

Determination of Differences between Quark and Gluon Jets in 3-jet Events

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Abstract

A comparison of the properties of quark and gluon jets has been made for the reaction $Z \rightarrow q\bar{q}g$ recorded by the ALEPH detector at LEP. A high purity sample of gluon jets is obtained by tagging b flavour events using a track impact parameter method. It is found that for jets of the same energy gluon jets have a larger average particle multiplicity than mixed flavour quark jets. Gluon jets are also broader. Results show that the multiplicity ratio of gluon to quark jets is dependent on both jet energy and event topology. The properties of b -quark jets are found to be similar to those of gluon jets.

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to the memory of my father
(1923 - 1995)

and

to my mother

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Chapter 1

Introduction

Electron-positron annihilation provides a clean environment for the study of jets. LEP energies are about three times those of PEP/PETRA and about 50% higher than at TRISTAN. Multijets produced at LEP are more resolvable than those in the lower energy interactions. This has enabled detailed studies of the differences in particle content between quark induced and gluon induced¹ jets. In the reaction $e^+e^- \rightarrow q\bar{q}g$ three hadronic jets are produced, the third jet resulting from hard gluon radiation. Such events are selected in this analysis and quark and gluon jets are identified by energy ordering and b -quark tagging. The quark and gluon comparisons are made for jets of the same energy and this analysis concentrates mainly on the multiplicity of particles within jets (jet multiplicity) and the broadness of jets. Gluon jets are compared to both mixed flavour quark jets and b -quark jets. The effect of event topology on quark and gluon jet differences is also investigated.

This thesis is organized in the following way. In Chapter 2 some aspects of the Standard Model will be summarized and a review will be given of current phenomenological models used to describe hadron production. Chapters 3 and 4 describe the ALEPH apparatus, data acquisition, and event reconstruction. Chapters 5 to 7 present the analysis of quark and gluon jet differences, and Chapter 8 gives the summary and conclusions.

¹Quark induced jets and gluon induced jets are shortly named as quark jets and gluon jets.

Chapter 2

The Standard Model and Theory of Quark and Gluon Jets

The purpose of high energy particle physics is basically to study and understand the ultimate constituents of matter, and the nature of the interaction between them. Experimental research in this field of science is carried out with giant particle accelerators and their associated detection equipment. High energies are employed first, in order to localize the investigations to the very small scales of distance associated with the elementary constituents, second, many of the fundamental constituents have large masses and require correspondingly high energies for their creation and study. This chapter contains some basic information about the standard model and fragmentation (hadronization). For more information on the standard model see references [1, 2].

2.1 The Standard Model

The standard model deals with the fundamental particles and their interactions. QCD was formulated in analogy to QED as a gauge theory. This field theory describes strong interactions between quarks via the exchange of *gluons* which are massless gauge bosons. They carry colour charge, and therefore gluons can couple directly to other gluons. A consequence is that the strong coupling, α_s , is energy dependent, it diverges at large distances and becomes small at short distances. This can explain why quarks are not observed as free particles.

STANDARD MODEL

FERMIONS spin 1/2							
ELECTRIC CHARGE	QUARKS			LEPTONS			ELECTRIC CHARGE
	<i>u</i> (4×10^3) <i>up</i>	<i>c</i> (1.5) <i>charm</i>	<i>t</i> (174) <i>top</i>	<i>e</i> (5.1×10^4) <i>electron</i>	μ (0.106) <i>muon</i>	τ (1.784) <i>tau</i>	
+ 2/3							- 1
- 1/3	<i>d</i> (7×10^{-3}) <i>down</i>	<i>s</i> (0.15) <i>strange</i>	<i>b</i> (5.1) <i>beauty</i>	ν_e ($< 2 \times 10^{-8}$) <i>electron neutrino</i>	ν_μ ($< 3 \times 10^{-4}$) <i>muon neutrino</i>	ν_τ ($< 4 \times 10^{-2}$) <i>tau neutrino</i>	0
BOSONS spin 1							
<i>em.</i>		<i>weak</i>		<i>strong</i>			
γ		$W^\pm, Z^0$		<i>gluons</i>			

Table 2.1: *Standard model fundamental particles quarks and leptons including their properties, and bosons. The numbers in the parenthesis show the mass of the particles in GeV/c^2 .*

2.1.1 The Fundamental Particles

The standard model particles; quarks, leptons, and bosons including their properties are shown in Table 2.1. All matter is composed of fundamental spin 1/2 fermions; the *quarks* carrying fractional electric charges ($+\frac{2}{3}e$, and $-\frac{1}{3}e$), and the *leptons*, like the electron and neutrino, carrying integral electric charges. There are six quarks, (u, d, s, c, b, t), in three families, each one grouping two quarks differing by one unit of charge. In parallel with these three quark families, there are three families of leptons, (e, μ, τ) containing each a negatively charged particle and a neutrino. Each quark exists under three varieties of *colour*, which are called *red, green, blue*, whereas the leptons have no *colour*. This altogether represents 24 fundamental particles, to which associates as many antiparticles, with the same masses but the opposite charges and *colours*.

In the quark composition of some baryons (i.e. Δ^{++} which is made from three u quarks with charge $+2/3$, Ω^- which is made from three s quarks with charge $-1/3$) three quarks are in the same state, which is a gross violation of the Pauli exclusion principle (which says that to have even two identical spin-half particles in the same state is forbidden). They have to possess a hitherto unknown quantum number able to take (at least) 3 different values, one for each quark in the baryon. This quantum number was given the name *colour*. They do not have any intrinsic meaning, to describe a 3-valued property of quarks. Antiquarks

carry anticolour, and if the q and $\bar{q}$ that make up a meson are the appropriate colour/anticolour pair, then the colours can cancel and make that meson colourless. Similarly baryons can have no net colour. The existence of antiparticles is the general property of both fermions and bosons, the antiparticle having the same mass as the particle, but opposite charge and magnetic moment. Fermions and antifermions can only be created or destroyed in pairs. Theoretically, particle and antiparticle states are connected by the process of particle-antiparticle conjugation. Fermion number is conserved if each fermion is assigned a fermion number +1 and each antifermion -1. So the process of particle-antiparticle conjugation for fermions gives an antifermion with opposite charge, magnetic moment, and fermion number, but identical mass and spin angular momentum.

Neutrons and protons are built from quarks, three at a time. In the standard model neutrinos have zero mass [3]. Figure 2.1 shows the theoretical predictions for the total hadronic cross-section in the cases of 2, 3, and 4 generations of neutrinos as a function of E_{cm} , compared with the ALEPH data for 1990 and 1991 at the Z resonance. The data are in agreement only with 3 generations of neutrinos.

These constituents can interact by exchange of various fundamental bosons (vector particles of spin 1) which are the carriers or quanta of four distinct types of fundamental interaction or field. Strong interactions are responsible for the interactions between nucleons, nucleons and mesons and a number of other particles. The mesons act as the quanta of the strong interaction on the nuclear scale. These interactions reflect the interaction between quarks due to the exchange of gluons on the sub-nucleon level. Electromagnetic interactions are responsible for the force between electrically-charged particles and are mediated by the exchange of photons, γ . Weak interactions are responsible for many particle decays such as radioactive decay, pion and muon decay and a number of other processes. $W^\pm$, Z are the mediators for this interaction. The electroweak theory of Glashow, Salam, and Weinberg combines the electromagnetic and weak interactions as a single unified theory. Gravitational force exists between all particles having mass and are believed to be mediated by graviton. This has not been placed in the standard model, the effect of gravity is negligible, therefore it is ignored.

Particle Mass

The masses of the quarks are not strictly defined [4]. The mass of a particle is equivalent to its rest energy in a state of zero potential energy, but as quarks are never free they are never in such a state. Alternatively, the mass prescribes the

acceleration produced by an applied force, but one cannot arrange for this force to be applied only to the quark whose mass is being measured, and not to the other quarks in the hadrons.

In the gauge theory, the gauge fields should all have a zero mass. This is the case for the photon and for the gluons but the W and Z are very massive, with masses close to a hundred times that of the proton. The strict invariance property used also seems to require all quarks and leptons to be massless, which

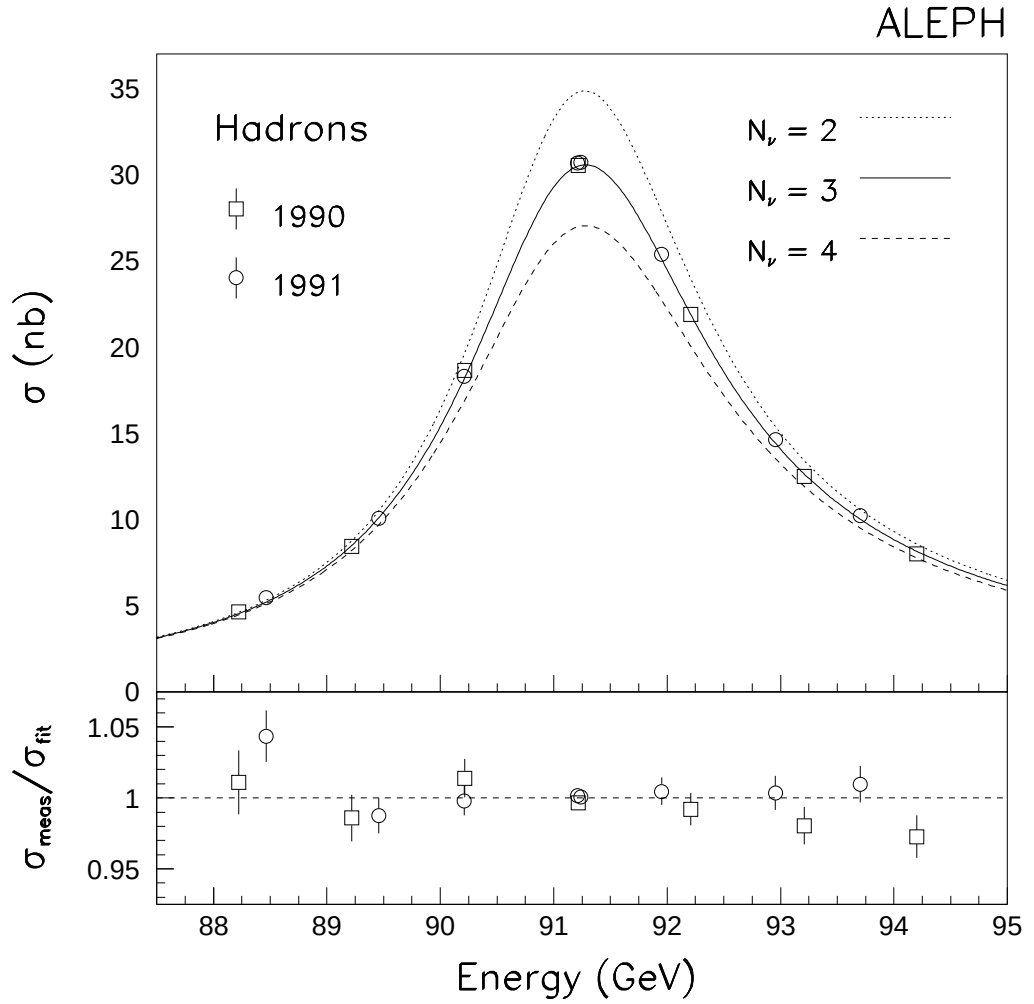


Figure 2.1: *The hadronic cross section as a function of center-of-mass energy, E_{cm} . In the upper plot; the dots show the measured values of the hadronic cross section, and the three curves are the expected line shape for 2, 3 and 4 neutrino families. Data has good agreement with the neutrinos number which is 3. The lower plot represents their ratios of measured to expected for $N_\nu=3$.*

is obviously not the case. The answer to this problem is however provided by the higgs mechanism. It allows a breaking of the primordial symmetry, providing masses to the particles but keeping enough relations untouched so that the theory remains renormalizable.

2.1.2 e^+e^- Annihilation into Hadrons

The reaction of $e^+e^- \rightarrow$ hadrons can be divided into four stages as illustrated in Figure 2.2.

- (i) In this stage the electron and positron annihilate into an intermediate vector boson (γ or Z) which decays into a quark-antiquark pair. This part of the process is well described by the standard model of electroweak interactions using perturbation theory.
- (ii) This stage is described by perturbative QCD. The initial quark and anti-quark pair move apart with a certain probability of radiating a hard (i.e. large momentum transfer, Q^2) gluon which in turn may radiate further gluons or split into secondary quark-antiquark pairs. That way the initial virtuality of the primary quarks gradually decreases in a parton showering process until it falls below a cutoff, at which point the cascade stops. In the case of 3- or more-jet events the produced quark or antiquark radiates an energetic gluon before it fragments into a jet. Hard gluon emission can be described by perturbation theory of Quantum Chromodynamics, since for sufficient large Q^2 the QCD coupling constant α_s is small. These primary partons are not directly observed. Instead one can observe the *jets* of hadrons, a jet being several or more particles whose momenta are more or less aligned along some axis.
- (iii) At this stage the final state partons are combined into colour neutral hadrons. The transformation of initial partons (quarks and gluons) into observable hadrons is known as fragmentation which is not calculable perturbatively, this is described by phenomenological models which are explained later in this chapter.
- (iv) Hadrons and decay products of short lived particles emerge as the visible products of the process. The observable (colour neutral) hadrons include resonances. The resonances decay into longer lived hadrons (e.g. pions, kaons, protons) which can be detected experimentally. After the primary

hadrons are formed, their decay can be modeled according to measured branching ratios and lifetimes.

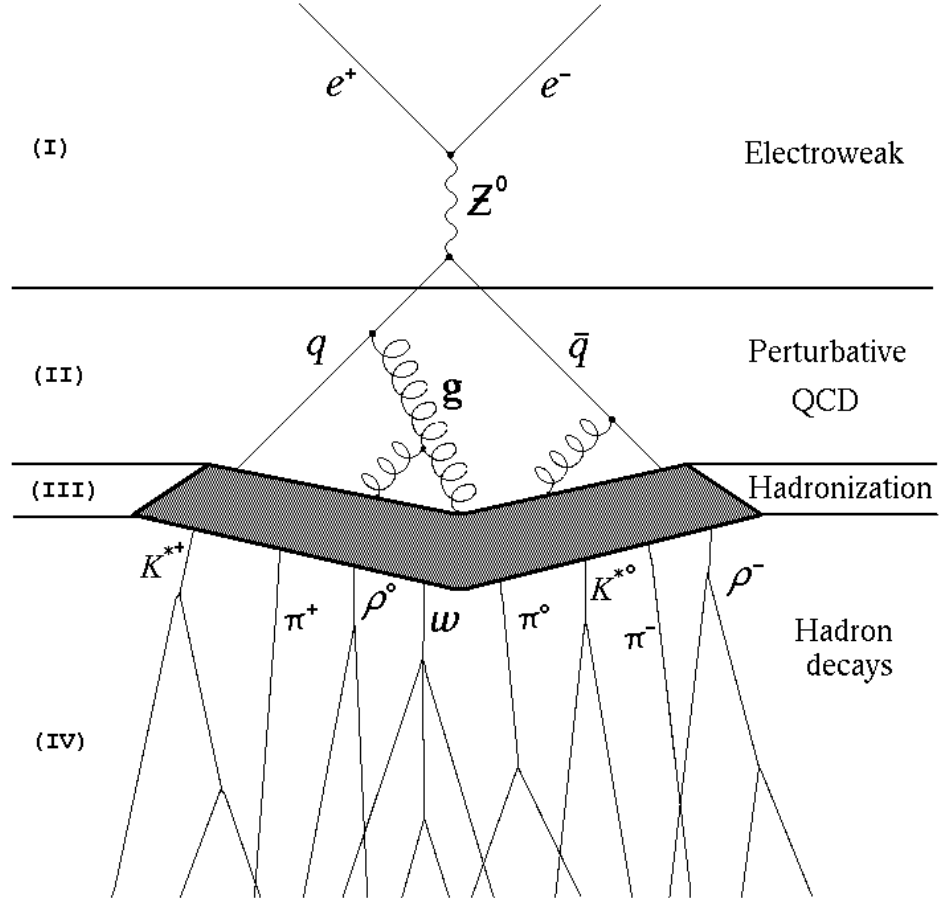


Figure 2.2: *Illustration of the four stages of e^+e^- annihilation into hadrons (i.e. $e^+e^- \rightarrow Z \rightarrow q\bar{q}g \rightarrow \text{hadrons}$); (I) Electroweak, (II) Perturbative QCD, (III) Fragmentation, and (IV) Hadron decays.*

2.1.3 Perturbative QCD and the Gluon

All interactions can be described in terms of a unique gauge principle. The deep origin of all the basic interactions is found in invariance properties, or symmetries, which the laws of physics should show with respect to some interchanges of the properties which we attach to the quarks and leptons, thus defining their different and specific characters. The universal validity of these symmetries calls for a

gauge formulation and the gauge properties imply the existence of forces and specify their properties.

Quantum Electrodynamics (QED) is a gauge theory that is determined by Lorentz invariance and by the gauge invariance property attached to the phase of the charged fields. Quantum Chromodynamics (QCD) is the field theory of strong interactions between quarks via exchange of massless gauge bosons, *gluons*. The formation of a gauge theory of the weak interaction, the only interaction which can change the nature of a quark or of a lepton, requires its combination with electromagnetism into a unique gauge theory covering both.

Lorentz invariance and specific gauge symmetries thus specify the nature and structure of all these interactions. The basic processes all correspond to the exchange of a quantum of the gauge field and the number of gauge fields is specified in each case by the gauge symmetry group. For the electroweak interaction it is $SU(2) \times U(1)$. Therefore four gauge fields and the basic physical processes correspond to the exchange of a photon (electromagnetic coupling), the exchange of a charged W (standard weak coupling) and to the exchange of a neutral Z (neutral current weak coupling). For the strong interaction the gauge group is $SU(3)$. One has therefore eight gluons each carrying *colour*.

The electroweak theory has two couplings. One can be chosen as the electromagnetic coupling. The coupling constant α at LEP is not the standard fine structure constant α , which is defined at zero momentum transfer and takes the well known value of $1/137.0459$.

The final quark-antiquark pair created in the annihilation process are not free from each other but they move apart with a relative speed close to c , interacting via gluon exchange. For sufficiently small distance ($d \sim 10^{-14}$ cm) the four-momentum transfers involved in the interaction are sufficiently large ($\sqrt{Q^2} \sim 1/d$) that perturbation theory can be used. This is because the coupling constant in QCD, α_s , decreases for large Q^2 . α_s , which depends on the separation between the interacting particles, is expressed by the equation (1st order);

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\ln(Q^2/\Lambda^2)} \quad (2.1)$$

where Q^2 is the momentum transfer scale at which α_s is obtained (on the Z peak $Q^2 = (91.2 \text{ GeV})^2$), n_f is the available number of quarks ($n_f = 5$ at LEP), and Λ is a free dimensional parameter determined by experiment. At short distances α_s is small and the quarks and gluons behave like free particles (known as asymptotic freedom). Conversely at large distances (low momenta) Q^2 decreases and α_s become very large leading to the breakdown of perturbative method.

Gravitational and electromagnetic forces obey an inverse square law. At large distance the force becomes weaker, such that its integral to infinity is finite, giving the binding energy of the particle. For the QCD force this not the case; at large distances (low momenta) the effective coupling constant increases. The colour charge of a quark is dispersed into the surrounding vacuum by its surrounding cloud of (colour-carrying) virtual gluons. Thus short distance interactions, which probe inside the cloud, see a smaller effective colour charge, conversely long range interactions see the increased effect of full charge. This means that the force does not obey an inverse square law - the exact large distance form is not established. The field of a colour dipole is restricted to a narrow region between the two charges, because gluons interact with one another, whereas photons do not. As the separation between two colour charges increases, the energy increases and is stored in the field between them, like a flux tube or string. As the separation between the two colour charges increases, more and more energy is stored in the string. Eventually it will break: a colour-anticolour pair of quarks will appear out of the vacuum by a spontaneous fluctuation, and each combine with the appropriate part of the original to form two colourless objects between which there is no colour force. Matrix element Monte Carlos employ the 2^{nd} order calculations to determine the relative fraction of two, three and four parton final states. The conversion of final state partons into hadrons cannot be described by perturbative QCD.

2.2 Fragmentation Models

The perturbative method gives a good description of processes for which the expansion parameter α_s (Equation 2.1) is reasonably small, i.e for short distances and large Q^2 . When the Q^2 of the interaction decreases below about 1 GeV^2 , the strong coupling constant, α_s , becomes of the order unity, and the methods of perturbation are inappropriate and exact calculations are impossible. Fragmentation which can be defined as the transformation of coloured partons into colourless hadrons is described by QCD at low Q^2 . To obtain quantitative predictions for the production rates of pions, kaons, and protons, phenomenological models must be used. These models were implemented as Monte Carlo programs. Two of the models are explained briefly later in this chapter. They are String and Cluster fragmentation models which are used to compare the experimentally measured distributions in this analysis. These two models are available in the form of Monte Carlo packages; JETSET and HERWIG respectively.

JETSET

JETSET deals with the fragmentation process which converts the partons into observable hadrons [5]. This is done in two stages: first the emission of gluons in a parton shower, and in the second stage the resulting shower is hadronized using string model fragmentation. The final state photon radiation is also simulated in the JETSET Monte Carlo programme.

HERWIG

The simulation of the hadronic Z decay is also done using the HERWIG Monte Carlo programme. This generates 2^{nd} order matrix element parton configurations which are subsequently showered. The HERWIG program is achieved using the cluster model fragmentation.

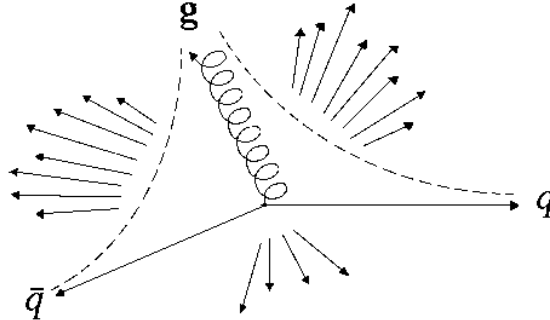


Figure 2.3: *Illustration of the first radiated hadron direction in $q\bar{q}g$ events in string model (string effect).*

2.2.1 String Hadronization

One of the approaches to hadronization is the string model [6]. As experimentally well established in $q\bar{q}g$ 3-jet events, less hadrons are produced in the region between the two quarks than between a quark and the gluon. The string fragments into mesons in its own rest frame which results in more soft particles between the q and g and between the g and $\bar{q}$ jets than between the q and $\bar{q}$ jets. This is called ‘string effect’ [7] which is illustrated in Figure 2.3. The method used in most experimental investigations relies on energy ordering: The two most energetic jets

have high probabilities to be quark jets, the least energetic jet has a probability of more than 60% to be gluon jet.

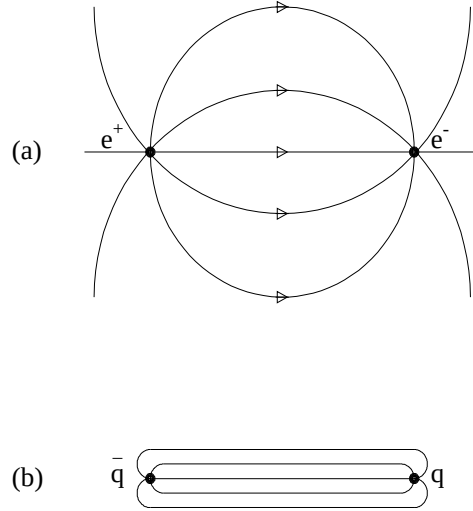


Figure 2.4: *a) The electric (QED) field lines between an electron and positron, spreading out to infinity. b) The colour (QCD) field lines between a quark and antiquark, confined in a narrow flux tube.*

In the String model the nonperturbative interaction between partonic colour charges and the formation of the final state hadrons is modeled by the breakup of a colour flux tube. This is motivated by the observation, that due to the gluon self-coupling the field lines of static colour field attract each other to form a flux tube. Figure 2.4 shows the electric field lines between an electron and positron, spreading out to infinity and colour field lines between a quark and antiquark. Assuming that this ‘string’ has a constant energy per unit length one expects the QCD potential to grow linearly at large distance. Such a large distance behaviour is supported by lattice calculation and provides a natural explanation for quark confinement. In the string fragmentation model as quark-antiquark pairs move apart, the potential energy stored in the string increases and string may break by production of new quark-antiquark pair, which terminates the resulting daughter-strings. Gluons which have the colour structure of a quark-antiquark state act as kinks in the original string often producing independent jets of hadrons clearly separated from the original quark and anti-quark jets. Figure 2.5 shows the string hadronization model. If the invariant mass of these strings is

large enough then further breaks occur until only on-shell hadrons remain, each hadron corresponding to a small piece of string. Again the break of the string is governed by a fragmentation function.

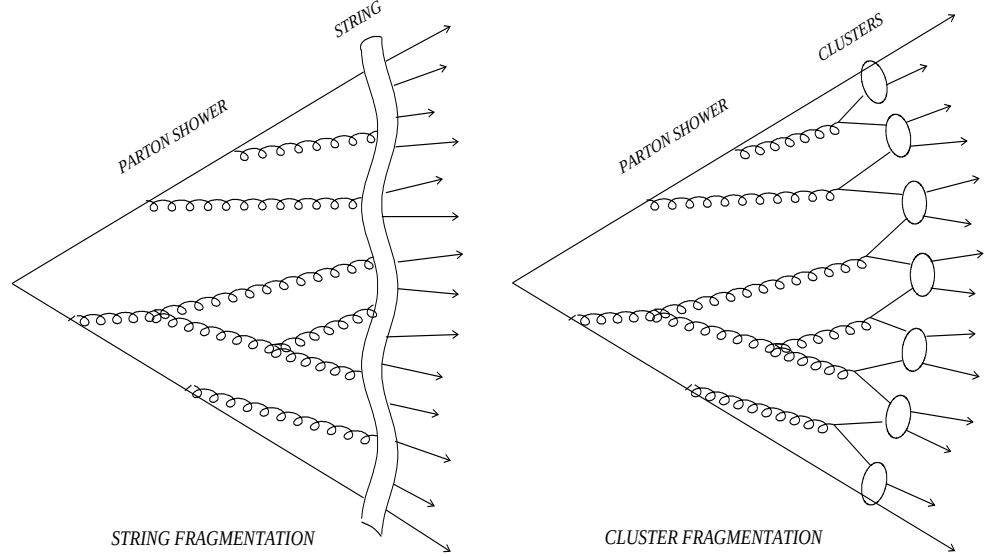


Figure 2.5: *Illustrations of string and cluster fragmentation models.*

2.2.2 Cluster Hadronization

Cluster model fragmentation has been introduced by Webber and Marchesini [8, 9]. An illustration of cluster model fragmentation is shown in Figure 2.5. As gluons carry a larger strong colour charge than quarks, one expects this to produce a difference in their fragmentation. In a very naive cluster model, when the parton virtuality falls below ~ 0.7 GeV, all gluons in the final state are split into $q\bar{q}$ pairs. The colour of each final state is carefully managed so that colourless quark-antiquark clusters are then combined to form colour singlet cluster. Afterwards these clusters subsequently decay into the final colourless pairs of hadrons.

2.2.3 Jet Production

In the strong interaction the simplest process consists of the formation, in an electron-positron collision, of a Z which decays into a quark-antiquark pair. The

quarks are never seen as isolated particles. Their energy and momentum is shared amongst several hadrons. At high energy the e^+e^- annihilation to hadrons is dominated by jets, which are narrow clusters of hadrons (mesons and baryons). Part of the time the production of the quark-antiquark pair is accompanied by the radiation of an energetic gluon. This gives a third jet. In e^+e^- annihilation quark jets occur predominantly in the two jet ($q\bar{q}$) topology, but gluon jets occur only in three or more jet topologies ($e^+e^- \rightarrow q\bar{q}g$). There are thus large kinematic differences superimposed on any dynamical difference. The nature of the jets reflects the nature of the quarks produced in

$$e^+e^- \rightarrow Z(\gamma) \rightarrow q\bar{q} \text{ or } q\bar{q}g \quad (2.2)$$

The quark and anti-quark should emerge in opposite direction in order to conserve momentum. Therefore two clusters of hadrons (jets) should be observed on opposite sides of the annihilation point. The particles are produced due to the fragmentation of the initial quarks or partons into hadronic states. In the range 14 - 44 GeV, e^+e^- annihilation produces jets from the fragmentation of quarks in the ratio of their charge-squared $u : d : c : s : b = 4:1:4:1:1$ [9]. Charm and beauty mesons can be produced from the leading c and b quarks, and lighter flavours from both leading and non-leading flavours in the fragmentation chain.

Figure 2.6 shows the lowest order Feynman diagram for (a) 2-jet and (b) 3-jet events. Using the Feynman diagram rules derivable from the Lagrangian of QCD, the cross section for when one of the quarks emit a gluon can be computed. The lowest order (1st order perturbative QCD) cross section σ , can be defined in terms of the kinematic variables of the $q\bar{q}$ pair for massless quarks;

$$\frac{1}{\sigma} \frac{d\sigma}{dx_q dx_{\bar{q}}} = \frac{\alpha_s}{2\pi} C_F \frac{x_q^2 + x_{\bar{q}}^2}{(1-x_q)(1-x_{\bar{q}})} \quad (2.3)$$

these scaled energy, kinematic, variables are;

$$\begin{aligned} x_q &= 2 \frac{E_q}{\sqrt{s}} \\ x_{\bar{q}} &= 2 \frac{E_{\bar{q}}}{\sqrt{s}} \\ x_g &= 2 \frac{E_g}{\sqrt{s}} \end{aligned} \quad (2.4)$$

where $\sqrt{s}$ is the centre-of-mass energy, and C_F is a colour factor for the process $q \rightarrow qg$. The cross-section diverges if the gluons energy approaches zero, leading to $x_q \rightarrow 1$ and $x_{\bar{q}} \rightarrow 1$, or if the gluon is collinear with either the quark or

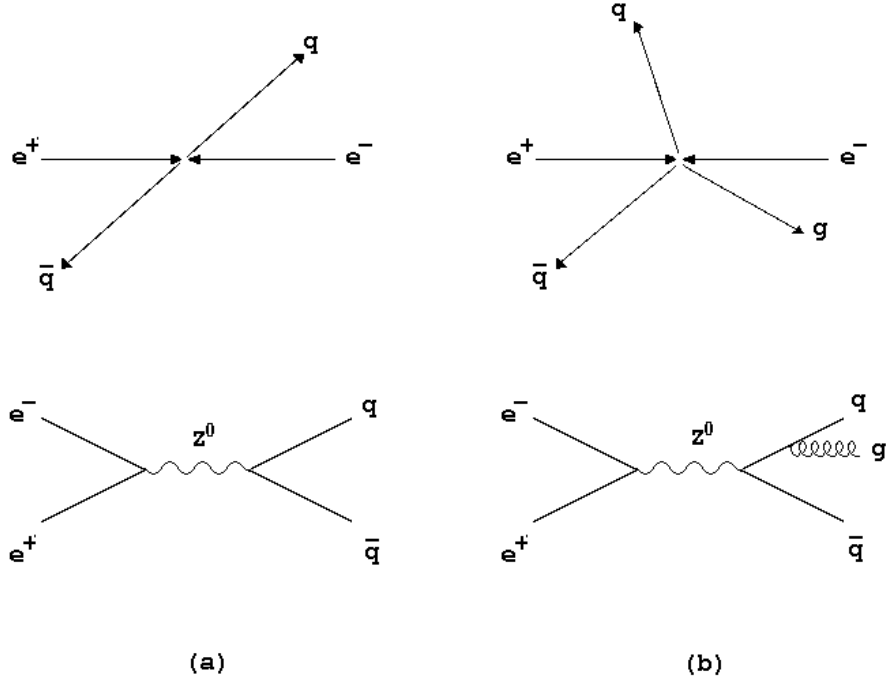


Figure 2.6: *Schematic and Feynman diagrams of (a) two-jet, (b) three-jet structures of an event.*

antiquark, leading to $x_q \rightarrow 1$ or $x_{\bar{q}} \rightarrow 1$. The 2^{nd} order perturbative QCD can be described in 4-jet events such as $Z \rightarrow \text{hadrons}$ ($q\bar{q}q\bar{q}$ and $q\bar{q}gg$). The calculation of it is complicated mathematically, more information can be found in reference [10].

According to equation 2.3 quark-antiquark pairs are more likely to carry off a high fraction of energy (x), and thus the gluon is more likely to carry lower x than the two other partons. Therefore the energy ordering can be used to separate quark and gluon jets.

2.3 Quark and Gluon Jet Differences

Particle contents (known as multiplicity) of the quark and gluon jets can be used to show their differences. In perturbative Quantum Chromodynamics (QCD), gluons carry a larger colour charge than quarks and are therefore more likely to radiate further gluons via bremsstrahlung. This is expected to result in softer

gluon jets which would be observed through a higher particle multiplicity¹, a softer particle momentum spectrum and broader jets [11].

The gluon is associated with a colour charge $C_A=3$ and the quark with a charge $C_F=4/3$, Therefore one naively expects the ratio of multiplicity in gluon jets to that in quark jets to be $\frac{C_A}{C_F} = \frac{9}{4}$ [12, 13]. However this ratio is calculated at the parton level for pairs of collinear gg and $q\bar{q}$ jets at infinite (asymptotic) energy and leading order. A large non-leading and finite energy correction of order $\sqrt{\alpha_s}$, heavy quark effects, and 2^{nd} order calculations significantly reduce the magnitude of gluon-quark jets multiplicity differences at present energy [14].

In this analysis, quark and gluon jets from $Z \rightarrow q\bar{q}g$ events are used for comparison. The naive prediction of $\frac{C_A}{C_F} = \frac{9}{4}$ for the ratio of multiplicity in gluon jets to that in quark jets in these events is expected to be too large due to three main processes:

- (i) Higher order terms producing additional multiplicity in both quark and gluon jets 'dilutes' the ratio of multiplicities.
- (ii) Colour conservation necessitates a communication of multiplicity between jets. This can result in some soft particles originating from a gluon jet being assigned to a quark jet thus reducing the multiplicity ratio.
- (iii) The multiplicity of b -jets is higher than that of light quark jets due to the decay of heavy flavour hadrons.

The comparisons made in this analysis concentrate mainly on jet multiplicity and broadness. Comparisons are made at similar energies to remove energy dependences. Gluon jets are compared to b -quark jets as well as mixed flavour quark jets.

¹Local-Parton-Hadron Duality (LPHD) assumes that the multiplicity of hadrons directly related to the multiplicity of partons.

Chapter 3

The ALEPH detector at LEP

3.1 The LEP Collider

The large electron-positron collider (LEP) which is the largest machine ever constructed is situated at the European Laboratory for Particle Physics, CERN, in Geneva. LEP is located in an underground 3.8 m diameter tunnel at a depth varying between 50 and 170 m. The circumference of the collider is about 26.7 km with an average diameter of 8.486 km. For geological reasons the tunnel is not horizontal, it is inclined by 1.42° .

LEP is designed to accelerate, store, and collide electrons and positrons up to beam energies as high as 55 GeV which is enough to produce the heaviest known elementary particles for studying the parameters of the standard electroweak model in detail, such as the production and decay modes of the Z and $W^\pm$ bosons, and QCD processes. At the center-of-mass energy of 91.2 GeV, it produces Z bosons with a luminosity of the order of $10^{31} \text{ cm}^{-2} \text{ s}^{-1}$. The beams of electrons and positrons circulate in separate orbits inside a vacuum tube of approximately 10 cm diameter, and are brought into collision at four points around the circle. At these points there are large particle detectors ALEPH, OPAL, DELPHI, L3, which are designed to study the nature and frequency of the different processes which occur in e^+e^- collisions. The data which are collected by ALEPH detector have been used in this analysis. The location of these four experiments, and the LEP tunnel are shown in Figure 3.1. LEP is the final stage of a chain of accelerators used to provide and accelerate positrons and electrons. In the near future, an increase of center of mass energy to 160 GeV is planned for the production of W^+W^- pairs (a project named LEP-II). It will allow the search for new phenomena, such as the Higgs bosons or supersymmetric particles.

Figure 3.1: *The LEP ring and location of the four experiments. N indicates the direction of the north, HP and LP the high and low points of the inclined ring.*

The LEP injection system

The LEP injection system is shown in Figure 3.2. In the LEP Injection Linac (linear accelerator), LIL, electrons are first accelerated to 0.2 GeV and directed onto a tungsten target from which emerge electrons and positrons. These are then accelerated to an energy of 0.6 GeV in the second Linac after which they are fed into an Electron-Positron Accumulator, EPA. This process continues until a sufficient number of electrons and positrons have been produced to pass into the Proton Synchrotron, PS, where they are accelerated up to an energy of 3.5 GeV. Before the beams are injected into LEP, the particles are accelerated to 20 GeV in the Super Proton Synchrotron, SPS. The 20 GeV electron-positron beams are injected (in bunches) into LEP with electrons travelling an anticlockwise direction when view from above. In LEP the beams are finally ramped up to the collision energy of about 45.6 GeV. During injection and ramping the beams are separated by electrostatic separators. The bunches collide every 22 μ sec (4 bunch mode) before 1993 and 11 μ sec (8 bunch mode) for 1993 running.

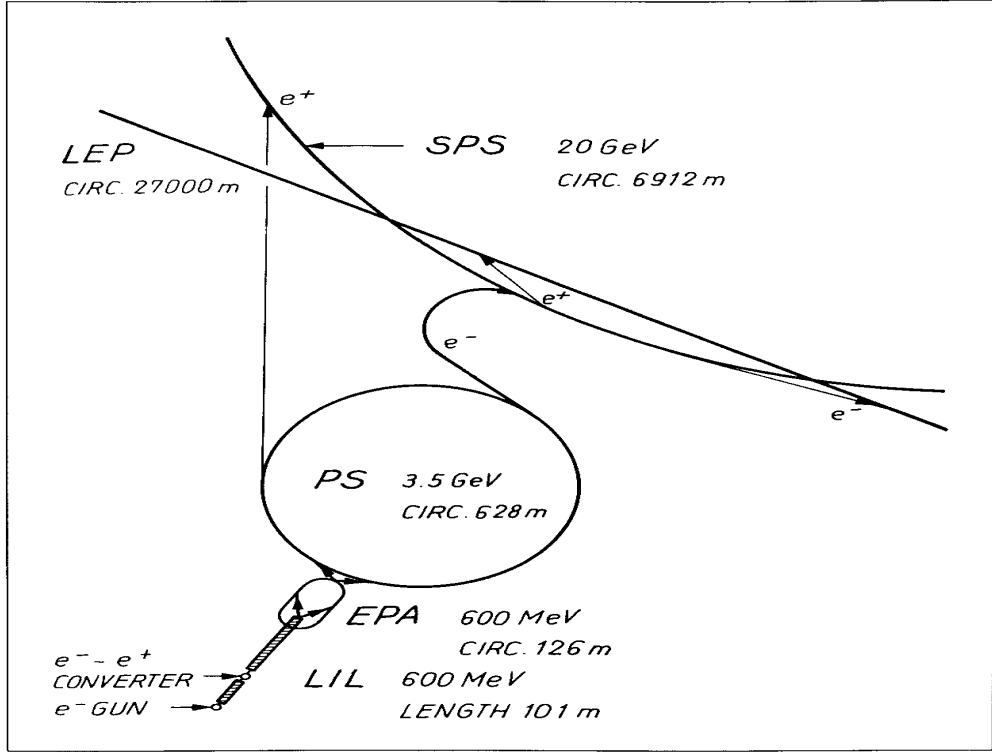


Figure 3.2: A schematic diagram of the LEP injection system.

3.2 The ALEPH detector

ALEPH has been built to determine, as precisely as possible, the nature, direction and energy of each particle in the event created in an e^+e^- collision at the Z resonance in LEP. It has been running since 1989.

An overall view of the ALEPH detector is shown in Figure 3.3. It is a collection of independent subdetectors [15, 16]. The experimental data are collected from 500,000 electronic channels which supply the necessary information to reconstruct the particle trajectories at the moment of the collision. The dimensions of the detector, located 140 m underground at Echenevex in France, are approximately 12x12x12 m, its weight is about 3000 tons and its cost is 70 million Swiss francs. It is designed to measure the momenta of charged particles, to measure the energy deposited in calorimeters by charged and neutral particles, to identify the three lepton flavours, and to measure the distance of travel of short-lived particles such as the tau lepton and the b and c hadrons.

For the tracking system, there are three subdetectors in ALEPH; a vertex detector composed of two layers of double sided silicon microstrips, a drift chamber with 30 cm outer radius, which is also important as part of the first level trigger

Figure 3.3: *A perspective view of ALEPH detector at LEP.*

system, and a time projection chamber, TPC with 180 cm outer radius.

Calorimetry consists of two subdetectors; the Electromagnetic Calorimeter (ECAL) and the Hadronic Calorimeter (HCAL). These calorimeters provide measurements of energy and position for both charged and neutral particles, they also provide some particle identification. A superconducting solenoid provides an axial magnetic field which bends the trajectories of charged particles for momentum measurements. The final detection layer contains of muon chambers for muon identification. For the luminosity measurement, luminosity monitors are positioned at each end of the detector.

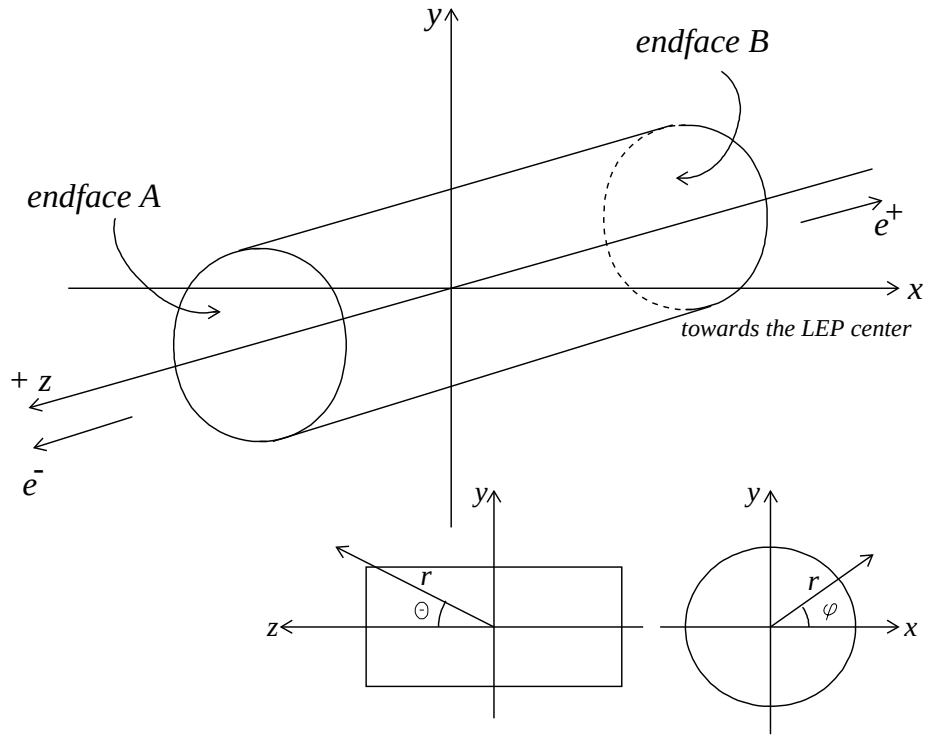


Figure 3.4: *The ALEPH Coordinate System.*

The ALEPH Coordinate System

The ALEPH coordinate system is shown in Figure 3.4. The positive z -direction is that in which the electrons flow. Because of the inclination of LEP ring, the z -axis is 3.587 mrad to the local horizontal. The positive x -direction points radially towards the centre of the LEP ring, and the positive y -direction is orthogonal to x and z and points skyward. The spherical components are obtained through the

relations; $x=r \sin \theta \cos \phi$, $y=r \sin \theta \sin \phi$, $z=r \cos \theta$. ϕ is the azimuthal angle and θ is the polar angle.

Figure 3.5: *Configuration of the ALEPH silicon vertex detector, VDET.*

3.2.1 Tracking Detectors

The Minivertex Detector, VDET

The VDET is a double layer silicon strip detector providing 3-dimensional coordinates for charged tracks close to the interaction point. The VDET consists of two concentric barrels of length 200 mm. The inner barrel is dodecagonal with a radius of 95 mm and covers 76% of 4π solid angle. The outer barrel is hexadecagonal with radius 114 mm and has an angular coverage of 67% of 4π (Figure 3.5). Each surface of the two barrels is constructed from silicon wafer microstrip detectors of thickness $300 \mu\text{m}$ and area $51.2 \times 51.2 \text{ mm}^2$. There are four wafers along the length of each module giving a total of 112 wafers on all 28 surfaces. Individual strips are mounted on both sides of the wafers, with the strips on one

side parallel to the beam to measure the ϕ coordinate, and on the other the strips are perpendicular to the beam to measure the z coordinate. The radial position r is determined from the position of wafer. The strip pitch is $25\text{ }\mu\text{m}$ in $r - \phi$ and $50\text{ }\mu\text{m}$ in z . However, the readout pitch is $100\text{ }\mu\text{m}$ in $r - \phi$ and $200\text{ }\mu\text{m}$ in z as only every fourth strip is used for the readout, but the three strips between are used to improve the position resolution. The inner layer has 12,288 $r - \phi$ and 21,505 z strips. The outer layer has 7,168 $r - \phi$ and 10,240 z strips. The total of 51,200 strips are readout through charge sensitive preamplifiers which are multiplexed by a factor $\simeq 60:1$ to give 1008 readout channels.

Performance: Single track resolution is $\sigma_{r\phi} = 13\mu\text{m}$, and $\sigma_z = 20\mu\text{m}$. Two tracks can be resolved to $200\text{ }\mu\text{m}$ in $r - \phi$ and $400\text{ }\mu\text{m}$ in z .

The Inner Tracking Chamber, ITC

The ITC which is a cylindrical multiwire chamber serves both tracking and level-1 triggering. Figure 3.6 shows an overall view of the ITC. For the trigger, the ITC has two associated processors that find, respectively, charged particle trajectories either in two dimensions (the $r - \phi$ projection) or in three dimensions. The speed of the trigger decision is dependent upon drift time, hence the choice of small cells. The ITC is the only track detector used in the first level trigger. Tracks, and thus a trigger decision are determined as follows. First; a hit wire latch is used to search for tracks in radial patterns of wire cells. This provides 2- d coordinates in $r - \phi$. Second; the pulsed outputs are used to determine the z -coordinate, and this allows 3- d coordinates in $r - \phi - z$ to be calculated.

Performance: Tracks with $-0.97 < \cos \theta < 0.97$ will traverse all layers. It provides up to eight $r - \phi$ coordinates with accuracy of $\sigma_{r\phi} = 100\text{ }\mu\text{m}$ calculated from the drift time, and z coordinates with an accuracy of $\sigma_z = 3\text{ cm}$ calculated from pulse arrival time difference at each end of the wires. This accuracy for the $r - \phi$ trigger decision is obtained in 500 nsec and $r - \phi - z$ trigger decision in $2\text{ }\mu\text{sec}$.

The Time Projection Chamber, TPC

The TPC is the main ALEPH central tracking detector. A view of the TPC detector is shown in Figure 3.7. It provides the information about the momentum and emission angle of charged particles and particle identification from energy loss through dE/dx measurements. The chamber has a cylindrical structure. Its axis lies parallel to the magnetic field axis. An electric field propagates from two end

Figure 3.6: *An overall view of the Inner Tracking Chamber, ITC.*

plates towards a central membrane which divides the chamber into two halves. Each end plate houses 18 wire sectors which measure up to 21 3-dimensional space points per track. The helical charged track trajectories are projected onto the end plate sectors as arcs. The electrons produced by the track ionization drift towards one of the end plates, where they induce an avalanche in one of the wire chamber planes. The z -coordinates are deduced from the drift time of the electrons as the drift velocity of the field is known. The $r - \phi$ coordinate is calculated by interpolating the signals induced on the cathode pads which are precisely located in the sectors. The r coordinate alone is simply determined from the pads radial position.

Performance: $r - \phi$ accuracy is about $180 \mu\text{m}$ at 0° pad crossing angle. z spatial resolution is 1.2 mm (wires) with small z dependence, and 0.8 mm (pads) at $\theta=90^\circ$. Momentum resolution for TPC only is $\delta p/p \simeq 1.2 \times 10^{-3} p(\text{GeV}/c)^{-1}$ at 45 GeV . The momentum resolutions for TPC plus ITC is $\delta p/p \simeq 0.8 \times 10^{-3} p(\text{GeV}/c)^{-1}$, and for TPC plus ITC plus VDET is $\delta p/p \simeq 0.6 \times 10^{-3} p(\text{GeV}/c)^{-1}$ at 45 GeV . The error on p_t of a track with 21 measured coordinate is $\delta p_t/p_t \simeq 0.001 p_t (\text{GeV}/c)^{-1}$.

Figure 3.7: *An overall view of the Time Projection Chamber, TPC.*

3.2.2 Calorimeters

The Electro-magnetic Calorimeter, ECAL

The ECAL is a lead/wire-chamber sampling device of nominal thickness 22 radiation lengths (X_o). The total energy and position of the e.m. showers are measured using small ($\sim 30 \times 30$ mm²) cathode pads. The cathode pads are connected internally to form ‘towers’ pointing to the interaction point. Each tower is read out in three sections in depth (‘storeys’), corresponding to the first 4, the middle 9, and the last 9 radiation lengths. Figure 3.8 shows an overall view of the ECAL. The calorimeter is a highly granular hermetic detector with 3.9π solid angle and 73,728 towers with cracks representing 2% of the barrel and 6% of the end-cap surfaces. Each of towers covers an angle of approximately $1^\circ \times 1^\circ$. It operates within the ALEPH solenoid magnetic field at 1.5 Tesla.

Performance:

$$\begin{aligned} \text{Energy resolution } \Delta E/E &= 0.01 + 0.18/\sqrt{E(\text{GeV})} \\ \text{Angular resolution } \sigma_\phi = \sigma_\theta / \sin \theta &= 0.32 + 2.7/\sqrt{E(\text{GeV})} \text{ mrad.} \end{aligned}$$

Figure 3.8: *A view of the Electro-magnetic Calorimeter, ECAL.*

The Hadronic Calorimeter, HCAL

The HCAL is a large sampling calorimeter which is designed to measure the energy and position of hadronic showers as well as providing a large proportion of the muon identification (Figure 3.9). The calorimeter uses the large iron return yoke of the magnet as its absorbing medium. The HCAL consist of 23 layers of plastic streamer tubes separated by iron sheets 5 cm thick. The tubes are ~ 7 m long, have a wall thickness of 1 mm and internal cross-section of 9×9 mm². The inner walls of the channels are graphite coated and 100 μ m diameter anode wire running the whole length of the channel is centred within each. They are similar in construction to proportional counters but operate at high voltage of 4250 V in limited streamer mode. Each tower covers a solid angle of $3.7^0 \times 3.7^0$. The hadronic showers which are produced from hadrons passing through the iron layers can be detected as signals. There are three signals derived from the HCAL. They are pad signals, strip signals and wire signals.

Figure 3.9: *A view of the Hadronic Calorimeter, HCAL.*

- Pad signals, which are used to measure the energy released from the showers in the calorimeter.
- Strip signals, which give the pattern of tubes fired in the event. The cathode strips are parallel to the wires and these provide digital hit patterns in $r\phi$.
- Wire signals, which measure the energy released in single planes, are summed over those individual planes and used as part of the trigger.

Performance: The energy resolution $\Delta E/E$ is $\sim 84\%/\sqrt{E(\text{GeV})}$ within an angular acceptance of $-0.99 \leq \cos \theta \leq 0.99$.

3.2.3 Muon Chambers

Muon chamber consists of two double layers of tubes known as the inner and outer chambers. The tubes within one double layer are perpendicular to each other. The muon chamber streamer tubes provide digital signals from strips running

parallel and perpendicular to the central anode wires, yielding two coordinates which are used to identify muon tracks which have traversed all of the HCAL and measure their angles with a typical accuracy of 10-15 mrad. The muon chamber helps to keep hadron/muon misidentification to a minimum.

Performance: Monte Carlo estimates for the typical muon misidentification probability at 5 GeV for 95% efficiency are; 0.7% to mistake a π for a μ and 1.6% to mistake a K for a μ .

3.2.4 ALEPH Magnet

The ALEPH magnet consists of a fully calorimeterized iron yoke and a liquid helium-cooled superconducting solenoid producing a uniform magnetic field parallel to the LEP beam axis. The iron yoke has three different functions:

- it returns the magnetic flux;
- it supports most of the experiment's detectors;
- it is the converter in the hadron calorimeter.

The iron yoke and a large superconducting solenoid produces a 1.5 T magnetic field at the current of 5000 A. This field is necessary for momentum measurement of a charged particle and sign from the resulting track curvature. The useful magnetic volume is 123 m³ storing a magnetic energy of 1.3 x 10⁷ J [15].

3.2.5 Luminosity Monitors

The luminosity is determined from the rate of Bhabha events at small scattering angles. In this kinematic region, the interference between γ and Z is almost negligible and the cross-section is well defined from QED. The reaction rate for a process is given by $R = \sigma L$ where L is the luminosity and σ is the interaction cross-section. The differential cross-section for small scattering angles θ is, in lowest order of α

$$\frac{d\sigma}{d\Omega} = \frac{4\alpha^2 (\hbar c)^2}{E^2 \theta^4} \quad (3.1)$$

where E is the electron energy. A precise measurement of angles (especially of polar angles) is required due to the strong dependence of the cross section on the $1/\theta^4$. A good energy determination of electron-positron pair is needed for their identification and for background rejection. The main luminosity monitor consists of the Luminosity Calorimeter (LCAL), and Silicon Luminosity Calorimeter

(SiCAL). The Bhabha Calorimeter, BCAL is used for providing a fast online luminosity measurement at very low angles.

The Luminosity Calorimeter, LCAL

The LCAL, comprising of lead sheets and wire chambers of 38 layers, is a sampling device which is very similar to ECAL mechanically and also electronically. It is situated around the beam pipe inside the ECAL end caps. Its inner radius and outer radius are 100 mm and 520 mm respectively. The LCAL measures events with a counting rate $\simeq 0.3$ Hz at luminosities of $\sim 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$.

The cathode pads which range in size from 28.6 x 28.6 - 31.8 x 31.8 mm² measure the energy and position. The pads are connected to form projective towers and each tower is read out in three depth sections or storeys. Each of the wire layers, which runs parallel to the ALEPH y -axis, houses 112 gold plated tungsten wires with 25 μm diameter on a 5 mm pitch.

Performance:

$$\begin{aligned} \text{Energy resolution;} \quad \Delta E / E &= 0.011 + 0.15/\sqrt{E(\text{GeV})} \text{ (wires)} \\ &\quad \Delta E / E = 0.014 + 0.15/\sqrt{E(\text{GeV})} \text{ (pads)} \\ \text{Angular resolution;} \quad \sigma_\theta &= 0.16 \text{ mrad} + 2.5 \text{ mrad}/\sqrt{E(\text{GeV})} \\ \text{Position resolution;} \quad \sigma_x = \sigma_y &= 2.5 \text{ mm.} \end{aligned}$$

Silicon Luminosity Calorimeter, SiCAL

The SiCAL is located on each side of the interaction area. It covers angles between 27.9 to 62.7 mrad from the beam direction and consists of 12 silicon/tungsten layers (23.3 radiation lengths) which are rotated in ϕ by 1/3 of the pad size. A polar angle of the incident particle is obtained by the spaced pads.

Performance:

$$\begin{aligned} \text{Energy Resolution ; } \Delta E / E &= 23\%/\sqrt{E} = 3.4\% \text{ at } 45.4 \text{ GeV} \\ \text{Phi Resolution} \quad &; \sigma_\phi = 0.3^\circ (R_{inner}) \\ &; \sigma_\phi = 0.2^\circ (R_{outer}) \\ \text{Radial resolution on fiducial cut ; } &12 \mu\text{m.} \end{aligned}$$

The Bhabha Calorimeter, BCAL

The BCAL is positioned next to the beampipe at 7.7 m away from the interaction point. This sampling calorimeter is made of tungsten layers and plastic scintillator. The very small angle events are measured at a rate of 5 Hz at luminosities of

$\sim 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$. The BCAL consists of two calorimeter modules. Each module is a rectangular box of dimension 3 x 5 x 14 cm and is constructed from 10 sampling planes. The planes are consecutive layers of plastic scintillator.

Performance: The Bhabha detection efficiency is expected to be about 75% for an energy threshold of 60% of the energy expected for a fully contained shower. Position resolution: $\approx 0.5 \text{ mm}$.

Chapter 4

Data Acquisition and Event Reconstruction

The DAQ (Data Acquisition system) and writing of online software are summarized in this chapter. More information about these subjects can be found in reference [17].

The real data from the e^+e^- collisions at ALEPH and the Monte Carlo simulated data are the two data sources used in the physics analysis. Figure 4.1 shows the flow chart of real and simulated data for ALEPH experiment. ALEPH detects the events in terms of the electronic signals which correspond to the energy deposition of the particles recorded by 8 subdetectors. At a bunch crossing there are up to 700000 channels per event delivering more than 500 Mbytes of raw digitizings per second. The DAQ is designed to keep this rate to below 100 kbytes/second; a rate which can be reasonably written to tape.

The detector simulation by GALEPH (Generator for ALEPH) and reconstruction program JULIA (Job to Unveil LEP Interactions in ALEPH) are the main parts of the offline software. They are discussed briefly in section 4.3.

4.1 The ALEPH Trigger System

The ALEPH trigger system was designed to accept all genuine e^+e^- interactions at the center of the interaction point. One of its the main purposes is to keep the background events to a minimum. The backgrounds for this process come from beam-gas interactions, cosmic rays, and the collision of off-momentum beam particles with the the vacuum pipe. The flexibility of this system is rather important because the rates of the background are not stable during fills and may vary with changes of some parameters in LEP. The trigger system was designed to be

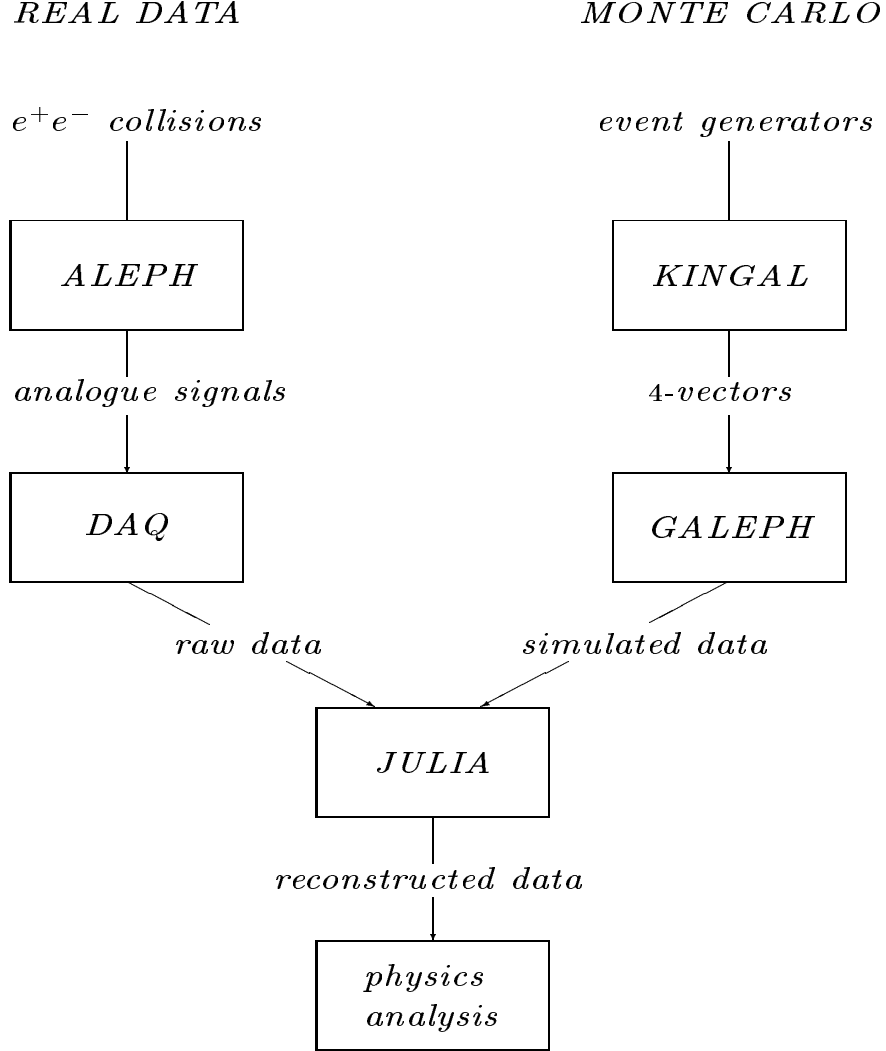


Figure 4.1: *The data flow in the ALEPH experiment.*

sensitive to single particle or single jets. The main LEP parameters affecting the design of trigger are

- the electron positron collision rate of ~ 1 Hz,
- the bunch crossing rate of 45.5 kHz ($22 \mu\text{sec}$).

The complexity and large size of the ALEPH detector does not allow simply adding the signals accepted from the 8 subdetectors. Therefore the ALEPH detector is subdivided into projective segments with the triggering requirements

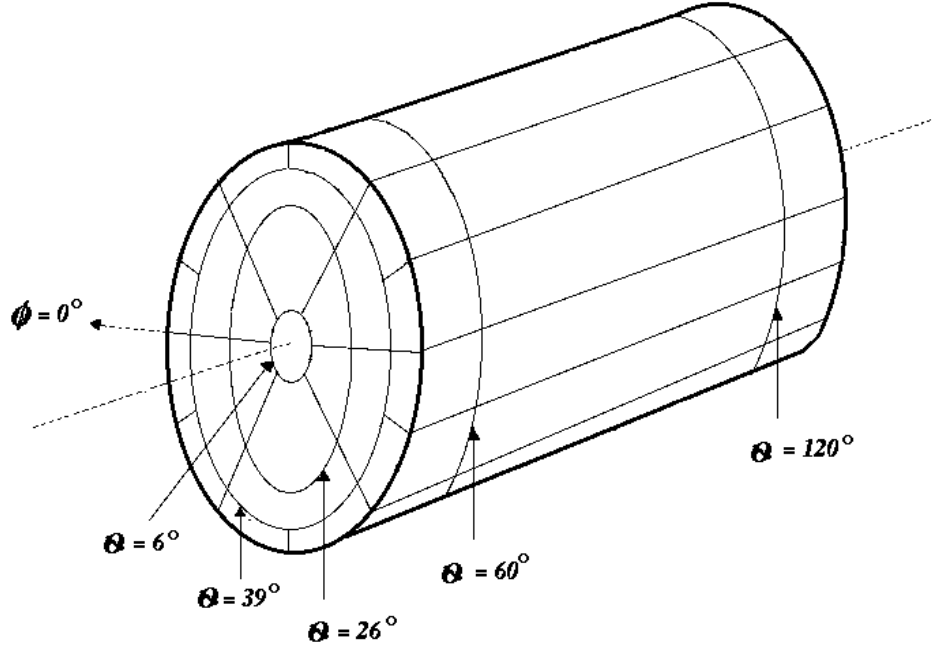


Figure 4.2: *The division of the ALEPH detector into trigger segments of projective geometry.*

imposed separately (and independently) for every segment. Figure 4.2 shows an overview of the ALEPH detector division into trigger segments (in solid angle) of projective geometry. In order to record data corresponding to events which are useful for physics analysis the trigger system consists of 3 individual trigger levels.

Level-1 Trigger

The trigger decision at first level is within about $5 \mu\text{sec}$ of a bunch crossing and it is designed to reduce the trigger rate to below 100 Hz. The level-1 trigger initiates the event digitization. In the formation of trigger system the subdetectors which play the main role are ITC, ECAL, and HCAL. They cover the same solid angle of almost 4π . In addition to these subdetectors, LCAL trigger data is used to trigger on the forward Bhabha events in order to monitor the e^+e^- collision rate. For the formation of physics triggers, the following source signals from the different detector components can be used:

- HCAL provides signal from;

- towers: 60 segments,
 - wires: 24 direct modules mapped onto the 60 segments,
- ECAL provides signal from;
 - towers: 60 segments,
 - wires: 36 direct modules mapped onto the 60 segments,
- ITC-hit pattern: track candidates in 60 ϕ segments,
- LCAL towers: 2x12 overlapping segments.
- SiCAL towers.

The trigger electronics sum the analog signals coming from the calorimeters to obtain segment signals. The signals are then accepted by four discriminators (i.e. four YES/NO signals per trigger segment). A particular physical trigger (up to 32 can be defined) is obtained by establishing the trigger condition first in each segment separately and then applying a logical OR to the segments. All these triggers are finally ORed to deliver a global level-1 decision (YES or NO) which can be produced within 5 μ sec of e^+e^- bunch crossing.

Level-2 Trigger

In the second level trigger the level-1 tracking information signals of ITC are replaced by tracking signals from the TPC. The level-2 trigger checks for charged particle trajectories in regions predicted by level-1 decision. The decision in this level can be made within 50 μ sec drift time of the e^+e^- bunch crossing. The event rate is reduced to less than 10 Hz by track information provided by TPC in order to keep the dead time to a minimum. The level-2 controls the readout so that; if the level-1 decision is YES the readout is initiated from the front-end electronics and data is sent to the DAQ system. If the level-1 is not confirmed the readout is stopped and cleared.

Level-3 Trigger

This third-level trigger (so called software trigger) is the final stage of the trigger system, and it is applied just before the data are recorded to disk. A decision is made by reconstructing an event until sufficient information on its quality has been obtained. The main purpose of level-3 trigger is to identify the genuine e^+e^- events and distinguish them from the background. It keeps the event rate to 1-2 Hz which is a reasonable rate for data storage.

4.2 Data Acquisition System, DAQ

The simplified view of DAQ system is shown Figure 4.3. ALEPH detector has a modular structure, this required a modular structure of data acquisition system. The main tasks of the DAQ are that;

- it reduces the incoming data (in the form of electronic signals) to a manageable level and a formatted output in a convenient form for recording to tape. There are two stages in the reduction of the raw-data volume;
 - The event rate can be decreased by the help of the trigger system(as described before).
 - Compacting the data through ‘zero-suppression’, performed by the preset threshold of the trigger system, is the second stage of the data reduction. This is done in the hardware in order to compare the measured analogue signal with a preloaded threshold. Only the signals from the front-end electronic stage passing threshold are sent to the next level of DAQ (readout controllers) for formatting and calibrations.
- it optimizes the event processing and minimizes the dead time.
- it ensures that the data readout from each of the subdetectors is from the same event.

Operation of DAQ

The complete data flow and control signals from the bunch crossing to storage of an event throughout the data taking period can be summarized as follows;

- A timing signal is received by the main trigger supervisor (MTS) from the T0 module. This module transmits signals that are synchronized with the LEP bunch crossing.
- The MTS transmits the same signal to the read out controllers (ROCs). ROCs initialize the front-end modules, read them out, format the data and do any initial calibration.
- Data reduction is performed by zero-suppression within the analog-to-digital converters by comparison with preloaded thresholds. With the reduced data the ROCs perform calibrations and formatting into the BOS data structure. The detailed results of each analysis routine are reported in the BOS banks

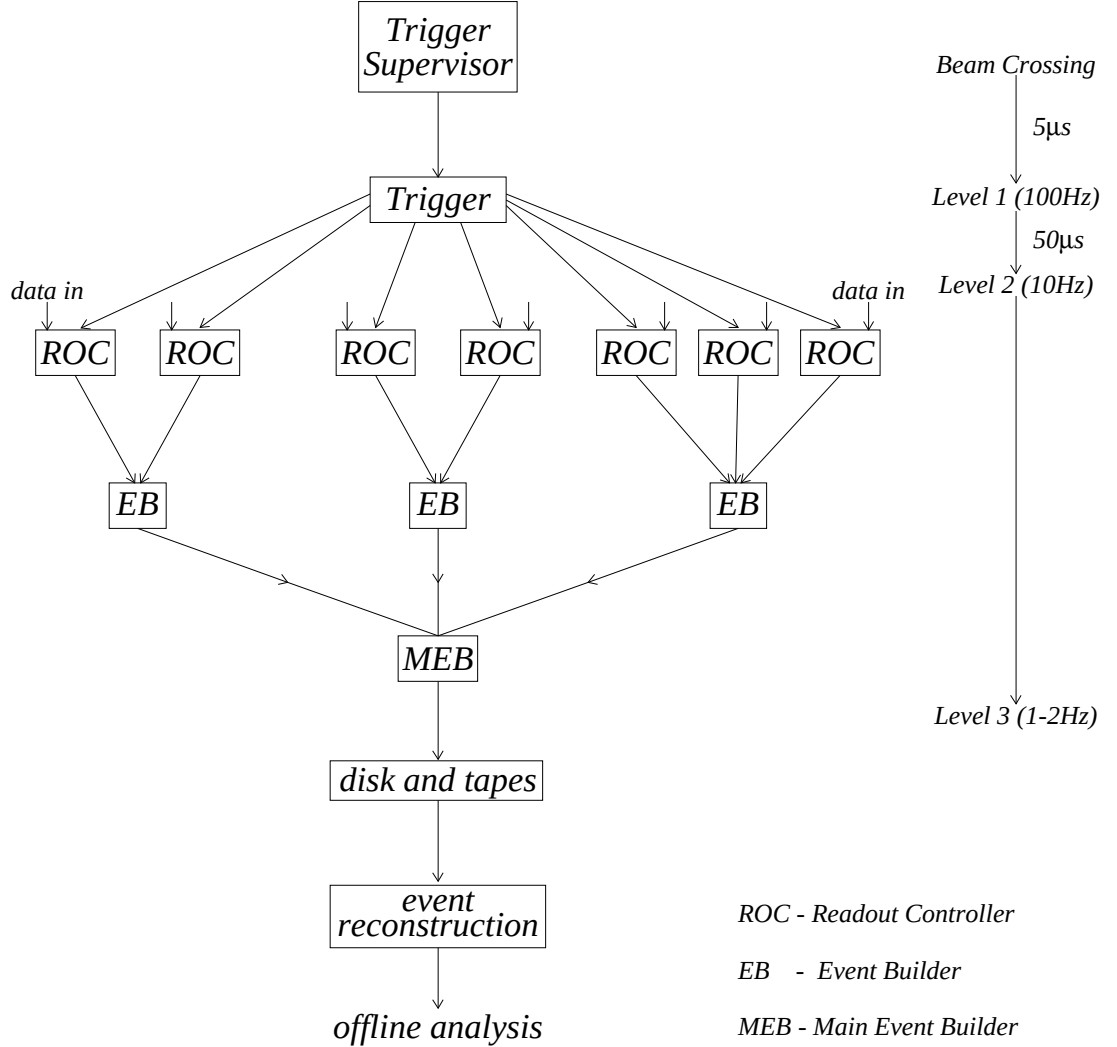


Figure 4.3: A simplified outline of the data acquisition (DAQ) system with triggering.

(BOS is the set of the memory management routines which allows the handling of data structures with varying size and format). The results are then stored in the output buffers of ROCs.

- The level-1 and level-2 trigger decisions are given to MTS by ALEPH trigger system and transmitted to the ROCs. A rejection halts the digitization process and causes a reset and ROC is prepared for the next event. If a trigger is accepted at level-2 a broadcast message containing some information such as the trigger mask and trigger number is passed to ROCs via MTS, and then the whole event is digitized.

- With an event in its output buffer a ROC sends a signal to the subdetector event builder (EB) to be read out. EB reads the ROCs in the order in which they are ready. It checks that the event is the correct one by checking that the events has the correct trigger number. When the reading of a ROC by the EB is completed the ROC is released to be used for the next event. The partial events read and processed by EBs are stored in their output buffers. The larger subdetectors are able to spy on their events as they pass through the event builder. This can be analysed in the subdetector computer.
- In the same manner as above, with an event in its output buffer an EB sends a request to the main event builder (MEB) to be read out. The MEB reads the subdetector EBs and assembles the whole event. MEB ensures resynchronization and completeness of the event.
- The complete event is now given to the event processor which performs the level-3 trigger analysis. If the decision of level-3 is YES the event is read by main host computer. After so many events are accepted they are sent to the storage medium for the event reconstruction.

4.3 Detector Simulation

Monte Carlo simulated data are generated by using the KINGAL and GALEPH software packages which produce the 4-vector and ALEPH hits respectively for these simulated events.

KINGAL

KINGAL is effectively an interface between the available event generators and GALEPH detector simulation package. The event generators produce the desired class of events by using Monte Carlo simulation techniques. KINGAL output gives a 4-vector kinematic representation of each simulated particle. The particle ‘truth’ information is produced by using the tabular data BOS banks for comparison of the particle information with the real data.

GALEPH

The GALEPH program is a simulation of ALEPH detector for KINGAL particles. GALEPH is responsible for tracking particles through the inner detectors and showering particles in the calorimeters. It converts the analog signals to the digital values, and all data into a raw data format.

The electromagnetic and hadronic interactions are simulated by GEANT package and GHEISHA software respectively. GEANT performs tracking of particles through the inner detectors allowing for multiple scattering, energy loss through ionization, and decays etc.. And it also describes the event construction details and detector geometry. The analog signal from the sub-detectors are converted to digital output by simulation of each sub-detectors electronics, allowing for noise, threshold, gain variation etc.. Finally the output from each subdetector is digitized and formatted just like if it were real data to produce a raw data file which can be interfaced to JULIA.

JULIA

JULIA takes the input information either from the DAQ or the simulated data from the GALEPH event generator program. It performs most of the track and calorimeter reconstruction. The charged particle reconstruction in JULIA is explained in section 4.4.

4.4 Event Reconstruction

The events, detected as electronic signals from the detector output, are measured, put into a reasonable format, and recorded on tape by DAQ in the form of digitized electronic pulses. The data after all these stages are reconstructed by using a reconstruction program, JULIA.

JULIA reconstructs the charged particle tracks traversing in the inner tracking chambers and the energy deposition in the calorimeters for physics analysis. For particle identification JULIA performs the following task;

- TPC space coordinate finding,
- TPC track fitting,
- calorimeter cluster formation,
- track and calorimeter cluster association,
- dE/dx calculation,
- vertex reconstruction.

The outputs are then sent to BOS bank to be formatted and then written to the Production Output Tape (POT) for physics analysis. The reconstruction output is stored on a large disk subsystem and written to magnetic cartridges.

4.4.1 Track Reconstruction

Charged particles form a helix in magnetic field of ALEPH. The radius of the circle in the $x - y$ plane depends on the particle momentum and its emission angle with respect to the z axis. Figure 4.4 shows the track parameters of a helix for track reconstruction in TPC tracking programs. The five parameters which are used to define the helix are listed below. They can be calculated from the fitting to TPC space coordinates.

- ω is the inverse radius of curvature, positive if the particle rotates counterclockwise in the $x - y$ plane.
- $\tan \lambda$ is the tangent of the dip angle in the $s_{xy} - z$ plane, where s_{xy} is the track length in the $x - y$ plane.
- ϕ_0 is the tangent to the trajectory in the $x - y$ plane relative to the positive x direction at the point of closest approach to the origin in that plane.
- d_0 is the distance of closest approach of the track to the origin in $x - y$ plane (impact parameter in $x - y$ plane).
- z_0 is the z coordinate at the point on the helix for which $x^2 + y^2 = d_0^2$.

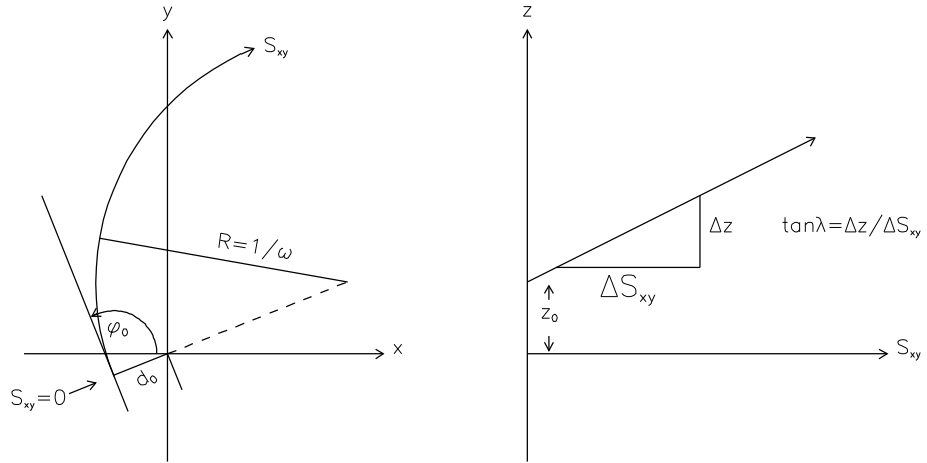


Figure 4.4: *The helix parameters used in the TPC. ω is positive if the tracks bend counterclockwise, d_0 is positive if the z axis encircled by helix.*

TPC Coordinate Determination

The TPC measures the charge and drift time of an ionization cloud produced by a charged track traversing the gas volume. The TPC raw data can be collected in two forms;

- the pad ‘hits’ which contain the pad address, the arrival time and the length of the pulse.
- digitized pulse heights per time-slice (or ‘buckets’) corresponding to each pad hit.

The first step in the space-coordinate finding procedure is the recognition of two dimensional cluster on a given pad row in the plane formed by the pad numbers versus the drift time. Only the hits are considered. Figure 4.5 illustrates an example of such a cluster. Clusters with abnormal size are rejected. These rejected clusters give ‘bad’ coordinates, but at least the position of them is recorded. A good cluster is defined as;

- The number of the pads in the cluster must be ≥ 2 and ≤ 20 .
- The length of the cluster in the sample must be ≥ 5 and ≤ 35 .

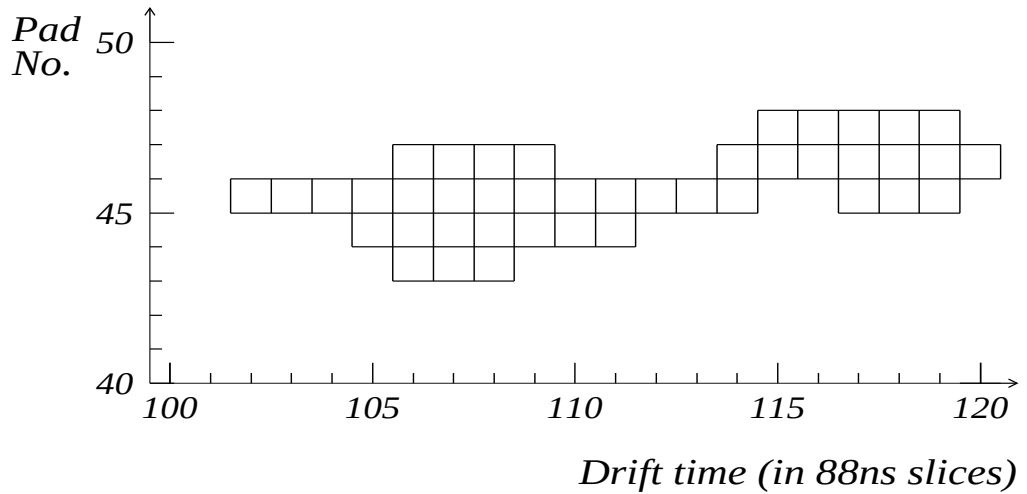


Figure 4.5: *Padrow cluster formed by two nearby tracks.*

Subpulses and Subcluster

The next step is to isolate within the cluster those contributions belonging to single tracks, and then to calculate the charge and time estimators to be used in the coordinate reconstruction algorithms. Each pad within the cluster is then considered individually (Figure 4.5). A sub-pulse is defined to be a set of samples within a pulse which has only one significant local maximum and sufficiently isolated from the peaks. The time and charge estimates are calculated for each subpulse.

The pulse-height distribution for a complex cluster is illustrated in Figure 4.6. Sub-clusters are defined to be sets of subpulses within a cluster from which the charge and time estimators are used to calculate single coordinates. There may be more than one sub-cluster, and hence coordinate, within a cluster (so that; each subpulse is from a unique pad within a cluster).

Each subcluster is used to calculate a z and $r\phi$ coordinates. For $r\phi$ coordinate calculation the sub-pulse charge estimator is used while z coordinate is calculated using both charge and time estimator for each sub-pulse within the sub-cluster. The time estimate is the mid way point between the threshold crossing of the leading and trailing edges. The z coordinate is determined by using the charge weighted average of sub-pulse times within the sub-cluster. The time is converted into a drift length using the known drift velocity. The $r\phi$ coordinate is calculated from a Gaussian fit, if the subcluster has 2 or 3 pads. If it contains more than 3 pads a charge-weighted average of the pad position is used. The subcluster has failed if any of the cuts at this point is accepted to calculate ‘bad’ coordinates, for which the z and $r\phi$ values are taken just to be somewhere around the center of the cluster. They are recorded on the data summary tape (DST) in order to mark the position of discarded data but not used during the standard track finding.

ITC Coordinate Determination

ITC provides 3- d coordinates (z , r and $r\phi$) for charged particles. The z coordinate is obtained by measuring the difference in the arrival times of a pulse at both ends of a wire. The $r\phi$ coordinate is determined from a measurement of drift time from a bunch crossing to the arrival of the pulse.

Track Fitting

The track fitting program performs the evaluation of the exact helix parameters, the removal of badly measured points, and the detection of small angle kinks

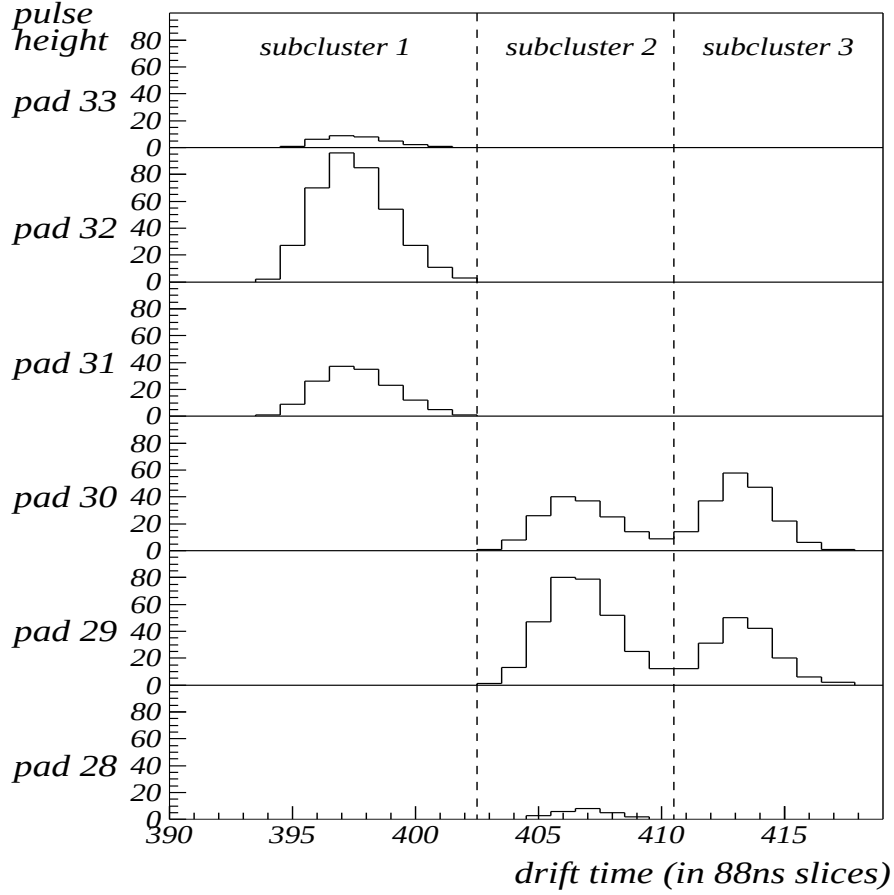


Figure 4.6: *An example of a complex cluster which has broken down into three sub-cluster. Each cluster can be used to calculate three individual coordinates (z , r and $r\phi$).*

using coordinate provided by the TPC and ITC. Fitting is done in three stages;

- Chain formation: radially ordered sets of TPC pad coordinates are called chains. The three coordinates from adjacent pad rows are found which are consistent with lying on a helix.
- The chains are combined to form of track candidates so that every track is a set of chains for the same particle.
- Finally a helix fit to the first half arc of all track candidates is performed. The points are fitted in two forms; a circle fit in $x - y$ plane yielding ω , d_0 , and ϕ_0 and a straight line fit in S_{xy}, z plane yielding z_0 and $\tan \lambda$. The circle fit parameters are used to calculate the values of S_{xy} .

The effect of multiple scattering is taken into account by increasing the error on a coordinate according to the length of arc travelled. At the end of these stages if the fit is not acceptable, then up to two points, corresponding those which contribute the most to the χ^2 of the overall fit, are removed. If this does not yield an acceptable fit then a search is made for a kink in the track candidate, if one is found the track is split. If no significant kink is found then a search is made for bad points by fitting a track candidate with one point at a time removed. If none of these methods leads to a good fit the track candidate is kept without modification.

After tracks are identified in the TPC, the measurement can be improved by using the ITC coordinates. The TPC tracks are projected back into the ITC and then a search is made for hits lying within a road (which is defined in z and ϕ around the predicted path and closest point to the prediction) around each trajectory. If there are no hits found in the two layers of the ITC, the search is abandoned. If more than 3 hits are found then a fit to both TPC and ITC coordinates is performed and then the track is accepted if the fit satisfies a χ^2 cut. An attempt is then made to find tracks using those ITC coordinates not associated with a TPC track.

VDET Hit Contribution to the Tracking

ALEPH tracking system provides up to 31 3-dimensional coordinates from each track; 21 points from the TPC, 8 from the ITC, and 2 from VDET. The spatial and momentum resolution of a track can be improved by using hits in VDET. The tracks from TPC and ITC are extrapolated to the detector plane. Then hits in this plane are associated with the extrapolated tracks. The tracks are then refitted using the new coordinates.

4.4.2 Calorimeter Reconstruction

The construction of energy and the identification of particles in the calorimeters is composed of the following three steps;

- In the HCAL and ECAL a search for ‘topological’ clusters of fired storeys is performed. Such a cluster is a group of combined neighbouring storeys. If two storeys have at least one common corner then they are combined into the same cluster.
- Reconstructed charged tracks are extrapolated into the calorimeters in order to associate them with ECAL and HCAL clusters. Many tracks can be

associated to a given cluster or many clusters can be associated to a given track. All those clusters associated to the same track are combined to form ECAL objects.

- If any of the ECAL and HCAL objects overlap they can be merged into combined calorimeter objects by using three different cluster types.
 - Tracks with ECAL clusters consistent with the Minimum Ionizing particles (MIPs) are extrapolated through the HCAL wire planes. In each plane the distance between the projection and any storey containing an energy deposit is calculated. Any HCAL cluster falling within a set distance of the track projection is associated to the track.
 - The association between HCAL and ECAL is made on the basis of p_t with respect to the track. The distance between the projection and HCAL clusters are determined, and the p_t associated with the distance measured. These clusters are then associated if the p_t is less than a given value.
 - ECAL clusters not associated to tracks are classified as neutral clusters and are assumed to be caused by neutral particles whose tracks are straight lines from the origin.

4.5 Energy Flow

4.5.1 Introduction

A simple way to calculate the energy flow of an event is to sum all the reconstructed energy in the calorimeters. This gives a resolution of $\sigma(E)/(E) = 1.2/\sqrt{E/\text{GeV}}$ [16]. For a perfect detector this resolution value would be expected around 3 GeV. To improve the resolution, some EFLOW reconstruction algorithms have been developed. The main idea of all those algorithms is to combine tracking and calorimetric information because the jet energy resolution for calorimeters alone is not good. To avoid double counting part of the energy in the calorimeter is masked out when the track and calorimeter information are combined.

4.5.2 Method

The cleaning operation is the first stage of the algorithm. It is performed on the charged tracks and calorimeter cluster in order to reject some bad signals

originating from non-beam spot interactions, occasional noise from the front-end electronics, data acquisition system or the reconstruction chain.

Track Selection

- (i) Using the information from VDET, ITC, and TPC, all the charged particles are required to; have at least 4 TPC hits, originated from the interaction point within a cylinder of radius 2 cm and length 20 cm and have transverse momentum greater than 200 MeV. If the reconstructed momentum is in excess of 15 GeV/c at least eight points are required in TPC, and one in ITC.
- (ii) The rejected charged particles in step one are recovered if they belong to a reconstructed V^0 compatible with originating from the nominal collision point within a cylinder of length 30 cm and radius 5 cm coaxial with the beam.
- (iii) The noisy channels occurring systematically in the ECAL and HCAL in an event are ignored. The fake energy deposits due to occasional noise in the towers of calorimeters are removed when the corresponding signal is incompatible with the signal measured independently on the wire planes.

4.5.3 Calorimeter Objects

After all these cleaning stages described above the charged tracks are extrapolated to the calorimeters and the groups of these topologically connected tracks and clusters, named as calorimeter objects, are formed. Every calorimeter object is processed according to following procedure.

- (i) For the energy determination of charged hadronic particles every charged particle track coming from the interaction point or belonging to a reconstructed V^0 is accepted as charged energy assuming they are pions.
- (ii) The charged particle tracks positively identified as electrons are discarded from the calorimeter object, together with the energy contained in the associated electromagnetic calorimeter towers. If the difference between this calorimeter energy and the track momentum is larger than three times the expected resolution, this difference is assumed to come from a bremsstrahlung photon, and is counted as neutral electromagnetic energy.

- (iii) The charged particle tracks identified as muons are discarded from the calorimeter object, together with a maximum of 1 GeV from the closest associated electromagnetic calorimeter cluster and a maximum of 400 MeV per plane fired around the extrapolation of the muon track from the corresponding hadron calorimeter cluster.
- (iv) The photons and π^0 's are counted as neutral electromagnetic energy and are removed from the calorimeter object. After all these steps the remaining particles should be the charged and neutral hadrons in the calorimeter object.
- (v) After all these steps there should be only charged and neutral hadrons left in the calorimeter object. The energy of the neutral hadrons is obtained so that; the remaining energy in the calorimeters is summed after first scaling that from the electromagnetic calorimeter by the ratio of the calorimeter's response to electrons and pions. If this sum exceeds the energy of any remaining charged particle tracks, and the excess is both larger than the expected resolution on that energy when measured in the calorimeters, and greater than 500 MeV, then it is counted as a neutral hadronic energy.

For all the calorimeter object in an event, these steps are repeated. Eventually a set of EFLOW objects which are electrons, muons, photons, and charged or neutral hadrons are built.

Chapter 5

Event Selection and Jet Reconstruction

The analysis is based on 2,322,592 hadronic events recorded by the ALEPH detector at centre of mass energies between 89.4 and 93.0 GeV in the 1992, 1993, and 1994 running periods of LEP. Some information about the data taking from ALEPH data for those years is listed in Table 5.1.

For the accepted events, jets are clustered with the DURHAM ($k_{\perp}$ jet) algorithm [18, 19, 20] with a resolution parameter $y_{cut}=0.01$, using the EFLOW particles.

5.1 Hadronic Event Selection

Hadronic events are selected by requiring events to have at least 5 good charged tracks and a total good charged energy of at least 15 GeV. The definition of a

ALEPH data years	1992	1993			1994
Energy mode	peak	peak-2	peak	peak+2	peak
Center of mass energy (GeV)	91.2	89.4	91.3	93.0	91.3
Fraction of hadronic events	100%	11%	72%	17%	100%
Luminosity (pb^{-1})	22.8	34.6			62.1
Number of hadronic events	484471	517579			1320542

Table 5.1: *Some information about the data taking from 1992, 1993, 1994 running period of ALEPH.*

‘good’ charged track is given in section 5.2.

Figure 5.1 shows the charged energy versus charged multiplicity distribution for events recorded by ALEPH in 1992. The multiplicity cut removes leptonic decays of the Z and t -channel Bhabhas. The charged energy cut removes most of the $\gamma\gamma$ events. Another cut is also applied on the polar angle of the event axis so that the events are chosen if the polar angle of the sphericity axis with respect to the beam pipe is in the range $35^\circ < \theta_{sph} < 145^\circ$ ($|\cos\theta| < 0.82$). This cut ensures that events are well contained within the sensitive region of the detector and further removes $\gamma\gamma$ events. The sphericity ($|\cos\theta|$) distribution is shown in Figure 5.2. The background to the hadronic signal after the hadronic event selection arises from tau decays and two-photon events and is estimated to be less than 0.3% [21].

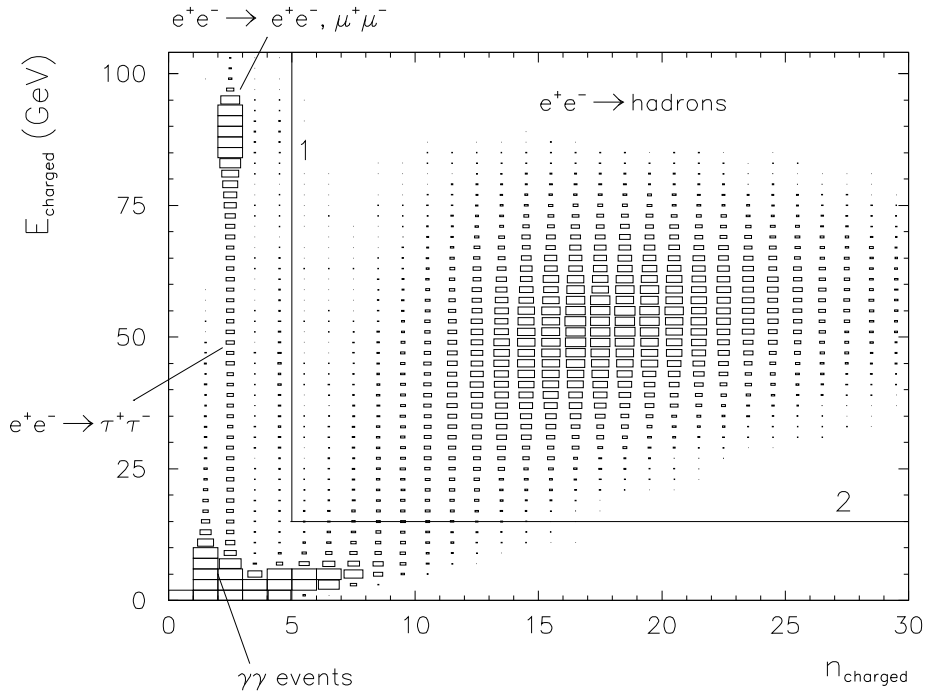


Figure 5.1: *Charged energy versus charged multiplicity for all particles in the events from 1992 ALEPH data before the hadronic event selection. The solid lines show the multiplicity (line 1) and energy (line 2) cuts for events so that every event has at least 5 good charged tracks and the total energy of the tracks must be greater than 15 GeV.*

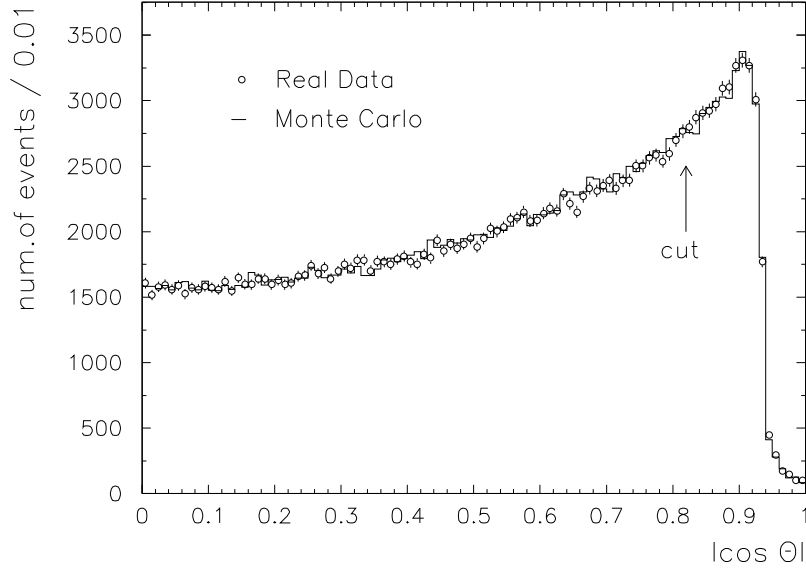


Figure 5.2: *The distribution of the polar angle of sphericity with respect to the beam axis for the hadronic events. The events are selected if $|\cos \theta| < 0.82$.*

5.2 Charged Track Selection

The origin of the tracks can be measured in terms of the impact parameters of each reconstructed track. These are the d_0 , which is the closest perpendicular distance of the track to the beam line in the x - y plane, and z_0 which is the distance along the beam axis at which the d_0 is measured. A ‘good’ charged track is defined as having

- at least 4 TPC coordinates;
- a $|d_0|$ of less than 2 cm;
- a $|z_0|$ of less than 5 cm;
- a polar angle of greater than 20° ;
- a transverse momentum p_t greater than 200 MeV/c.

The number of TPC coordinates for real data and Monte Carlo is shown in Figure 5.3 after all other cuts have been imposed. Figure 5.4 and 5.5 show the charged particle d_0 and z_0 distributions respectively. The cuts on d_0 and z_0 should be tight enough to remove tracks from beam-gas interactions and cosmic rays. Figure 5.6 shows the distribution of polar angle $\cos \theta$ relative to the beam

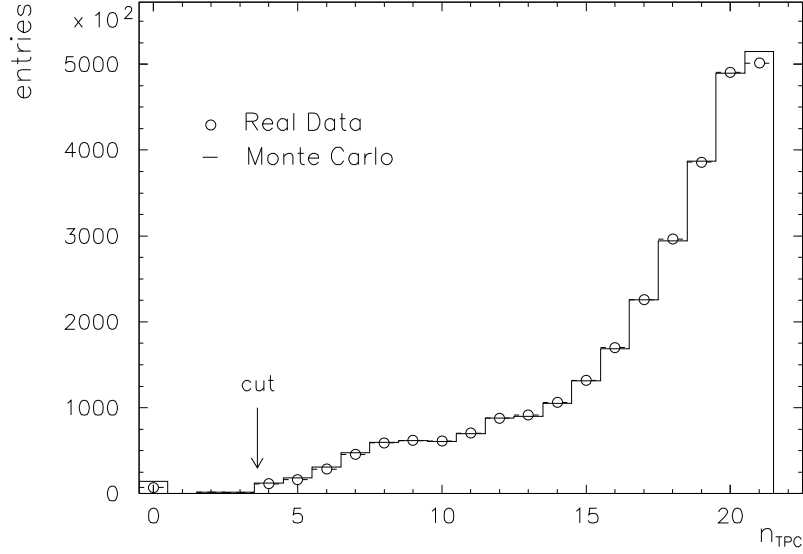


Figure 5.3: *The TPC hits distribution for charged tracks after all other track cuts are applied.*

axis for the charged particles. This cut ensures that tracks are clear of the TPC boundary and the tracks traverse at least four pad rows. The cut on the transverse momentum of a track is applied to remove bad tracks. The tracks which have very low transverse momentum are likely to turn over and spiral, resulting in poor momentum resolution for the track due to multiple scattering and the low number of TPC pads traversed. The p_t distribution of charged tracks is shown in Figure 5.7.

5.3 Energy Flow Particles

The energy flow (EFLOW) reconstruction algorithm is described in detail in Chapter 4. EFLOW objects provide the input to the jet clustering algorithm. Whilst it is important to reconstruct as much of the event energy as possible, it is necessary to apply some kinematic cuts on the EFLOW particles to gain a reasonable agreement between Monte Carlo and real data.

5.3.1 Cuts for EFLOW Objects

Figure 5.8 shows the energy spectra for EFLOW particles. For charged tracks, the ‘good’ track criteria give a good agreement between Monte Carlo and real data.

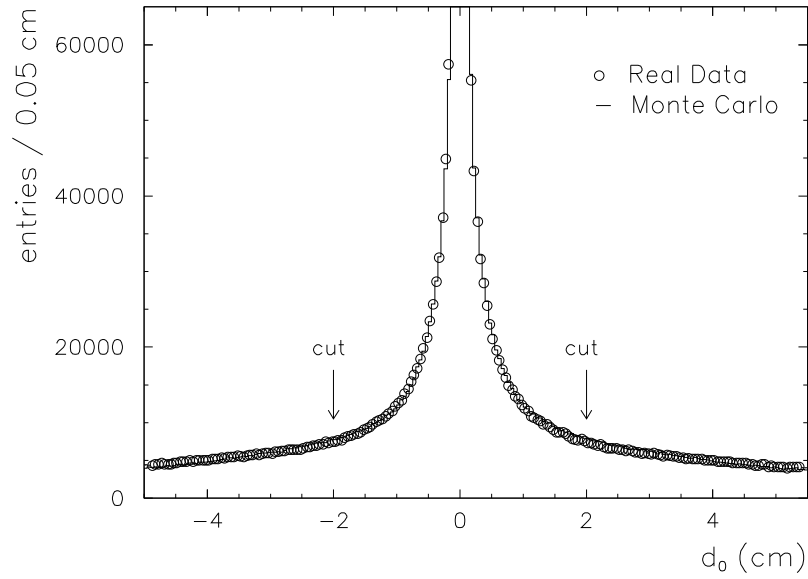


Figure 5.4: *The d_0 distribution for charged tracks without applying all the other track cuts.*

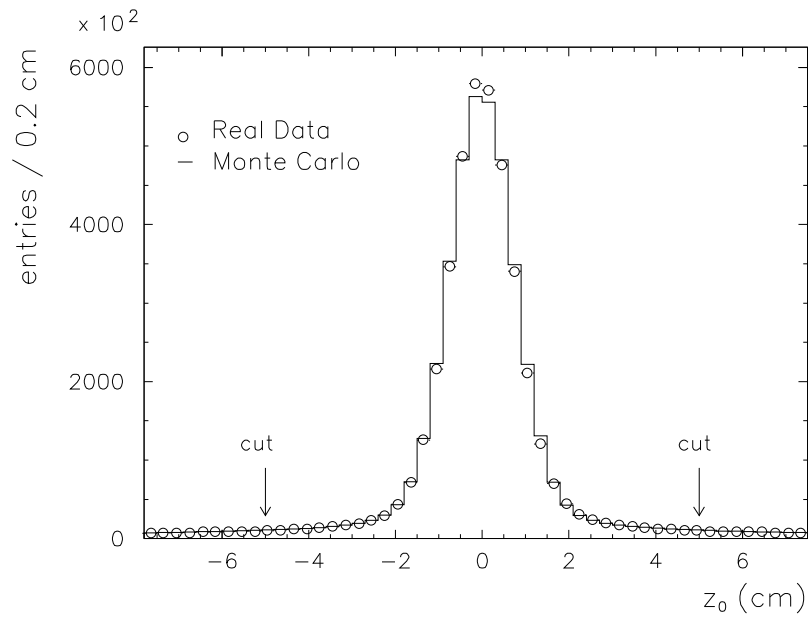


Figure 5.5: *The z_0 distribution for charged tracks without applying all the other track cuts.*

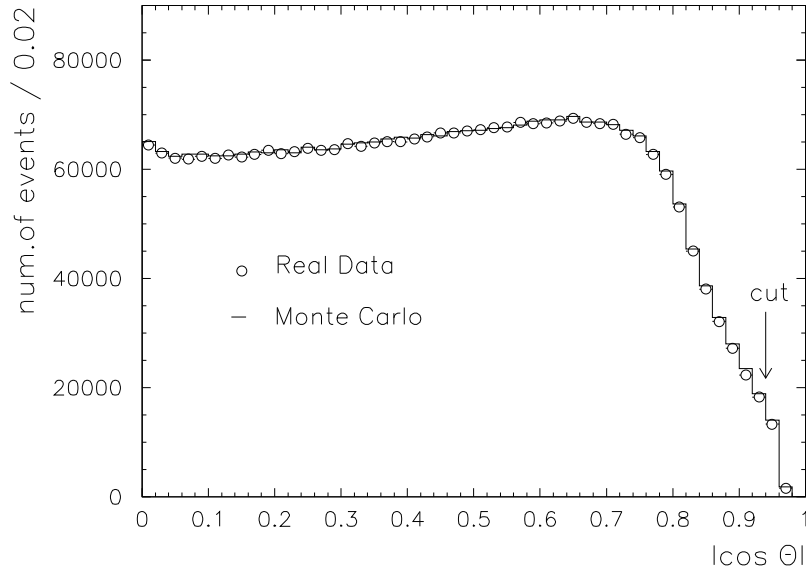


Figure 5.6: *The polar angle $\cos \theta$ distribution for charged tracks after all other track cuts have been applied.*

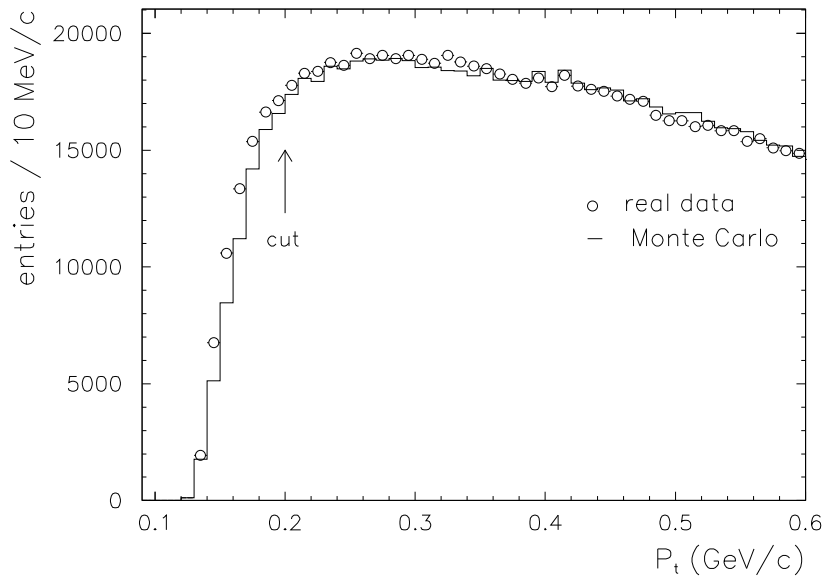


Figure 5.7: *The transverse momentum p_t distribution of the charged tracks after all other track cuts have been applied.*

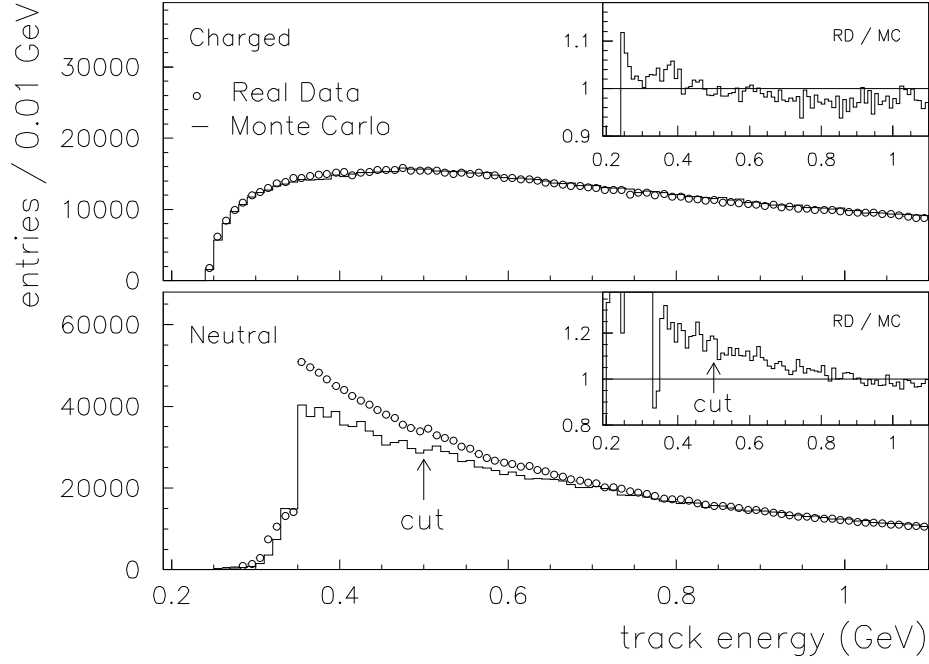


Figure 5.8: *The energy distributions of the charged and neutral EFLOW particles for 200000 hadronic events from 1992 real data and Monte Carlo . The ratio of real data / Monte Carlo is shown inset in each plot.*

For neutral EFLOW objects reconstructed in the ECAL (photons) and HCAL (neutrals), a cut of 0.5 GeV is applied.

5.3.2 Performance of the EFLOW Algorithm

The performance of the algorithm (after the above cuts have been applied) was examined by using 200000 hadronic events recorded by ALEPH at the Z resonance in 1992. Figure 5.9 shows the total event energy distribution for EFLOW objects. The distributions are fitted with a Gaussian above 85 GeV to avoid the low energy tails (for example initial state radiation, or lost neutrino energy in the semileptonic decay of heavy quarks [16]). For real data the Gaussian gives a peak value of 89.2 ± 0.1 GeV and a resolution of 6.5 ± 0.1 GeV. For the Monte Carlo the peak position is slightly lower at 88.5 ± 0.1 GeV and has a resolution of 6.4 ± 0.1 GeV. The fitted values for the resolution agree between Monte Carlo and real data. The higher average energy seen in the real data reflects the excess of

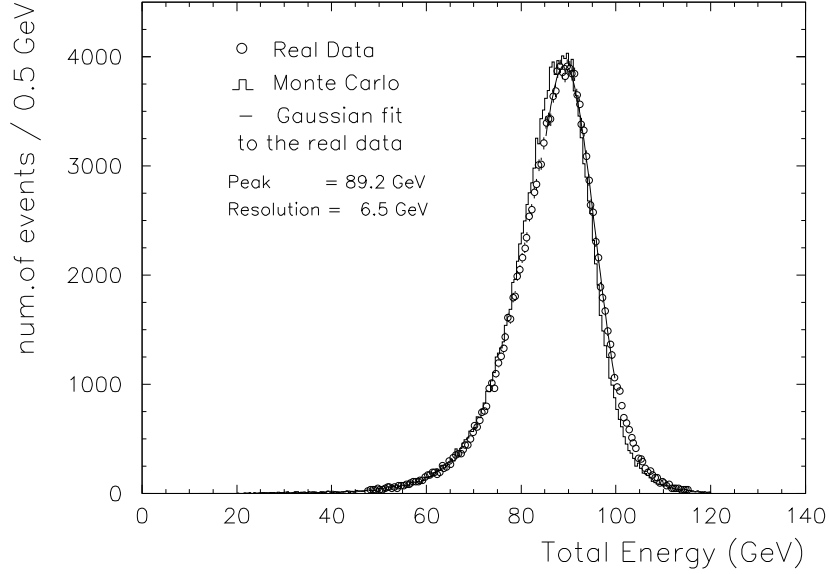


Figure 5.9: *The event energy distribution for EFLOW objects for 1992 real data and Monte Carlo after the hadronic event selection. For the real data, the Gaussian fit gives a peak of 89.2 ± 0.1 GeV and the resolution is 6.5 ± 0.1 GeV. For Monte Carlo events the peak value is 88.5 ± 0.1 GeV, and the resolution is 6.4 ± 0.1 GeV.*

neutral objects (see Figure 5.8).

5.4 3-Jet Event Selection

In order to compare the quark and gluon jet properties the 3-jet hadronic events $e^+e^- \rightarrow q\bar{q}g$ are selected. An example of a rare 3-jet ‘Mercedes’ event from 1990 real data is shown in Figure 5.10. Generally a good jet definition is one that must;

- be able to combine final state hadrons to give the best possible measure of initial partons,
- be simple to implement both theoretically and experimentally.

For clustering the jets, several different algorithms have been written. The next two sections describe two commonly-used jet-finding algorithms. The latter is used in this analysis.

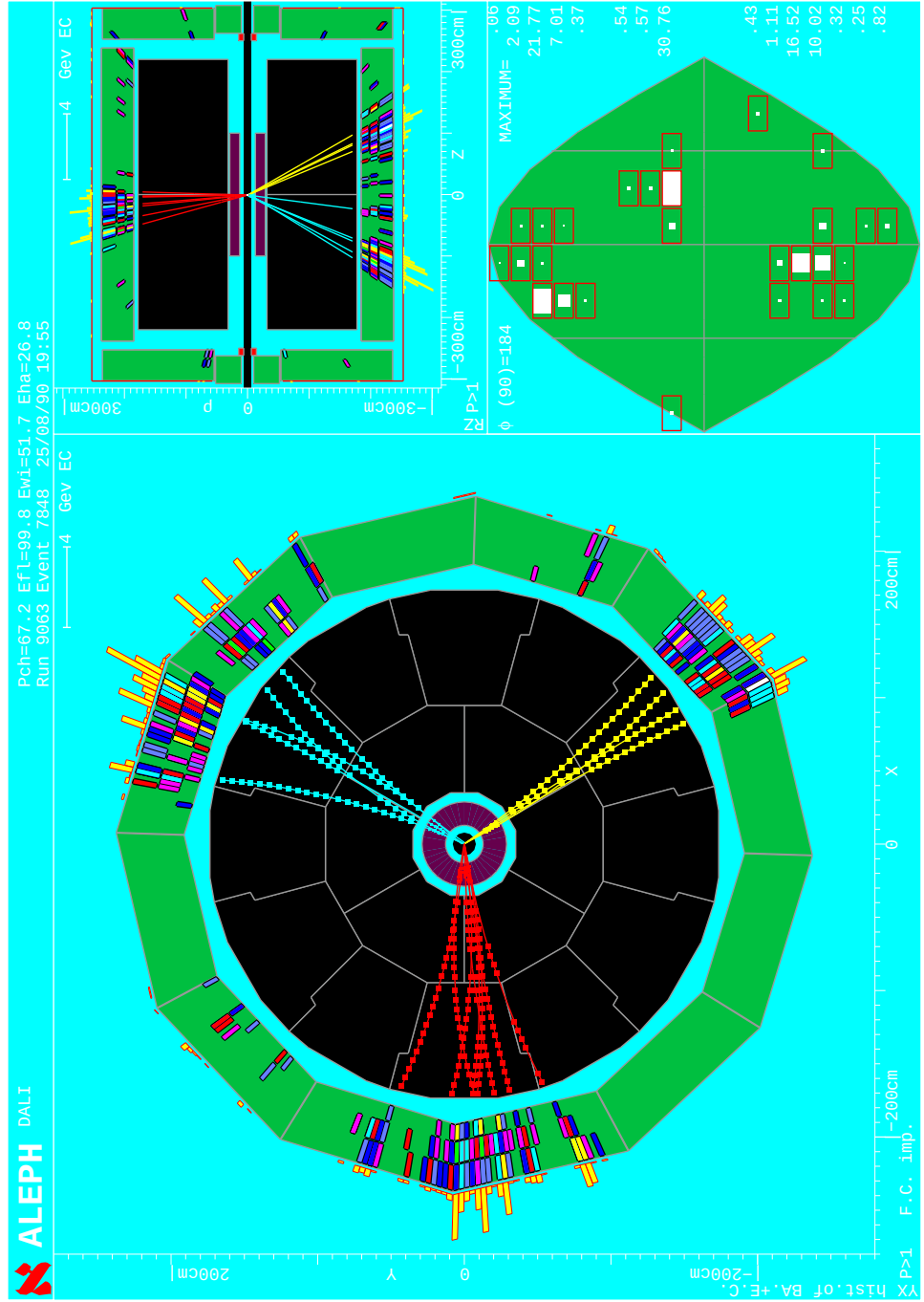


Figure 5.10: An example of a rare 3-Jet ‘Mercedes’ hadronic event in the ALEPH detector. The overall reconstruction energy in this event is 99.8 GeV.

5.4.1 Jet-Finding Algorithms: JADE and DURHAM

Jet finding algorithms in the e^+e^- annihilation are based on the concept of hierarchical, clustering combining "nearby" particles pairwise to form pseudoparticles. This continues iteratively to combine the particles until the event consist of a few well-separated pseudoparticles, which are the output jets. Mass and momentum cut off are used to define "nearby".

Basically a jet clustering algorithm of the type most commonly used in e^+e^- annihilation is defined according to the following procedure;

- (i) Define a jet resolution parameter, y_{cut} .
- (ii) Calculate the corresponding separation¹, y_{kl} for every pair of the particles h_k, h_l .
- (iii) If y_{ij} is the smallest value of y_{kl} calculated in (ii) and ($y_{ij} < y_{cut}$), combine (p_i, p_j) into a single 'pseudoparticle' momentum p_{ij} according to a recombination scheme which is explained below.
- (iv) Repeat this procedure from step (ii) until all pairs of particle and/or pseudoparticles have $y_{kl} > y_{cut}$. The remaining objects at this stage are called jets. The number of pseudoparticles gives the number of the jets in the event.

The DURHAM jet finder algorithm is applied to form jets using the EFLOW particles because it is well-defined in perturbation theory.

JADE

The scaled invariant mass squared algorithm, JADE [22], can be used to construct the jets in hadronic events by merging particles together adding their 4-vectors to form pseudo-particles. In this algorithm the invariant mass of every pair of hadrons in the final state is calculated. If any are less than a certain fraction y_{cut} of the total centre of mass energy, s , then the momenta of the pair with the lowest invariant mass are added together. This combined momenta is considered to be that of a single 'particle'. The invariant masses are recalculated and the combining procedure continued until none of the invariant masses are less than y_{cut} . For all pairs of particles k and l the scaled invariant mass squared y_{kl} is calculated by

$$y_{kl} = M_{kl}^2 / E_{vis}^2 \quad (5.1)$$

¹The definitions of the separation y_{kl} for JADE and DURHAM algorithms are defined in the next two sections.

where E_{vis} is the visible energy of the event computed as the sum of the input particle energies². The squared invariant mass, M_{kl}^2 for JADE algorithm is³

$$M_{kl}^2 = 2E_k E_l (1 - \cos\theta_{kl}) \quad (5.2)$$

where E_k and E_l are the energies of k and l tracks which are separated by an angle θ_{kl} . Figure 5.11 shows the y_{cut} distributions for different jet event rates using the JADE algorithm.

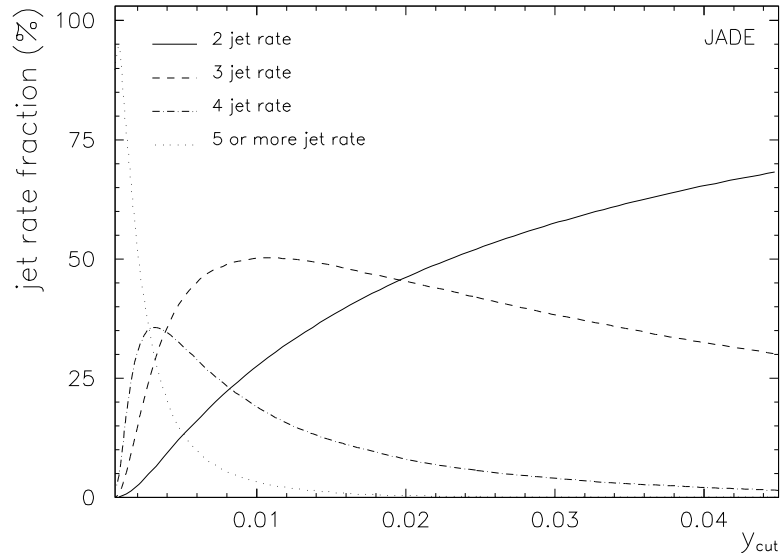


Figure 5.11: *Jet resolution parameter, y_{cut} distribution for different jet event rates using the JADE algorithm for real data.*

DURHAM

JADE has been the most commonly used Jet-Finder algorithm within the ALEPH collaboration for many years. An alternative algorithm ‘Durham’ has been introduced because JADE is theoretically unsatisfactory at small y_{cut} values, since all-orders resummation cannot be performed.

The DURHAM algorithm is defined in a similar way to the JADE algorithm just replacing invariant mass by transverse momentum as jet resolution variable.

²All charged particles are assigned the pion mass.

³Note that M_{kl}^2 as so defined is only the true invariant mass for massless particles. It is used in the algorithm because it works better than using the true invariant mass.

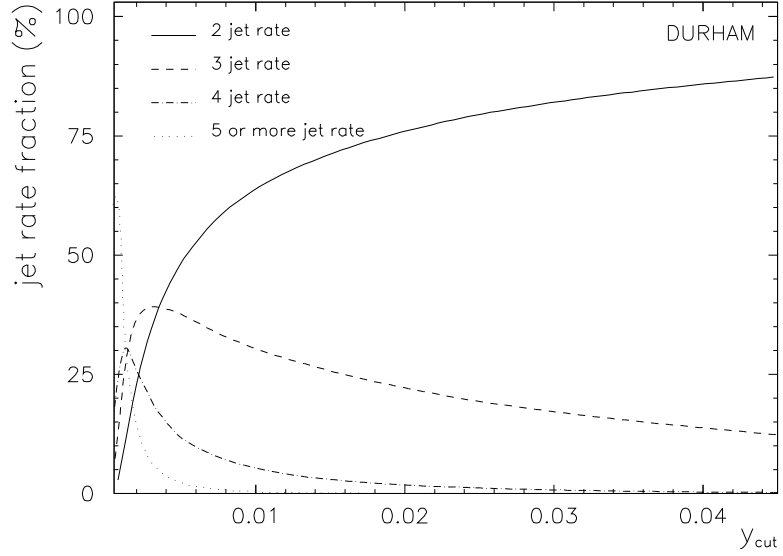


Figure 5.12: *Jet resolution parameter, y_{cut} distribution for different jet event rates using the DURHAM algorithm for real data.*

The scaled transverse momentum is defined as

$$y_{kl} = \frac{(M_T^2)_{kl}}{s} \quad (5.3)$$

$$(M_T^2)_{kl} = \min(E_k^2, E_l^2) 2(1 - \cos \theta_{kl}) \quad (5.4)$$

where E_k and E_l are the energies of the particles or jets and θ_{kl} is the angle between their momenta. At small θ_{kl} , y_{kl} measures the minimal transverse momentum squared of one jet relative to the other, while at large angles the definition is such that y_{kl} always increases with angle.

Figure 5.12 shows the y_{cut} distributions for different jet event rates using the DURHAM algorithm. For small values of y_{cut} ($y_{cut} < 0.005$) a sharp rise in the 4 and 5 jet rates is observed, this implies that some jets are being artificially split into two. This region can be avoided with only a small loss in the 3-jet rate by applying y_{cut} value of 0.01. For this cut the 3-jets events are considered to be well defined, a 3-jet rate of $\sim 31\%$ is obtained.

The behaviour of the two jet finding algorithms differ greatly with respect to the treatment of soft particles between jets. In the JADE algorithm if two particles have low enough energy they will be merged together, possibly forming a new jet, regardless of how far apart they are in angle. In the DURHAM algorithm such particles tend to be assigned to nearby jets. It is for this reason that the DURHAM algorithm is used in this analysis in preference to the JADE algorithm.

Recombination Scheme

The recombination scheme decides how to choose the particles and combine them together. Several different recombination schemes (E , E_0 , P) [22] have been introduced and used. The E-scheme has been chosen in this analysis: this means that when clustering particles to form a jet the four-momenta are simply added together:

$$\begin{aligned}\vec{p}_{(ij)} &= \vec{p}_i + \vec{p}_j \\ E_{(ij)} &= E_i + E_j\end{aligned}\tag{5.5}$$

cuts applied	# of remaining events									
	ALEPH data								Monte Carlo	
	1992	%	1993	%	1994	%	Total	%	JETSET	%
Hadronic	484k	—	517k	—	1321k	—	2322k	—	792k	—
3-jet	145k	70.1	156k	69.8	397k	69.9	698k	69.9	252k	68.2
chrd. mult.	109k	24.8	117k	24.9	298k	24.8	525k	24.8	191k	24.3
event enr.	109k	0.2	117k	0.2	298k	0.1	524k	0.1	190k	0.4
planarity	106k	2.8	114k	2.8	290k	2.6	510k	2.7	185k	2.6
χ_E	98k	7.4	105k	7.6	269k	7.1	473k	7.3	170k	8.0
overall fraction %	20.23±0.06		20.31±0.06		20.41±0.04		20.35±0.03		21.49±0.05	

Table 5.2: *Effect of cuts for 1992, 1993, and 1994 real data, and JETSET Monte Carlo. ‘%’ shows the fraction of events removed by each cut. The final row shows the fraction of events remaining after all cuts applied.*

5.4.2 Event Quality Cuts

After the 3-jet selection, a few further cuts are applied to ensure that each event contains three well-reconstructed jets. These are:

- **Charged multiplicity cut:** The total number of the good charged particles in each jet must be greater than 3.

- **Event energy cut:** Total energy in an event must be less than 115 GeV.
- **Planarity:** The event might not be planar because of some measurement errors and missing tracks. The sum of the angles between the jet axes must be greater than 358.5° . This removes the small number of events where the jet axes are not coplanar.
- **χ_E cut:** A cut is applied on jets where the reconstructed energy is significantly different to the expected energy calculated from the topology of the 3-jet events (see Chapter 7, Section 7.2.1). This cut attempts to remove events which are kinematically unphysical. Selected events are those where all 3 jets satisfy the condition $|\chi_E| < 0.5$, where $\chi_E = (E_{vis} - E_{cal})/E_{cal}$, E_{vis} and E_{cal} represent the visible and calculated jet energy, respectively. They will be explained in detail in Chapter 7.

Table 5.2 summarises the effects of these cuts on 1992, 1993, 1994 real data and on JETSET Monte Carlo data (1992 geometry). The Monte Carlo is seen to have a slightly higher proportion of 3-jet events, but the effect of the cuts is well reproduced.

Chapter 6

Tagging Heavy Flavour Events

6.1 Introduction

To compare the properties of quark and gluon jets it is necessary to be able to distinguish the two types. One way to do this is by identifying jets initiated by heavy quarks. This chapter discusses the selection of b quark events, from the preselected 3-jet events, using lifetime tagging.

The long life and large mass of the heavy quarks cause their decay products to have large impact parameters, allowing a separation from other quarks. The cross section of $b\bar{b}$ at Z resonance is around 6 nanobarns, almost 5 times bigger than at the $\Upsilon(4S)$. The average lifetime of b hadrons is about 1.6 picosecond to be compared with 0.4 ps for a D^0 and 1.1 ps for a D^+ . The b quark mass which is about 5.1 GeV/c² [23], is much bigger than any other quark produced at LEP, leading to greater average transverse momentum for beauty decay products. These properties of the b quark allow the study of beauty particles with reasonable statistics in a significant kinematic range.

Two tagging methods are commonly used for heavy quarks: semileptonic decays and track impact parameters (lifetime tagging). Semileptonic decays of heavy quarks yield prompt leptons with high transverse momentum. These have been widely used in the identification of heavy flavour events (e.g. [24]). Figure 6.1 shows an example of typical 3-Jet hadronic b events in the ALEPH detector.

6.2 Track Impact Parameter Method

As mentioned above, hadrons containing b quarks can be separated from the other hadrons by using the tracks with large impact parameter or tagging the

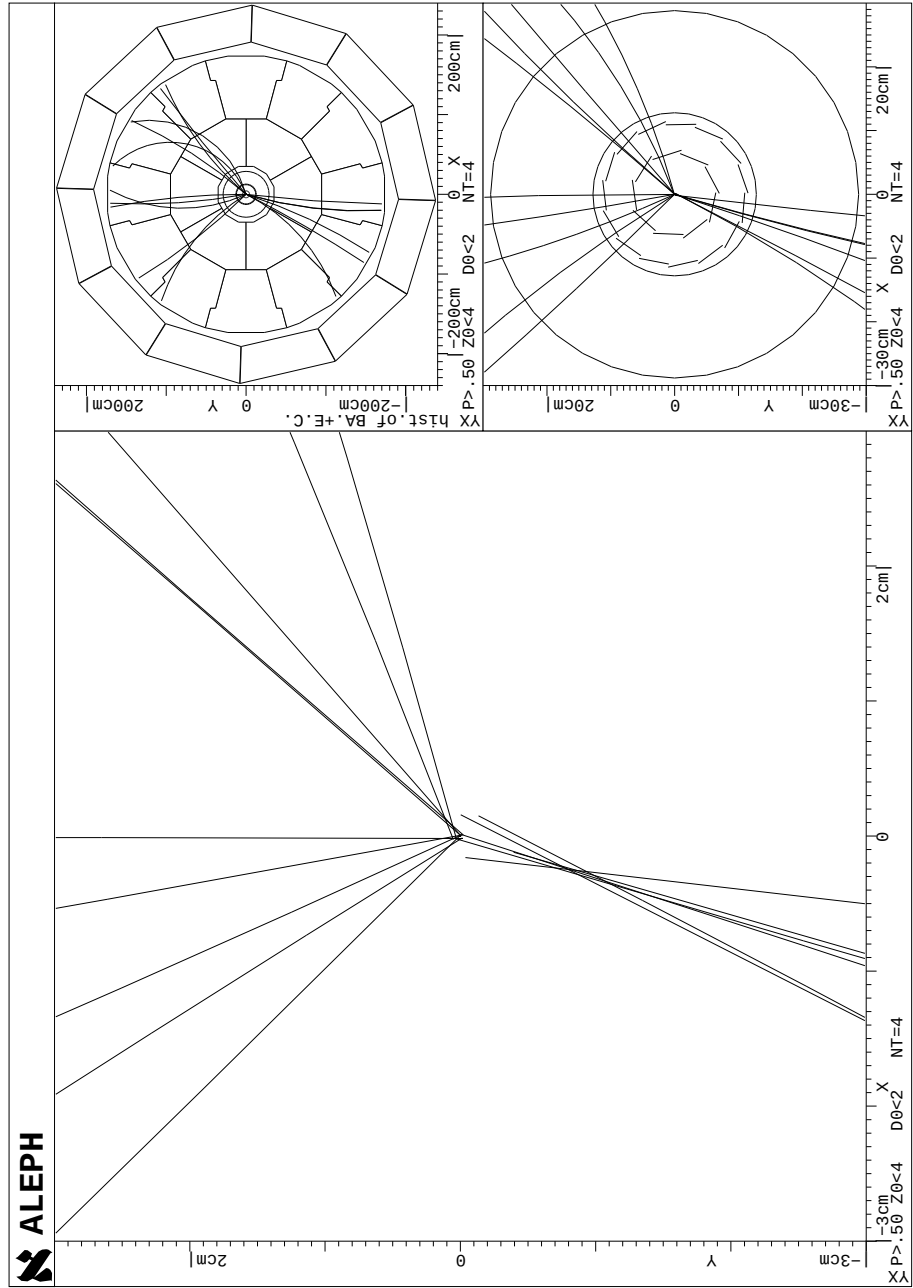


Figure 6.1: An example of a 3-Jet b event in the ALEPH detector. A secondary vertex is clearly visible several millimeters from the interaction point.

secondary vertex. The advantages of the impact parameter technique over explicitly reconstructing a secondary vertex are:

- It is conceptually simple.
- Tertiary vertices occur as b hadrons typically decay into c hadrons. The tracks from these vertices contribute to the statistical power of the impact parameter method.

6.2.1 QIPBTAG Algorithm

In this analysis QIPBTAG is used for tagging b hadrons by the impact parameter method. The QIPBTAG algorithm [25] specifies b hadrons by examining the signed impact parameter of all tracks produced in hadronic Z decays. For each track in a jet, the probability that it came from the primary vertex is calculated. These track probabilities are combined to provide event, hemisphere, and jet tag variables. QIPBTAG with its support routines goes through the following procedure for every event;

- perform jet clustering using EFLOW ¹.
- remove V^0 (e.g. K_s^0 , photon conversions, Λ^0) and other long lived decaying particles (e.g. $\pi^\pm$, $\Sigma^\pm$, $K^\pm$).
- get the beamspot position with the GET_BP routine. This routine computes an average beam position every 100 Z events from the Real data. This is also applied to the Monte Carlo where the beam spot resolution is simulated. The average error on these positions are 30 microns in x and 10 microns in y .
- locate the primary interaction point using QFNDIP. This is a standard ALEPH routine to find the interaction point (IP), given the beamspot (BP), the jet axes, and the tracks. The routine projects the tracks perpendicular to their closest jet axis, and combines their positions in that plane with the beamspot to calculate the interaction point. The routine was designed to be used with tracks which have associated hits in the silicon vertex detector (VDET).
- calculate track impact parameter with respect to the interaction point.
- compute the probabilities discussed above.

¹EFLOW algorithm is explained in Chapter 4.

6.2.2 Magnitude and Sign of Impact Parameter

The signed impact parameter of every track in an event produced in a hadronic Z^0 decay is computed. The impact parameter is constructed from 3 dimensional information, fully exploiting the VDET. The original b hadron direction is obtained from the direction of the jets. Jets are clustered using the JADE algorithm with a y_{cut} value of 0.02, operating on EFLOW objects.

The primary vertex position is calculated by the QFNDIP program from the jet direction, the beamspot position, and all tracks in the event. The impact parameter magnitude and sign definition in 3-dimension is shown in Figure 6.2. The point $\vec{P}$ shows the position of the primary vertex. $\hat{J}$ is the direction of the b momentum, as approximated by the jet direction. The circular arc represents a track, assumed here to have originated from the b decay point. $\vec{S}_t$ is the point on the track where it comes closest to the jet axis. $\vec{S}_j$ is an approximation of the b decay point. The track is linearized at $\vec{S}_t$, and the impact parameter magnitude D is defined as the distance of closest approach between linearized track and primary vertex.

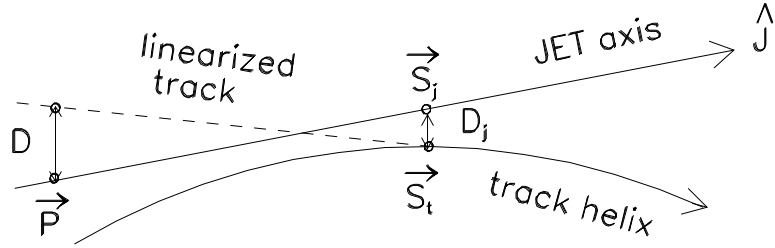


Figure 6.2: *Diagram of the impact parameter magnitude and sign definition in 3 dimensions.*

The physics principle of signing is that the decay point of the b must lie along the flight path of the hadron. The sign is then defined as positive when the vector $\vec{S}_j - \vec{P}$ lies in the same direction as the jet direction $\hat{J}$. The experimental resolution generates a random sign for tracks which originate from the primary vertex. Since only positive tracks are used in the tag, this reduces by 50% the background from tracks without lifetime. The negative sign tracks form a control sample which can be used to measure the resolution. The signed impact parameter $\tilde{D}$ is defined

Figure 6.3: *Impact parameter significance for Monte Carlo simulated data.*

for each track by;

$$\tilde{D} = \frac{(\vec{S}_j - \vec{P}) \cdot \hat{J}}{|(\vec{S}_j - \vec{P}) \cdot \hat{J}|} D \quad (6.1)$$

The statistical resolution of this value varies as a function of the track momentum, angle, and number of the hits in VDET. Therefore the QIPBTAG algorithm works with the value of $\tilde{D}/\sigma_D$, defined as the estimated statistical significance of the measured impact parameter.

Because the major functional dependences on momentum are removed, using $\tilde{D}/\sigma_D$ treats the impact parameter information from all tracks nearly uniformly. Figure 6.3 shows the $\tilde{D}/\sigma_D$ distribution for Monte Carlo, after the final track selection explained in the next section. In the absence of a non-zero lifetime, one would expect the positive and negative halves of the figure to look the same, as is seen for light quark events. The positive tail is then the lifetime signal which the tag is trying to detect. A probability function represents the probability that the measured positive $\tilde{D}/\sigma_D$ is consistent with the curve fitted to the negative $\tilde{D}/\sigma_D$ (the probability that the particle originated at the primary vertex). The track probability P_T is then defined as the result of this function applied to the measured $\tilde{D}/\sigma_D$ for that track.

6.2.3 Track Probability

Figure 6.4 shows the track probability distribution for b , c , and $u d s$ quarks. The figure shows there is a large spike near 0 on positive side which is the lifetime signal in the events. A similar spike is seen in charm events coming from the lifetime of the c hadrons. The negative side of the distributions represents the tracks with negative $\tilde{D}$. For light flavour events the primary quarks contribute no lifetime, so that the spectrum between 0 and 1 is expected to be flat as seen on the negative side of the spectrum.

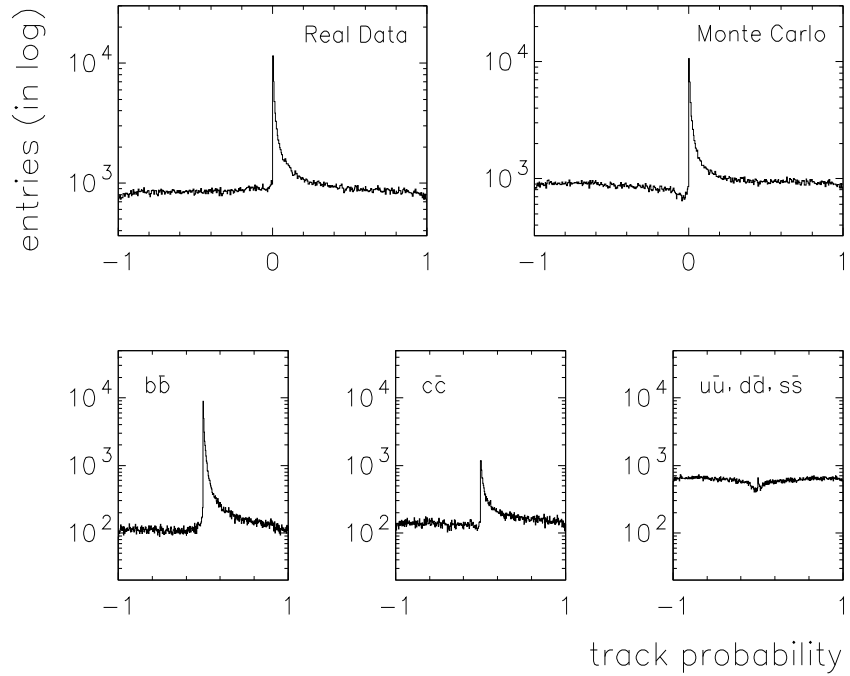


Figure 6.4: *The track probability distribution for real data and Monte Carlo. The lower plots show the Monte Carlo events divided into $b\bar{b}$, $c\bar{c}$, light flavours respectively.*

Event Selection

Events are selected by requiring them to have the momentum of at least 2 of the reconstructed jets above 10 GeV. This momentum cut has been applied to remove the jets unlikely to be associated with a b hadron, most of those removed come from gluon radiation. The two highest momentum jets in the event lie within the approximate solid angle acceptance of the VDET, $|\tan \lambda_{jet}| < 2$.

Track Selection

Good tracks are selected for tagging the b hadrons by using the set of cuts listed below:

- Track must have at least 4 TPC hit points.
- 3-dimensional tracking; at least one good VDET hit, in both the $r - \phi$ and z dimensions. For a track with only one VDET hit the $r - \phi$ and z hits should both be in the same layer. A track is considered to have two hits only if it has associated $r - \phi$ and z hits in both layers.
- $d_o < 0.5$ cm and $z_o < 0.5$ cm ; the track originates near the primary vertex.
- $|p| > 0.4$ GeV, where p is the momentum.
- $\cos \theta > 0.7$, where θ is the angle between the track and the nearest jet to that track. This cut discards the tracks which are unlikely to have been produced by b hadrons.
- $|D| < 0.25$ cm; where D is the impact parameter (see Figure 6.2). This cut removes both badly measured tracks and tracks coming from decays of very long lived particles (K^0, Λ^0 , etc). Very few b hadron decay tracks are lost by applying this cut.
- $\sigma_D < 0.075$ cm; to avoid tracks with poor statistical resolution.

The tracks from the b decay must be close to jet axis (i.e associated with a b hadron). Therefore a further cut on D_j , which is the distance of closest approach of the track to the axis (see Figure 6.2), is applied to reduce the number of badly-measured tracks included. Some background comes from tracks which have misassigned VDET hits (mostly in the case of tracks with only one VDET hit). Such tracks have a large value of D and fake the b signal. The background due to these track is reduced by cut on D_j of 0.4 mm for tracks with one VDET hit and 0.7 mm for tracks with two VDET hits. The physics principle applied is that, even if a track comes from a b hadron decay and thus has a large impact parameter at the origin, it must still come close to some point on the hadron trajectory. Conversely tracks which have a large impact parameter as a result of mis-associated VDET hits are subject to no such constraint. The tracks from b decays must not be too far from the primary vertex (since the mean lifetime length is in the order of mm). To reduce the contamination from long-lived particle decays, a cut on S_j is applied, requiring the distance along the jet axis

from the primary vertex to the point of closest approach of the track to the jet axis to be less than 1 cm.

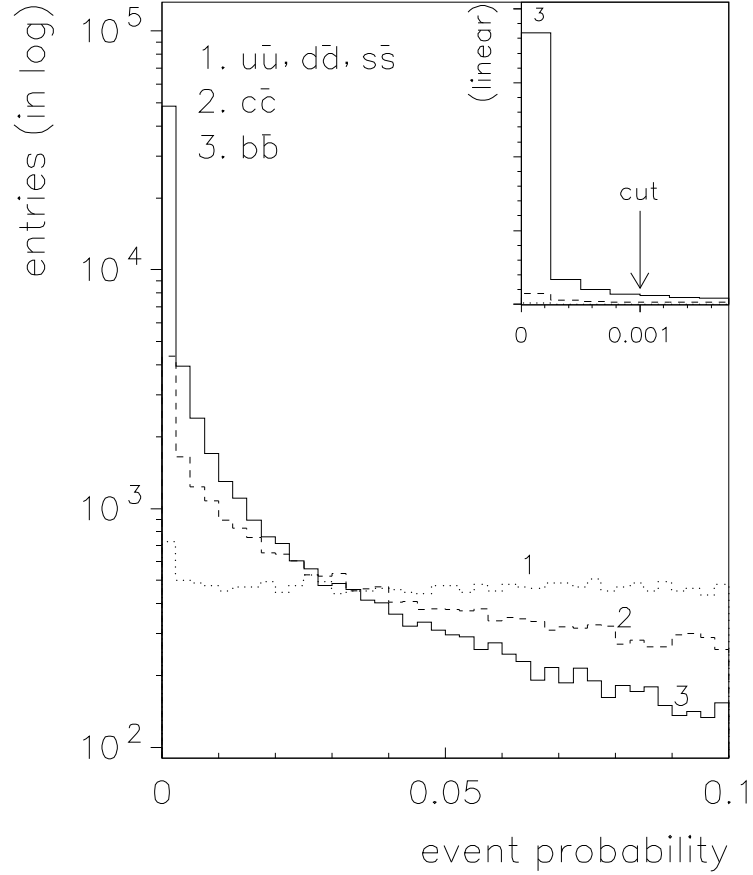


Figure 6.5: *The event probability distribution for $b\bar{b}$, $c\bar{c}$, and light (uds) quarks using Monte Carlo simulated events. The cut which is used for the b event selection is shown on the linear scale plot (inset). This cut value gives high purity with acceptable efficiency of b events.*

6.2.4 Impact Parameter Tag

The number of tracks with large impact parameters can be used to distinguish b hadrons from the others. Beauty hadrons typically produce about 5 charged tracks that contain lifetime information in their impact parameters. Event, hemisphere, and jet tag variables are then obtained by using the individual track probabilities. The tag variable P_N (combined probability, i.e. P_{Event} , $P_{Hemisphere}$, or P_{Jet}) is defined as the probability that any group of N tracks without lifetime produce the observed values of track probabilities or any other set of values

equally or more unlikely. More information on the mathematical calculation of the probabilities can be found in reference [25].

The event probability distributions for $b\bar{b}$, $c\bar{c}$, and light (uds) quarks using Monte Carlo simulated events are shown in Figure 6.5. As expected, in $u\bar{u}$, $d\bar{d}$, $s\bar{s}$ events the event probability distribution is flat indicating no lifetime in these events. The event cut which is used for b event selection is shown on the linear scale plot (inset). Events are selected if event probability less than 0.001, which gives high purity with a reasonable efficiency of b events.

Purity and Efficiency For b -Event Tag

The event tag efficiency and purity for individual events are examined by using Monte Carlo truth information for tagging different quark species. Figure 6.6 shows the efficiency and purity distributions as a function of the $\log$ of the cut variable for event tags in $Z \rightarrow q\bar{q}g$ hadronic events. Table 6.1 shows the $b\bar{b}$ efficiency and purity for different values of the event probability cut. The $b\bar{b}$ event efficiency and purity are 53% and 93% respectively if the cut is 0.001. After this cut has been applied $\sim 13\%$ of 3-jet events are accepted.

6.3 Event Selection and b -tagging for Analysis

The b -quark sample used in the following chapter is selected from the 3-jet event sample using cuts on event and jet probabilities. Events are selected if $P_{event} < 0.001$. The jets are ordered in energy, jet1 being the most energetic, and are required to have $P_{jet1} < 0.01$, $P_{jet2} < 0.1$, and $P_{jet3} > 0.2$ (note that jet3 is assumed to be the gluon jet, and should therefore have no lifetime). Finally, to ensure good-quality, well-reconstructed jets, each jet is required to have kinematic energy > 10 GeV and polar angle $> 30^\circ$ from the beam axis. This last cut removes the events where part of a jet may have been lost down the beam pipe.

The effect of these cuts is summarized in Table 6.2. A slight difference between real data and Monte Carlo can be seen.

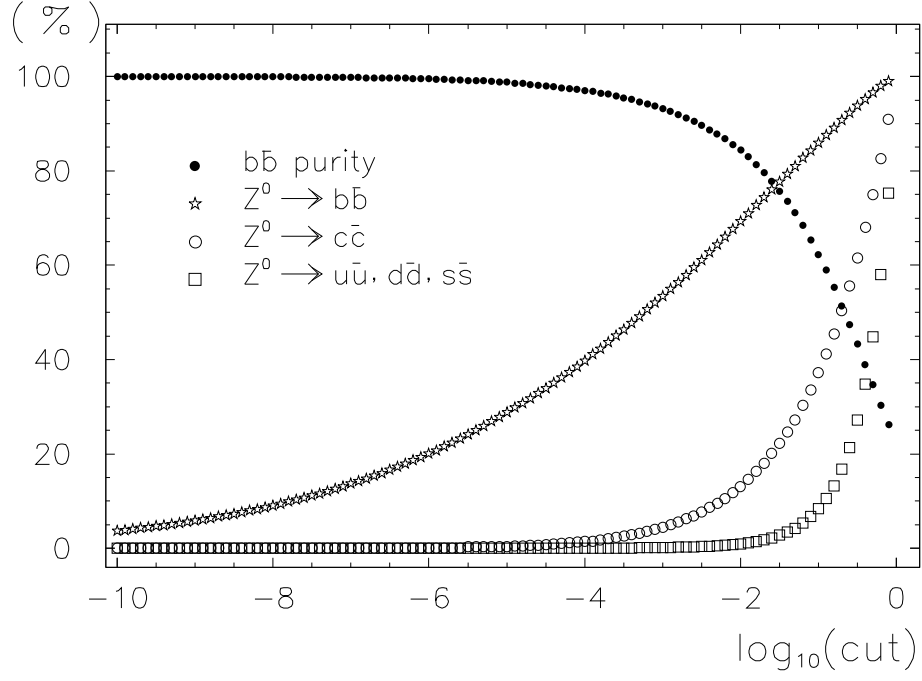


Figure 6.6: *The purity and efficiency for event tagging with different quark species, as a function of the log of event probability cut.*

Prob. cuts	0.0001	0.001	0.003	0.005	0.01	0.03	0.05	0.1
ε_b (%)	40	53	60	64	69	77	81	86
b purity (%)	97	93	90	88	84	76	71	62

Table 6.1: *The event tag efficiency and purity for $b\bar{b}$ events for different event tag values using Monte Carlo simulated events.*

cuts applied	# of remaining events									
	ALEPH data								Monte Carlo	
	1992	%	1993	%	1994	%	Total	%	JETSET	%
preselected	98k	–	105k	–	269k	–	473k	–	170k	–
$P_{evt} < 0.001$	12174	87.6	12763	87.8	35456	86.8	60393	87.2	18884	88.9
$P_{jet1} < 0.01$	10508	13.7	10995	13.9	30789	13.2	52292	13.4	16059	15.0
$P_{jet2} < 0.1$	9024	14.1	9487	13.7	26670	13.4	45181	13.6	13595	15.3
$P_{jet3} > 0.2$	4952	45.1	5007	47.2	14062	47.3	24021	46.8	8005	41.1
$E_{jet} > 10\text{GeV}$	4211	15.0	4274	14.6	12083	14.1	20568	14.4	6964	13.0
Jet-beam ang.	3907	7.2	3962	7.3	11150	7.7	19019	7.5	6491	6.8
overall fraction %	3.98 ± 0.06		3.78 ± 0.06		4.14 ± 0.04		4.02 ± 0.03		3.81 ± 0.05	

Table 6.2: *Number of the remaining events after b -event selection and b -tagging selection for 1992, 1993, and 1994 real data, and JETSET Monte Carlo. ‘%’ shows the fraction of events removed by each cut. The final row shows the fraction of events remaining after all cuts applied.*

Chapter 7

Quark and Gluon Jet Study

7.1 Introduction

As has already been mentioned, quarks cannot be observed as free particles but rather generate additional $q\bar{q}$ pairs as they decay apart from other quarks and gluons in the e^+e^- annihilation. They are then observed as jets. So their properties can be studied by analysing the jets. Quarks and gluons have different colour charge, and because of this one can expect to observe some differences in the properties of quark-induced and gluon-induced jets.

Generally from the theory of quark-gluons, gluon jets are expected to have higher multiplicity, a softer momentum spectrum, and broader profiles than quark jets. In this chapter these properties are studied using particle energy flows in jets, mean multiplicity as a function of energy as well as opening angle between jets, track rapidity, energy fraction carried by the particles in an event, and total energy fraction in a cone centred around the jet axis.

To make a comparison of quark and gluon jets only 3-jet events are selected. An event sample is chosen to investigate how the properties change with topology [27] and energy.

7.2 Energy Ordering

The energy ordering of jets can be used to separate samples of quark and gluon jets. Because of the nature of the bremsstrahlung-like spectrum of gluons in $e^+e^- \rightarrow q\bar{q}g$ decays the least energetic jet (called jet3) should have the highest probability of being a gluon jet.

To compare quark and gluon jets, 3-jet events are selected as described in Chapter 5. The jets within each event are then energy ordered with the most

energetic jet labelled jet1, the second most energetic labelled jet2 and the least energetic jet labelled jet3, using their calculated energies (explained below).

7.2.1 Jet Energy Measurement

The energy of each jet is calculated in two different ways, giving the visible energy, E_{vis} , and the calculated (kinematic) energy, E_{cal} .

Visible Energy

The visible energy of a jet can be described as the sum of the energy of each energy flow objects. The visible energy, E_{vis} , of a jet is simply defined by

$$E_{vis} = \sum_{i=1}^{n_j} E_{ij} \quad (7.1)$$

where n_j is the number of energy flow particles in jet j ($j=1,2,3$), and E_{ij} is the energy of the i^{th} particle in jet j . The particle energy assumes the pion mass for charged particles and zero mass for all neutrals. Figure 7.1 shows the visible energy distributions (E_{vis}) of jet1, jet2 and jet3 for real data and Monte Carlo.

Calculated Energy

An improved estimate of the jet energies can be obtained by using the angles between the jet projections in a plane. The event plane is defined using the momentum tensor

$$M_{\alpha\beta} = \frac{\sum_i P_{i\alpha} P_{i\beta}}{\sum_i P_i^2} \quad (7.2)$$

where α and β represent the three momentum components (x , y , and z) of the i^{th} particle. The eigenvectors corresponding to the the eigenvalues λ_1 , λ_2 , λ_3 of this 3×3 symmetric tensor ($\lambda_1 < \lambda_2 < \lambda_3$) define the event plane. The cross product of the first two eigenvectors gives a normal vector to the event plane of the event. The projection of each jet (as a unit vector) into the event plane is determined, and the angles between these projections are used to calculate the calculated energies of the jets in every event.

The angular distributions between the jet projections for real data are shown in Figure 7.2, the angles θ_{12} , θ_{23} , and θ_{32} represent the plane angles, e.g. θ_{12} is the angle between the projections of jet1 and jet2 in the event plane. The angle between the two most energetic jets is larger than the others. The calculated

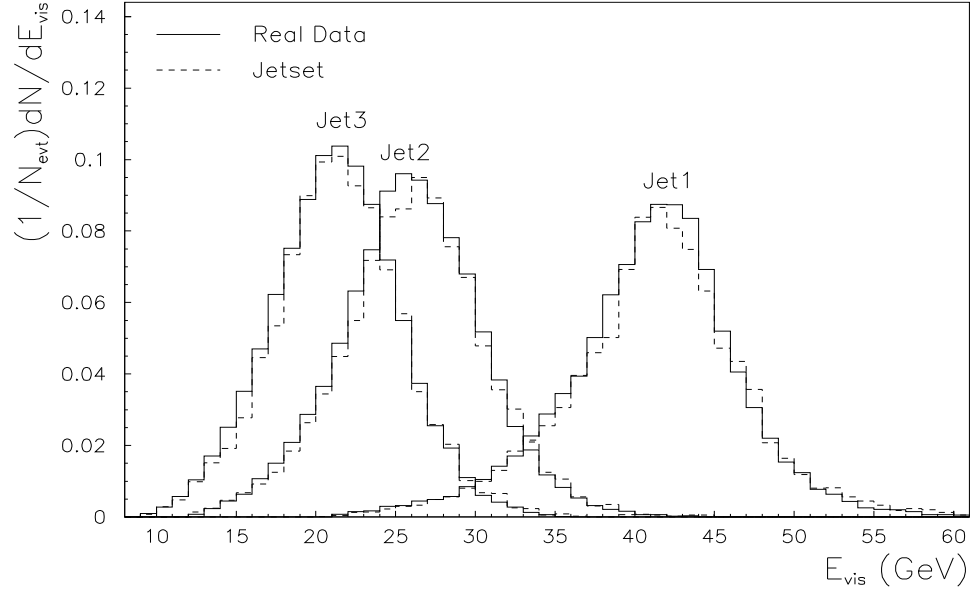


Figure 7.1: *Visible energy distributions of the jet1, jet2 and jet3 for Real data, and Monte Carlo JETSET data.*

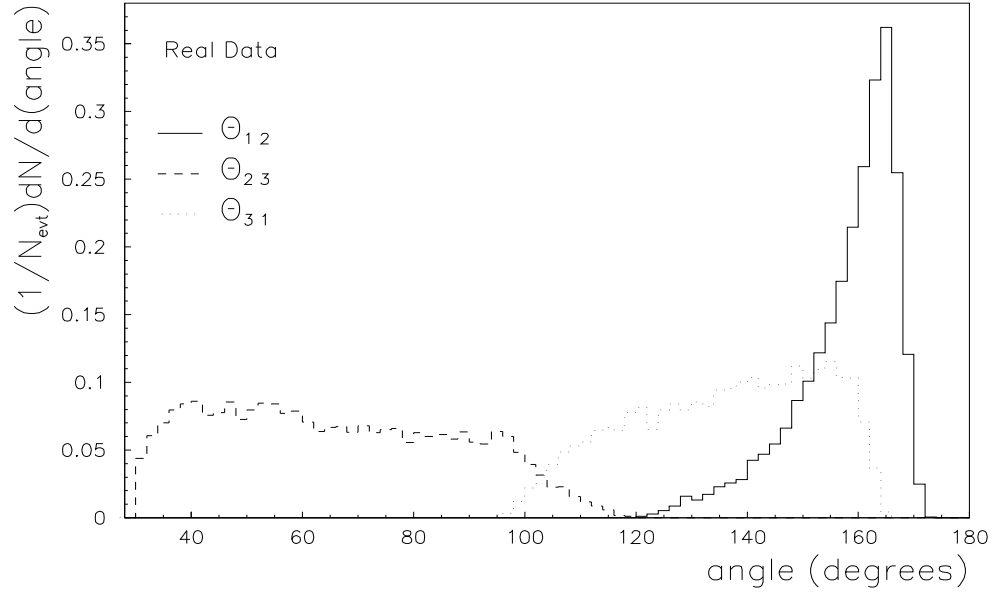


Figure 7.2: *The angular distributions between the jet projections in each three jet event for real data, e.g. θ_{12} is the angle between jet1 and jet2.*

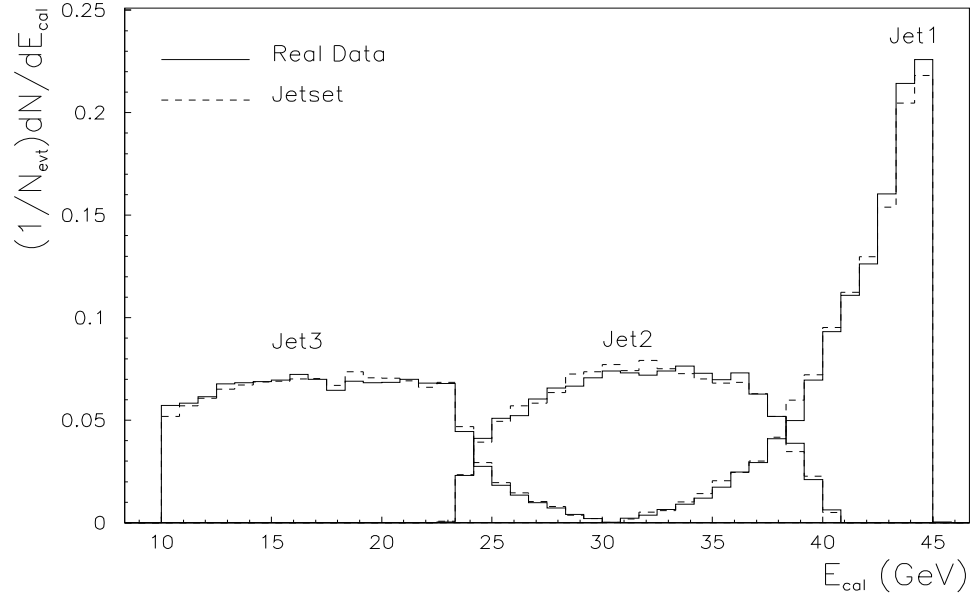


Figure 7.3: *Calculated energy distributions of jet1, jet2 and jet3 for real data and Monte Carlo JETSET data.*

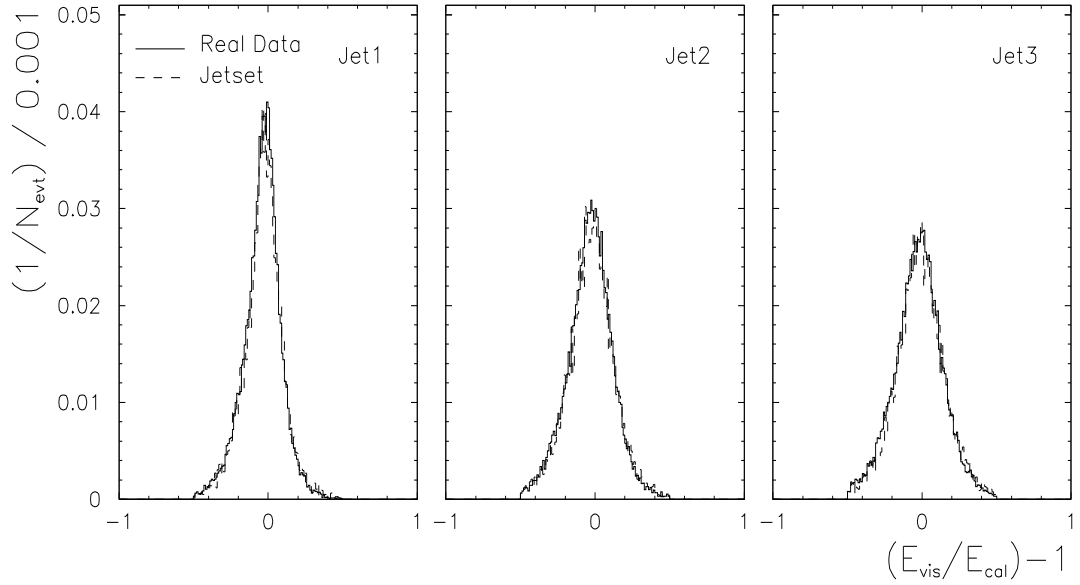


Figure 7.4: *Comparison of the visible and calculated jet energies of the jet1, jet2 and jet3 for Real data, and JETSET Monte Carlo data.*

energy of every jet in an event is determined by using the formula:

$$E_{cal}^i = \frac{\sin \theta_{jk}}{\sin \theta_{12} + \sin \theta_{23} + \sin \theta_{31}} \sqrt{s} \quad (i, j, k \text{ cyclic}) \quad (7.3)$$

where i, j, k represent the jet numbers with their inter-jet angles $\theta_{ij}, \theta_{ik}, \theta_{jk}$, and $\sqrt{s}$ is the center of mass energy. The jets are then ordered according to their calculated energies such that $E_{cal}^1 > E_{cal}^2 > E_{cal}^3$. Calculating energy in this way improves jet resolution by reducing the effect of reconstruction inefficiencies and track resolution.

The calculated jet energy (E_{cal}) distributions of jet1, jet2 and jet3 are shown in Figure 7.3 after energy ordering has been done, real data is compared with JETSET¹ Monte Carlo data. The size of the correction can be seen by plotting $(E_{vis}^i/E_{cal}^i) - 1$, where E_{vis}^i , and E_{cal}^i are the measured and calculated energy of the jets. Figure 7.4 shows the distributions for Real data, Monte Carlo JETSET data. The correction is typically 13% (Gaussian fit is applied).

7.3 Y-shape Event Configurations

To avoid bias arising from the varying energies of quark and gluon jets the analysis is based on a symmetric event configuration. The commonly used y-shape event topology is employed [26, 27]. Another reason for this is that in y-shape events the most energetic jet can be assumed to be quark jet with a very high purity. This gives a higher probability of labelling the remaining jets correctly.

The selection of three-jet events is described in Chapter 5. Y-shape events are defined as those where the angles between the most energetic and each of the remaining jets are 150 ± 10 degrees. This is illustrated in Figure 7.5. The angular separations and jet energies of the selected events are shown in Figures 7.6 and 7.7. The two lower energy jets overlap in energy. This allows the comparison of quark and gluon jets at the same energy to be made.

Figure 7.8 indicates the region the selected y-shape events occupy on a Dalitz plot with x_1, x_2, x_3 representing the scaled jet energies $x_i = E_i/E_{beam}$ where i is the jet number, E_i is the energy of jet i , and E_{beam} is the beam energy.

¹Version 7.3 of (ALEPH tuned) JETSET is used.

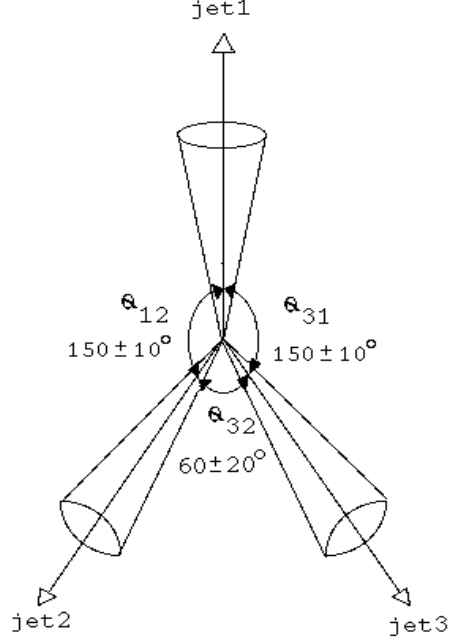


Figure 7.5: An illustration of the definition of the *y*-shape event topology used in this analysis.

7.4 Event and Jet Samples

7.4.1 Event Samples

Two event samples are used: ‘mixed flavour sample’, S_{mix} , selected as described in Chapter 5 and so consisting of a mixture of quark flavours, and a sub-set of this where a double *b*-tag is applied. The tagging method is explained in Chapter 6. This sample will be termed the ‘*b*-tagged sample’, S_{btag} . Although the double *b*-tag sample contains a much smaller number of events, jet3 is known to be a gluon jet with a very high purity and so purity corrections are negligible when using these samples. Table 7.1 shows the number of the selected events for S_{mix} and S_{btag} samples before and after *y*-shape selection.

7.4.2 Jet Comparison Methods

For the comparison of quark and gluon jets, three methods are used. The first method takes the 2nd jets (quark candidates) from the sample S_{mix} , and 3rd (gluon candidates) from the double *b*-tagged sample S_{btag} . The second and third

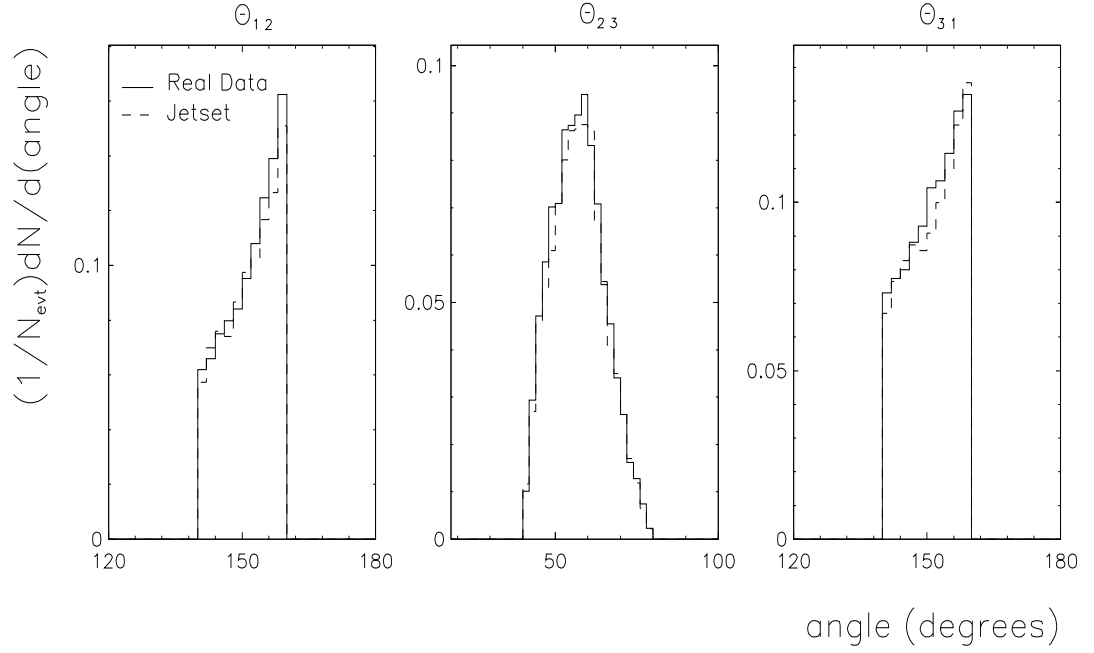


Figure 7.6: *The angular distributions between the jets in each three jet event sample for (a) real data (b) JETSET Monte Carlo data after the y-shape event selection. θ_{12} , θ_{23} , and θ_{31} are the angles between jet1 and jet2, and jet2 and jet3, and jet3 and jet1 respectively.*

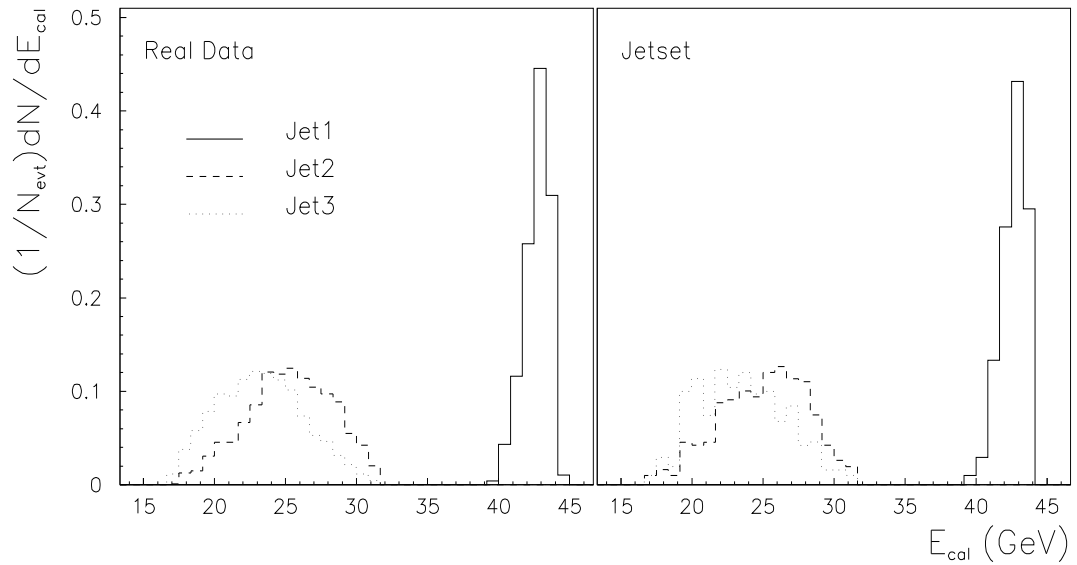


Figure 7.7: *Calculated energy distribution of the jet1, jet2 and jet3 for y-shape events for real data and JETSET Monte Carlo data.*

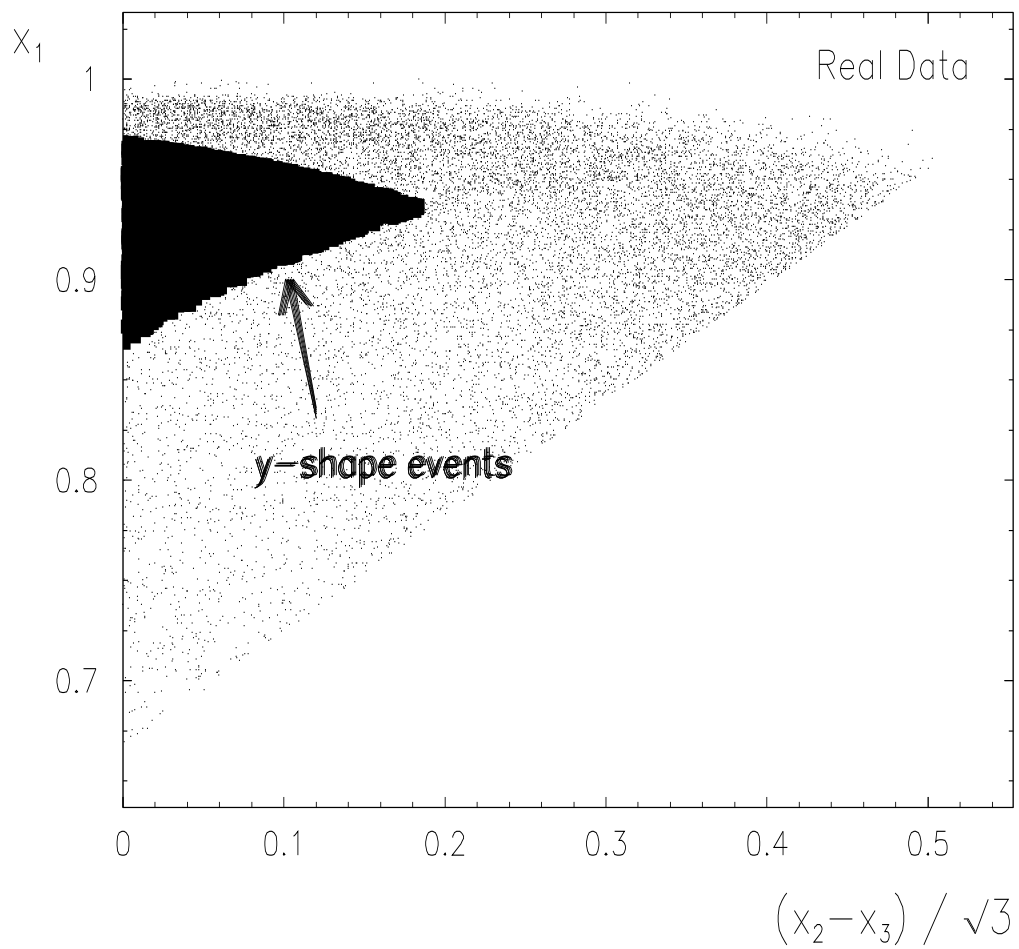
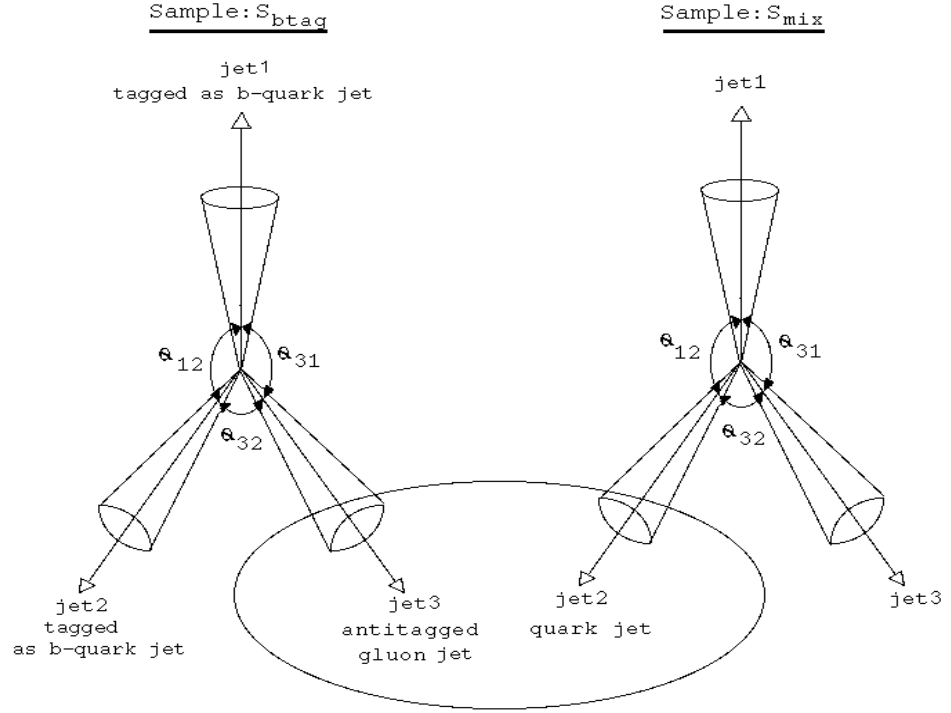
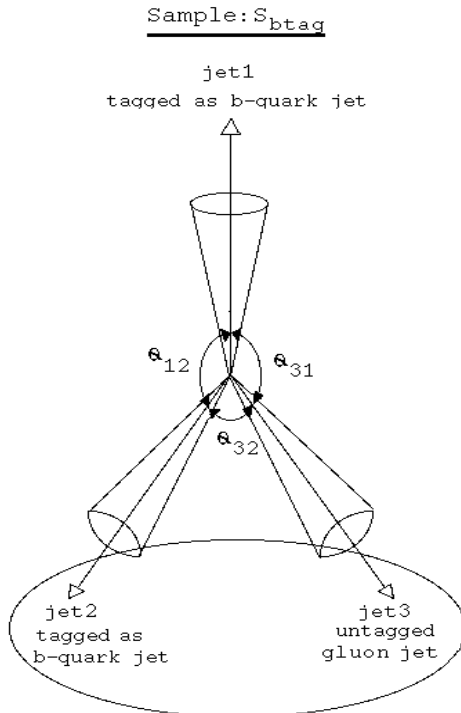


Figure 7.8: *The Dalitz plot of x_1 as a function of $(x_2 - x_3) / \sqrt{3}$ for real data and Monte Carlo data. The position of the 150° y-shape events is shown.*

Method 1



Method 2



Method 3

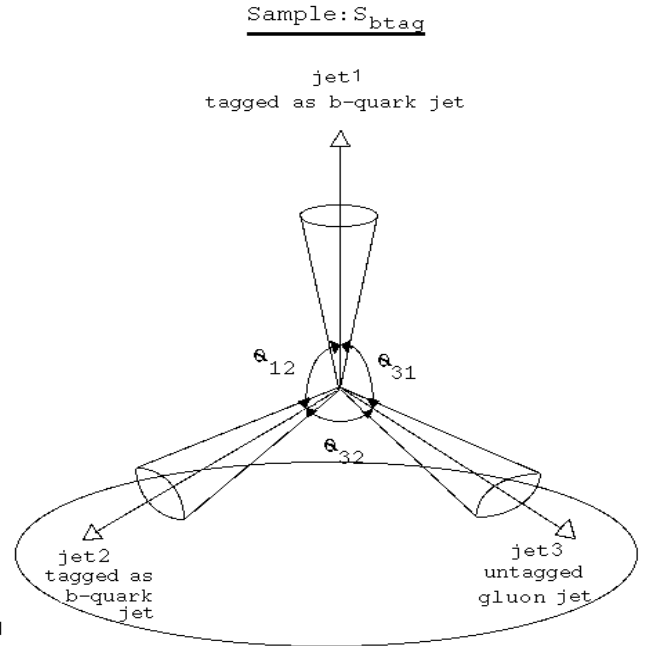


Figure 7.9: The methods for the comparison of quark and gluon jets. For method 1 and 2 the angles θ_{12} and θ_{31} are $150 \pm 10^\circ$, and θ_{23} is $60 \pm 20^\circ$.

samples used	# of remaining events				
	Real data				Monte Carlo data
	1992	1993	1994	total	JETSET
S_{btag}	3907	3962	11150	19019	6491
$y - shape S_{btag}$	237	222	665	1124	370
$y - shape S_{mix}$	4343	4627	11891	20861	7662

Table 7.1: *Number of the remaining events for event samples used in quark - gluon comparison for real data and JETSET Monte Carlo data.*

methods simply compare the 2^{nd} jet in the sample S_{btag} to the 3^{rd} jet in the same sample. For methods 1 and 2, only y-shape events are used; this constraint is not applied in method 3. These three methods are illustrated in Figure 7.9.

7.5 Monte Carlo Parton Level Analysis

The efficiency and purity of samples is obtained using the JETSET Monte Carlo model. At the parton level the primary quarks are identified as the daughter particles of the initial Z bosons. The final state partons are clustered into three jets using the DURHAM algorithm previously explained. To cluster the particles into jets, instead of using a particular y_{cut} value, the y_{cut} is varied until three jets are found. This is because with the use of $y_{cut} = 0.01$ almost 20% of the events would not be clustered into three jets.

In the event plane every jet at the parton level is matched to the closest detector level jet. The jets are then identified as quark-induced or gluon-induced and each parton is then given a parton number such that $q=1$, $\bar{q}=-1$ and $g=0$. Only the events where the three jets had numbers 1, -1, 0 are accepted as a candidate quark, antiquark or gluon, and jet is then named according to its jet number.

7.5.1 Ambiguous Events

The sources of the ambiguous events are various. In this analysis ambiguous events are defined as:

- events with no gluon decays, such that there are only $q\bar{q}$ at the parton level.
- events where any two jets are clustered into the same jet.
- events where a minimum matching angle between the parton level and detector level is greater than 40 degrees.

7.6 Purity Measurements

7.6.1 Purity of b -quark Sample

As already mentioned the purity of selected samples is measured using the JET-SET parton shower Monte Carlo.

The purity of the b -quarks in the S_{btag} sample is defined by:

$$P = \frac{\text{number of } Z \rightarrow b\bar{b} \text{ events selected}}{\text{the total number of events selected}} \quad (7.4)$$

For the selected samples S_{btag} , y -shape S_{btag} and y -shape S_{mix} the flavour contributions are listed in Table 7.2.

samples	flavour contribution %				
	b	c	d	u	s
S_{btag}	95.69	3.84	0.14	0.11	0.23
$y - shape S_{btag}$	96.76	2.97	–	0.27	–
$y - shape S_{mix}$	21.29	18.57	21.70	17.24	21.09

Table 7.2: *The flavour content of selected events for S_{btag} , y -shape S_{btag} and y -shape S_{mix} samples.*

7.6.2 Quark and Gluon Jet Purity

For the purity calculation Monte Carlo simulated events are selected and classified as correctly tagged, wrongly tagged and ambiguous events. Events are named as ‘correctly tagged’ events if the lowest energy quark jet on the parton level matches to the 2^{nd} jet on the reconstructed level, and if the gluon jet on the parton level

matches to the 3rd jet on the reconstructed level. If the lowest energy quark jet on the parton level matches to the 3rd jet on the reconstructed level, or the gluon jet on parton level matches to the 2nd jet on the reconstructed level then the event is named as ‘wrongly tagged’. Ambiguous events are those satisfying the conditions outlined in Section 7.5.1. The samples are unfolded to correct for wrongly-tagged events. The unfolding procedure will be described later.

The purity of quark and gluon jets are obtained by using the formula:

$$P = \frac{N_{cor} + N_{amb}/2}{N_{cor} + N_{wro} + N_{amb}} \quad (7.5)$$

where N_{cor} and N_{wro} are the number of selected $Z \rightarrow q\bar{q}g$ events correctly and wrongly matched to the parton level events, respectively, and N_{amb} is the number of the ambiguous events. The purity calculation includes the ambiguous events, assuming that on average half of these are tagged correctly. The associated systematic error is calculated using

$$P_{max} = \frac{N_{cor} + N_{amb}}{N_{cor} + N_{wro} + N_{amb}} \quad (7.6)$$

$$P_{min} = \frac{N_{cor}}{N_{cor} + N_{wro} + N_{amb}} \quad (7.7)$$

where in the first equation, the maximum purity is calculated by supposing that the ambiguous events are correctly tagged, while in the second one all of the ‘ambiguous’ events are considered as tagged wrongly. The statistical errors on the purity of jets are calculated using

$$\Delta P_{stat} = \sqrt{\frac{P(1-P)}{N_{event}}} \quad (7.8)$$

where N_{event} is the number of the selected events. The results for the three samples are summarized in Tables 7.3 and 7.4.

7.6.3 Purity Correction for Unfolding Distributions

For the unfolded distributions of pure quark and pure gluon jets, a purity correction is applied to the measured distributions. From the two different sets of samples, S_{mix} and S_{btag} , one can obtain the following equations;

$$\xi_{S_{mix}} = (1 - P_g^{S_{mix}})\xi_q + P_g^{S_{mix}}\xi_g \quad (7.9)$$

$$\xi_{S_{btag}} = (1 - P_g^{S_{btag}})\xi_q + P_g^{S_{btag}}\xi_g \quad (7.10)$$

where $\xi_{S_{mix}}$, and $\xi_{S_{btag}}$ represent the measured values in the S_{mix} , and S_{btag} data respectively. $P_g^{S_{mix}}$ and $P_g^{S_{btag}}$, which are the gluon sample purities, have already been calculated in S_{mix} and S_{btag} samples from Monte Carlo measurements. ξ_q and ξ_g represent the corresponding values measured for pure gluon and quark jets. (Here it is assumed that the values measured for the complete quark sample are the same as those of the misidentified jets). From equations 7.9 and 7.10 one can solve for ξ_q and ξ_g .

$$\xi_q = \frac{P_g^{S_{btag}}\xi_{S_{mix}} - P_g^{S_{mix}}\xi_{S_{btag}}}{P_g^{S_{btag}} - P_g^{S_{mix}}} \quad (7.11)$$

$$\xi_g = \frac{(1 - P_g^{S_{mix}})\xi_{S_{btag}} - (1 - P_g^{S_{btag}})\xi_{S_{mix}}}{P_g^{S_{btag}} - P_g^{S_{mix}}} \quad (7.12)$$

Unfolded multiplicity distributions are obtained using these two equations.

samples	total matched events	jet	correctly matched	wrongly matched	ambiguous
S_{btag}	6491	1	6402	89	6
		2	6309	182	
		3	6221	270	
$y - shape\ S_{btag}$	370	1	365	5	2
		2	363	7	
		3	362	8	
$y - shape\ S_{mix}$	7662	1	7442	220	98
		2	5593	2069	
		3	5210	2452	

Table 7.3: *Number of correctly tagged, wrongly tagged and ambiguous events for jet1 (quark or antiquark), jet2 (quark or antiquark), and jet3 (gluon) in the three event samples.*

samples	purity %		
	jet1	jet2	jet3
S_{btag}	$98.58 \pm 0.15 \pm 0.05$	$97.15 \pm 0.21 \pm 0.04$	$95.80 \pm 0.25 \pm 0.04$
$y - shape\ S_{btag}$	$98.39 \pm 0.65 \pm 0.27$	$97.85 \pm 0.75 \pm 0.27$	$97.58 \pm 0.80 \pm 0.27$
$y - shape\ S_{mix}$	$96.53 \pm 0.21 \pm 0.63$	$72.71 \pm 0.51 \pm 0.64$	$67.78 \pm 0.53 \pm 0.68$

Table 7.4: *The purities of jet1 (as quark or antiquark), jet2 (as quark or antiquark), and jet3 (as gluon) for the three event samples. The first error is statistical and the second systematic.*

7.7 Observation of Quark-Gluon Jet Differences

The jet properties are studied by examining rapidity (η), fragmentation function, energy fractions within cones centred around the jet axis, and the mean multiplicity as a function of jet energy using comparison method 1. The quark jet mean multiplicity is also compared with gluon jet as a function of energy and angle using comparison method 3.

7.7.1 Jet Rapidity Measurement

The longitudinal momentum of particles in a jet can be studied in terms of the rapidity. The rapidity of a particle with respect to the jet of which it is part is defined by

$$\eta = \frac{1}{2} \ln \left(\frac{E + p_L}{E - p_L} \right) \quad (7.13)$$

where E is the energy of the particle, and p_L is its longitudinal momentum relative to the jet axis.

A wider momentum distribution and high multiplicity of particles in gluon jets would imply that particles in gluon jets should have lower rapidity. The rapidity distributions of charged and charged-plus-neutral particles are studied.

The comparisons of rapidity distributions for method 1 are shown in Figure 7.10. Real data is compared with JETSET and HERWIG² Monte Carlo data. The parton rapidity distribution obtained from Monte Carlo is shown inset. Here the distributions are normalized to unit area so that the shape of the distributions are compared. The mean multiplicities are compared later, in section 7.7.4. This shows that the quark jet particles have harder longitudinal momentum spectra than the particles in a gluon jet. A comparison of rapidity distributions for b -quark jets and gluon jets (method 2) is shown in Figure 7.11 for real data. This shows that for b -events the quark and gluon have almost the same rapidity distribution. The same behaviour is seen in the Monte Carlo data (Figure 7.12). Again the distributions are normalized to unit area.

²Version 5.6 of (ALEPH tuned) HERWIG is used.

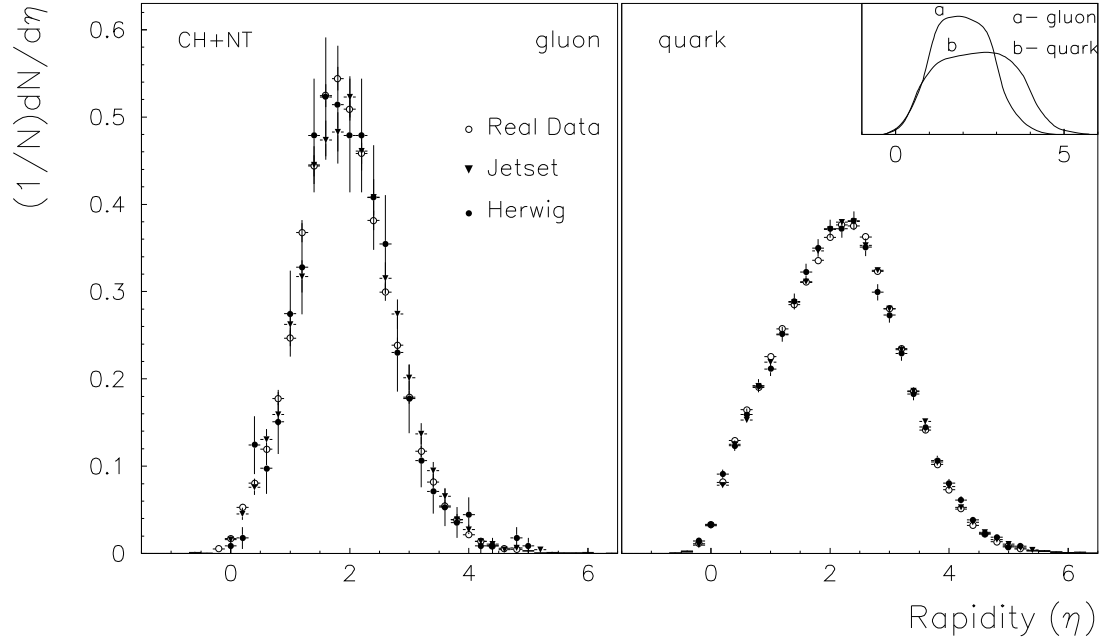


Figure 7.10: For method 1, quark and gluon jets rapidity distributions for charged-plus-neutral particles; comparison with JETSET and HERWIG Monte Carlo data. Inset; the parton rapidity distribution from the Monte Carlo.

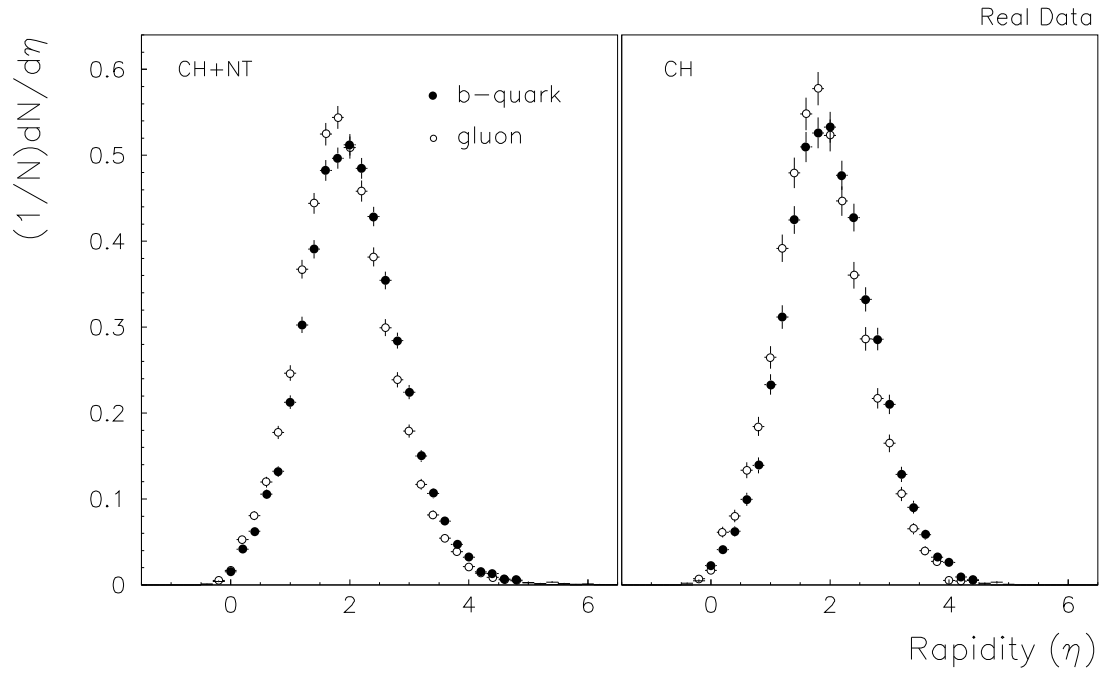


Figure 7.11: For method 2, b-quark and gluon jets rapidity distributions including charged-plus-neutral particles for real data.

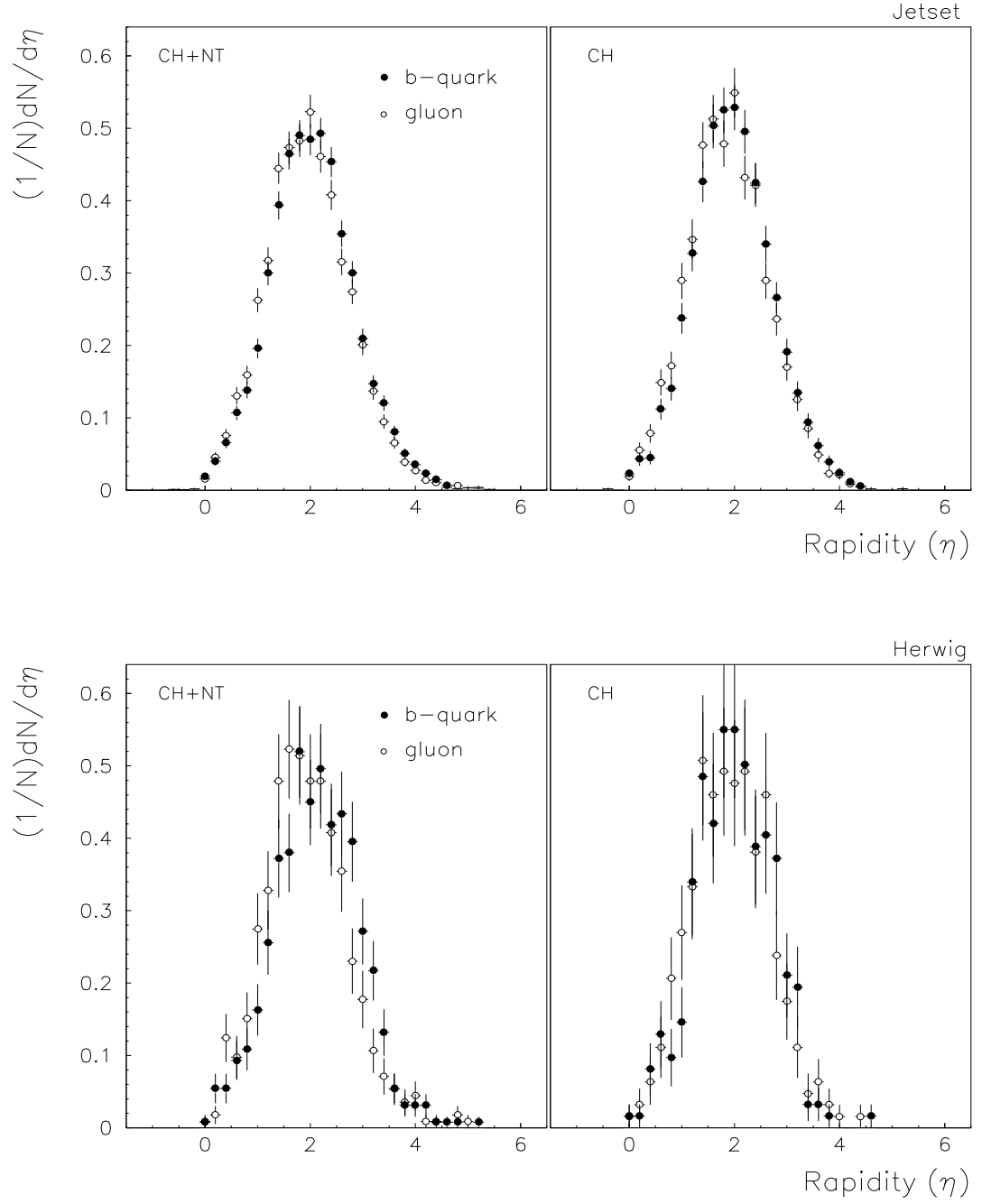


Figure 7.12: For method 2, b-quark and gluon jets rapidity distributions of charged-plus-neutral and charged particles only, for JETSET (upper plots) and HERWIG (lower plots).

7.7.2 Fragmentation Function

The energy of each particle is scaled by the calculated energy of that jet, so $X_E = E_{par}^i / E_{jet}^i$, where E_{par}^i represents the particle energies in the i^{th} jet and E_{jet}^i is the visible energy of that jet. This gives us a measure of the fraction of the jet energy carried by the particles.

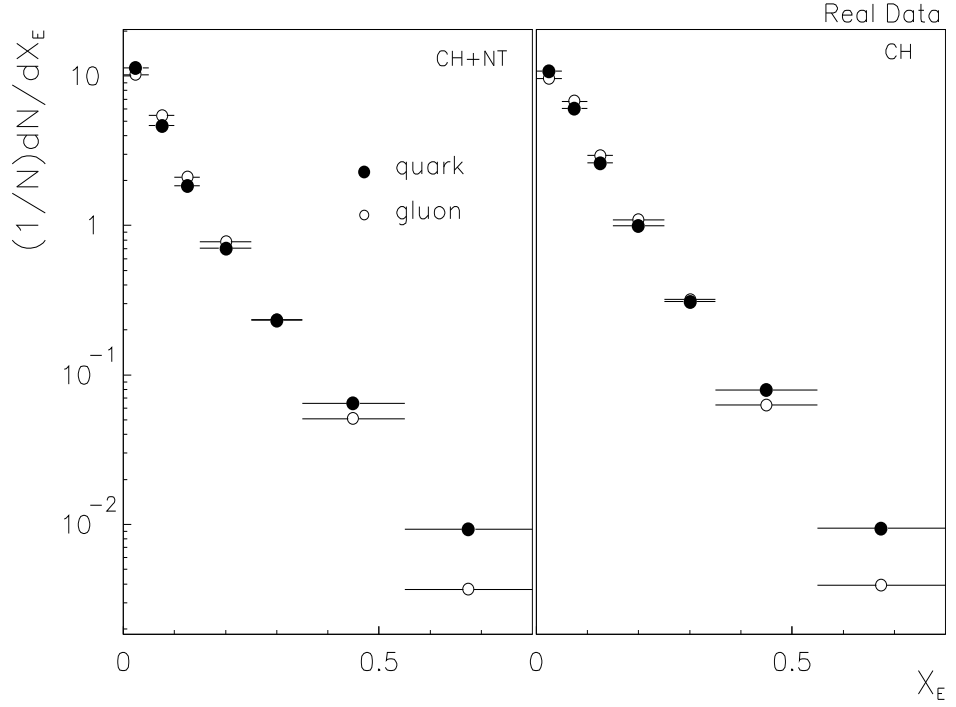


Figure 7.13: *For method 1, fragmentation function distributions for quark and gluon jets for charged-plus-neutral particles, and charged particles only, from real data.*

For method 1 Figure 7.13 shows fragmentation function distributions for particles in quark and gluon jets for charged and charged-plus-neutral real data as a function of scaled energy X_E . The distributions are normalized to unit area so that the shape of the fragmentation function is compared. As seen from the figure, gluon jets have a softer particle spectrum. The similar distributions are obtained for real data compared with JETSET and HERWIG Monte Carlo data (see Figure 7.14). In Figure 7.15 b -quark jet are compared with gluon jets both obtained from the S_{btag} sample (method 2).

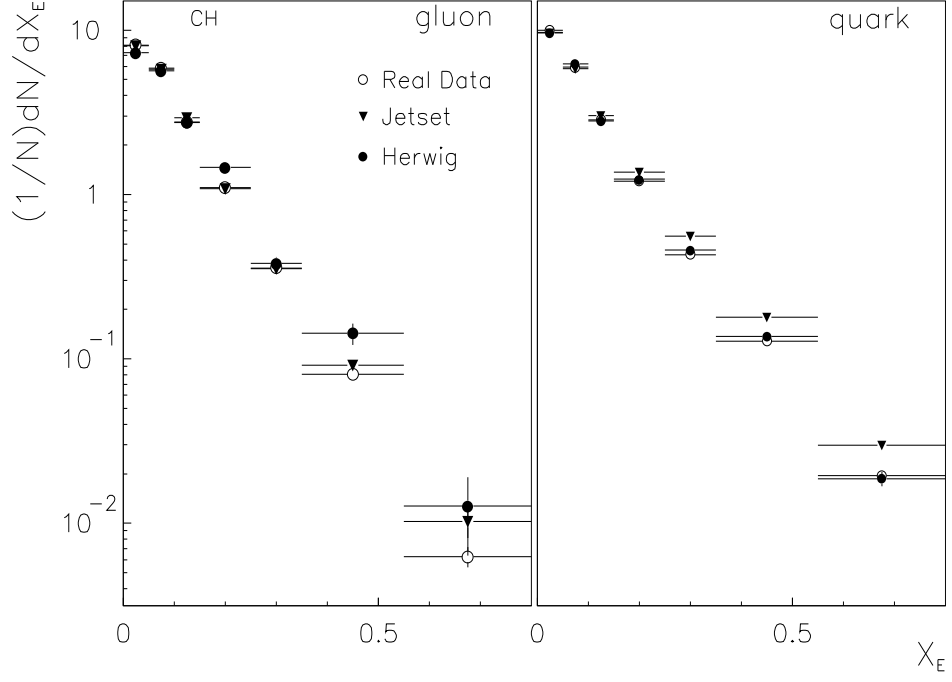


Figure 7.14: *For method 1, fragmentation function distributions for quark and gluon jets for charged particles. Real data are compared with JETSET and HERWIG Monte Carlo data.*

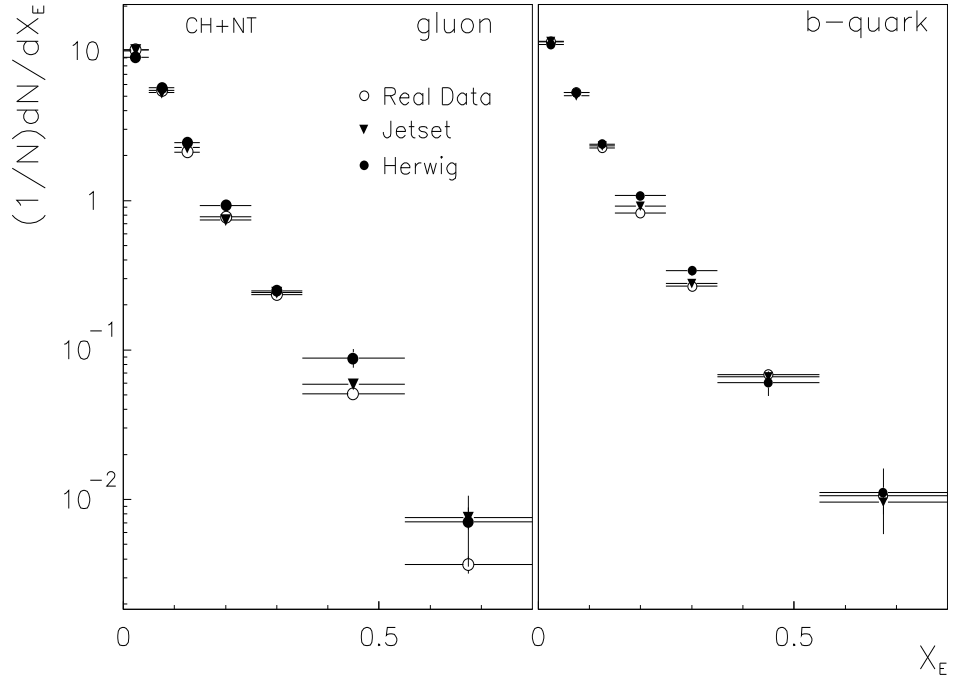


Figure 7.15: *For method 2, fragmentation function distributions for b-quark and gluon jets for charged particles. Real data are compared with JETSET and HERWIG Monte Carlo data.*

7.7.3 Cone Energy Fraction

If gluon jets are broader than quark jets at the same jet energy, the particles in the jets must be spread over a wider angular range. The fraction of the jet's visible energy within a cone around the jet axis is used as a way of measuring the broadness of the jets. For every jet in an event sample, a cone of half angle θ (for $0^\circ < \theta < 45^\circ$) is defined and the cone energy is then scaled by the energy of the jet:

$$E_f^i(\theta) = \frac{E_{cone}^i(\theta)}{E_{jet}^i} \quad (7.14)$$

where E_{cone}^i represents the energy within a cone half-angle θ at a given cone angle range and E_{jet}^i is the visible energy of that i^{th} jet. The integrated energy fraction is then obtained for every 3° of cone angle. For the distributions both charged and neutral particles are considered as well as charged particles only.

The energy fraction distributions of quark and gluon jets (method 1), and b -quark and gluon jets (method 2) for charged particles are shown in Figure 7.16. For real data the ratio of quark to gluon jets is shown in the inset. Figure 7.17 plots the integrated cone energy contained within a cone of half angle θ , scaled by the total visible energy for method 1. Real data are compared with

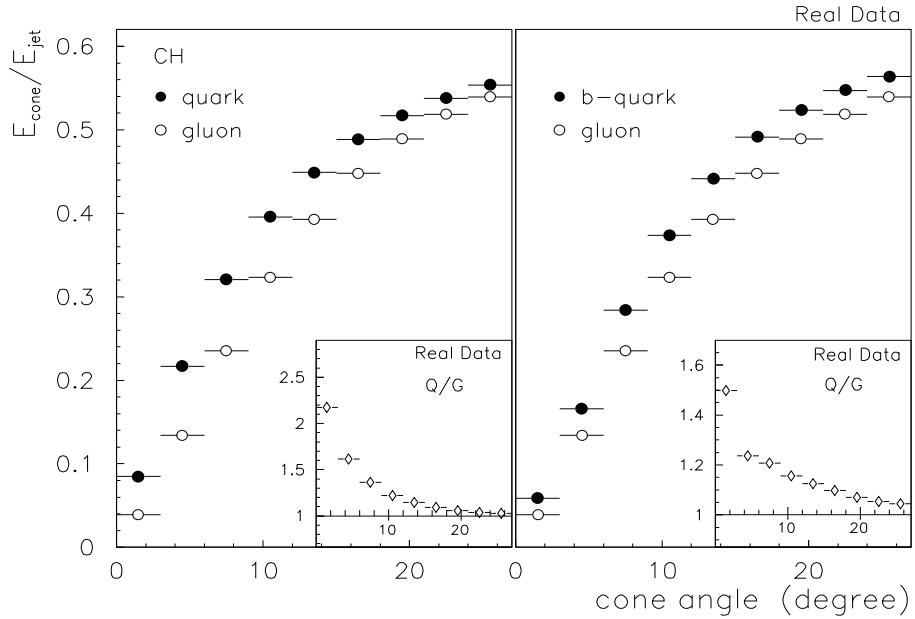


Figure 7.16: *For real data, the integrated charged energy fraction distributions into cones centred around the jet axis for quark and gluon jets, method 1, (left plot), and, for b -quark and gluon jets, method 2, (right plot). The ratio of quark to gluon jets is shown in the inset.*

JETSET and HERWIG Monte Carlo data. Both charged particles and neutral objects are considered. Similar distributions are obtained by comparing the most energetic quark jet with the gluon jet, as shown in Figure 7.18, real data is compared with JETSET and HERWIG Monte Carlo data. As seen from the distributions, in general both Monte Carlo models JETSET and HERWIG are in good agreement with real data. For real data the quark and gluon jet ratios are shown in the insets. The ratios show a greater fraction of the quark jet energy lies close to the jet axis than in the case for gluon jets - confirming that gluon jets are broader than quark jets. The difference in broadness increases when gluon jets are compared to the most energetic quark jets (jet1). This implies that jet broadness is energy dependent: higher energy jets are more collimated. The quark-gluon jet comparisons shown in Figures 7.16 and 7.17 are for y-shape events where jet2 and jet3 are at similar energy. However, as an energy dependence check the comparison are repeated selecting only jets in the energy range of 22 - 25 GeV, so that the quark and gluon jets are closer in energy. Although the lower statistics give larger error bars, the results of check confirms that gluon jets are significantly broader, even at the same energy.

The decay of heavy flavour hadrons adds to the broadness of b-jets; the broadness of b-quark jets lies between that of gluon jets and mixed quark jets (Figure 7.17).

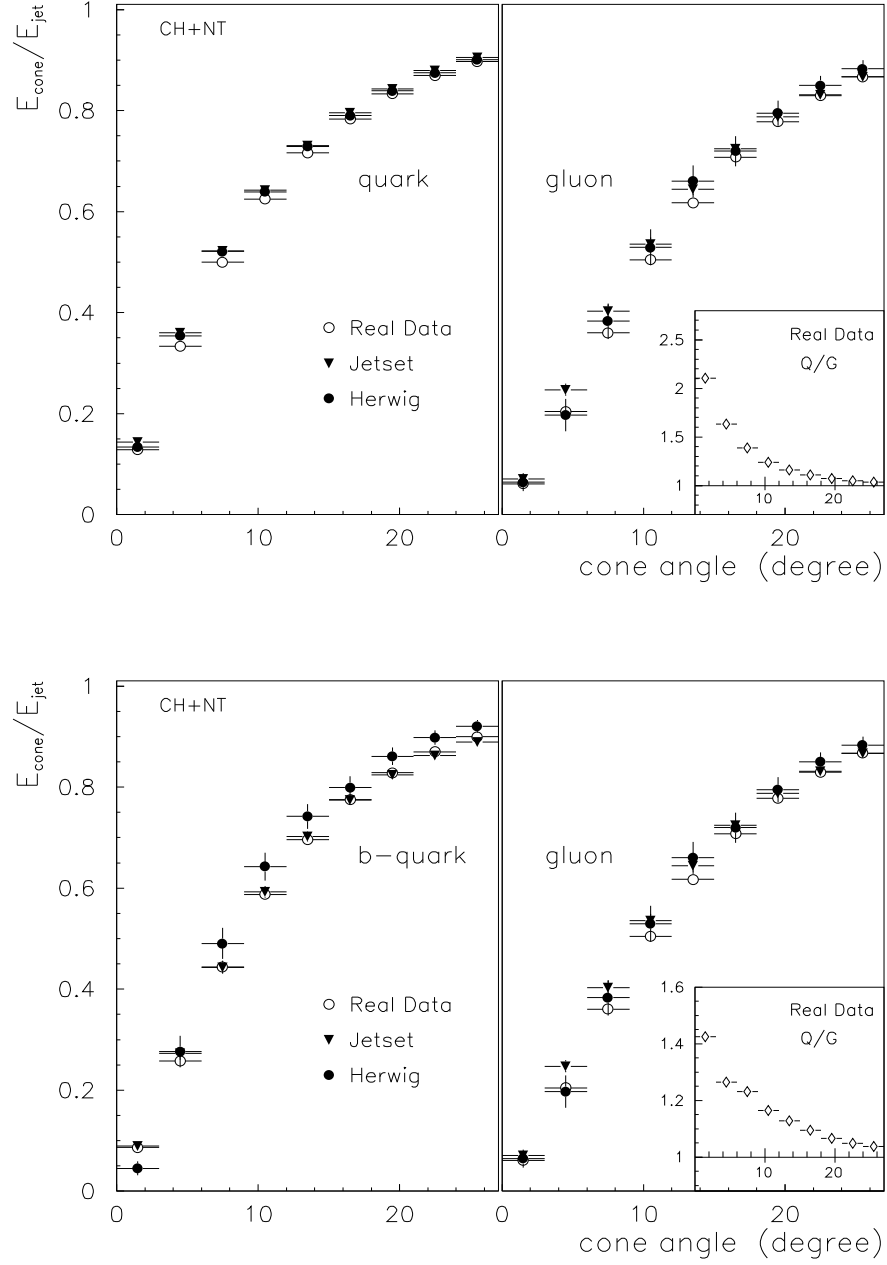


Figure 7.17: *Integrated energy fraction distributions into cones centred around jet axis. Upper plots: for quark and gluon jets, method 1. Lower plots: for b-quark and gluon jet, method 2. Both charged particles and neutral objects are considered. Real data are compared with JETSET and HERWIG Monte Carlo data. For real data the ratio of quark to gluon jets is shown in the inset.*

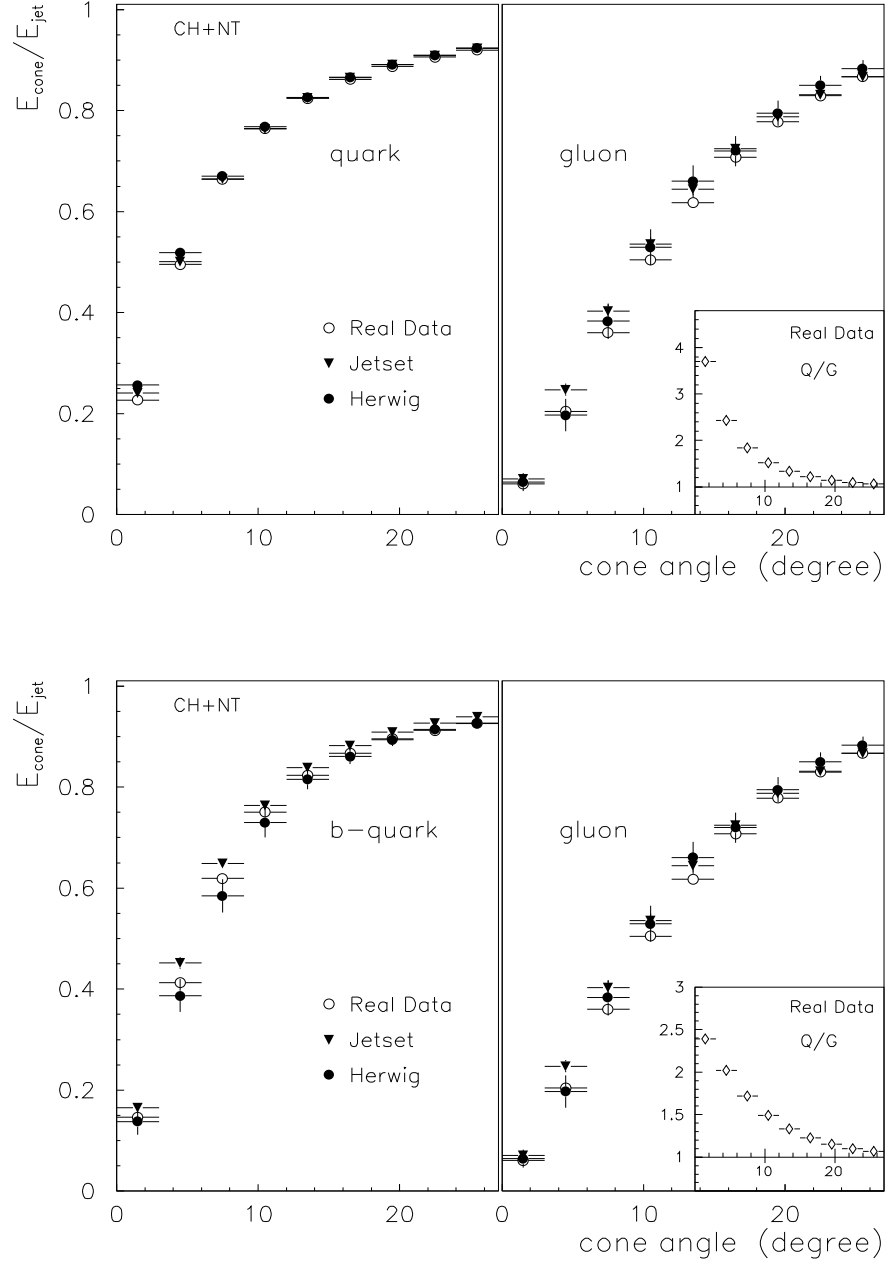


Figure 7.18: *Integrated energy fraction distributions into cones centered around jet axis. Upper plots: the most energetic quark jet (jet1) compared with gluon jet, method 1. Lower plots: The most energetic b-quark jet (jet1) compared with gluon jet, method 2. For these distributions both charged particles and neutral objects are considered. Real data are compared with JETSET and HERWIG Monte Carlo data. For real data the ratio of quark to gluon jets is shown in the inset.*

7.7.4 Mean Particle Multiplicity Measurements

The mean particle multiplicity of jets is studied in two ways: first as a function of energy, using the sample defined by method 1, and secondly as function of both energy and inter-jet opening angle; for this case the sample defined by method 3 is used.

Mean Particle Multiplicity for b and Light Quarks

To compare the particle multiplicity in quark and gluon jets as a function of energy method 1 is used instead of method 2. As discussed in section 2.3, a Monte Carlo study confirms that b -quarks are not suitable for studying quark - gluon jet differences due to the effect of b decay. Figure 7.19 plots the track multiplicity

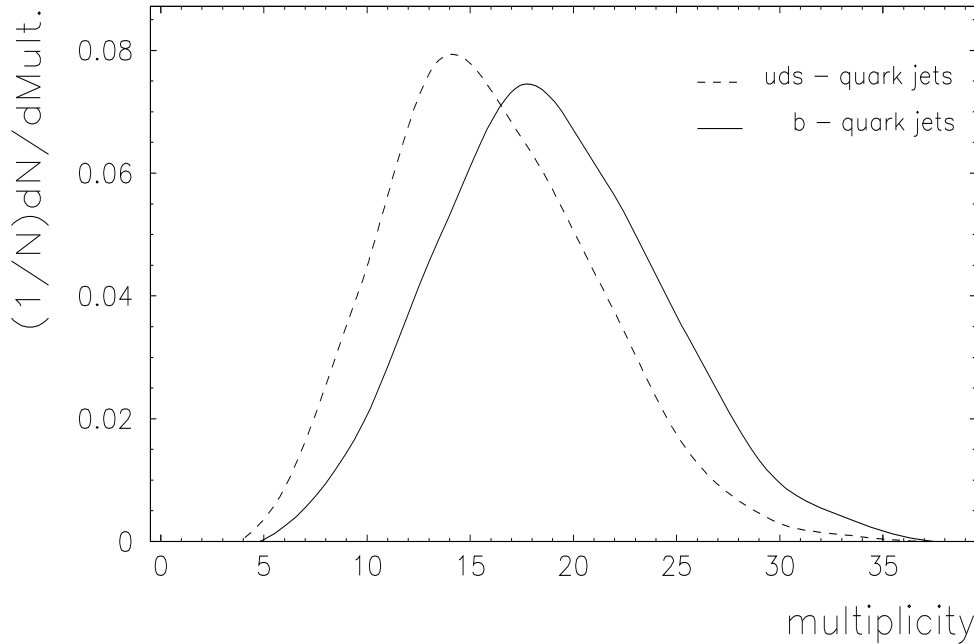


Figure 7.19: A Monte Carlo study of multiplicity for b - and light- quarks. The mean multiplicity is found that ~ 14.6 for uds and ~ 18.1 for b .

for b and light quark jets for Monte Carlo data. The mean multiplicities of b - and uds - quarks are around 18.1 and 14.6 respectively. The jet particle multiplicity is higher for a $b\bar{b}$ event than for a light quark event. This is because of the decay products from the primary b -hadron, which are present in $b\bar{b}$ jets but not in light quark or gluon jets.

Mean Particle Multiplicity as a Function of Energy

For the y-shape events, method 1, the mean particle multiplicities of quark and gluon jets are obtained as a function of the jet energies. The multiplicity of every jet is calculated in 3 GeV energy bins between 15 and 30 GeV. The multiplicity distributions of b -quark and gluon jets from method 2 are also compared. Separate measurements of charged particles and charged-plus-neutral particles are made for Monte Carlo and real data. The multiplicities in quark and gluon jets for Monte Carlo are found slightly higher than real data. The contribution of systematic errors in the gluon purity arising from Monte Carlo model on the multiplicity calculations is practically negligible, therefore it is not included. The measurements are dominated by the statistical errors.

For method 1, for real data Figure 7.20 shows the unfolded mean multiplicity of tracks in quark and gluon jets as a function of the jet energy. The mean charged-plus-neutral particle multiplicities for gluon and quark jets at 25 ± 1 GeV are:

$$\begin{aligned} \langle N_g \rangle &= 15.888 \pm 0.281 \\ \langle N_q \rangle &= 13.412 \pm 0.051 \\ \langle N_g \rangle / \langle N_q \rangle &= 1.185 \pm 0.021. \end{aligned}$$

The same distributions are repeated for charged particles in Figure 7.21; the charged particle multiplicities of gluon and quark jets at 25 ± 1 GeV are:

$$\begin{aligned} \langle N_g^{ch} \rangle &= 7.801 \pm 0.192 \\ \langle N_q^{ch} \rangle &= 6.530 \pm 0.036 \\ \langle N_g^{ch} \rangle / \langle N_q^{ch} \rangle &= 1.194 \pm 0.033. \end{aligned}$$

For Method 1; for Monte Carlo the mean charged-plus-neutral particle multiplicities for gluon and quark jets at 25 ± 1 GeV are:

$$\begin{aligned} \langle N_g \rangle &= 15.917 \pm 0.476 \\ \langle N_q \rangle &= 13.156 \pm 0.103 \\ \langle N_g \rangle / \langle N_q \rangle &= 1.210 \pm 0.037. \end{aligned}$$

For charged particles:

$$\begin{aligned}
\langle N_g^{ch} \rangle &= 8.292 \pm 0.391 \\
\langle N_q^{ch} \rangle &= 6.731 \pm 0.059 \\
\langle N_g^{ch} \rangle / \langle N_q^{ch} \rangle &= 1.232 \pm 0.059.
\end{aligned}$$

For method 2, for real data Figures 7.22 and 7.23 show the mean multiplicity distributions as a function of energy and the mean multiplicity ratio of gluon to b -quark jet for charged-plus-neutral and charged particles respectively. For charged-plus-neutral particles at 25 ± 1 GeV the multiplicities for gluon and b -quark jets and the ratio are:

$$\begin{aligned}
\langle N_g \rangle &= 15.301 \pm 0.289 \\
\langle N_b \rangle &= 14.990 \pm 0.227 \\
\langle N_g \rangle / \langle N_b \rangle &= 1.021 \pm 0.024.
\end{aligned}$$

For charged particles:

$$\begin{aligned}
\langle N_g^{ch} \rangle &= 7.489 \pm 0.201 \\
\langle N_b^{ch} \rangle &= 7.330 \pm 0.159 \\
\langle N_g^{ch} \rangle / \langle N_b^{ch} \rangle &= 1.022 \pm 0.035.
\end{aligned}$$

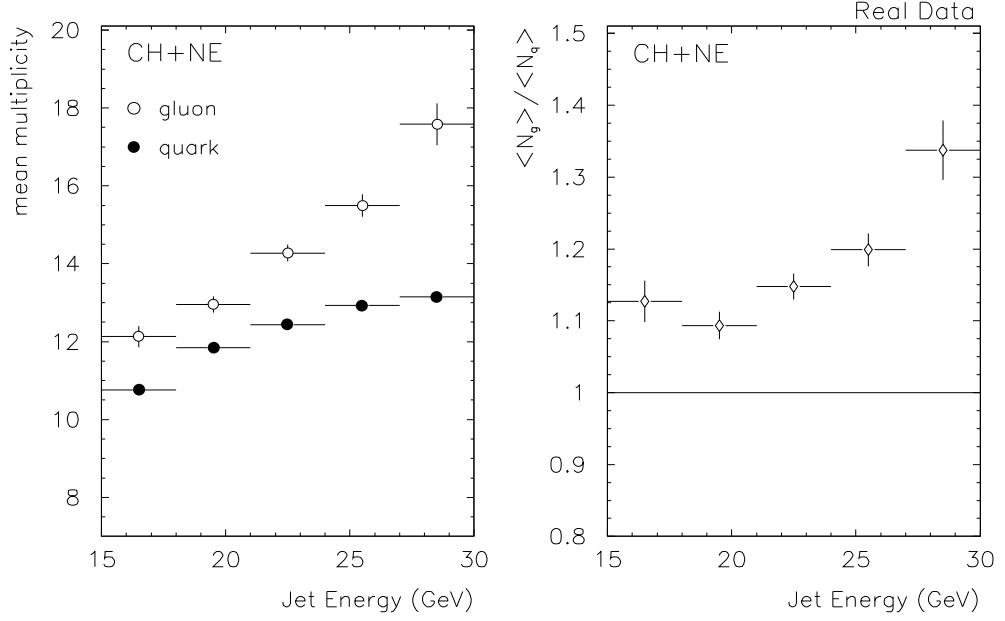


Figure 7.20: For method 1, unfolded mean multiplicity distributions of quark and gluon jet. Both charged and neutral particles are considered. The multiplicity ratio of gluon jet to quark jet is 1.185 ± 0.021 at 25 ± 1 GeV.

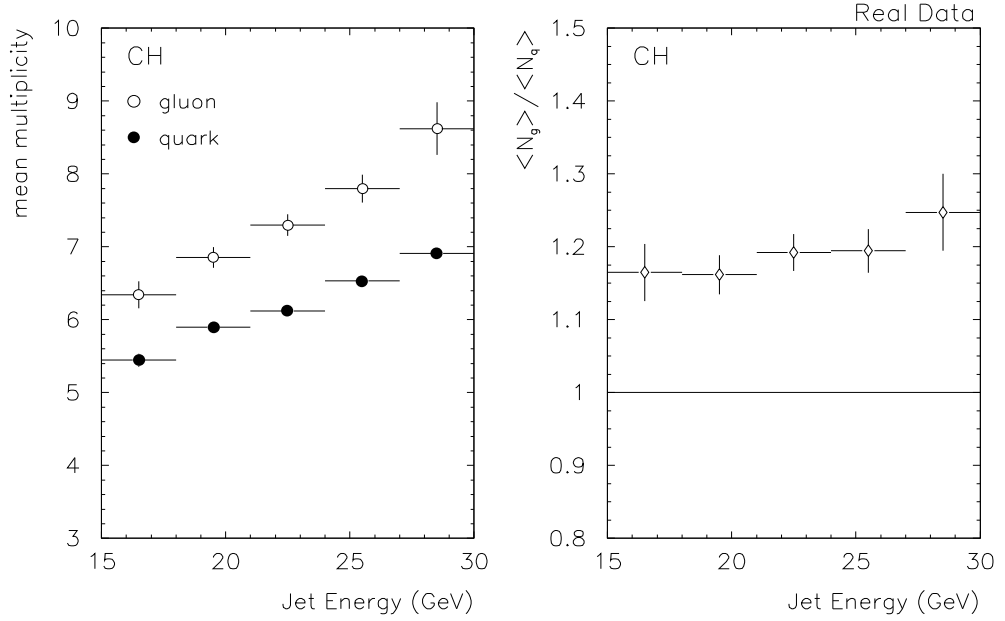


Figure 7.21: For method 1, unfolded mean charged particle multiplicity distributions of quark and gluon jets. The multiplicity ratio of gluon jet to quark jet is 1.194 ± 0.033 at 25 ± 1 GeV.

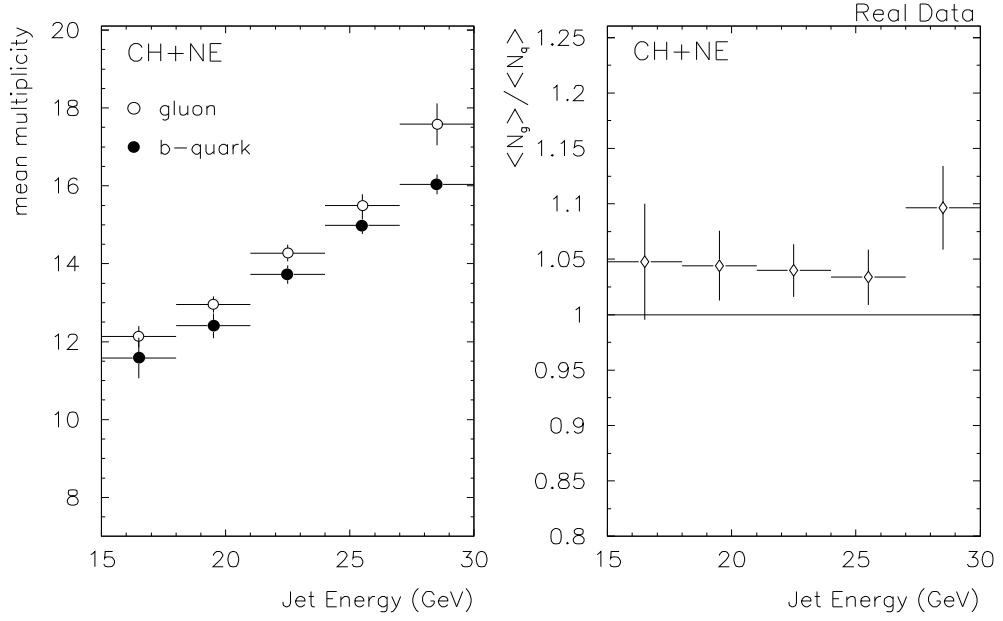


Figure 7.22: For method 2 unfolded mean multiplicity distributions of b-quark and gluon jets for charged-plus-neutral particles. The multiplicity ratio of gluon jets to b-quark jets is 1.021 ± 0.024 at 25 ± 1 GeV.

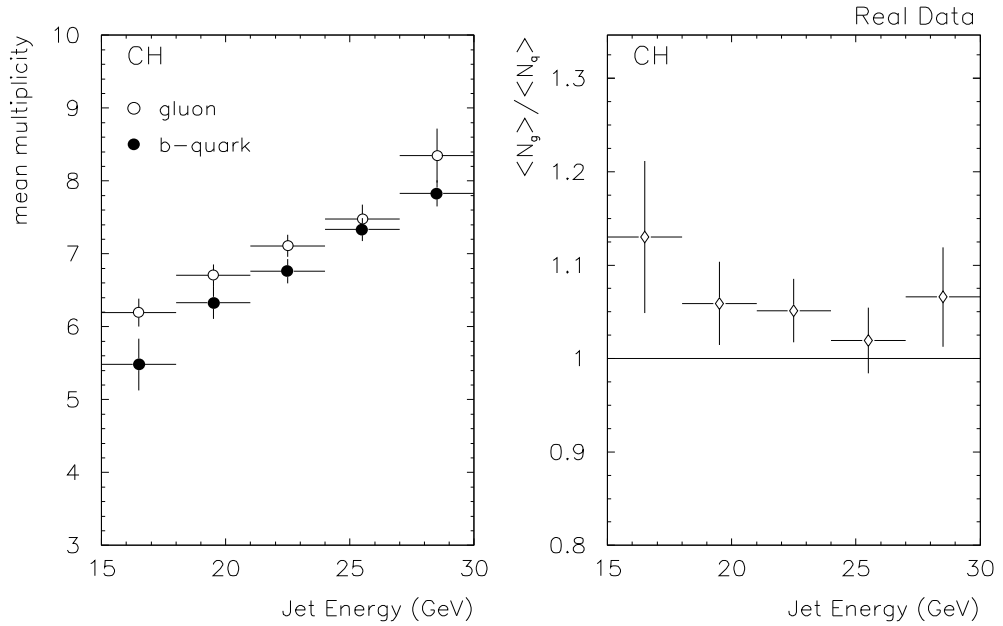


Figure 7.23: method 2, unfolded mean multiplicity distributions of b-quark and gluon jets for charged particles only. The multiplicity ratio of gluon jet to b-quark jet is 1.022 ± 0.035 at 25 ± 1 GeV.

Mean Multiplicity as a Function of Opening Angle and Energy

As well as the energy dependence of particle multiplicity in quark and gluon jets, a dependence on the angles between the jets is seen. For method 3, the mean charged and charged-plus-neutral particle multiplicity of jets (jet2 and jet3) are obtained as a function of the opening angle between jet2 and jet3 (θ_{32}) at fixed jet energy. The jet energies are divided into sub-samples between 15 and 30 GeV for every 5 GeV according to calculated energies.

For real data the corrected charged-plus-neutral and charged mean particle multiplicities for quark jets as a function of the opening angle at fixed jet energy are shown in Figure 7.24. The same distribution obtained for gluon jet is shown in Figure 7.25. Figure 7.26 shows the mean multiplicity ratio of gluon to quark jets. For Monte Carlo data, Figure 7.27 and 7.28 show the mean particle multiplicities as function of the opening angle at fixed jet energy for quark and gluon jets respectively. Their ratio is plotted in Figure 7.29.

As seen from these plots, the multiplicity in jets depends not only on energy but also on the angle between the jets. The multiplicity increases with increasing angle and energy. If the multiplicity depends only on the jet energy, we could not be seeing that the multiplicity is rising with the increasing θ_{32} , otherwise it would have been constant with θ .

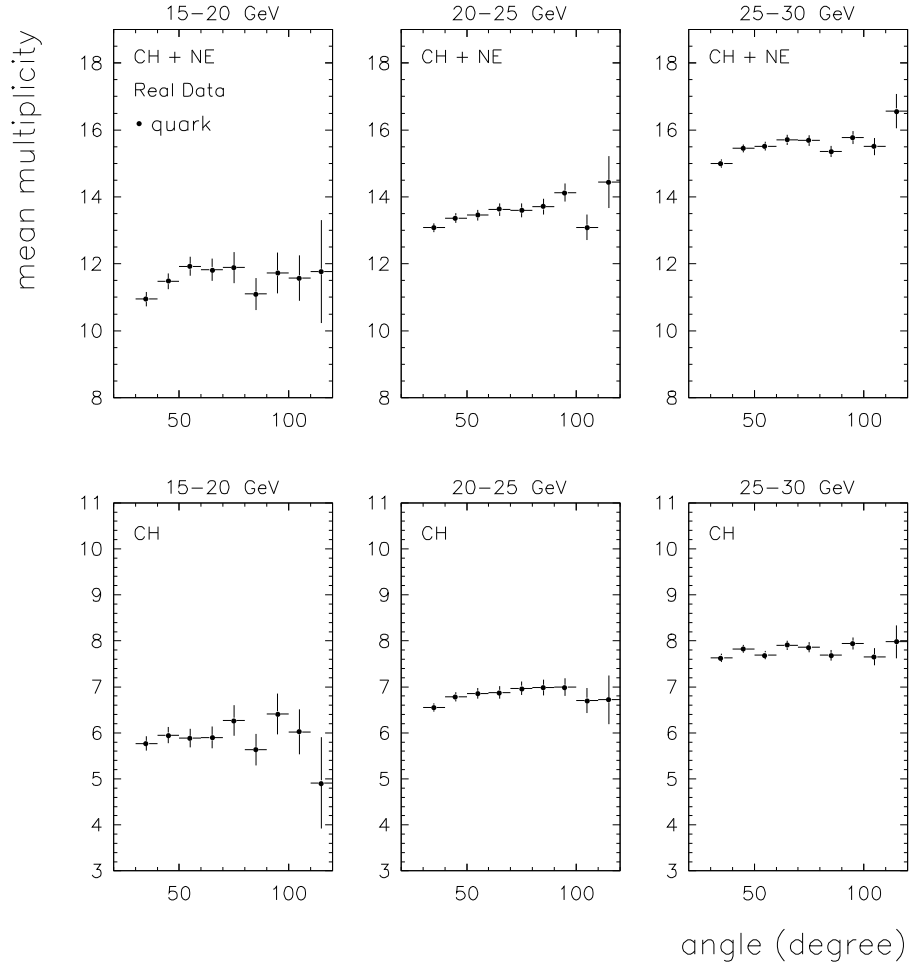


Figure 7.24: For method 3, mean b -quark jet multiplicity as a function of angle, θ_{32} , for 3 jet energy bins between 15 and 30 GeV, for real data. Both charged plus neutral particles (upper plots) and charged particles only (lower plots) are considered.

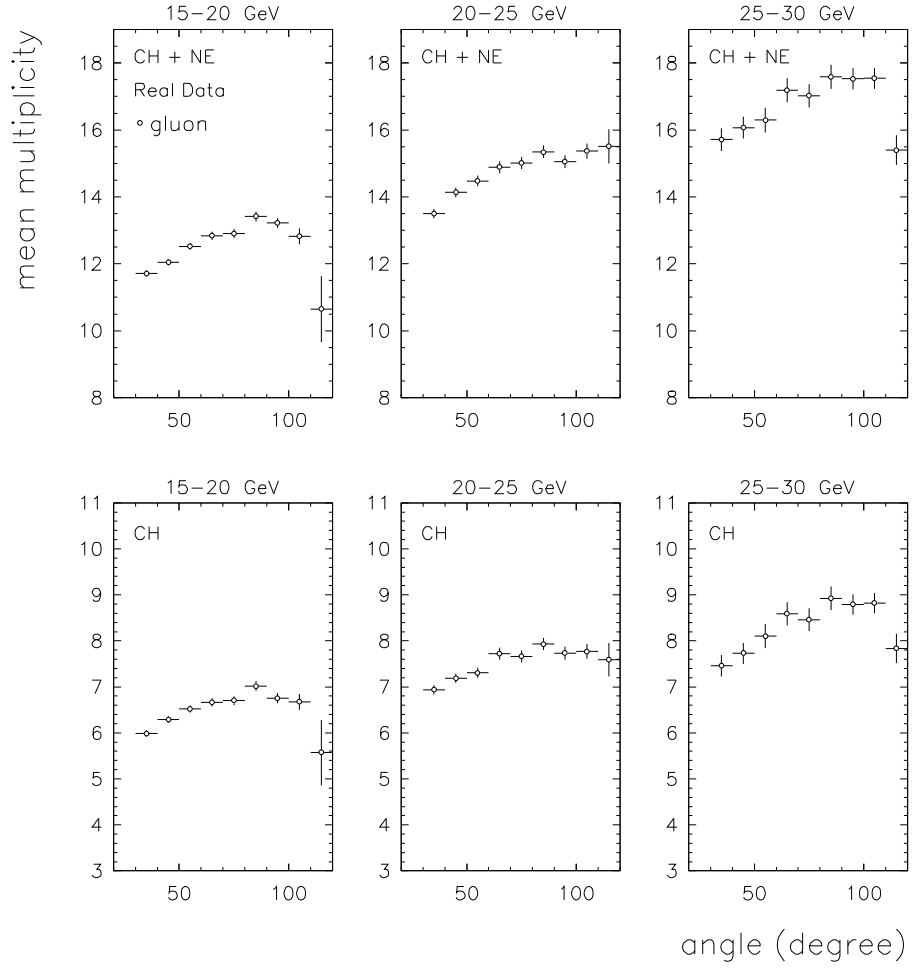


Figure 7.25: *For method 3, mean gluon jet multiplicity as a function of angle, θ_{32} , for 3 jet energy bins between 15 and 30 GeV, for real data. Both charged plus neutral particles (upper plots) and charged particles only (lower plots) are considered.*

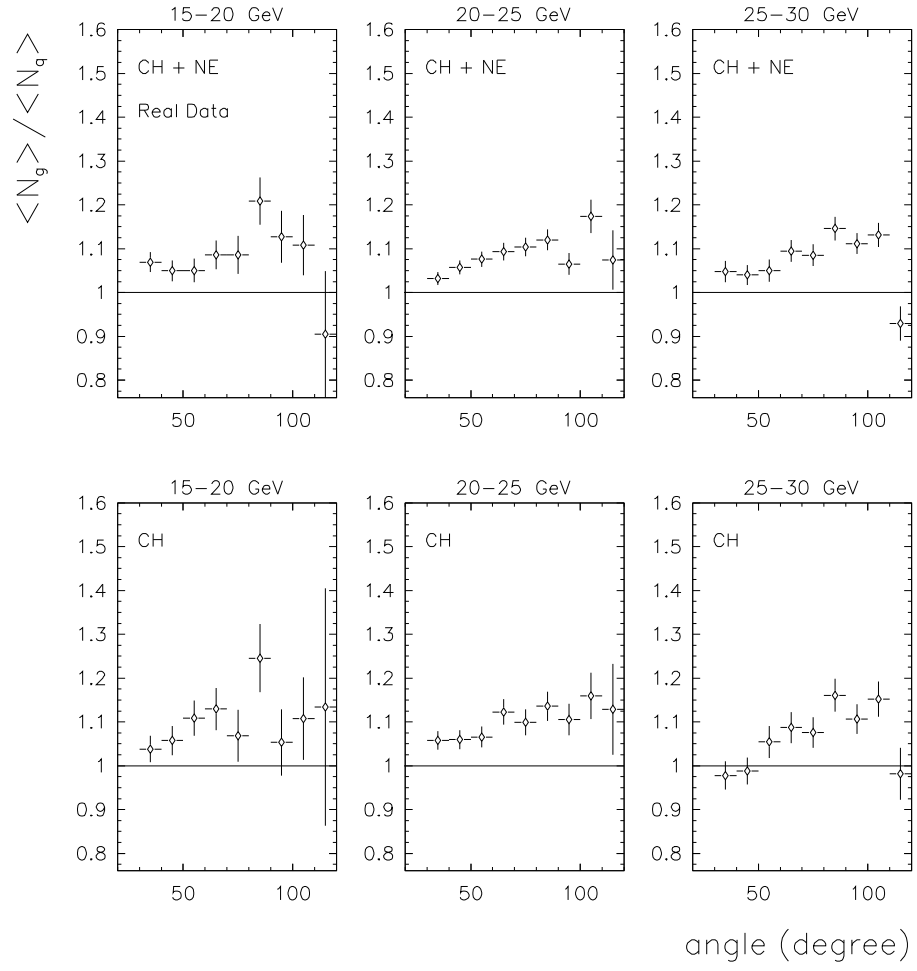


Figure 7.26: For method 3, the mean multiplicity ratio of gluon to b -quarks for real data. Upper plots: charged plus neutral particles; lower plots: charged particles only.

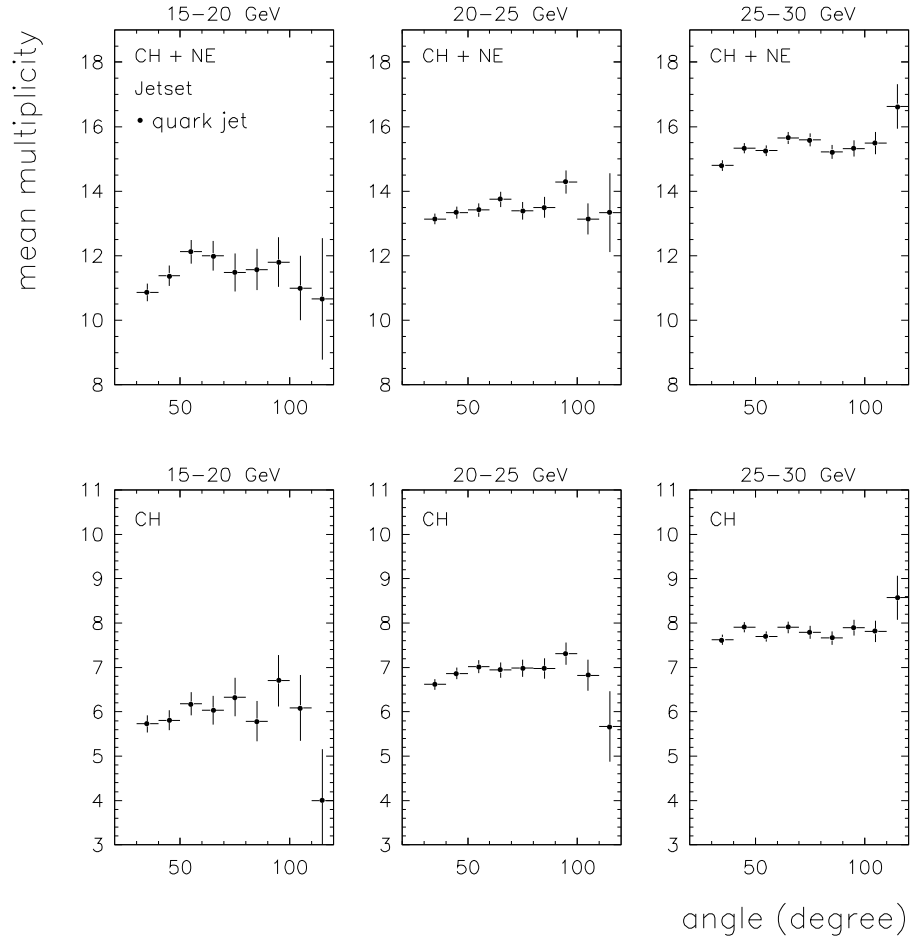


Figure 7.27: For method 3, mean b -quark jet multiplicity as a function of angle, θ_{32} , for 3 jet energy bins between 15 and 30 GeV, for JETSET Monte Carlo data. Both charged plus neutral particles (upper plots) and charged particles only (lower plots) are considered.

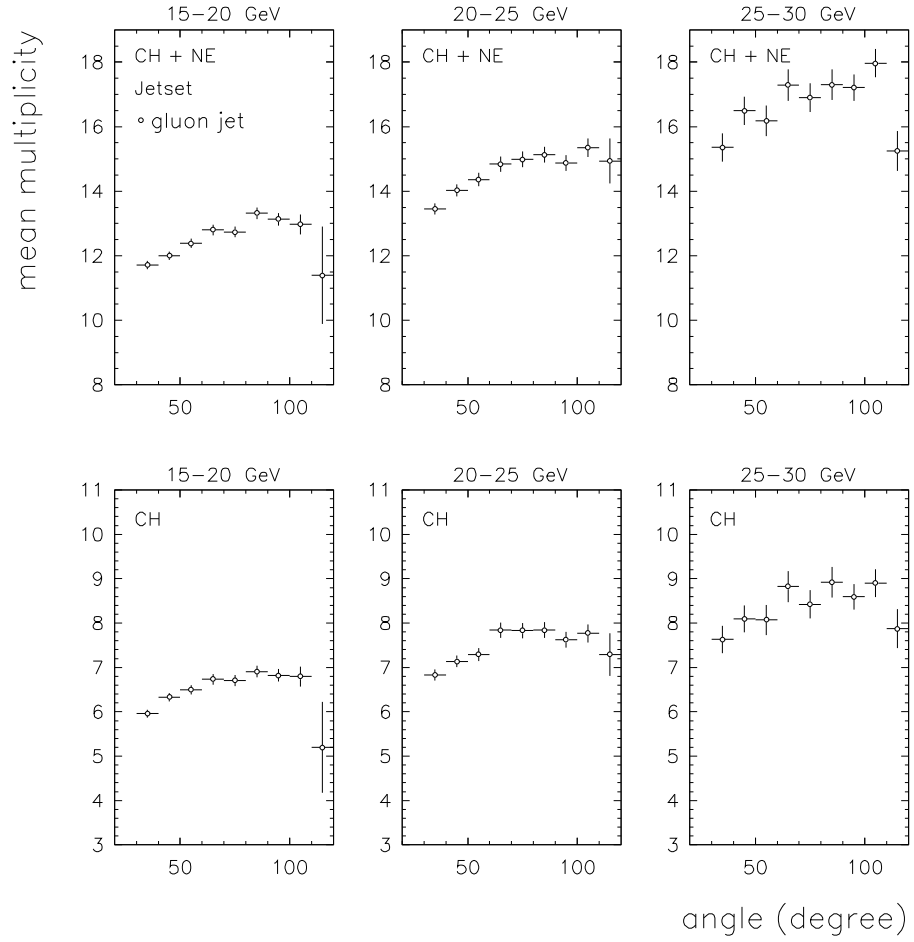


Figure 7.28: *For method 3, mean gluon jet multiplicity as a function of angle, θ_{32} , for 3 jet energy bins between 15 and 30 GeV, for JETSET Monte Carlo data. Both charged plus neutral particles (upper plots) and charged particles only (lower plots) are considered.*

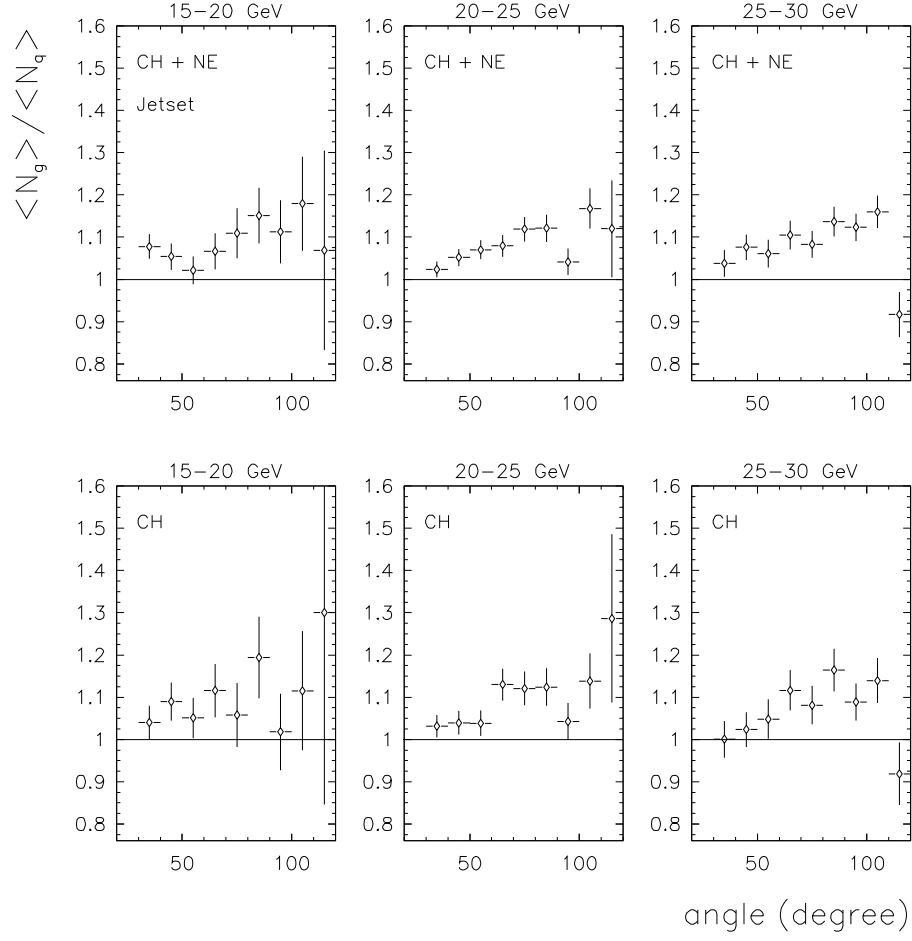


Figure 7.29: For method 3, the mean multiplicity ratio of gluon to b-quark jet for JETSET Monte Carlo data. Upper plots: charged plus neutral particles; lower plots: charged particles only.

Chapter 8

Summary and Conclusions

Quarks and gluons have different coupling strengths to an additional gluon. According to QCD the colour charge of a gluon is $C_A/C_F=9/4$ larger than the colour charge of a quark. This implies that gluon jets are more likely to radiate than quark jets. For quark and gluon jets of the similar energy, QCD therefore predicts that the gluon particle multiplicity should be higher, that the gluon jet should be wider and that it should have softer particle energy spectrum than quark jets. However, the ratio $C_A/C_F=9/4$ is calculated at the parton level for pairs of collinear gg and $q\bar{q}$ jets at infinite (asymptotic) energy and leading order. A large non-leading and finite energy correction of order $\sqrt{\alpha_s}$, heavy quark effects, and 2^{nd} order calculations significantly reduce the magnitude of gluon-quark jets multiplicity differences at present energy (see Chapter 2).

One still expects that for quark and gluon jets produced with the same energy¹, a difference in the jet properties will be observed.

The properties of the quark and gluon jets are compared according to their mean multiplicity, fragmentation function, and angular width. The comparisons are done by using three methods from two different sets of event samples. Here these methods and the results obtained are summarised and discussed.

¹Gluon jet energy is considerably lower in average than quark jet energy. Therefore gluon jets can be compared with quark jets selected from two jet events at a lower center of mass energy [30, 31]. This is not possible at LEP. So to compare the quark and gluon jets at the similar energy the symmetric event topology is employed.

8.1 Summary

The procedure used in this analysis is summarized as follows;

- After the hadronic event selection, all accepted events are clustered with the DURHAM jet finding algorithm with a resolution parameter of $y_{cut}=0.01$ in the ‘E’ recombination scheme. Good charged tracks plus neutral EFLOW objects are used as input to this algorithm. The data sample comes from the 1992, 1993, and 1994 running periods of ALEPH.
- The event plane is determined from the normalized jet momentum tensor and the 4-vectors projected on to the event plane. The jet energies are recomputed from the angles between jets in this event plane, assuming massless planar kinematics. By using the calculated energies of jets, the energies of jets are ordered so that $\text{jet1} > \text{jet2} > \text{jet3}$. After all selections, at this stage the purity obtained by assuming jet3 is the gluon jet is about 67%. The quark purity for the most energetic jet is about 97%. This set is named the ‘ S_{mix} ’ sample.
- The JETSET parton shower Monte Carlo model is used to obtain the purity of the quark and gluon jets to correct the observed distributions. The correction is made bin by bin. The systematic errors are calculated from the number of ambiguous events.
- As a sub sample of the S_{mix} sample, b -tagged samples are chosen by tagging the first and second jets originating from a b -quark using the standard ALEPH package QIPBTAG for lifetime tagging. The working principle of the QIPBTAG package is basically to combine all the track information and to form the jet probabilities from all tracks coming from the primary vertex. The algorithm is explained in detail in Chapter 6. The antitagged jet, which is the third jet, is assumed to be the gluon jet. This increases the gluon purity from 67% to 97% on average.
- Quark jets are compared with gluon jets by using y-shape event topology. Events are selected by requiring that the angle in the event plane between the most energetic jet and the other two is 150 ± 10 degrees. Symmetric events are selected to avoid the kinematic differences between the quark and gluon jets. Comparisons have been made between quark jets taken from y-shape S_{mix} sample, and gluon jets taken from y-shape S_{btag} sample. The jet multiplicities are compared within the same energy range which is around 25 ± 1 GeV and using the same topology.

- The charged and charged-plus-neutral particle multiplicities of gluon and quark jets are studied as a function of the angle between the two least energetic jets, θ_{23} , at fixed energy, for 5 GeV energy bins between 15 and 30 GeV jet energies.

The purities of quark and gluon jets given below are obtained by using Monte Carlo parton level truth information. The errors are statistical and systematic. The systematic errors are calculated using the ambiguous events found from truth information. For the multiplicity measurement the statistical errors dominate.

The y-shape mixed flavour sample (*y-shape* S_{mix}) consists of a mixture of quark flavours. The flavour composition of the sample is found to be 21.29% for *b*-quarks, 18.57% for *c*-quarks and on average of 20% for light quarks. The number of the events for y-shape S_{mix} samples is 20861 for Real data, 7662 for Monte Carlo. The quark and gluon jets purities are $(72.71 \pm 0.51 \pm 0.64)\%$ for jet2 (as quark or antiquark jet) and $(67.78 \pm 0.53 \pm 0.68)\%$ for jet3 (as gluon jet). The first energetic quark jet purity is $(96.53 \pm 0.21 \pm 0.63)\%$.

The flavour compositions of the *b*-tagged sample are found to be 95.69% for *b*-quarks, 3.84% for *c*-quarks, and on average of 0.16% for light quarks. The quark and gluon jets purities are $(97.15 \pm 0.21 \pm 0.04)\%$ for jet2 (as quark or antiquark jet) and $(95.80 \pm 0.25 \pm 0.04)\%$ for jet3 (as gluon jet). The flavour compositions of the *b*-tagged sample after y-shape selection applied are found to be 96.76% for *b*-quarks, 2.97% for *c*-quarks, and 0.27% for light quarks. The number of the events is 1124 for Real data, and 370 for Monte Carlo. The quark and gluon jets purities are $(97.85 \pm 0.75 \pm 0.27)\%$ for jet2 (as quark or antiquark jet) and $(97.58 \pm 0.80 \pm 0.27)\%$ for jet3 (as gluon jet).

8.2 Conclusions

From the results given in Chapter 7 the following conclusions are made.

Rapidity

Rapidity measurements are made using method 1 and method 2. Method 1 shows that mixed-quark jets contain more particles with large longitudinal momentum with respect to the jet axis than gluon jets. In method 2, there are much smaller differences between rapidity distributions of *b*-quark jet and gluon jets.

Fragmentation Function

For method 1 the measurements show that gluon jet fragmentation is softer than that of quark jet because of gluon's enhanced colour charge. For method 2 that particles in b -quark jets are slightly softer than those in gluon jets. The same distributions are repeated for charged particles as well as charged-plus-neutral.

Cone Energy Fraction

The integrated cone energy fraction distributions are obtained for method 1 and 2. The higher energetic jets are also compared with the other jets. The results again demonstrate that gluon jets are wider than quark jets. The differences between mixed-quark and gluon jets are clearly observed. Again less difference is observed between b -quark jets and the gluon jets than mixed-quark jets and the gluon. It is observed that the JETSET and HERWIG Monte Carlo models are in a good agreement with real data.

Mean Multiplicity as a Function of Energy

In the method 1 and 2 using the y-shape events the jets are compared approximately at the similar energy range which is 25 ± 1 GeV. For method 1 the gluon jet particle multiplicity is observed to be higher than the quark jet multiplicity. The ratio of mean charged multiplicity is:

$$\langle N_g^{ch} \rangle / \langle N_q^{ch} \rangle = 1.194 \pm 0.033.$$

The identical measurements are made for Monte Carlo events and the multiplicity ratio of quark and gluon jets found similar with Real data. There is not much difference observed between b -quark and gluon jets. For the method 2 the ratio is:

$$\langle N_g^{ch} \rangle / \langle N_b^{ch} \rangle = 1.022 \pm 0.035.$$

The results are in agreement with the results obtained by OPAL collaboration [26, 32].

Mean Multiplicity as a Function of Energy and Angle

For Method 3 the mean multiplicity of b -quark and gluon jets are obtained as a function of the energy and angle between them. The jet energy is held fixed for every 5 GeV between 15-30 GeV energies. The conclusion is that the jet

properties not only depend on the jet energies but also on the angle between the jets.

In conclusion

It is observed that the multiplicity ratio of gluon jets to quark jets is dependent on both jet energy and event topology. For jets of the same energy gluon jets are found to have larger multiplicity (and therefore have a softer particle spectrum), and a broader angular distribution. The results are qualitatively consistent with those expected by QCD.

In the case of b -quark jets the decay of heavy flavour hadrons adds to the broadness (Figure 7.17) and multiplicity of b -jets (Figure 7.26). It has been reported that for y-shape events the multiplicity of b -jets is the same as gluon jets [29, 32]. These results are reproduced by the analysis in this thesis. However, significant differences are observed when the event topology is varied. This clearly seen from Figure 7.26, the ratio $\langle N_g \rangle / \langle N_b \rangle$ clearly increases as the angle between jet2 and jet3 increases. An explanation of this may be that the particles of the gluon jet are only correctly assigned to the gluon jet when it is well separated in angle from the nearest neighbour jet. b -quarks are broader and softer than light quarks jet but they are slightly narrower than gluon jets.

The good agreement with Monte Carlo indicates that the differences in fragmentation between quark and gluons are well modelled.

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