20 ± 0.38
1 - 2	1115.3 ± 0.14	1.71 ± 0.09	1115.3 ± 0.13	2.40 ± 0.17
2 - 3	1115.8 ± 0.14	1.71 ± 0.08	1115.3 ± 0.18	2.19 ± 0.15
3 - 4	1115.8 ± 0.07	1.93 ± 0.10	1115.7 ± 0.19	2.31 ± 0.21
4 - 5	1116.0 ± 0.12	2.13 ± 0.13	1116.1 ± 0.27	2.57 ± 0.30
5 - 7	1116.0 ± 0.07	2.08 ± 0.10	1116.3 ± 0.14	2.63 ± 0.22
7 - 10	1116.3 ± 0.15	2.30 ± 0.13	1116.6 ± 0.27	2.82 ± 0.33
10 - 15	1116.2 ± 0.14	2.82 ± 0.21	1116.5 ± 0.38	3.08 ± 0.35
15 - 20	1116.6 ± 0.28	3.79 ± 0.40	- $\pm$ -	- $\pm$ -
20 - 30	1116.3 ± 1.13	5.77 ± 1.22	- $\pm$ -	- $\pm$ -
Average	1115.80 ± 0.04		1115.70 ± 0.08	

Table 4.7: Mass and σ from fits to the invariant mass distributions as a function of momentum.

each of the distributions. The fit was applied over the same range covered by the background subtraction method. Table 4.7 gives the mass and σ values for all of the fits. The values in Table 4.7 have been plotted in Figure 4.19.

The average value of the mass determined from the fits is 1115.80 ± 0.04 MeV for the Monte Carlo and 1115.70 ± 0.08 for the data. In both cases only the values between 0.5 and 15 GeV were used in the calculation of the average. The latest Particle Data Group value is 1115.63 ± 0.05 [8] and is shown as a line on Figure 4.19(a) and (b). The σ of the fits increase with momentum as would be expected due to the poorer determination of the track parameters with increasing track momentum.

In Table 4.8 a comparison is made between the number of events in the mass peaks obtained from each of the two methods. In both the data and the Monte

Figure 4.19: Mass and σ values from Gaussian fits to the distributions shown in Figures 4.17 and 4.18. No fits were done to the data distributions above 15 GeV.

Carlo the results obtained from the two methods are in good agreement. No fits were done to the data distributions above 15 GeV due to very low statistics; the sums are only for the first 8 bins. It was decided to use the values obtained from the background subtraction method due to the different background shapes in the various mass distributions. In some cases the backgrounds appear quite linear and in other cases they are irregularly shaped. The background subtraction technique is also known to be more robust in cases of limited statistics.

4.6 Summary

The selection procedure for multihadronic Z^0 decays has been presented and the background to the selected sample is estimated to be at a level of 0.1 %. Most

Momentum (GeV)	MONTE CARLO			1990 DATA	
	# Generated Reconstructed	# From Sideband Subtraction	# From Fit	# From Sideband Subtraction	# From Fit
0.5 - 1	223	265 $\pm$ 37	261 $\pm$ 34	267 $\pm$ 35	170 $\pm$ 21
1 - 2	1047	1064 $\pm$ 66	1083 $\pm$ 57	929 $\pm$ 61	879 $\pm$ 37
2 - 3	1146	1115 $\pm$ 63	1107 $\pm$ 58	798 $\pm$ 55	749 $\pm$ 35
3 - 4	881	939 $\pm$ 52	906 $\pm$ 38	466 $\pm$ 46	518 $\pm$ 27
4 - 5	689	677 $\pm$ 43	677 $\pm$ 34	391 $\pm$ 35	385 $\pm$ 25
5 - 7	982	961 $\pm$ 47	923 $\pm$ 39	500 $\pm$ 39	535 $\pm$ 29
7 - 10	851	714 $\pm$ 41	679 $\pm$ 35	383 $\pm$ 34	389 $\pm$ 26
10 - 15	614	487 $\pm$ 33	476 $\pm$ 27	208 $\pm$ 26	240 $\pm$ 22
15 - 20	243	176 $\pm$ 19	219 $\pm$ 24	- $\pm$ -	- $\pm$ -
20 - 30	115	68 $\pm$ 12	91 $\pm$ 12	- $\pm$ -	- $\pm$ -
TOTAL	6791	6466 $\pm$ 141	6422 $\pm$ 121	3942 $\pm$ 122	3865 $\pm$ 80

Table 4.8: Comparison of the number of Λ found using sideband subtraction and the number obtained from a fit to the invariant mass distributions. No fits were done to the data distributions above 15 GeV due to very low statistics.

of the background is believed to be from $\tau^+\tau^-$ decays. Very good agreement is shown for several global event characteristics when the data sample is compared to a JETSET Monte Carlo sample. While the p_t distributions compare quite well between the 2 samples, the d_0 , z_0 and $\cos\theta$ distributions show some differences.

At a loss of an improved signal to background ratio cuts in the Λ search procedure were chosen to be rather loose. This was in an attempt to reduce any significant systematic effects due to differences between the data and the Monte Carlo simulation. The number of events extracted from the Monte Carlo sample using sideband subtraction and Gaussian fits are both in good agreement with the number of generated Λ that were known to have been found.

Chapter 5

RESULTS

Results of a detailed study of Λ production are presented and compared to JETSET and HERWIG predictions. A total inclusive rate is determined and compared to previous measurements at lower energies and at the Z^0 resonance. Inclusive cross sections are also given for several kinematic variables. Measurements are made of the Λ lifetime, and the Λ production and decay angles. The Λ rate as a function of event sphericity is studied, and to conclude the Chapter an investigation into $\Lambda - \bar{\Lambda}$, $\Lambda - \Lambda$ and $\bar{\Lambda} - \bar{\Lambda}$ production in the same event is presented. Unless explicitly noted, " Λ " refers to both Λ and $\bar{\Lambda}$ combined.

5.1 Λ Detection Efficiency

Not all Λ that are produced in hadronic events can be detected. Almost one third of produced Λ decay into neutral particles which leave no detectable charged tracks in the central detector. Losses can occur due to tracks not being reconstructed in a dense jet environment or because of problems in associating hits to particular tracks. Some are lost to hadronic interactions in the detector material while others

travel sufficiently far out as to leave no tracks in the central detector. Many decay close to the primary vertex and thus produce no separated secondary vertex. Others fail the various V^0 selection cuts.

Before any comparisons can be made to model predictions it is necessary to determine the efficiency for detecting a Λ in the detector. Once this efficiency is calculated a total corrected number of Λ is obtained and this can then be compared to a model prediction. The detection efficiency is found by passing a Monte Carlo sample, in which the total number of Λ produced is known, through an analysis procedure identical to that to which the data is subjected.

For each bin of each variable studied the number of Λ found from the Monte Carlo sample after application of all selection procedures and cuts is found using the background subtraction technique. An efficiency correction, the number found divided by the number generated, is then calculated for each bin. Tables 5.1 and 5.2 give the number of generated Λ (all Λ , including unseen decays to neutral particles), the number found after the analysis procedure and the calculated detection efficiency values for 10 bins of momentum.

The efficiency values are quoted for the decay mode $\Lambda \rightarrow p\pi$ only. A branching fraction of 0.641 was used to allow for the unseen decay modes. Only the momentum range between 500 MeV and 30 GeV was considered due to the very small efficiency outside this range. In calculating a total corrected number of produced Λ the excluded momentum regions are taken into account.

The efficiencies were calculated separately for the full JETSET and HERWIG samples. Given enough statistics any differences would be due to different event topologies from the different fragmentation models used in the generators. For example, in one case Λ may be produced more often in a denser region of a jet,

Momentum (GeV)	# Generated	# Found	Efficiency (%)
0.5 - 1	5834	265 $\pm$ 37	7.08 $\pm$ 1.00
1 - 2	12191	1064 $\pm$ 66	13.62 $\pm$ 0.84
2 - 3	9120	1115 $\pm$ 63	19.08 $\pm$ 1.09
3 - 4	6319	939 $\pm$ 52	23.18 $\pm$ 1.28
4 - 5	4870	677 $\pm$ 43	21.68 $\pm$ 1.39
5 - 7	6679	961 $\pm$ 47	22.44 $\pm$ 1.11
7 - 10	6304	714 $\pm$ 41	17.67 $\pm$ 1.01
10 - 15	5556	487 $\pm$ 33	13.68 $\pm$ 0.94
15 - 20	2525	176 $\pm$ 19	10.87 $\pm$ 1.17
20 - 30	1436	68 $\pm$ 12	7.39 $\pm$ 1.29
TOTAL	60834	6466 $\pm$ 141	16.58 $\pm$ 0.36

Table 5.1: Detection efficiency for $\Lambda \rightarrow p\pi$ as a function of momentum (JETSET).

Momentum (GeV)	# Generated	# Found	Efficiency (%)
0.5 - 1	3508	199 $\pm$ 27	8.85 $\pm$ 1.20
1 - 2	6808	598 $\pm$ 48	13.70 $\pm$ 1.09
2 - 3	4656	697 $\pm$ 46	23.35 $\pm$ 1.54
3 - 4	3213	401 $\pm$ 38	19.47 $\pm$ 1.86
4 - 5	2294	300 $\pm$ 31	20.40 $\pm$ 2.11
5 - 7	3024	313 $\pm$ 33	16.15 $\pm$ 1.70
7 - 10	3078	327 $\pm$ 30	16.57 $\pm$ 1.53
10 - 15	3370	258 $\pm$ 25	11.95 $\pm$ 1.15
15 - 20	1858	105 $\pm$ 15	8.81 $\pm$ 1.26
20 - 30	1040	51 $\pm$ 10	7.64 $\pm$ 1.50
TOTAL	32849	3249 $\pm$ 102	15.43 $\pm$ 0.48

Table 5.2: Detection efficiency for $\Lambda \rightarrow p\pi$ as a function of momentum (HERWIG).

causing reduced efficiency because of tracking losses in such an environment.

Figure 5.1 presents both sets of values and the curve represents the weighted average of the two. The curve has not been smoothed. The very low efficiency at low momentum is due to a combination of requiring a secondary vertex at least one cm away from the primary vertex and the cut on track p_t of 150 MeV. As the momentum increases the Λ travel further away from the primary vertex and fewer are found. Losses at high momentum also occur due to the longer tails present on the mass distributions. Events out in the tail regions will not be counted in the mass window that is used to define the peak. A contribution to the systematic error due to the method of determining the efficiency corrections will be discussed in Section 5.4.

5.2 Determining The Λ Multiplicity

The actual efficiency values used in determining the total corrected number of Λ are not those given in Table 5.1 and Figure 5.1. Two additional corrections are included in the efficiencies before calculating a corrected number of events for each bin. These additional corrections are due to the CZ matching efficiencies and the unseen decay modes of the Λ .

Since the CZ matching efficiencies are different in the data and the Monte Carlo a correction must be applied when determining the corrected number of events found in the data. To take into account this correction factor, the invariant mass distributions are weighted. This weighting factor is calculated for each V^0 and is $1/\epsilon_1\epsilon_2$ where ϵ_i is tabulated as a function of the track p_t and $\cos\theta$ for each of the two tracks in the V^0 . The ϵ values are given in Tables 4.1 to 4.4

Figure 5.1: Efficiency function for $\Lambda \rightarrow p\pi$ decays only. Values were determined separately for JETSET and HERWIG. The curve is drawn through the weighted average of the two sets of data points.

of Chapter 4. This weighting procedure is applied to both the Monte Carlo and the data mass distributions. Unweighted distributions give the actual number of Λ events observed, while weighting the distributions includes the CZ matching efficiency differences between data and Monte Carlo.

The numbers of events extracted from the full data sample as a function of momentum are given in Table 5.3. The corrected number of events in the data for each momentum bin is simply the number found divided by the efficiency correction for that bin. The efficiency corrections given in Table 5.3 are the weighted average

Momentum (GeV)	Efficiency (%)	# Found in Data	# in Data (Corrected)
0.5 - 1	7.98 ± 0.62	471 ± 74	5903 ± 748
1 - 2	12.60 ± 0.52	1568 ± 80	12444 ± 814
2 - 3	17.79 ± 0.66	1302 ± 72	7319 ± 487
3 - 4	18.09 ± 0.79	739 ± 59	4085 ± 372
4 - 5	17.09 ± 0.84	621 ± 45	3633 ± 318
5 - 7	16.10 ± 0.65	784 ± 49	4870 ± 361
7 - 10	13.42 ± 0.59	604 ± 42	4501 ± 370
10 - 15	9.89 ± 0.51	317 ± 33	3205 ± 373
15 - 20	7.39 ± 0.60	88 ± 18	1191 ± 262
20 - 30	5.66 ± 0.69	63 ± 12	1113 ± 252
TOTAL		6557 ± 158	48264 ± 1496
CORRECTED			49774 ± 1544
RATE			0.356 ± 0.011

Table 5.3: Corrected number of $\Lambda + \bar{\Lambda}$ in 1990 data.

of the JETSET and HERWIG values which include the CZ matching efficiency correction. The unseen neutral $\Lambda \rightarrow n\pi^0$ mode is also taken in to account in the efficiency values of Table 5.3.

To determine the data to Monte Carlo ratio and overall Λ multiplicity a high statistics (10^6 events) generator-only JETSET run was used. From the results of this run, the number of events that would be expected from our data sample is determined. A ratio is then calculated between this expected number and the number actually found, after all efficiency corrections. This ratio is given in Table 5.4. Below 2 GeV the ratio is greater than 1 while above 3 GeV the value is slightly less. The overall ratio between 500 MeV and 30 GeV is 0.93 ± 0.03 .

A correction must be made for the momentum interval below 500 MeV and above 30 GeV. From JETSET it is found that 2.9 % of all Λ are below 500 MeV and 0.3 % are above 30 GeV. The bottom two lines in Table 5.3 include this

Momentum (GeV)	# Expected From MC	Data To MC Ratio
0.5 - 1	5063	1.17 ± 0.15
1 - 2	10507	1.18 ± 0.08
2 - 3	7591	0.96 ± 0.06
3 - 4	5475	0.75 ± 0.07
4 - 5	4105	0.88 ± 0.08
5 - 7	5744	0.85 ± 0.06
7 - 10	5308	0.85 ± 0.07
10 - 15	4812	0.67 ± 0.08
15 - 20	2205	0.54 ± 0.12
20 - 30	1278	0.87 ± 0.20
Average		0.93 ± 0.03

Table 5.4: Corrected data to Monte Carlo ratio.

correction. The number of Λ found per multihadron event in the data is then calculated to be 0.356 ± 0.011 (statistical). The systematic error will be discussed in Section 5.4.

This rate is in reasonable agreement with the value of 0.384 predicted by JETSET 7.2 with the default OPAL parameters. It is significantly less than the value of 0.427 predicted by HERWIG 5.0. The value measured here is compared to previous results at lower energies as well as measurements made by DELPHI [39] and Mark II [40] at 91 GeV in Table 5.5 and in Figure 5.2. The JETSET and HERWIG predictions are also shown on the Figure. The measurement in this analysis, although more precise, is consistent with both previous measurements at 91 GeV.

In the HERWIG Monte Carlo, the baryon rate is very sensitive to the parameter CLMAX, which controls the cluster mass. Adjusting this parameter to a value of 3.33 ± 0.09 GeV from the default value of 3.5 GeV gives excellent agreement with

Experiment	Reference	$\sqrt{s}(\text{GeV})$	Λ multiplicity
OPAL		91	$0.356 \pm 0.011 \pm 0.028$
DELPHI	[39]	91	$0.36 \pm 0.03 \pm 0.06$
MARK II	[46]	91	$0.47 \pm 0.10 \pm 0.05$
TASSO	[41]	42.1	$0.256 \pm 0.030 \pm 0.025$
JADE	[42]	35	0.234 ± 0.064
CELLO	[43]	35	$0.211 \pm 0.027 \pm 0.027$
TASSO	[41]	34.8	$0.218 \pm 0.011 \pm 0.021$
HRS	[44]	29	$0.217 \pm 0.009 \pm 0.022$
TPC	[45]	29	$0.197 \pm 0.012 \pm 0.017$
MARK II	[46]	29	$0.213 \pm 0.012 \pm 0.018$
MARK II	[40]	29	$0.170 \pm 0.015 \pm 0.018$
TASSO	[41]	22	$0.22 \pm 0.05 \pm 0.04$
TASSO	[41]	14	$0.13 \pm 0.04 \pm 0.03$
CLEO	[47]	10.5	0.066 ± 0.010
ARGUS	[48]	10	$0.092 \pm 0.003 \pm 0.008$

Table 5.5: Λ multiplicity as measured at different centre-of-mass energies.

the Λ rate measured here and also maintains good agreement with the measured K^0 rate [49] and the charged multiplicity [50]. JETSET on the other hand has several parameters which can be adjusted to affect the Λ rate. Rates for the production of other strange baryons and the K^0 are also affected by changing these parameters. A discussion of the various parameters, and the rates for other strange particles as measured by OPAL will be deferred to Chapter 6.

The JETSET Monte Carlo was run both with initial state radiation on and off. The difference between the two cases is of order two parts in one thousand, therefore no correction to the rate has been made due to initial state radiation.

As a check of the counting of the number of Λ in the Monte Carlo, the number counted is compared to the number of events predicted directly from the generator. As can be seen in Table 5.6 the ratio between the two is consistent with unity. It is

Figure 5.2: Λ multiplicity as a function of $\sqrt{s}$ as well as JETSET and HERWIG predictions made using default OPAL parameters.

important that Λ from hadronic interactions in the detector not be included when determining the detection efficiency. As can be seen from Table 5.7, a large number of Λ originate from hadronic interactions in the detector. These are virtually all Λ rather than $\bar{\Lambda}$ and most are produced in the material outside of the central detector. The number from hadronic interactions includes both Λ produced directly in a hadronic interaction as well as those Λ that come from a parent that was produced in such an interaction. Primary Λ are those produced directly in the fragmentation, short secondaries include those from decays of short-lived particles such as Λ_c^+ , Σ^0 , etc. and long secondaries are those from decays of long-lived baryons (Ξ^- , Ξ^0 and

Momentum (GeV)	Number From MC	JETSET 7.2 Prediction	Ratio
0. - 0.5	1755	1738	0.990 ± 0.034
0.5 - 1	5834	5944	1.019 ± 0.019
1 - 2	12191	12333	1.012 ± 0.013
2 - 3	9120	8911	0.977 ± 0.014
3 - 4	6319	6427	1.017 ± 0.018
4 - 5	4870	4819	0.989 ± 0.020
5 - 7	6679	6743	1.010 ± 0.018
7 - 10	6304	6231	0.988 ± 0.018
10 - 15	5556	5649	1.017 ± 0.015
15 - 20	2525	2588	1.025 ± 0.028
20 - 30	1436	1500	1.045 ± 0.038
30 - 45	182	175	0.960 ± 0.099
Total	62,771	63,058	1.005 ± 0.006

Table 5.6: Number of Λ as predicted by JETSET 7.2 compared to the number counted from the Monte Carlo after applying the detector simulation (excluding hadronic interactions).

Ω^-).

5.2.1 Separate Λ and $\bar{\Lambda}$ Production

Λ and $\bar{\Lambda}$ production were studied separately to see if there were any differences. Figure 5.3 shows the separate Λ and $\bar{\Lambda}$ unweighted mass distributions for the data. The fits shown are a Gaussian peak with an exponential plus linear background applied over the same region that sideband subtraction was used. The fitted number of events in each case is 1994 ± 76 Λ and 1966 ± 74 $\bar{\Lambda}$, in excellent agreement with the total obtained from applying background subtraction to the separate Λ and $\bar{\Lambda}$ mass distributions as a function of momentum (2082 ± 87 Λ and 1957 ± 86 $\bar{\Lambda}$ respectively).

In a further study, the cut on the minimum number of CJ hits required on each

Momentum (GeV)	Primary	Short-Lived Secondary	Long-Lived Secondary	Hadronic Interaction
0. - 0.5	676	834	245	3916
0.5 - 1	2238	2761	835	2976
1 - 2	4697	5786	1708	1331
2 - 3	3565	4305	1250	340
3 - 4	2407	3011	901	184
4 - 5	1882	2318	670	110
5 - 7	2462	3312	905	133
7 - 10	2171	3185	948	104
10 - 15	1894	2823	839	60
15 - 20	913	1221	391	15
20 - 30	670	596	170	8
30 - 45	114	52	16	1
Total	23689	30204	8878	9178

Table 5.7: Sources of Λ for the JETSET Monte Carlo sample.

track was varied from 40 to 50 to 60 to 80. Because of differences in the number of CJ hits for positive and negative tracks at low momentum some differences might be expected. As the cut on the number of hits is increased the number of positive tracks failing the cut will be different between the data and Monte Carlo. From Figures 4.13 and 4.14 in Chapter 4 it is clear that a cut of 80 CJ hits will throw away nearly all the positive tracks at momenta below 200 MeV in the Monte Carlo but only about half of those in the data.

Table 5.8 gives, separately, the total corrected Λ and $\bar{\Lambda}$ rates as the cut on the number of CJ hits is varied. In the case of the Λ the rate remains constant at about 0.189 ± 0.011 . At 40 hits the $\bar{\Lambda}$ rate is consistent with the Λ rate and the total rate of 0.360 agrees very well with the overall rate of 0.356 ± 0.011 from Table 5.3 in which combined $\Lambda + \bar{\Lambda}$ mass distributions were used. The number of $\bar{\Lambda}$ events found in the Monte Carlo drops significantly as the cut on the number of

Figure 5.3: Invariant mass spectra of Λ candidates for the $p\pi^-$ and $\bar{p}\pi^+$ decay mode separately.

hits required is increased to 80, even at momenta of 5 - 10 GeV. This is because the low momentum π^+ in the $\bar{\Lambda}$ decay are being thrown away because the positive charged tracks have a smaller number of hits than negative charged tracks of the same momentum. This occurs preferentially in the Monte Carlo. These reduced numbers of events found in the Monte Carlo lead to smaller efficiency values. In the 80 hit case for the $\bar{\Lambda}$, the signal disappears entirely below 1 GeV. Since the drop in the number of events found in the data is not as great as it is in the Monte Carlo, the smaller efficiency corrections lead to a higher overall corrected rate for $\bar{\Lambda}$ as the cut on the number of CJ hits is increased.

# of CJ Hits	Λ Rate	$\bar{\Lambda}$ Rate
40	0.189 ± 0.011	0.171 ± 0.011
50	0.188 ± 0.011	0.175 ± 0.011
60	0.188 ± 0.011	0.198 ± 0.011
80	0.190 ± 0.011	see text

Table 5.8: Separate Λ and $\bar{\Lambda}$ production rates.

It is concluded that, with the minimum requirement of 40 CJ hits, no significant difference exists between Λ and $\bar{\Lambda}$ production. However, there is a significant systematic effect introduced in changing the number of CJ hits required on each track from 40 to a higher value.

5.2.2 Systematic Errors

Several sources of systematic errors were studied. The effects of changing the $\cos \theta$ acceptance and of varying several of the V^0 cuts were investigated. Possible track reconstruction systematics at low momentum were checked by increasing the p_t cut. The choice of the width of the signal region affects the number of events found and thus has a systematic error associated with it. In the investigations of systematic errors only the JETSET Monte Carlo was used to calculate the efficiency corrections. In the case of determining a systematic error associated with these corrections and possible fragmentation differences between the two models, samples of both HERWIG and JETSET events were used.

In each of the investigations of a possible systematic effect the total inclusive Λ multiplicity is recalculated. The difference between the newly calculated rate is compared to the rate calculated when using all nominal values of the cuts and using JETSET only to calculate the efficiency corrections.

In Figure 4.16 of Chapter 4 the curve for the $|\cos \theta|$ range from 0.6 to 0.7 is noticeably different than for the other $\cos \theta$ ranges. In order to check the effect of including this outer range of $\cos \theta$, the analysis was repeated including only V^0 within $|\cos \theta| \leq 0.6$. Due to the sometimes poor determination in CJ of the slope of a track in the $s-z$ plane an effect will occur near the edges of the CZ acceptance (around $|\cos \theta| = 0.7$). Tracks which are actually within the CZ acceptance may be poorly measured and they will appear outside the CZ region. When the central detector track merging process attempts to match these tracks, no CZ hits will be found although in actual fact the tracks passed through CZ. Similarly, tracks in CJ that shouldn't pass through CZ will appear to do so. These tracks will have no CZ match and will also reduce the CZ matching efficiency. The difference in the Λ rate calculated in this case (0.349 ± 0.013) and the rate calculated when using JETSET only (0.358 ± 0.013) is 2.5 %. This is the systematic error assumed due to edge effects near the edge of the CZ acceptance of the central detector.

To check possible systematic contributions due to track reconstruction at low p_t the cut was increased to 250 MeV from 150 MeV and the analysis repeated. Due to the low momentum of the pion in the Λ decay, this effectively removed the 0.5 - 1 GeV region from the analysis and reduced the number of events found at momentum values up to several GeV. To estimate a systematic error the total number of corrected events from 1 to 30 GeV is compared. The difference is 1.8 %, which is the systematic error assumed due to track reconstruction at very low p_t .

The distributions of several of the V^0 variables were studied in order to look for differences between the data and the Monte Carlo in the application of these cuts. A signal region within ± 6 MeV of the Λ mass was used when looking for differences in these distributions.

Figures 5.4 (Monte Carlo) and 5.5 (data) show the distributions of several cut variables after application of all other V^0 cuts. These distributions are "background subtracted" in that a "sideband" distribution was subtracted from a "peak" distribution for each of the cuts. In the Λ mass region chosen, the relevant distributions are $\Sigma|d_0|$, impact parameter of the V^0 (d_{0v}), and the invariant mass assuming an e^+e^- hypothesis. On each Figure the regions removed by the cuts are indicated. Also shown are the distributions for the number of CJ hits, $\cos(\vec{r} \cdot \vec{p})$ and χ^2_{s-z} . From these last three distributions it can be seen that no sharp cut-offs occur at the chosen cut values of 40, 0.98 and 200 respectively.

Table 5.9 gives the percentage of events lost to each of the cuts for the data and Monte Carlo. The $\Sigma(d_0)$ cut removes the same amount of events from the data as the Monte Carlo. The other two cuts each remove 2 - 3 % more data than Monte Carlo.

CUT	MONTE CARLO	DATA
$\Sigma(d_0)$	17.1 ± 0.4	16.7 ± 0.5
d_{0v}	7.2 ± 0.3	10.4 ± 0.4
$m_{e^+e^-}$	0.7 ± 0.1	2.8 ± 0.3

Table 5.9: Percentage of events lost by application of each V^0 cut within ± 6 MeV of m_Λ .

To determine the systematic error associated with the choice of each cut, the cuts were varied and the analysis repeated. The corrected total rates for each of several cases are given in Table 5.10. The $\Sigma(d_0)$ cut was varied to 0.2 and 0.8 from its nominal value of 0.5 cm. In varying the cut to 0.2, the difference in the final corrected number of events is 1.1 %, while the difference when the cut is changed to 0.8 is 3.1 %. A 3.1 % systematic error is therefore assigned due to this

Figure 5.4: Distributions of some geometric V^0 cut variables after all other cuts have been applied (JETSET). The hatched areas indicate the region removed by that particular cut.

Figure 5.5: Distributions of some geometric V^0 cut variables after all other cuts have been applied (data). The hatched areas indicate the region removed by that particular cut.

Cut	Value Error	Λ Rate	Difference (%)
$\Sigma(d_0)$	0.2 cm	0.362 ± 0.013	+1.1
	0.8 cm	0.347 ± 0.013	-3.1
d_{0v}	0.2 cm	0.349 ± 0.013	-2.5
	0.6 cm	0.348 ± 0.013	-2.8
$\cos(\vec{r} \cdot \vec{p})$	0.9962	0.358 ± 0.013	0.0
χ^2_{s-z}	50	0.356 ± 0.013	-0.6
$m_{e^+e^-}$	0.	0.368 ± 0.013	+2.8

Table 5.10: Systematic differences due to varying V^0 geometrical selection cuts.

cut. Similarly the d_{0v} cut was changed from 0.4 to values of 0.2 and 0.6 cm. A systematic error of 2.8 % is therefore assigned due to this cut.

The cuts on $\cos(\vec{r} \cdot \vec{p})$ and χ^2_{s-z} were tightened up to values of 0.9962 and 50 respectively. The results of recalculating the corrected rates give systematic differences of 0 and 0.6 %. Finally, the cut on the invariant mass assuming an e^+e^- hypothesis was removed and the rate recalculated. This lead to a systematic error of 2.8 %.

In Table 4.1 of Chapter 4 the number of events in each of the Monte Carlo mass distributions as a function of the width of the signal region were given. The differences between the various choices is of order 3 to 4 %. The difference between the number of reconstructed Monte Carlo Λ (6791) and the number actually found (6466 ± 141) is 4.8 %. This is the systematic error that will be assumed due to the choice of the signal window widths and the background subtraction method of extracting a number of events in the mass peaks.

The detection efficiency corrections were also calculated using a sample of HERWIG events that were passed through an identical selection and analysis procedure as the JETSET events. The difference between the HERWIG rate (0.363)

Source	Systematic Error
$\cos \theta$ acceptance	2.5 %
low p_t tracks	1.8 %
$\Sigma(d_0)$	3.1 %
d_{0v}	2.8 %
$\cos(\vec{r} \cdot \vec{p})$	0.0 %
χ^2_{s-z}	0.6 %
$m_{e^+e^-}$	2.8 %
background subtraction	4.8 %
detection efficiency	2.0 %
Total Systematic Error	7.9 %

Table 5.11: Sources of systematic error.

and the rate using a weighted average (0.356, see Table 5.3) is 2 %, while the difference between the JETSET only rate (0.358) and the rate from Table 5.3 is 0.6 %. A systematic error of 2 % is therefore assigned due to the determination of the efficiency corrections.

Table 5.11 lists the contributions to the systematic error for the various cases considered. Adding all the contributions in quadrature gives a total systematic error of 7.9 %. Contributions such as the effects due to radiative corrections have not been included and are expected to be negligible.

5.3 Normalized Inclusive Cross Sections

A procedure similar to that given in the previous Section was used to determine the Λ rate as a function of x_E (= energy of the Λ divided by the beam energy) and ξ (= $\ln(1/x_p)$, where x_p is the Λ momentum divided by the beam energy). The data were divided into suitably chosen bins and the efficiency corrections were again

x_E	$\bar{x}_E$	Weighted Efficiency (%)	$\frac{1}{\sigma_{\Lambda\beta}} \frac{d\sigma}{dx_E}$
0.027 - 0.033	0.030	8.29 ± 0.62	$11.29 \pm 1.43 \pm 0.89$
0.033 - 0.050	0.0415	12.56 ± 0.52	$6.45 \pm 0.42 \pm 0.51$
0.050 - 0.070	0.060	17.69 ± 0.66	$2.89 \pm 0.19 \pm 0.23$
0.070 - 0.090	0.080	18.12 ± 0.79	$1.51 \pm 0.14 \pm 0.12$
0.090 - 0.110	0.100	16.83 ± 0.85	$1.25 \pm 0.12 \pm 0.10$
0.110 - 0.155	0.131	16.43 ± 0.64	$0.82 \pm 0.06 \pm 0.06$
0.155 - 0.220	0.182	13.33 ± 0.60	$0.51 \pm 0.04 \pm 0.04$
0.220 - 0.330	0.261	9.91 ± 0.51	$0.21 \pm 0.03 \pm 0.02$
0.330 - 0.440	0.371	7.37 ± 0.60	$0.084 \pm 0.017 \pm 0.007$
0.440 - 0.655	0.505	5.60 ± 0.70	$0.037 \pm 0.008 \pm 0.003$

Table 5.12: Weighted efficiency as a function of x_E and $\frac{1}{\sigma_{\Lambda\beta}} \frac{d\sigma}{dx_E}$ in 1990 data as a function of x_E (using weighted average of JETSET and HERWIG efficiency values). Statistical and systematic errors are given separately.

calculated as a weighted average of separately determined values from JETSET and HERWIG.

Table 5.12 gives the weighted detection efficiency corrections, the inclusive cross section and mean x_E values for each of the x_E bins. Including a 3.62 % correction for the x_E ranges not covered in the analysis gives a total multiplicity of 0.356 ± 0.011 , in excellent agreement with the result determined in Section 5.2.

Figure 5.6 shows the normalized inclusive cross section as a function of x_E as well as the JETSET and HERWIG predictions. The predicted rates have been normalized to the measured rate so that the shape of the distribution may be directly compared. While the data points follow the general shape of the predictions, the points at small x_E lie above the curve while those at larger x_E values fall below. Thus, the indication from Figure 5.6 is that the Λ fragmentation is softer than is predicted by the models. This trend has been noted in the past by HRS [44] and MARK2 [46].

Figure 5.6: Normalized inclusive cross section as a function of x_E and default predictions of JETSET 7.2 and HERWIG 5.0.

Figure 5.7 shows the OPAL result as compared to the DELPHI [39] result, the HRS [44] result at 29 GeV and the CELLO [43] and TASSO [41] results at 35 GeV. The cross sections have been normalized by dividing by the total Λ cross section whereas in Figure 5.6 the cross section was normalized to the total hadronic cross section. The OPAL data agrees with the DELPHI result up to about 0.2 where the DELPHI data stops. The overall shape is reproduced at 91 GeV and show significant scaling behavior with respect to the lower energy data. This is understood in terms of increased hard gluon radiation at 91 GeV as compared to PEP and PETRA energies of about 30 GeV. The initial energy is more likely to be

Figure 5.7: Normalized inclusive cross section as a function of x_E . OPAL results are compared to previous measurements at 29, 35 and 91 GeV.

shared between two outgoing quarks and one or more gluons than just two quarks.

The results of the determination of the inclusive cross section as a function of ξ are presented in Table 5.13 and shown in Figure 5.8. The correction factor for the excluded ξ regions is 3.15 %, and once again, the total corrected rate of 0.359 ± 0.011 is in excellent agreement with the result of Section 5.2. The previously published OPAL results for the K^0 [49] and all charged particles [50] are also shown. QCD calculations in a modified leading-log approach [51] suggest that the peak of the distribution should shift towards lower ξ values as the particle mass increases. However, within the limits of the Λ measurement, there appears to be

ξ	ξ	Weighted Efficiency (%)	$\frac{1}{\sigma_h} \frac{d\sigma}{d\xi}$
0.419 - 1.419	1.131	7.47 ± 0.34	$0.031 \pm 0.003 \pm 0.009$
1.419 - 1.819	1.64	11.86 ± 0.52	$0.087 \pm 0.007 \pm 0.007$
1.819 - 2.019	1.92	14.40 ± 0.81	$0.115 \pm 0.011 \pm 0.009$
2.019 - 2.219	2.12	17.55 ± 0.88	$0.096 \pm 0.009 \pm 0.008$
2.219 - 2.419	2.32	17.59 ± 0.88	$0.112 \pm 0.010 \pm 0.009$
2.419 - 2.619	2.52	17.61 ± 0.92	$0.111 \pm 0.011 \pm 0.009$
2.619 - 2.819	2.72	18.93 ± 0.95	$0.108 \pm 0.011 \pm 0.009$
2.819 - 3.019	2.92	17.60 ± 0.94	$0.134 \pm 0.013 \pm 0.011$
3.019 - 3.219	3.12	15.56 ± 0.95	$0.121 \pm 0.013 \pm 0.010$
3.219 - 3.419	3.32	15.57 ± 0.93	$0.133 \pm 0.013 \pm 0.011$
3.419 - 3.819	3.60	10.12 ± 0.69	$0.135 \pm 0.013 \pm 0.011$
3.819 - 4.519	4.07	8.04 ± 0.61	$0.061 \pm 0.007 \pm 0.005$

Table 5.13: Weighted efficiency as a function of ξ and $\frac{1}{\sigma_h} \frac{d\sigma}{d\xi}$ in 1990 data as a function of ξ (using weighted average of JETSET and HERWIG efficiency values). Statistical and systematic errors are given separately.

little difference between the position of the peak of the Λ distribution and that of the K^0 distribution. This is in agreement with the observation of DELPHI [39].

5.4 Λ Properties

5.4.1 Λ Production and Decay

In this Section several properties of the Λ will be compared to predictions. The background subtracted $c\tau$ (decay length) distribution, angular production and decay distributions are compared with expectations. The peak region is defined as being within ± 6 MeV around the Λ mass.

The $c\tau$ ($= \Lambda$ mass $\times$ length/momentum) distributions for the Monte Carlo and the data are shown in Figure 5.9. An exponential fit to the distributions gives

Figure 5.8: Normalized inclusive cross section as a function of ξ . Also shown are OPAL measurements for all charged particles and the K^0 .

consistent $c\tau$ values (4.92 ± 0.14 for the Monte Carlo and 5.08 ± 0.12 for the data). A value close to the PDG value of 7.89 cm [8] is not obtained since no acceptance corrections have been performed on the distributions. Since the data and the Monte Carlo were treated in exactly the same manner, the important point is that one obtains the same value in both cases.

The production of Λ is expected to be independent of ϕ and to behave like $1 + \cos^2 \theta$, where the azimuthal and polar angles, ϕ and θ , are measured in the laboratory. Figure 5.10 shows the ϕ distribution. The histogram is the Monte Carlo result normalized to the number of data events. No acceptance corrections

Figure 5.9: A comparison of the Λ $c\tau$ distributions for the JETSET sample and the data sample. No acceptance corrections are included.

have been made to the distribution. The region above $\phi = 4$ is shifted downward slightly compared to the region below $\phi = 4$. Two cells in the zed chambers in the region between $\phi = 4.6$ and 5.1 were not in operation during the data collection. This loss of acceptance would account for at least part of the difference in Figure 5.10. The dead cells are also included in the detector simulation program and the data does follow the Monte Carlo trend. With the effect of the dead CZ cells included the ϕ distribution is isotropic, as expected.

Since the efficiency of detecting Λ drops off as the edge of the barrel region of the central detector is approached an efficiency correction was made to the $\cos \theta$

Figure 5.10: Production angle ϕ .

distribution. The $\cos \theta$ distribution, normalized to the total number of hadronic events is shown in Figure 5.11. The solid curve on the Figure is from JETSET, and it is normalized to the observed Λ rate. Within the limited statistics the expected $1 + \cos^2 \theta$ behaviour is apparent but not clearly favoured over a linear fit to the data. In both cases the χ^2 per degree of freedom is about 0.5. Higher statistics and points at larger $|\cos \theta|$ values are needed to confirm the expected behavior.

Figure 5.11: Λ angular distribution ($\cos \theta$).

5.4.2 Λ Polarization

Since the decay of the Z^0 to $f\bar{f}$ pairs is parity violating, the outgoing fermions will, in general, be polarized. Within the Standard Model the polarizations for up and down type quarks are calculated to be 0.652 ± 0.006 and 0.940 ± 0.006 respectively. However, it is not clear how this initial polarization is reflected in the observed hadrons. Many of the Λ originate during the fragmentation process and these would be expected to carry zero net polarization. Only those Λ that contain the original strange quark from the Z^0 vertex are expected to carry any information about the polarization of the initial s quark.

The distribution of the cosine of the decay angle of the proton (or the helicity angle, Θ^*) is expected to be flat in the absence of any longitudinal polarization of the Λ . This angle is defined as the angle between the proton in the Λ centre-of-mass frame and the original direction of the Λ as measured in the laboratory. A complicating factor in the analysis is a significant contamination due to a kinematic overlap from the K^0 , as can be seen in Figure 5.12(a) where $m_{p\pi}$ is plotted versus Θ^* . A clear overlap region is seen in the range from 0.0 to 0.5 where the K^0 band crosses the Λ band. Because the mass sidebands intersect the K^0 band at different values of Θ^* than does the peak mass band, the region above -0.2 in the projection shown in Figure 5.12(b) shows very strongly the K^0 contamination. Below -0.2 the agreement between the Monte Carlo (histogram) and the data points is reasonable and shows a constant behavior, indicating that the Λ show no significant longitudinal polarization.

This result is not unexpected, since no additional selection of Λ was made beyond the standard selection used throughout this analysis. An exclusive selection of high momentum Λ might show some evidence for a polarization effect since it is likely that these would contain the original strange quark. However, from Figure 4.18 in Chapter 4 it can be seen that the number of Λ above 10 - 15 GeV in the 1990 data sample is limited. More statistics would be clearly required for any meaningful analysis. Using the 1990 plus 1991 data from OPAL (about 500,000 multihadronic events), an analysis [52] has determined the longitudinal polarization for Λ above 13 GeV to be $-0.13 \pm 0.11 \pm 0.07$. This null result indicates that any polarization present at the initial Z^0 decay vertex is lost during the hadronization process.

Figure 5.12: (a) $M_{p\pi}$ versus $\cos \theta^*$ (the proton helicity angle). The K^0 background to the Λ can be seen clearly. (b) the $\cos \theta^*$ distribution compared to JETSET expectation (histogram).

Sphericity	$\bar{S}$	Efficiency (%)	Λ Per Event	# $\Lambda/\bar{n}_{ch}$ Per Event
0. - 0.01	0.006	10.85 ± 0.70	$0.190 \pm 0.029 \pm 0.015$	$0.0115 \pm 0.0017 \pm 0.0009$
0.01 - 0.02	0.015	12.89 ± 0.54	$0.177 \pm 0.018 \pm 0.014$	$0.0098 \pm 0.0010 \pm 0.0008$
0.02 - 0.03	0.025	11.61 ± 0.62	$0.292 \pm 0.028 \pm 0.023$	$0.0146 \pm 0.0014 \pm 0.0012$
0.03 - 0.04	0.035	12.23 ± 0.71	$0.367 \pm 0.035 \pm 0.029$	$0.0172 \pm 0.0017 \pm 0.0014$
0.04 - 0.06	0.050	14.07 ± 0.60	$0.351 \pm 0.027 \pm 0.028$	$0.0155 \pm 0.0012 \pm 0.0012$
0.06 - 0.08	0.070	14.41 ± 0.74	$0.393 \pm 0.036 \pm 0.031$	$0.0164 \pm 0.0015 \pm 0.0013$
0.08 - 0.1	0.090	13.14 ± 0.86	$0.401 \pm 0.048 \pm 0.032$	$0.0160 \pm 0.0019 \pm 0.0013$
0.1 - 0.15	0.123	13.70 ± 0.67	$0.381 \pm 0.036 \pm 0.030$	$0.0146 \pm 0.0014 \pm 0.0012$
0.15 - 0.2	0.173	13.50 ± 0.82	$0.600 \pm 0.056 \pm 0.047$	$0.0220 \pm 0.0021 \pm 0.0017$
0.2 - 0.3	0.244	11.95 ± 0.77	$0.547 \pm 0.056 \pm 0.043$	$0.0195 \pm 0.0020 \pm 0.0015$
0.3 - 0.8	0.442	14.41 ± 0.68	$0.580 \pm 0.046 \pm 0.046$	$0.0190 \pm 0.0015 \pm 0.0015$

Table 5.14: Weighted detection efficiency, number of Λ per event and number of Λ divided by the corrected mean charged multiplicity per event as a function of event sphericity.

5.4.3 Λ Multiplicity as a Function of Event Sphericity

Λ production has also been investigated as a function of event sphericity. In the sphericity calculation, no additional correction to the total corrected number of events was required since no intervals of sphericity were excluded from the analysis. Table 5.14 gives the sphericity bins, the mean value in each bin and the efficiency correction factors. At lower values of sphericity the detection efficiency is lower due to the higher track density in such events. Also given in Table 5.14 are the Λ multiplicity and the Λ multiplicity divided by the mean total charged track multiplicity for each sphericity interval. The total Λ multiplicity is calculated to be 0.356 ± 0.010 , in excellent agreement with the value calculated using bins of momentum, x_E and ξ .

Figure 5.13(a) is a plot of the Λ multiplicity as a function of event sphericity. As the sphericity increases, the Λ multiplicity increases as well. A similar trend at 35 GeV has been observed by TASSO [41]. The observed trend appears to

be reproduced by the JETSET prediction. The JETSET prediction has not been normalized to the observed Λ rate.

It is more interesting to determine if the Λ multiplicity increases with sphericity faster than the charged multiplicity. A correction factor, calculated from the Monte Carlo, is applied to the data to determine a corrected mean charged multiplicity for each sphericity bin. After corrections, the Λ multiplicity divided by the mean total charged multiplicity is calculated. In the case of JETSET this quantity is a constant value of about 0.0167. In Figure 5.13(b) it appears that the rate of increase of Λ production with sphericity is higher than that for all charged particles and is not reproduced by the JETSET Monte Carlo. This effect has also been noted by TASSO [41].

The χ^2 for the fit of the straight line representing the JETSET prediction to the data points shown on Figure 5.13(b) is 4.5 per degree of freedom. Thus the hypothesis that the Monte Carlo prediction (a constant value) fits the data is not supported. A two-parameter linear fit to the data points gives a χ^2 of 2.2 per degree of freedom. There is no a priori reason to assume that the observed trend should be linear. However a linear fit clearly represents the observations better than does the assumption that there is no effect at all.

Higher sphericity events are produced mainly through hard gluon radiation. This result would suggest that Λ are produced more frequently in gluon jets than in quark jets. It has been noted in experiments around the Υ resonances [48] [47] that baryon production is enhanced by factors of 2 to 3 in direct Υ decays as opposed to continuum decays. The former decays are via three gluons rather than a quark-antiquark pair. Evidence has been presented for increased Λ production in lower thrust [46] and higher sphericity events [41]. At around 30 GeV $b\bar{b}$ events

Figure 5.13: Λ multiplicity as a function of event sphericity. In (b) the Λ multiplicity is divided by the mean charged multiplicity.

tended to have higher sphericity so no firm conclusions could be drawn. At 91 GeV all events in the absence of hard gluon radiation are expected to be narrow, two-jet type events with low sphericity.

There are two further pieces of information that indicate the possibility of increased baryon production in gluon fragmentation: possible increased proton production and a lack of increased K^0 production. The TPC Collaboration has presented evidence for possible increased proton production as a function of event sphericity at 29 GeV [53]. In an analysis of K^0 meson production using the same data as analyzed in this thesis [54], a similar study of K^0 production as a function of sphericity showed no effect. Therefore, it would appear that the production of baryons rather than mesons increases with increased event sphericity.

In an attempt to further clarify the issue of increased baryon production in gluon fragmentation the data were divided into two samples consisting of 2-jet events and events with 3 or more jets. Several schemes exist for defining jets. The JADE [55] (also called E0) scheme was used in this selection. For all pairs of particles i and j of an event, the quantity $y_{ij} = (p_i + p_j)^2 / E_{vis}^2$ is calculated, where the p are the particle momenta and E_{vis} is the visible energy of the event. In a recursive process, pairs of particles m and n are replaced by a pseudo-particle k with four-momentum $p_k = p_m + p_n$ as long as y_{mn} is less than y_{cut} , where y_{cut} is the jet resolution parameter. The procedure is repeated until all pair masses y_{ij} are larger than y_{cut} and the remaining groups of particles are called jets. Figure 5.14 shows the measured OPAL production rates of n -jet events in the E0 scheme as a function of y_{cut} . A value of y_{cut} of 0.03 was used for the selection of events into the 2 categories mentioned above. This gave a ratio of 2-jet to 3 or more jet events of 56 % to 44 %.

Figure 5.14: Measured production rates of n -jet events.

The Λ multiplicities were then calculated separately for the two samples. In the 2-jet sample the multiplicity was determined to be 0.153 ± 0.009 while for the 3 or more jet sample the multiplicity was 0.201 ± 0.008 . The total multiplicity is then 0.354 ± 0.012 , in excellent agreement with that obtained from the full data sample. The sample of events with 3 or more jets, although less than 50 % of the total, contains significantly more of the observed Λ rate. The procedure repeated with y_{cut} values of 0.02 and 0.04 gives consistent results.

In the JETSET Monte Carlo sample the total multiplicity was 0.384. In the 2-jet sample the multiplicity was 0.191 while in the 3 or more jet sample it was 0.193. In the Monte Carlo there is no difference in the Λ rate between the two samples. This would be expected since there is no difference in the way quarks and gluons fragment in the Monte Carlo. However, in the data there does appear to be increased Λ production in the ≥ 3 -jet sample, which could be due to increased production in the gluon fragmentation.

5.5 $\Lambda - \Lambda$ Correlations

Events which contain more than one Λ have been studied. Baryon number is predicted to be conserved locally, i.e., in the same jet. This hypothesis is checked by searching for $\Lambda - \bar{\Lambda}$, $\Lambda - \Lambda$ and $\bar{\Lambda} - \bar{\Lambda}$ combinations in the same event. The number of background combinations is also calculated and a background subtraction performed. The peak region chosen was from 1.111 to 1.121 GeV and the sideband regions covered from 1.097 to 1.102 GeV and from 1.130 to 1.135 GeV. A slightly narrower peak region is chosen in this part of the analysis in order to enhance the signal to background. Figure 5.15 shows the distribution of the cosine of the opening angle between the pair of Λ for "opposite-sign" ($\Lambda - \bar{\Lambda}$) and "like-sign" (Λ

- $\Lambda + \bar{\Lambda} - \bar{\Lambda}$) pairs. The histogram is the JETSET prediction normalized to the number of data events observed.

In the Monte Carlo sample of 154,070 events we find 257 ± 27 opposite sign pairs and 159 ± 23 like sign pairs (68 ± 17 $\Lambda - \Lambda$ pairs and 91 ± 15 $\bar{\Lambda} - \bar{\Lambda}$ pairs). To determine an efficiency correction, the number of events found in the Monte Carlo for $\cos \Theta$ greater than zero and less than zero separately are divided by the expected number from JETSET. After including a CZ matching efficiency correction, the total efficiency corrections are found to be 0.0350 ± 0.0039 and 0.0246 ± 0.0018 for opposite sign pairs with $\cos \Theta$ less than and greater than zero respectively. The smaller detection efficiency corresponds to the case in which both the reconstructed Λ and $\bar{\Lambda}$ are in the same jet. For the like sign pairs the efficiency did not vary significantly between the $\cos \Theta$ greater than or less than zero regions, so an average value of 0.0499 ± 0.0076 was used for the efficiency correction.

In the 131,253 data events we find 165 ± 19 $\Lambda - \bar{\Lambda}$ pairs, 47 ± 13 $\Lambda - \Lambda$ pairs and 43 ± 14 $\bar{\Lambda} - \bar{\Lambda}$ pairs. Correcting these observations by the estimated detection efficiency gives an estimated total production rate of $0.105 \pm 0.014 \pm 0.012$ $\Lambda - \bar{\Lambda}$, $0.016 \pm 0.005 \pm 0.002$ $\Lambda - \Lambda$ and $0.015 \pm 0.005 \pm 0.002$ $\bar{\Lambda} - \bar{\Lambda}$ pairs per multihadron event. The first error is statistical and the second is $\sqrt{2}$ times the 7.9 % systematic uncertainty. The measured $\Lambda - \bar{\Lambda}$ rate is about a factor two larger than previous measurements of $0.042 \pm 0.017 \pm 0.014$ by the TPC [45] experiment, $0.051 \pm 0.017 \pm 0.011$ by the HRS [44] experiment and $0.052 \pm 0.014 \pm 0.012$ by TASSO [41].

JETSET predicts 0.090 $\Lambda - \bar{\Lambda}$, 0.015 $\Lambda - \Lambda$ and 0.014 $\bar{\Lambda} - \bar{\Lambda}$ per event, while HERWIG predicts 0.180, 0.021 and 0.021 pairs per event. The rates measured here agree quite well with the JETSET predictions as do the shapes of the angular distributions as shown in Figure 5.14. $\Lambda - \bar{\Lambda}$ pairs appear predominantly in the

Figure 5.15: Measured distributions of $\cos \Theta_{\Lambda-\bar{\Lambda}}$ and $\cos \Theta_{\Lambda-\Lambda}$.

same jet and $\Lambda - \Lambda$ or $\bar{\Lambda} - \bar{\Lambda}$ pairs appear more often in opposite jets. This supports the hypothesis that baryon number is conserved locally in e^+e^- collisions.

In Figure 5.16 the rapidity difference between the opposite-sign and like-sign pairs is shown. The rapidity is defined with respect to the event thrust axis. As was mentioned in Section 2.3.1 if the baryon pairs are produced close together in the fragmentation chain, they should then also be close together in rapidity. It can be seen from Figure 5.16 that the difference for the opposite-sign pairs peaks towards zero as would be expected for $\Lambda - \bar{\Lambda}$ pairs that are produced close together in the fragmentation process. The data points follow the trend of the Monte Carlo which is indicated by the histogram. In the case of the like-sign pairs there appears to be no correlation between the rapidities of the baryon pair. The rapidity differences between the Λ and $\bar{\Lambda}$ pairs also provides further evidence for the local compensation of baryon number in e^+e^- collisions.

A comparison of the the opposite sign rate ($0.105 \pm 0.014 \pm 0.012$) with the inclusive Λ rate ($0.356 \pm 0.011 \pm 0.028$) indicates that the strangeness/baryon number of the Λ is compensated a $\bar{\Lambda}$ 59 ± 11 % of the time. In the context of the JETSET "popcorn" model changing the "popcorn" parameter from the default value of 0.5 to a value of 1.0 gives better agreement with both the measured inclusive Λ rate and the measured inclusive opposite sign double Λ rate. A value of 1.0 for the "popcorn" parameter implies that 33 % of the Λ events have no "popcorn" meson.

Figure 5.16: Rapidity difference between $\Lambda - \bar{\Lambda}$ and $\Lambda - \Lambda$ pairs.

5.6 Summary

The total inclusive rate for Λ production at 91 GeV has been measured to be 0.356 ± 0.011 (statistical) ± 0.028 (systematic). No differences are found in separate Λ and $\bar{\Lambda}$ production. This rate agrees with the JETSET 7.2 prediction of 0.384 and is in disagreement with the HERWIG 5.0 predicted rate of 0.427. Adjustment of CLMAX, the cluster mass parameter in HERWIG, to a value of 3.33 ± 0.09 from the default of 3.5 GeV gives good agreement with the measured Λ rate as well as the previously measured (by OPAL) K^0 rate and total charged multiplicity. Tuning of the JETSET parameters affecting baryon production is deferred until the next Chapter when the Λ rate is discussed in conjunction with the measured rates for other strange particles at OPAL.

The Λ fragmentation function is found to be softer than that predicted by either JETSET or HERWIG, in agreement with observations made at 30 GeV. Significant scaling violations with respect to measurements made at lower energy are found. There is an indication that Λ are produced more frequently in events containing hard gluon radiation.

Production rates of Λ pairs in the same event have been determined. The results support the local compensation of baryon number within a jet and agree with the JETSET predictions. In 59 ± 11 % of cases the strangeness and baryon number of the Λ ($\bar{\Lambda}$) is compensated by a $\bar{\Lambda}$ (Λ).

Chapter 6

CONCLUSIONS

The previous Chapter presented measurements of several aspects of Λ production and compared the results to two different hadronization models. The measurement of the Λ rate by itself, while interesting, must be considered along with the observed rates of other baryons in order to provide a more complete test of models of baryon production.

Measurements by OPAL of several other strange baryons are presently under investigation [56]. In Table 6.1 the rate for Λ production as measured in this study is given along with the production rates for the Ξ^- , $\Sigma^{\pm}(1385)$, $\Xi^{*0}(1530)$ and Ω^- baryons. Rates measured by OPAL for the K^0 [49], $K^{*0}(890)$, and $\phi(1020)$ mesons [57] are also given along with the total charged multiplicity [50]. Table 6.1 also lists the predictions of the default versions of JETSET 7.2 and HERWIG 5.0 tuned only to the observed OPAL event shapes. Parameters in JETSET affecting strange quark, diquark, strange diquark, and spin 1 diquark rates are unchanged from values used at lower energies.

From Table 6.1 it is seen that the observed rates for the K^0 and total charged

Particle	Observed Rate	JETSET	HERWIG	HERWIG Tuned
Λ	0.356 ± 0.030	0.385	0.427	0.354
Ξ^-	0.021 ± 0.002	0.027	0.062	0.048
$\Sigma^{\pm}(1385)$	0.038 ± 0.006	0.074	0.134	0.116
$\Xi^{*0}(1530)$	0.0063 ± 0.0014	0.0053	0.0308	0.0219
Ω^-	0.0050 ± 0.0015	0.0007	0.0097	0.0052
K^0	2.10 ± 0.14	2.03	1.95	2.01
$K^{*0}(890)$	0.76 ± 0.09	1.06	0.77	0.77
$\phi(1020)$	0.086 ± 0.018	0.191	0.113	0.112
n_{charged}	21.40 ± 0.43	21.34	20.95	21.10

Table 6.1: Observed rates for several particles and the JETSET and HERWIG predictions. The errors are the combined statistical and systematic uncertainties.

multiplicity agree with both JETSET and HERWIG. In the case of the baryons only the Λ and $\Xi^{*0}(1530)$ rates agree with JETSET. The Ξ^- rate is slightly low while the $\Sigma^{\pm}(1385)$ rate is down by a factor of two and the Ω^- rate is a factor seven too low. The HERWIG rates for the baryons are all somewhat higher than the JETSET rates. Interestingly, the HERWIG rates for the two vector mesons are lower than JETSET and they are in reasonable agreement with the observations.

HERWIG, with only very few tunable parameters is able to provide reasonable agreement with the observations for the charged multiplicity and the mesons. However it is clear that the simple phase-space method of cluster decay predicts rates for the baryons that are significantly higher than the observations. The predicted HERWIG momentum spectrum for the Λ was found to be harder than the JETSET prediction, which itself is harder than that which was observed in the data. Even with HERWIG tuned to provide agreement with the Λ rate it can be seen that the rates for the other baryons, with the exception of the Ω^- , are still significantly higher than the observations.

In JETSET several parameters affect the rates of the various particles. Adjusting one parameter can give agreement with one or more observed rates, however the rates of other particles are also affected at the same time. Tuning the parameters to give agreement with all of the observations is not trivial. As it is, the current version with parameters tuned only for global event shapes does not do a bad job. While further parameter tuning can be done, the simple model of diquark production in the string fragmentation model does a reasonable job of predicting the observed baryon rates.

The Ω^- is somewhat of a puzzle. Its observed rate is not significantly different than that of the $\Xi^{*0}(1530)$ although it contains an additional strange quark. Either, (a) the addition of a third strange quark is not additionally suppressed, or, (b) there is a source of Ω^- that is not included in the Monte Carlo, or, (c) the measurement given in Table 6.1 is a large statistical fluctuation.

While the overall rate of Λ production is in agreement with JETSET, the fragmentation function is softer than predicted by either model. The softening of the Λ momentum spectrum has also been noted at centre-of-mass energies around 29 GeV by HRS [44] and MARK II [46]. One possible explanation for this observation is that a different form of the fragmentation function should be used when a baryon is created in the breakup of the string. There is no reason to suppose that baryon fragmentation functions should have the same universal form as that for mesons [58].

In [58] the form of the function used for baryons is

$$f(z) = \frac{1}{z}(1-z)^{\alpha}\left(\frac{1-z}{z}\right)^{1-\alpha}\exp(-bm_T^2/z)$$

which is the same as the default Lund fragmentation function used in JETSET (see

Chapter 3) except for the $((1 - z)/z)^{1-\alpha}$ factor. The quantity α is related to the probability of producing a "popcorn" meson between the baryon and antibaryon, with the popcorn probability given by

$$1 - \frac{1}{2 - \alpha}$$

The popcorn probability is then zero for $\alpha = 1$ and 0.5 for $\alpha = 0$. With a value of $\alpha = 1$ the standard form of the fragmentation function is recovered. It is shown that the Λ data at 29 GeV is consistent with values of α in the range 0 to 0.5, and that changes of the fragmentation function parameters a and b do not significantly affect the result. The authors also show that a value of α between 0 and 0.5 provides a better fit to the TPC proton data at 29 GeV than does an α value of 1. Thus, the indications are that a form of the fragmentation function that explicitly includes a "popcorn" term leads to better agreement with the observed baryon momentum spectra. This fragmentation function is softer than that for mesons and since baryon production could occur through colour fluctuations on the string there is no reason that the two fragmentation functions need be the same. It should also be noted that although changing the popcorn parameter (PARJ(5)) itself within JETSET does change the Λ rate, it does not significantly affect the momentum spectrum.

The shape of the normalized Λ cross section shows significant scaling violations with respect to the lower energy data at 29 - 35 GeV, a trend that is followed by the Monte Carlo. This effect can be attributed to increased gluon radiation at the higher centre-of-mass energy. With an increased number of gluons radiated the available energy must be shared between more partons than just the initially produced $q\bar{q}$ pair. The particles created in the fragmentation will have a smaller

fraction of the initial quark momentum than they would had no gluons been radiated.

The inclusive cross section as a function of ξ ($= \ln(1/x_p)$) has been studied. For the Λ , the position of the maximum, ξ^* , is seen to be consistent with that of the K^0 . A downward shift in the ξ^* values between the distribution for all charged particles and that of the K^0 has been noted by OPAL [49] and DELPHI [39]. QCD calculations in the Modified Leading Log approach have suggested that as the particle mass increases the value of ξ^* should decrease; no evidence is seen for this effect in comparing the Λ and K^0 distributions, in agreement with the DELPHI [39] observation.

The lifetime ($c\tau$) and angular distributions of the Λ that were found were studied. No significant differences were found between the distributions from the data and those from a JETSET Monte Carlo sample. The production of the Λ was observed to be consistent with being isotropic in ϕ and of the form $(1 + \cos^2 \theta)$. This is what would be expected for Λ arising from the hadronization of a fermion-antifermion pair produced in a Z^0 decay. No evidence was found in the decay angle distribution of the protons from Λ decay that would indicate a longitudinal polarization of the Λ . A subsequent study using a method of selecting only high momentum Λ from a larger data sample also showed no evidence for any polarization [52].

An investigation into the production of Λ as a function of event sphericity indicates a possible increase in production as the sphericity of the event increases. This is attributed to the increased production of baryons in gluon fragmentation since events with higher sphericity are due mostly to radiation of a hard gluon at a large angle to the initial $q\bar{q}$ direction.

This trend of increased baryon production in gluon fragmentation is corroborated by several additional observations:

- baryon production in Υ decays (via 3 gluons) is 2 - 3 times higher than that from neighbouring continuum decays (via a $q\bar{q}$ pair) [48] [47]
- at centre-of-mass energies between 29 and 35 GeV there were indications of increased Λ production in higher sphericity [41] and lower thrust [46] events
- there was an indication of increased proton production in events of higher sphericity at 29 GeV [53]
- no evidence was noted for increased K^0 production in higher sphericity events at an energy of 91 GeV. [54]
- the Λ multiplicity in a sample of 3 or more jet events was significantly larger than in a sample of 2-jet events.

It would appear that production of baryons, but not strange mesons, is enhanced in gluon fragmentation. It has also been observed by OPAL [59] that the overall particle multiplicity is 6.1 ± 2.6 % higher in gluon jets than in quark jets. At what level this increase is due to increased baryon production requires further investigation.

Correlations between $\Lambda - \bar{\Lambda}$, $\Lambda - \Lambda$ and $\bar{\Lambda} - \bar{\Lambda}$ in the same event have also been investigated. The distribution of the opening angle between the pairs shows that $\Lambda - \bar{\Lambda}$ are more often produced in the same jet. The $\Lambda - \Lambda$ and $\bar{\Lambda} - \bar{\Lambda}$ pairs tend to be observed more often in opposite jets. This indicates that the conservation of baryon number occurs locally within a jet, rather than globally

over the entire event. The distribution of rapidity differences between the pairs is consistent with the JETSET model predictions and also supports local baryon number conservation.

The observed rates for double lambda production are consistent with the JETSET predictions. The HERWIG rate for $\Lambda - \bar{\Lambda}$ production is significantly higher than the observation however this is not surprising since the HERWIG rate for individual Λ production is also high. The HERWIG rates for $\Lambda - \Lambda$ and $\bar{\Lambda} - \bar{\Lambda}$ agree with the observations.

The rates for $\Lambda - \bar{\Lambda}$ production can be used along with the rate for single Λ production to investigate baryon number and strangeness compensation in the production. The rates for $\Lambda - \bar{\Lambda}$, and Λ total (assumed to be 1/2 the total rate since no differences were seen between Λ and $\bar{\Lambda}$ production) and their ratio are given in Table 6.2.

	$\Lambda - \bar{\Lambda}$ Rate	Λ Total Rate	Ratio
HERWIG	0.180	0.214	0.77
JETSET	0.090	0.193	0.47
Data	0.105 ± 0.018	0.178 ± 0.015	0.59 ± 0.11

Table 6.2: Observed rates for $\Lambda - \bar{\Lambda}$ production and the JETSET and HERWIG predictions.

The ratios in Table 6.2 indicate the fraction of the time that the strangeness and baryon number of the Λ ($\bar{\Lambda}$) are compensated by a $\bar{\Lambda}$ (Λ). In JETSET this ratio is influenced by the “popcorn” parameter. The data indicate that the amount of “popcorn” meson production is consistent with the 50 % default value of JETSET.

In this thesis the production of Λ baryons in Z^0 decays has been studied. The observed rate is consistent with predictions of Monte Carlo fragmentation models

based either on string fragmentation or cluster fragmentation. However, the momentum spectrum is better modelled by the string fragmentation model. Evidence indicates that there are significant scaling violations at 91 GeV and that there is increased baryon production in the fragmentation of gluons. Observations indicate that baryon number is compensated locally and that in a significant fraction of the events an intervening meson is produced between the baryon and antibaryon.

When the measurement of the Λ rate is included with the rates for other baryons it is seen that the string fragmentation model does a reasonable job of predicting the observed rates. Further observations of the various baryon species and correlations between them will help to shed additional light into fragmentation in general and the baryon production mechanism in particular.

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