

A SEARCH FOR MASSIVE NEUTRAL PARTICLES

IN e^+e^- ANNIHILATION

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ABSTRACT

This thesis presents a search for new neutral massive particles produced in e^+e^- interactions at a centre of mass energy above 40 GeV. The data were taken with the TASSO detector at the PETRA e^+e^- storage ring at DESY Hamburg. A brief description of this detector is given.

The theoretical background to the possible existence of new neutral particles is discussed. A monte carlo program which simulates the production and decay of both singly and doubly produced particles is described. This simulation is used in deciding which selection criteria are to be used on the data and these criteria are discussed.

Particular emphasis is placed on the use of lepton identification in TASSO and on the use of a high precision vertex detector to look for particles with short decay distances. The effect of background processes on the search are described and limits on the production of new neutral particles are given.

No evidence has been found for electron type heavy neutral leptons in the mass range up to 23 GeV/c². There is no evidence for the production of monojets. No events have been observed which were consistent with the production of a pair of neutral heavy leptons having a decay length in the range from 1 mm to 10 cm.

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Chapter I

INTRODUCTION

1.1 A GUIDE TO THE THESIS

This thesis presents the results of searches for the production of new types of neutral leptons in e^+e^- annihilation at centre of mass energies from 40 to 46.7 GeV. The data used were obtained with the TASSO (Two Arm Spectrometer SOlenoid) detector at the PETRA (Positron Electron Tandem Ring Anlage) e^+e^- storage ring in Hamburg West Germany.

The thesis is set out as follows: The first chapter is an introduction to the work presented here, it then goes on to describe PETRA, gives some general information on its operation and states the amount of data taken during the operation of TASSO. Chapter two gives the theoretical background which motivated the searches for new neutral particles. The standard model is described, then some of the difficulties associated with it which leads to a discussion of several ideas for new particles which might help to resolve these difficulties. Extensions of the model are also discussed in this context. Chapter three describes the experimental apparatus with particular emphasis on the high precision vertex detector and on the components used for lepton identification. An account is given of the triggers, data taking and standard data reduction procedures including track

finding and fitting in the wire chambers. Chapter four is entitled "Modelling some new physics". It is an explanation of a program written to simulate events of the type for which one is searching. Calculations of signatures and acceptances for singly and doubly produced massive neutral leptons are presented. Chapter five is an analysis of the data to look for singly produced heavy neutral leptons characterised by events of the single isolated jet type. Backgrounds are taken into account and limits on such new particles in the framework of some possible theoretical models are presented. Chapter six is an analysis to search for pair produced neutral leptons. Two approaches are used, one involves using the lepton identification capabilities of the detector. The other uses the vertex detector to look for objects with a non-zero lifetimes. These methods are described and results are given from studies of certain classes of events containing leptons and for fitting tracks to vertices. Final conclusions are presented.

The reasons for carrying out the work presented here at this time is that recent new observations and discoveries have led on the one hand to consolidation and clarification of many aspects of high energy physics but on the other hand have raised puzzles and shown where the theoretical framework is incomplete. The search for new particles of many kinds is an area which is being vigorously pursued at this time. It is particularly relevant to the question of the dark matter in the universe. There are good theoretical reasons for assuming a closed universe but this

raises the interesting possibility that up to 90% of all the matter could be in a non baryonic form such as exotic particles.

At PETRA there now exists e^+e^- annihilation data at the highest energy so far reached. These data are in sufficient quantity that a search for new neutral particles can be made, The data also contain information from TASSO's high precision vertex detector which will allow the detection of new particles with a flight path in the range of a fraction of a millimetre to around 10 cm.

Before going on to discuss the motivation behind this work it is interesting to explain how PETRA operates and comment on the operation of TASSO since 1978.

1.2 PETRA

PETRA is a 2.2 km circumference ring in which two bunches of electrons and two of positrons counter-rotate and interact in four intersection regions in which are situated large general purpose detectors of which TASSO is one.

The high energy of PETRA makes it necessary to have other accelerators to accelerate the electrons and positrons before they can be injected into PETRA. The layout of the complex is shown schematically in Fig. 1.

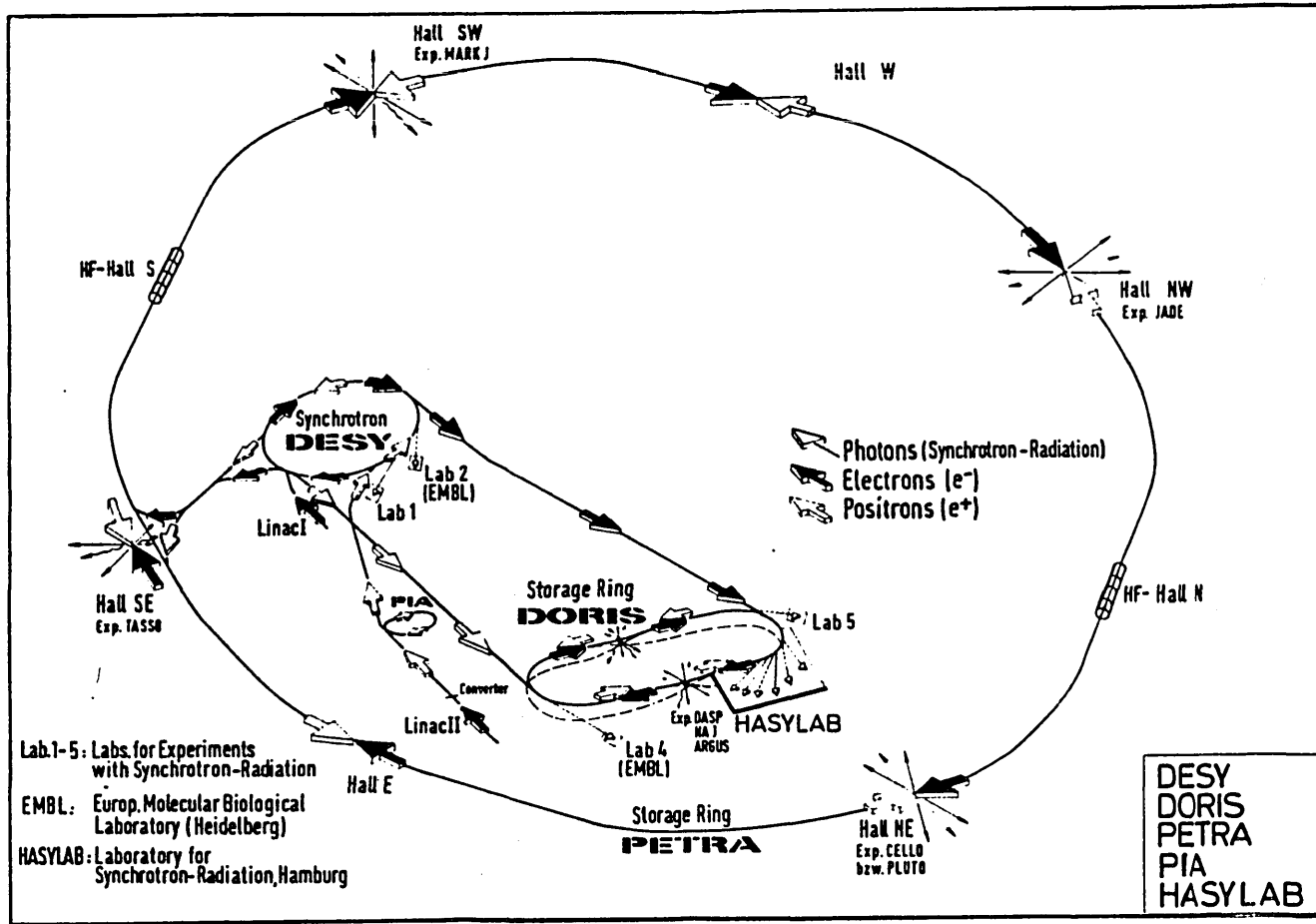


Figure 1: The DESY Accelerators

1.2.1 Production, Acceleration and Storage

The electrons are produced and accelerated to 40 MeV in the linear accelerator LINAC 1. They then go into the synchrotron DESY, for acceleration to 7 GeV at which energy they can be injected into PETRA.

The positrons are produced by allowing a 150 MeV electron beam from LINAC 1 to strike a target. The positrons are collected, accelerated in LINAC 2 and stored in a small ring, the Positron Intensity Accumulator (PIA). When a sufficient number have been accumulated to form a bunch they are also accelerated to 7 GeV in DESY and injected into PETRA.

In PETRA the electron and positron bunches are accelerated to the desired interaction energy by Radio Frequency (RF) cavities driven by klystrons situated in the four long straight sections. To accelerate from 7 GeV to over 20 GeV takes around 15 minutes, the beams are then stored for a period of several hours, energy lost by synchrotron radiation being replaced by that from the cavities.

The beams are maintained in their orbit by dipole magnets in the eight arcs and the spread of the beams are controlled by quadrupole magnets. The bunches measure typically 0.1 cm horizontally (x) by 0.01 cm vertically (y) by 1 cm along the beam (z). This size will be discussed in more detail in section 6.3.4.1.

1.2.2 The Luminosity and Energy of PETRA

The luminosity of an e^+e^- collider is defined by :

$$L = n^+ n^- g b / f = I_+ I_- / e^2 g b f$$

where n^+ (n^-) are the number of positrons (electrons) per bunch, b is the number of bunches, f is the bunch cross section, g is the rotation frequency, e the electron charge, I_+ (I_-) the positron (electron) currents. For a process with a cross section σ , the number of events produced for a luminosity L is given by

$$N = L \sigma$$

PETRA was originally designed in 1978 to achieve a maximum beam energy of 19 GeV and for the first three years of its operation it mainly ran at energies around 17 GeV per beam.

Between 1979 and 1982 a total luminosity of 84.0 pb^{-1} was taken, the greater part 78.7 pb^{-1} at centre of mass energies between 30 and 36.5 GeV (the average being 34.5 GeV.) The rest consisted of 1.7 pb^{-1} at around 14 GeV and 3.6 pb^{-1} at around 22 GeV.

In 1982 a program was begun to increase the energy of PETRA by the installation of more RF cavities, in the summer of 1984 a maximum beam energy of 23.390 GeV was reached. The object of this program was to search for new resonance states in the higher energy region. For much of the running during 1983 and 1984 data were not taken at a constant energy but the machine scanned taking a luminosity of usually 50 or 60 nb^{-1} at one energy then increasing by 15 MeV per beam, (which is the energy resolution of the machine.) When the scan was complete there was a period of running at 22.1 GeV. The instantaneous (differential) luminosity obtainable at beam energies above 20 GeV was lower than that possible at energies below 20 GeV, therefore in the two years of running 1983 and 1984 a total integrated luminosity of 25.0 pb^{-1} was collected by TASSO. (9.5 pb^{-1} of this at 22.1 GeV.) This was substantially lower than would have been obtained had the machine ran at 18 GeV in this period.

Fig. 2 shows the integrated luminosity per month in 1983 and 1984. Fig. 3 shows the integrated luminosity as a function of beam energy over this period, using a logarithmic scale to allow the 22.1 GeV point to fit in. A small amount of data below 20 GeV was taken intermittently when the machine had technical problems preventing running at a higher energy.

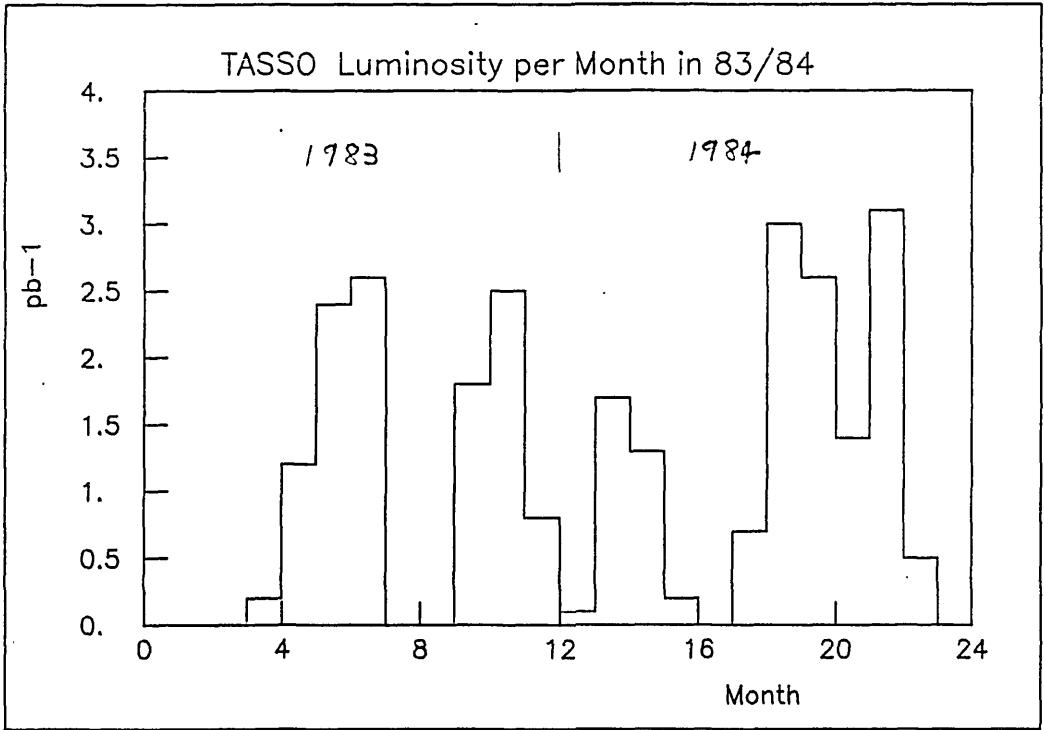


Figure 2: Luminosity per Month

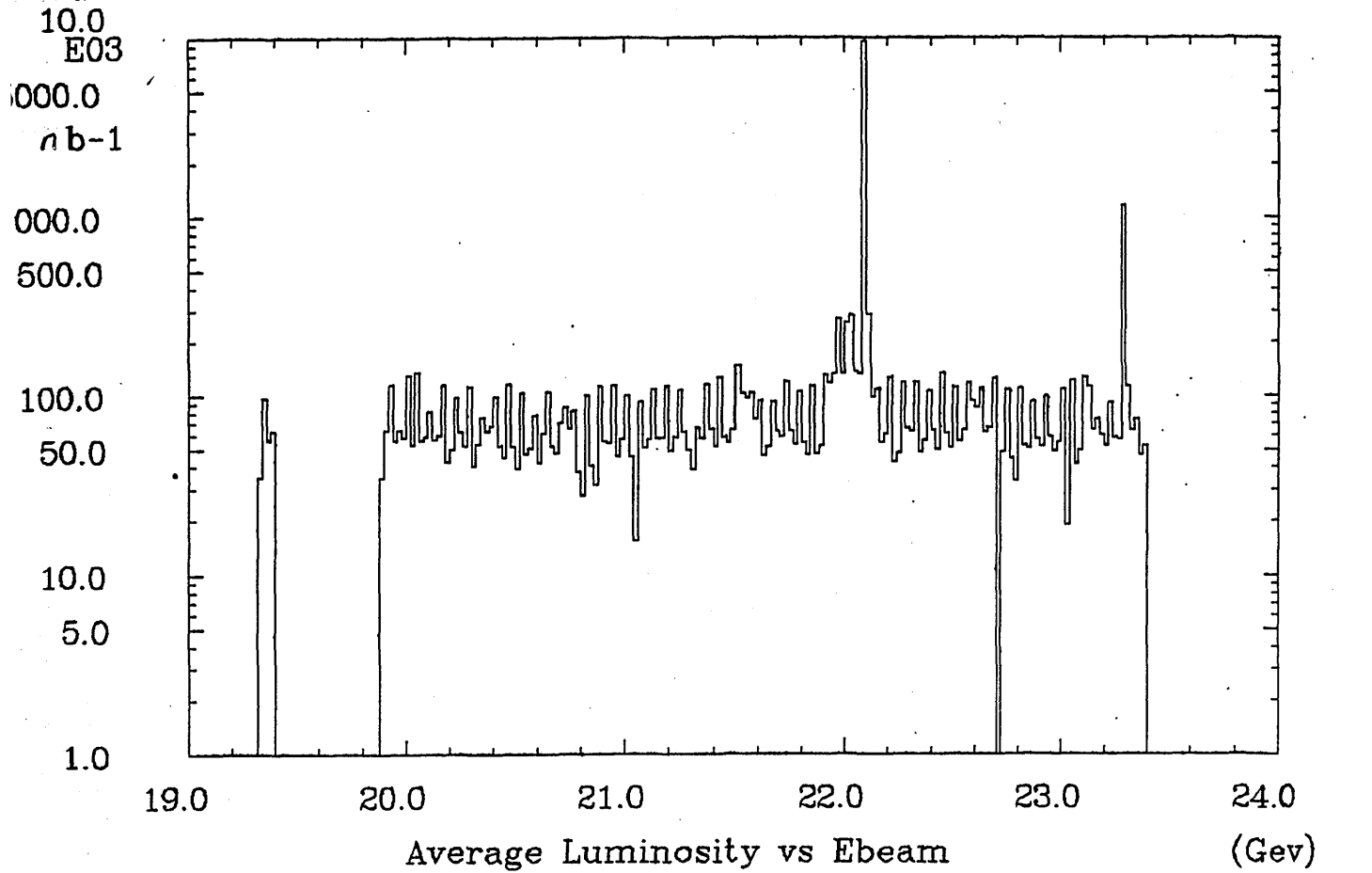


Figure 3: Luminosity vs Beam Energy

Chapter II

THEORETICAL BACKGROUND

2.1 INTRODUCTION

This chapter gives the theoretical background and motivation for the work presented in this thesis. In the last few years many experimental results have appeared which support the so called standard model of electroweak physics. This model has been outstandingly successful in interpreting the many observations made over the last 50 years and in the following short overview some of these great successes are mentioned.

Despite its successes there are things which the model cannot explain and outstanding questions which require experimental investigation. The fact that at PETRA e^+e^- data at the highest energy so far achieved are available makes this a good place to perform such investigations.

2.2 THE STANDARD MODEL

2.2.1 Brief Description

The standard model of strong and electroweak interactions is a gauge theory based on the group $SU(3) \times SU(2) \times U(1)$. [1]. Each part of this group represents a particular type of transformation at each space-time point. $U(1)$ is a simple phase transformation of the type $\Psi \rightarrow \Psi \exp(i\alpha(\underline{x}, t))$. Note that if α is the same at

all space and time points the transformation is called global, if a is a function of $(\underline{x}, t)$ as here then the transformation is local and it is these types of transformations which are of interest in constructing physical theories. $SU(2)$ can be represented by the set of all rotations in a three dimensional real space and therefore has three free parameters. $SU(3)$ can be represented by the set of all rotations in a three dimensional complex space and therefore has eight free parameters.

A gauge theory is described by a Lagrangian which contains terms for the fields involved and their interactions. The Lagrangian must be invariant under a local gauge transformation of the fields and this property constrains the form of the Lagrangian. In the case of the standard model a Lagrangian invariant under the transformations of the full group has been constructed and has been required to contain terms representing particular fields and interactions, these seem to be ones that correspond to things in nature.

The simplest example to illustrate this invariance is electromagnetism where a gauge (phase) transformation of the $U(1)$ type can be made to the electromagnetic field, $\Psi \rightarrow \Psi' = \Psi \exp(ia(\underline{x}, t))$. It can then be shown that such a transformation will only leave the Lagrangian invariant if, as well as the field Ψ it contains a vector field A which represents the photon, and terms in the form of currents which represent the interactions in the theory.

The $SU(3)$ group is associated with the colour forces binding quarks into hadrons by the interchange of massless vector gluons, with coupling g_s . The $SU(2) \times U(1)$ group is the electroweak part and has four vector boson fields which mix to produce the photon of electromagnetism and the heavy W and Z^0 of the weak interaction. The production of the massive vector bosons has been seen recently in proton antiproton collisions [2].

In nature we have only so far observed left handed states, to accommodate this the $SU(2)$ is considered as only operating in a left handed space - (The rotations of $SU(2)$ can be described by their effect on a massless particle of either positive or negative helicity. The two descriptions are distinct and complete. As neutrinos are only seen with left handed helicity, we use a description in terms of this helicity, conventionally written $SU(2)_L$.) Only the left handed quarks and leptons are placed in doublets under $SU(2)$. Right handed fermions must be placed in singlets. So far there is no experimental evidence showing the existence of the right handed partners of the known fermions.

The standard model is one of three generations, each generation containing a quark doublet (each quark can have three colours) and a lepton doublet, as shown in Table 1.

There is preliminary evidence for the production of the top quark in proton-antiproton interactions [3].

The Lagrangian for the weak and electromagnetic interactions can be written in the form :

$$L(GSW) = L_0 + L(em) + L(cc) + L(nc) + L(h) \quad (2.1)$$

TABLE 1		
The Generations		
1st	2nd	3rd
u	c	t
d	s	b
e	μ	τ
ν_e	ν_μ	ν_τ

- 1) L_0 is a kinetic term.
- 2) $L(em)$ is for the electromagnetic interactions.
- 3) $L(cc)$ is for the charged current (W mediated) interactions.
- 4) $L(nc)$ is for the neutral current (Z^0 mediated) interactions.
- 5) $L(h)$ is for the Higgs, (discussed below).

The three interaction parts 2,3,4 have the structure
Coupling constant x Current x Gauge boson field. As a
consequence of the unification of electromagnetism and weak
interactions, the three coupling constants from these parts can
be expressed in terms of only two, the electromagnetic coupling e
and a weak interaction mixing angle θ .

The final part of the Lagrangian (5), is for the Higgs fields,
without this all the particles in the theory are massless. The
particles are given masses through the process of spontaneous
symmetry breaking. A field known as the Higgs field is
introduced which has a non zero vacuum expectation value, this
can be done as a consequence of the freedom given by gauge

invariance under the group. Its introduction is compensated by making a gauge transformation on the gauge fields but this requires them to be given mass. The Higgs field itself leads to a physical massive scalar boson but no prediction of its mass can be made and there is so far no experimental evidence for its production. A full discussion of the Higgs mechanism can be found in Ref. 4.

The quarks appearing in the weak interaction Lagrangian are not the same ones as in the strong interactions but are mixed, so instead of d, s, b one uses d', s', b' . The mixing can be parameterised by :

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = U \begin{bmatrix} d \\ s \\ b \end{bmatrix} \quad (2.2)$$

where U is a unitary matrix usually known as the Kobayashi-Maskawa matrix.

2.2.2 The Incompleteness of This Model

The model as described above has been very successful but it is complicated in that it has many free parameters which have to be determined from experiment such as the couplings e , θ , g_s , the lepton, fermion and heavy boson masses and the Kobayashi-Maskawa mixing parameters. There are also fundamental questions which it does not attempt to answer.

2.2.2.1 The Generation Puzzle

So far there are only three generations. Fig. 4. is a plot of the masses of the component particles of each generation, it suggests that there maybe more generations with particles of each type at higher masses.

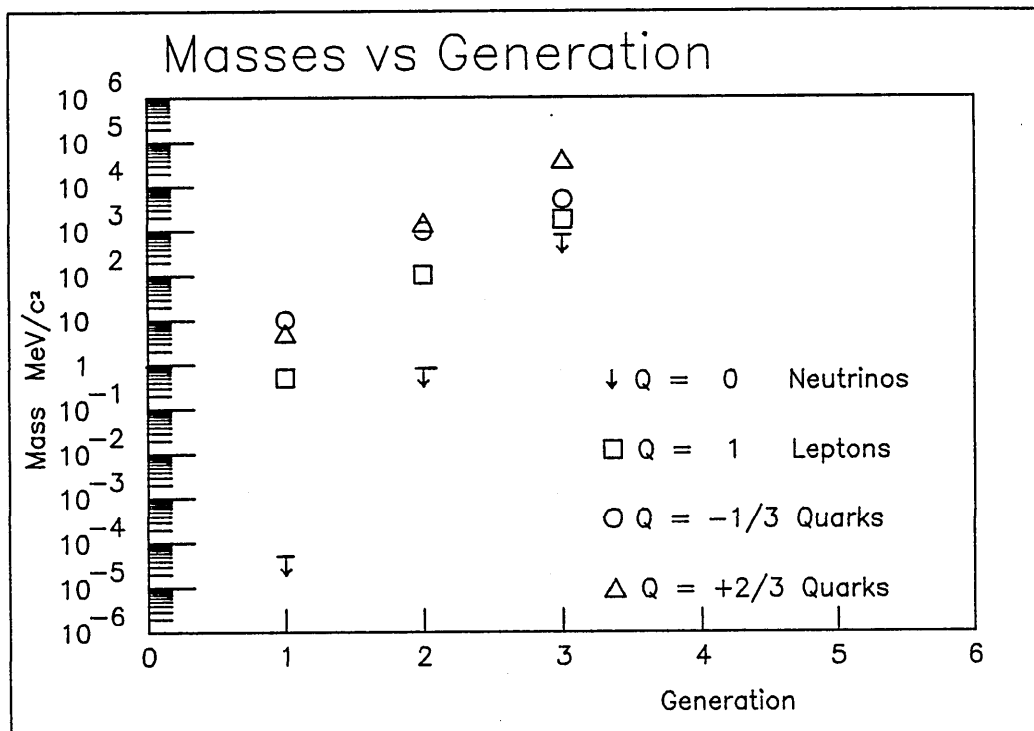


Figure 4: Masses vs Generation

2.2.2.2 The Handedness Problem

We do not know why there are only left handed particles in the quark and lepton doublets which participate in weak interactions. Right handed partners may exist, if they have conventional couplings (within the standard model) then their masses must be beyond those reachable in present experiments otherwise they would already have been observed. On the other hand if their

couplings are anomalously small then the masses could be in the range reachable by PETRA, they would however only be observable as small effects in large event samples.

2.3 POSSIBLE NEW PARTICLES

2.3.1 Quarks of Higher generations

For new charge 2/3 quarks limits can be obtained on their production in e^+e^- annihilation by measuring the ratio :

$$R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-) \quad (2.3)$$

Limits can also be obtained on the production of charge 1/3 quarks from this, [5].

2.3.2 A New Sequential Charged Lepton

If a new type of sequential charged lepton with standard couplings were produced then it would be revealed by its leptonic decays into electrons or muons. As an example the occurrence of events containing electrons and muons was the signature which first revealed the production of the Tau in 1975 at SLAC [6]. From Tau pair production one Tau can decay to $e\nu$, the other to $\mu\nu$ so an event is observed with only two tracks, one an e, one a μ . The decay of a new lepton might also give unusual event topologies. It must be heavy so it will decay to hadron jets but with electrons or muons isolated from these jets. The detectable momentum in the event also need not balance because of the presence of neutrinos in the decays. Searches have been performed for further sequential leptons in e^+e^- experiments. The best mass limit so far is $\geq 22 \text{ GeV}/c^2$ at 95% confidence level [7].

2.3.3 New Neutral Particles

2.3.3.1 Pair Production

There are however other possibilities for new unseen neutral particles. It has been speculated that were neutrinos not massless a possible scenario is that the neutrino mass spectrum starts with a low mass but rises rapidly as is the case for the other fermions [8]. One could then look for new generations by observing the decay of heavy unstable neutrinos. While the neutrino mass problem is still very open there are no fundamental objections to non-zero neutrino masses in the standard model.

The production of a heavy neutrino could occur through the formation of an intermediate Z^0 with a cross section :

$$\sigma = \frac{G_F^2 E^2}{192\pi} \left(\frac{(1 - 4\sin^2 \theta_W)^2 + 1}{\left(1 - \frac{E^2}{m_Z^2}\right)^2 + \frac{\Gamma_Z^2}{m_Z^2}} \right) \beta(3 + \beta^2), \quad (2.4)$$

where M is the Z^0 mass (93 GeV/c²) and Γ_Z is the Z^0 width (2.8 GeV/c²), see Fig. 5. At a centre of mass energy $\sqrt{s} = 42$ GeV this gives $\sigma = 8 \times 10^{-37}$ cm² = 0.8 pb so for an integrated luminosity of 25 pb⁻¹, 20 events would be produced.

See also Ref. 9 where a more general discussion of the possible production and decay of heavy neutral lepton pairs, (referred to as $L^0 \bar{L}^0$), in e^+e^- annihilation is given. A standard model cross section for such a reaction is :

$$\sigma = \frac{G^2 s}{96\pi} (a_e^2 + v_e^2)(a_{L^0}^2 + v_{L^0}^2) T(\beta) \quad (2.5)$$

where a, v are the axial, vector couplings of the e, L^0 at the Z^0 vertices. $T(\beta) = \beta(3 + \beta^2/4)$ is the threshold factor and β is the

velocity of the L^0 in units of c . See Fig. 6. This cross section corresponds to $59 T(\beta)$ pairs/100 pb^{-1} , for a PETRA energy of $\sqrt{s} = 42$ GeV. The cross section only becomes strongly dependent on the L^0 mass close to threshold, for example at an L^0 mass of 5 GeV/c^2 , $\sigma = 1.85 \text{ pb}^{-1}$, while at an L^0 mass of 20 GeV/c^2 , $\sigma = 0.54 \text{ pb}^{-1}$.

In the following discussion $L^0\bar{L}^0$ pairs will be referred to as heavy neutrinos

It has been taken here that the production of a heavy neutrino via an intermediate Z^0 is much more important than production via W exchange.

It should be noted that this is a weak interaction process and therefore independent of the mass of the neutrino provided that the coupling of the neutrinos to electrons is small. The cross section in eqn. 2.4 also rises with s , (see again Fig. 5) which therefore offers the interesting possibility that a very light object may exist but could not have been seen previously in lower energy experiments.

The decays are assumed, by analogy with charge $-1/3$ quark decays, to be to a conventional charged lepton plus a virtual W which then gives a lepton or quark doublet, Fig. 7. In Ref. 8, the first lepton is assumed to be the most massive charged lepton allowed by energy conservation. This is in apparent contradiction of usual phase space arguments which would favour the lightest.

There is the possibility that the lifetime of such a neutrino could be long enough to produce distinct decay vertices. This lifetime is given by :

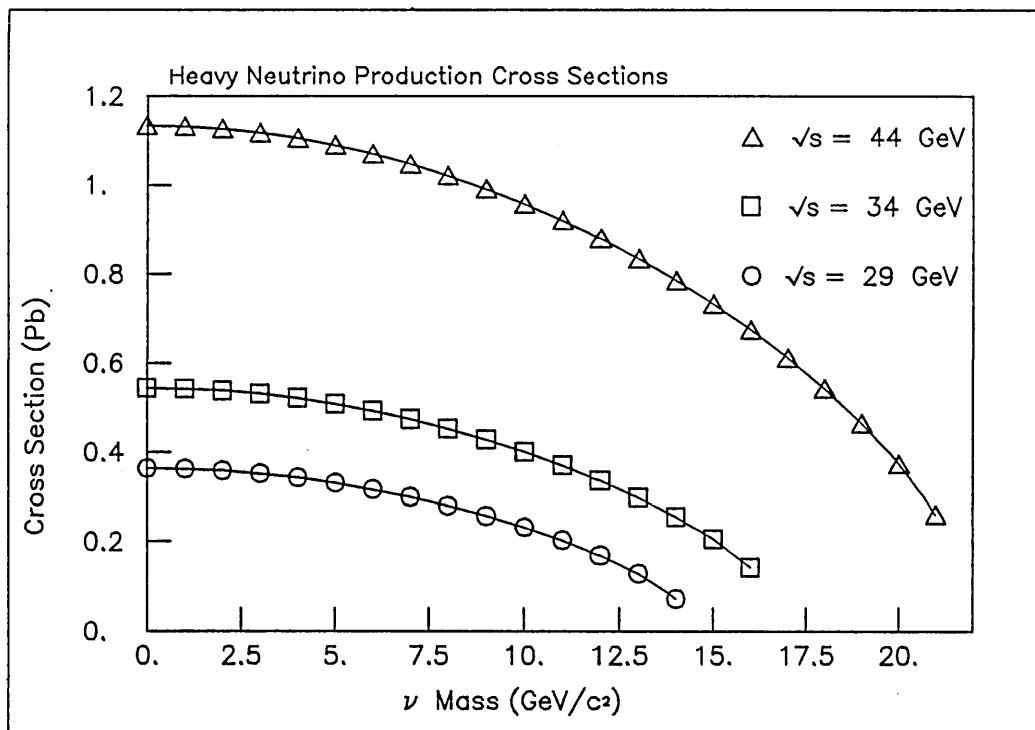


Figure 5: Heavy Neutrino Production Cross Section

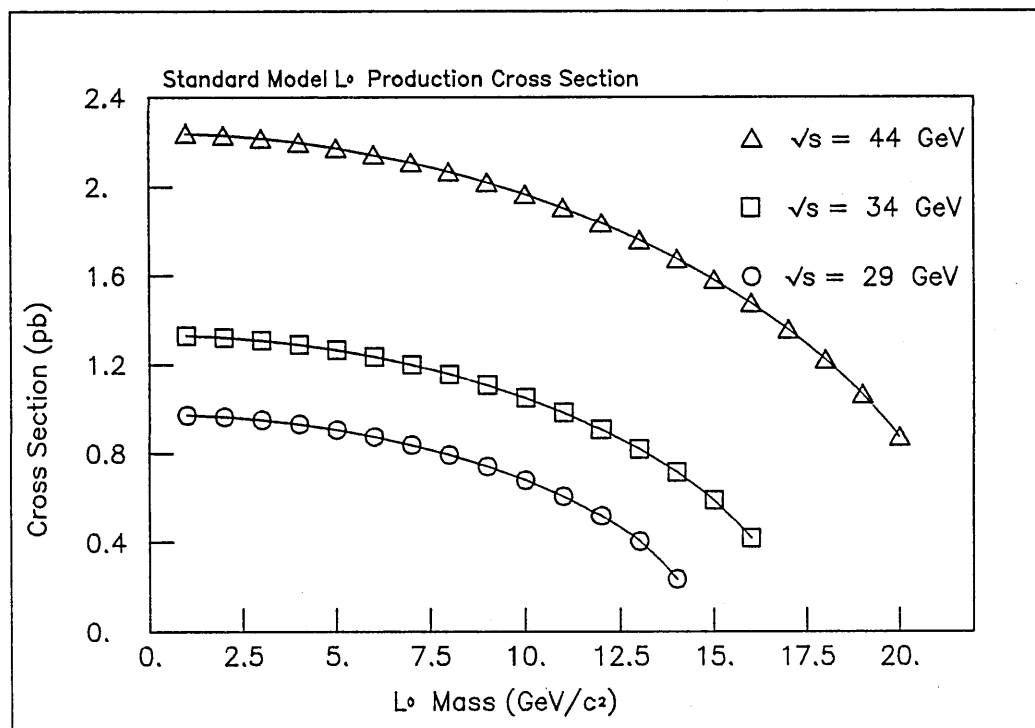


Figure 6: Standard Model Cross Section for $L^0 \bar{L}^0$

$$T\nu = (1/\epsilon N) \times (M\mu/M\nu)^3 T\mu \quad (2.6)$$

where $M\mu$ is the muon mass = 0.106 GeV/c², $T\mu$ is the muon lifetime = 2×10^{-6} sec, N is the number of fermion doublets that the W can couple to (at PETRA energies 5) and ϵ is a mixing parameter describing the coupling of the ν to the charged lepton. This is an unknown which will be ≤ 1 . For $\epsilon = 1.0$ and $\epsilon = 0.01$, at a beam energy of 22 GeV the decay length $l = \gamma c T\nu$ is shown as a function of the heavy neutral lepton mass in Fig. 8.

2.3.3.2 Singly Produced Electron Type Neutral Leptons

There were several early theoretical works in the history of the Standard Model which discussed the production of neutral heavy leptons which could have left or right handed couplings and would be produced in e^+e^- annihilation via virtual W 's [10]. They would be produced singly in association with electron type neutrinos via t channel exchange, Fig. 9. These objects will be referred to as E^0 's. Predicted production cross sections for mass M are :

$$\sigma_{\text{r}}(e^+e^- \rightarrow E^0\nu) = \frac{1}{4\pi} \left[1 - \frac{M^2}{s} \right]^2 (a-1)^2 \left[\frac{s}{a-1} + (s - M^2) + \frac{1}{2} [s + a(s - M^2)] \ln \frac{a-1}{a+1} \right] \quad (2.8)$$

$$\text{where } a = \frac{(s + 2M^2 - M^2)}{(s - M^2)} \frac{W}{W} \quad (2.9)$$

$$\sigma_{\text{r}}(e^+e^- \rightarrow E^0\nu) = \frac{G^2 s}{2\pi} \left[1 - \frac{M^2}{s} \right] \left[1 + \frac{s - M^2}{M^2} \right]^{-1} \quad (2.10)$$

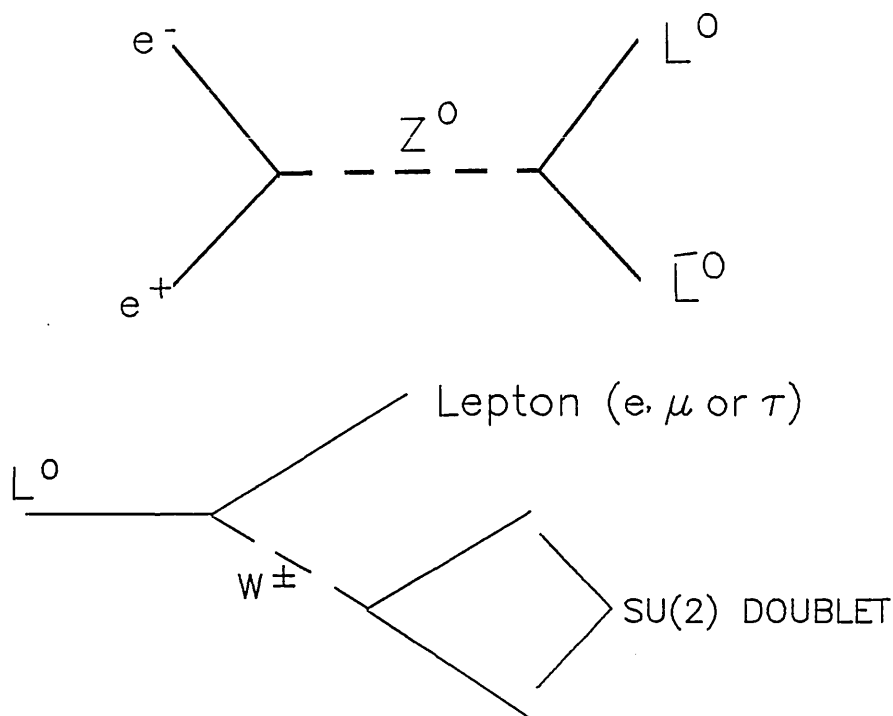


Figure 7: Production and Decay of a Heavy Neutral Lepton (Neutrino)

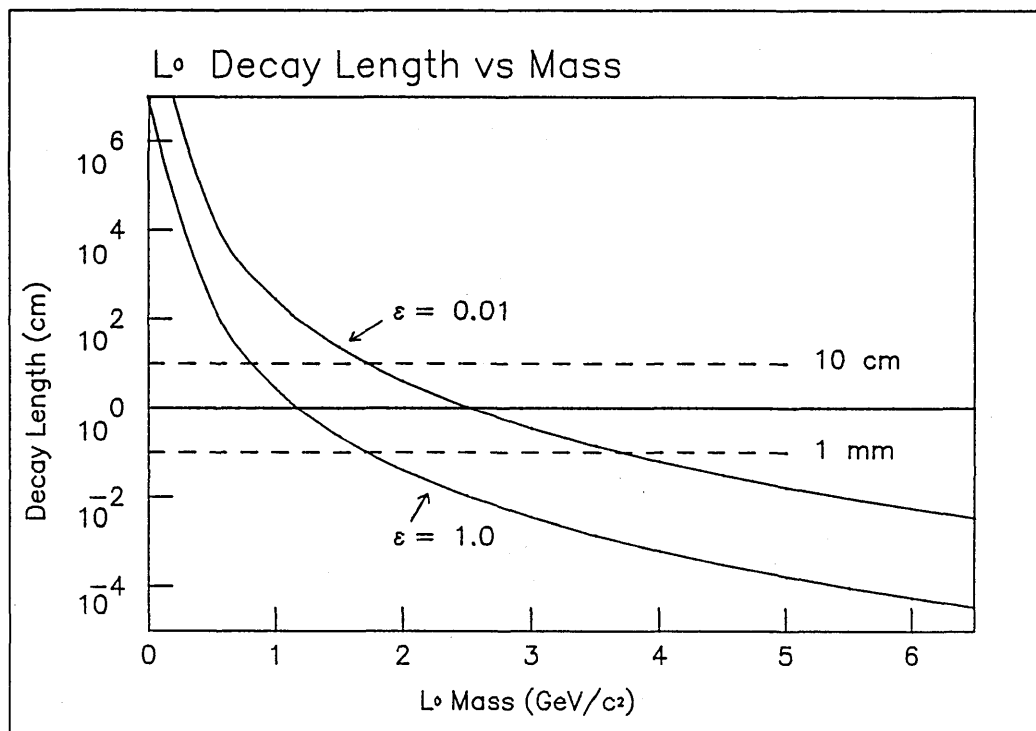


Figure 8: Heavy Neutrino Decay Length

This gives for an E^0 mass of $22 \text{ GeV}/c^2$ at a beam energy of 22 GeV , a cross section $\sigma = 7.5 \text{ pb}$ (left) and $\sigma = 4.8 \text{ pb}$ (right). The cross section as a function of heavy lepton mass is shown in Fig. 10. This cross section can be compared to the hadronic cross section at this energy :

$$\sigma(e^+e^- \rightarrow \text{hadrons}) = 4 \times 87.6/(4E^2) \text{ nb} = 0.18 \text{ nb} \quad (2.11)$$

R is taken as 4 so the E^0 cross section represents 20 % of a unit of R .

The E^0 decays to an electron and a virtual W which can then decay to all quark or lepton pairs kinematically allowed. Such decays would produce distinct topologies containing isolated leptons and single isolated hadronic jets depending on the mass of the E^0 . An E^0 of mass substantially less than the beam energy would be boosted into one hemisphere giving a single isolated jet, as the mass is increased the jet will become broader and such events will become more difficult to distinguish from events of the type $q\bar{q} \rightarrow 2 \text{ jets}$.

A search has previously been performed for such objects by the JADE group but with a smaller data sample at a lower centre of mass energy [11].

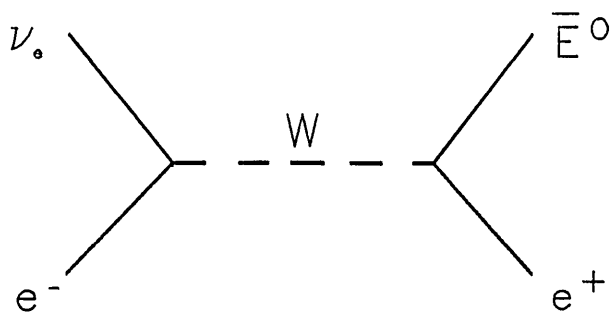


Figure 9: E^0 Production Diagram

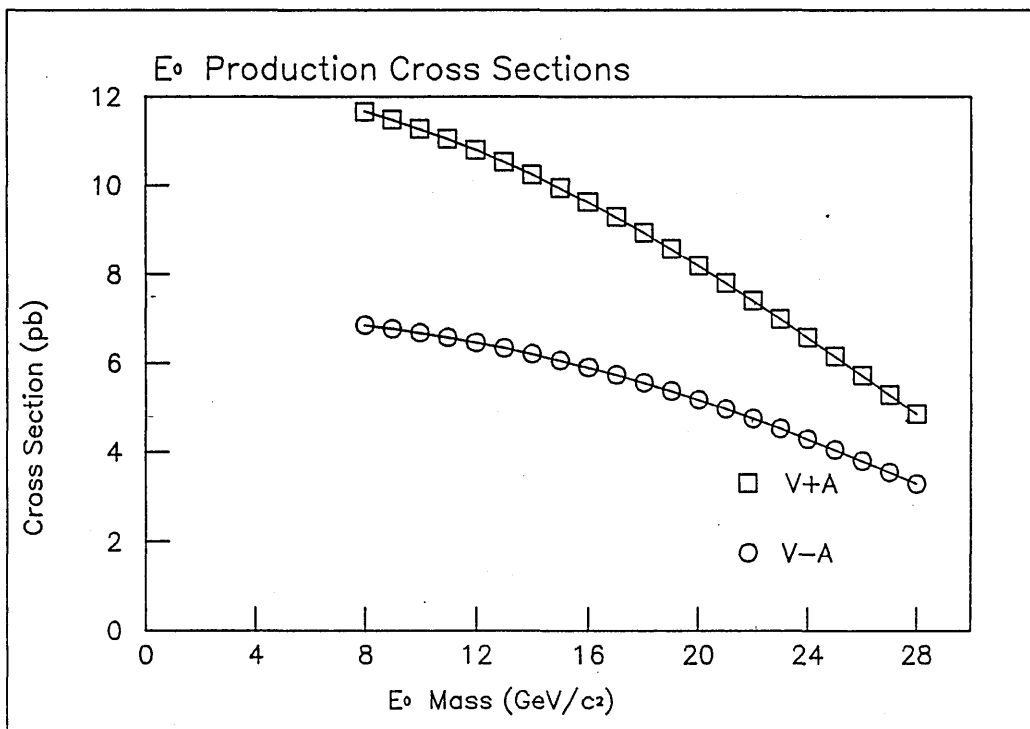


Figure 10: Production Cross Section vs E^0 Mass

2.3.4 Extensions of The Standard Model

Recently a small number of unusual events in proton-antiproton collisions have been observed [12], such as :

1. Single jets having low charged multiplicity and low invariant mass but with large missing transverse momentum, (called monojets).
2. Jets with an isolated energetic electron and also missing transverse momentum.
3. An electromagnetic shower isolated from a lepton pair where the invariant mass of the combined lepton pair photon system is around the mass of the Z^0 .

These observations have led to speculation by theorists and the creation of extensions to the standard model in an attempt to account for them. These extensions also lead to predictions of possible new phenomena in e^+e^- collision at PETRA energies.

2.3.4.1 Monojets

The new phenomena which would give the most spectacular signature are those which, like the E^0 described previously produce a single particle which can decay to normal hadrons and leptons balanced by another object not visible in the detector. This latter object is not seen because it is either, 1) stable enough to escape before decaying or, 2) decays into other 'invisible' particles. Single jet (Monojet) events will result from such cases. Several possible such models are discussed in Ref. 13.

They consider the monojets to result from novel decays of the Z^0 . Decays of the Z^0 to a particle antiparticle pair can be ruled out because the chance of one of the pair decaying immediately to a jet while the other escapes from the detector before decaying are statistically negligible. It is therefore necessary to consider decays to two different objects having widely different lifetimes.

In a 'Two Higgs extension' of the Standard Model the Z^0 could decay into a scalar (h_1) which is long lived and escapes detection, and into a pseudoscalar (h_2) which can decay to ordinary hadrons to form a monojet. The low multiplicity of the CERN monojets would suggest that m_2 could be below the bottom pair production threshold and hence h_2 would mainly decay to $c\bar{c}$, $\tau\bar{\tau}$ or $s\bar{s}$.

2.3.4.2 Supersymmetry

In another scenario - Supersymmetry, where all presently known particles must have partners differing in their spin, then decays $Z^0 \rightarrow \chi_1 \chi_2$ are possible where χ_1 and χ_2 are mass eigenstates of some kind of gaugino (the supersymmetric partners of the gauge bosons) or of the Higgsino (the supersymmetric partner of the Higgs). Again one is short, one long lived. The predictions for the production cross section for such objects in e^+e^- annihilation as a function of $\sqrt{s}$ is shown in Fig. 11.

These discussions are all somewhat speculative but are very useful as a guide to what to look for and what possible new physics one should write computer programs to simulate.

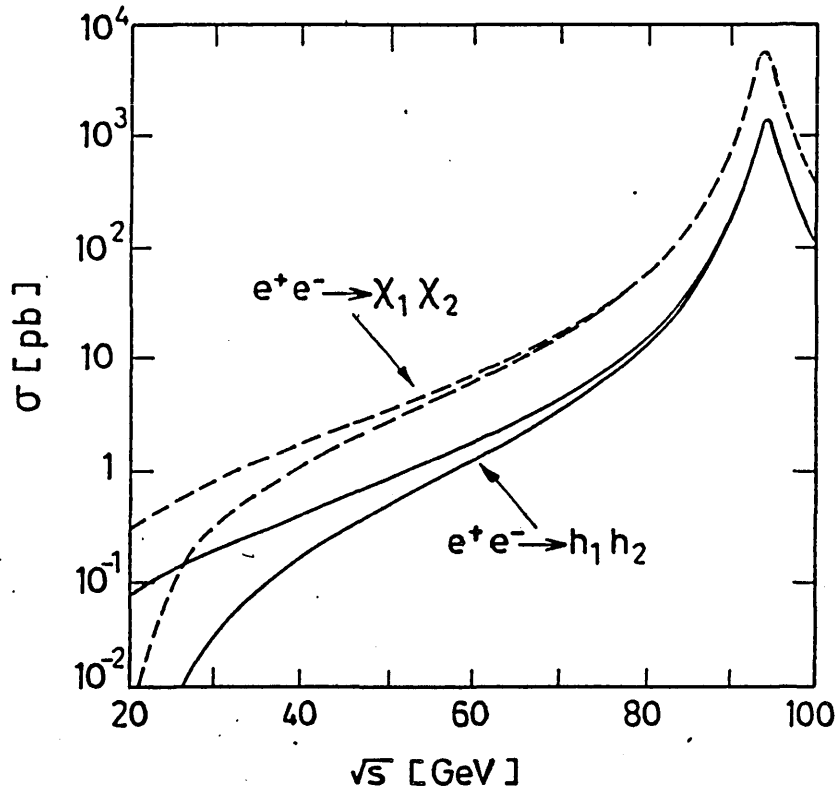


Figure 11: Predicted Monojet Production Cross Sections

Chapter III

THE TASSO DETECTOR

3.1 INTRODUCTION

In this chapter the components of the TASSO detector will be described with special emphasis on those which have an important role in the work presented in this thesis, that is the vertex detector used to look for decays and the Calorimeters used for lepton identification. Fuller information can be found in Ref. 14. Fig. 12 shows the detector in transverse section and Fig. 13 in longitudinal section from the top.

The detector can be divided into two major parts, those components inside the magnet coil and those outside. The components inside detect only charged particles and were used to obtain points on the flight path of such particles. These points can be used to reconstruct their paths. The presence of a 0.49 Tesla axial magnetic field caused a charged particle to move in a circular trajectory, measurement of the curvature of the trajectory was used to determine the particles' momentum. The components outside the coil were for detecting neutral particles, for detecting muons and for separating pions, kaons and protons in certain momentum ranges, but only over a limited angular region.

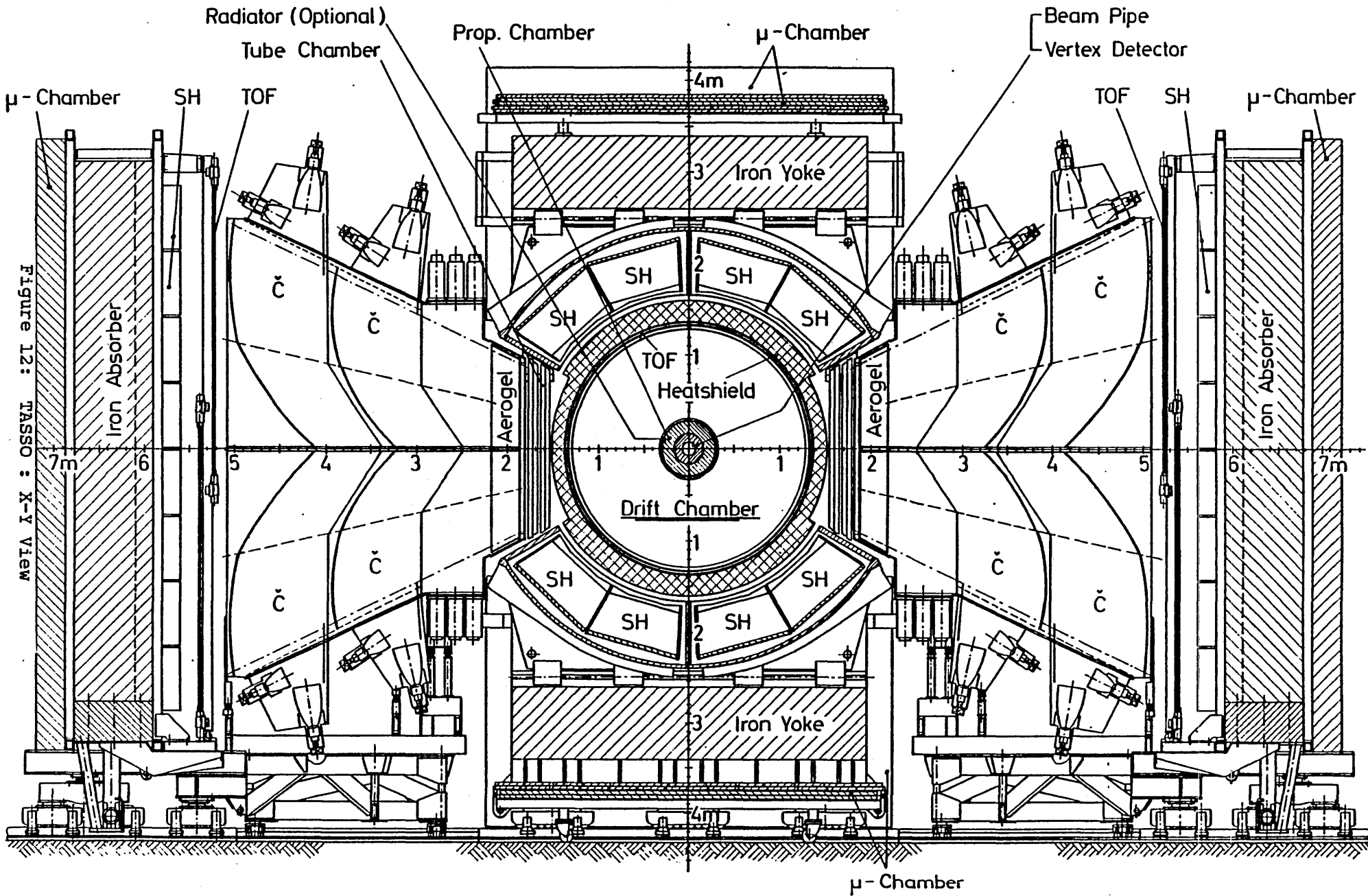


Figure 12: TASSO : X-Y View

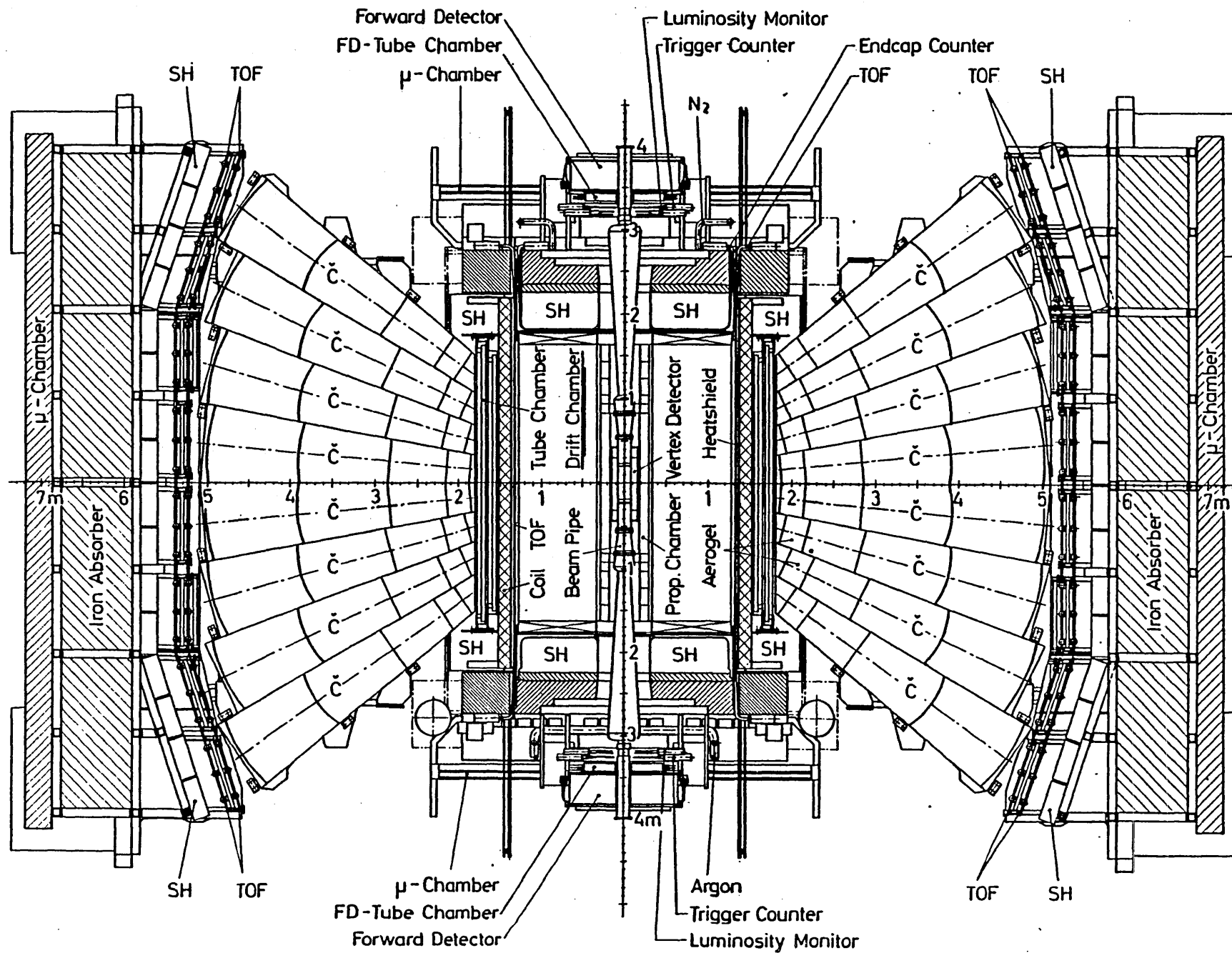


Figure 13: TASSO : X-Z View

3.2 THE INNER DETECTOR

The components comprising the inner detector were the beam pipe, Vertex detector (VXD), Cylindrical Proportional Chamber (CPC), Large Drift Chamber (DC), and 48 Time of flight counters (TOF). These were all situated in a 0.49 Tesla axial magnetic field provided by the coil.

3.2.1 The Vertex Detector

The Vertex Detector was installed in TASSO in the summer of 1982. It was a high precision drift chamber having 8 layers of signal wires, the innermost situated at a radius of 8.1 cm and the outermost at 14.9 cm. It had an active length of 57.2 cm and was mounted on a thin Beryllium beam pipe, see Fig. 14. The four inner layers each contained 72 drift cells, each of the four outer 108 cells. A cell consisted of one signal (anode) wire maintained at a voltage around 3 KV and 2 cathode wires which were grounded.

The chamber was filled with a gas mixture of 95 % argon / 5 % CO₂ at a pressure of 3 Bar. When a charged track passed through the chamber ionization was produced which drifted to the anode wires. Timing measurements were made in 0.5 ns intervals of the arrival of this ionization at the wires relative to the crossing of the e⁺e⁻ beams. After the relationship between the measured times and the drift distances had been determined, a resolution of around 90 μ m was obtained for clean events with only 2 tracks. A full description of the design and construction of the chamber can be found in Ref. 15.

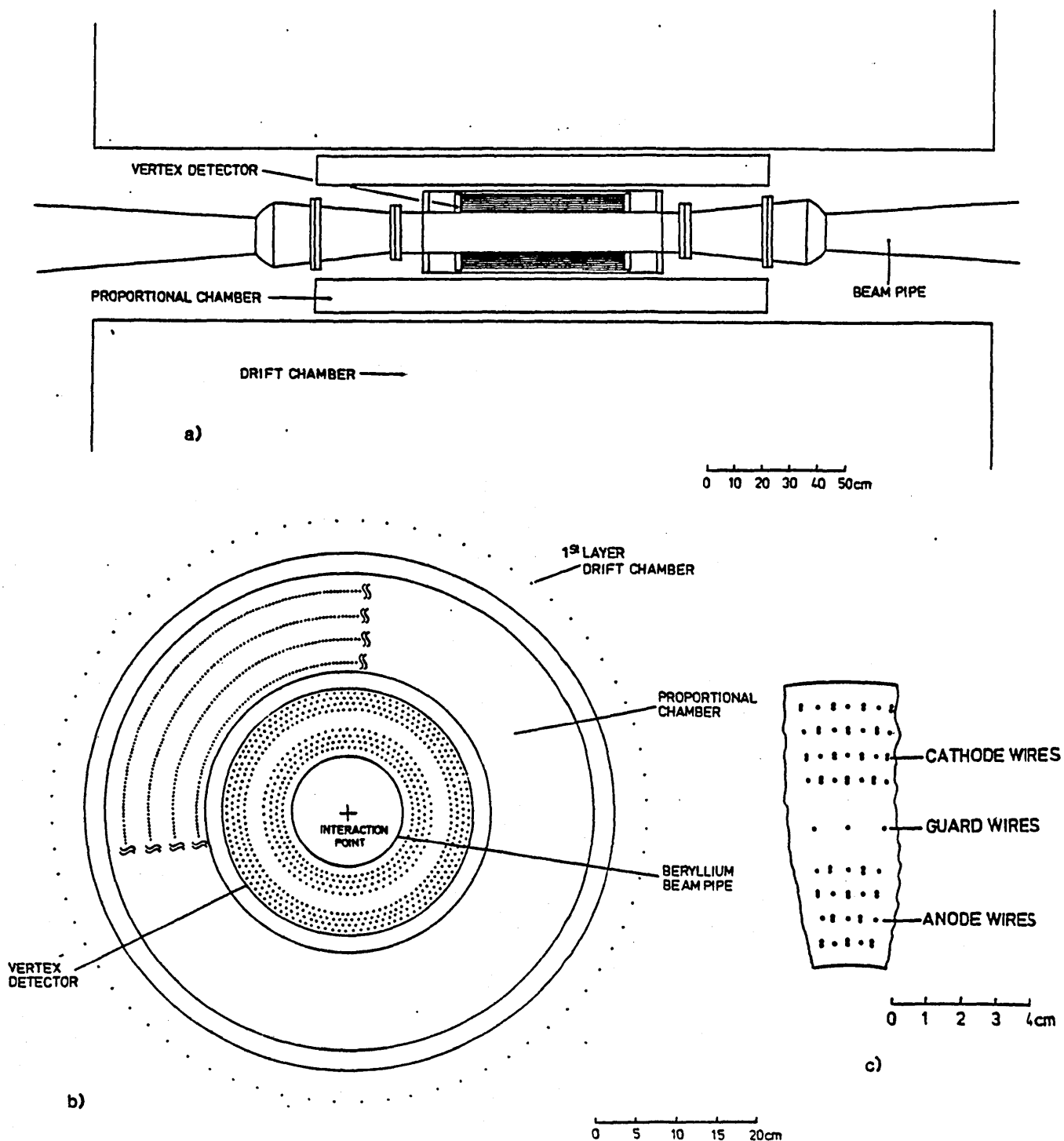


Figure 14: (a) Y-Z View (b) X-Y View (c) Drift Cell Design

3.2.2 The Cylindrical Proportional Chamber

Before the vertex detector was installed the Cylindrical Proportional chamber was the innermost tracking chamber, extending from a radius of 17 cm to 29 cm. It had 4 layers of anode wires, separated by shells with helical cathode strips on each side. Its main function was to trigger the experiment, using the anode signals and using the cathode strips, which gave a crude but fast determination of the Z position of tracks and therefore indicated if they came from the origin. See Ref. 16.

The signals from the anode wires went into the CPC anode processor which divided Φ into 48 sectors. A track segment existed in a sector if at least three out of four anode layers had a hit.

3.2.3 The Drift Chamber

The main tracking device in TASSO was the large Drift Chamber. It extended from a radius of 30 cm to 130 cm and was 320 cm long. There were 15 layers of cells (2340 signal wires in total), 9 of the layers parallel to the z axis, the other 6 inclined at a small angle of 4.5° to facilitate the measurement of the z position of tracks. The position resolution in the r/Φ plane was around 200 μm for tracks measured at the centre of the drift cell, in z the resolution was around 5 cm. The momentum resolution was given by $\sigma(p)/p = 0.016 p$. where p is in GeV/c, see Ref. 17.

The drift chamber had a processor into which signals were fed from six of the nine anode layers parallel to the z axis. Φ was divided into 48 sectors corresponding to those of the CPC. A track segment existed in one of these sectors if there were five hits out of the selected six layers.

3.3 THE OUTER DETECTOR

Outside the coil but on the main assembly were the Liquid Argon Barrel Calorimeter (LABC), the Planar Drift chamber and the Yoke and endcap muon chambers. The hadron arms contained Cerenkov counters of three different types for particle identification, Shower counters (HASC), for photon and electron identification and further muon chambers. (Nothing further will be said about the Cerenkov counters as they played no part in the analysis presented here).

3.3.1 The Liquid Argon Barrel Counter

The barrel calorimeter consisted of 4 separate modules covering the angular ranges, in θ between 42° and 138° and in azimuth Φ , from 30° to 150° and from 210° to 350° . This is 35% of the solid angle. Each module was divided into two submodules, made up of a stack of 35 lead plates, each plate 2 mm thick separated by 5 mm gaps filled with liquid argon. The lead plates were divided up into towers; to allow measurement to be made of the energy of showers; and strips to enable the measurement of their position. Fig. 15 shows the structure of one submodule.

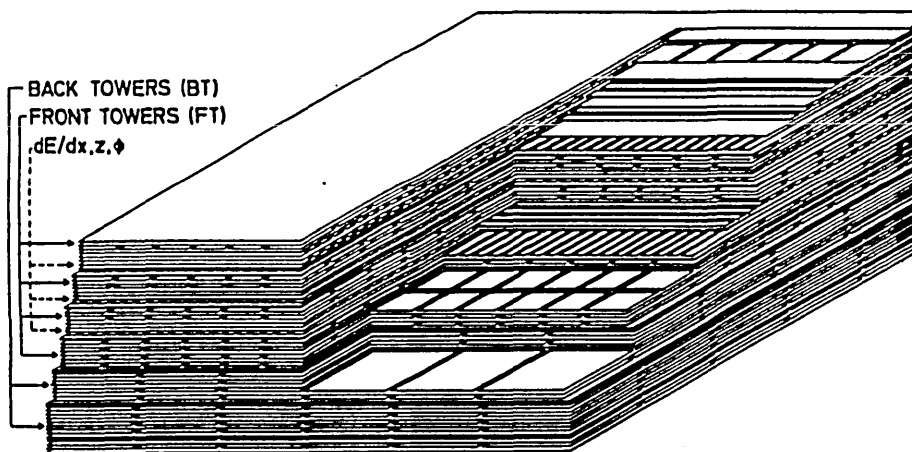


Figure 15: A Liquid Argon Barrel Submodule

The front tower plates measured 7 cm x 7 cm, the back tower ones 14 cm x 14 cm and the strips which ran both parallel and orthogonal to the beam axis were 2 cm wide. There were 5088 front towers, 1248 back towers and 4592 strips. These gave a total of 14 radiation lengths of material.

The energy and spatial resolution were determined using an electron test beam and from bhabha scattering $e^+e^- \rightarrow e^+e^-$ events. Electron tracks in the drift chamber were extrapolated and associated with clusters of deposited energy. The energy resolution can be shown theoretically, (for an ideal calorimeter) to be proportional to $\sqrt{E}$, but for a real calorimeter this simple relationship is modified and here the resolution was parameterised by:

$$\sigma_E/E = (0.11 + 0.02/(E - 0.5))/\sqrt{E} \quad \text{where } E \text{ is in GeV}$$

The formula is valid for energy deposits ≥ 1 GeV. The spatial resolution was : $\sigma(\theta) = \sigma(\phi) = 2 \text{ mrad}$ [18].

The criteria used to identify electrons in these counters are described in chapter 6.

There were also endcap liquid argon calorimeters (LAEC), with coverage in θ from 12° to 30° and from 150° to 168° and all of ϕ . They have not been used in the work presented here.

3.3.2 The Hadron Arm Shower Counters

Situated behind the Cerenkov counters at a distance of 5 m from the interaction point were the Hadron Arm Shower Counters, constructed out of lead scintillator stacks. They covered the angular range in θ from 53° to 127° and in azimuth from -26° to $+26^\circ$ from the horizontal, this is 18% of the solid angle. In each arm there were 80 counters, each counter measuring 100 cm by 70 cm by 13 cm deep consisted of 8 layers of lead each 0.5 cm thick, interleaved with 9 layers of scintillator each 1 cm thick. Electrons and photons entering the counters produced electromagnetic showers, Light produced in the scintillator was detected via wavelength shifter by photomultiplier tubes, one for each counter. The position resolution was therefore worse than that of the liquid argon calorimeter. The shower counters represented 7.4 radiation lengths of material and with the coil, a photon from the interaction point traversed 9 radiation lengths in all. See Ref. 19.

The energy resolution has been determined using bhabhas for high energy deposits, and using events containing lower energy electrons such as $e^+e^- \rightarrow e^+e^-e^+e^-$ and $e^+e^- \gamma$, for lower energy deposits. It has been found to be approximately independent of energy and is given by $\sigma(E)/E = 17\%$

3.3.3 The Muon Chambers

The layout of the muon chambers can be seen in Fig. 16. They consisted of 4 cm X 4 cm aluminium tubes each containing a single proportional wire. They were arranged in 4 layers and offset as shown in Fig. 17. A spatial resolution of 6 mm has been obtained using these tubes. To reach the muon chambers particles from the interaction point had to traverse iron of thickness shown in table 2.

TABLE 2		
TASSO Muon Chambers		
Chamber	Iron Thickness	Coverage (% of 4π)
Yoke	80 cm	19
Arms	87 cm	13
Endcaps	50 cm	13

		Total 45

To penetrate the iron a muon had to have a momentum greater than ~ 1 GeV/c. The muon identification efficiency was determined from events of the type $e^+e^- \rightarrow \mu^+\mu^-$. The single track identification efficiency was around 90% in 1983 and 96% in 1984 (The lower value in 1983 resulted from problems in some of the electronics during this period.) The contamination by pions from decays in flight and punch through has been determined to be 2% per track [20].

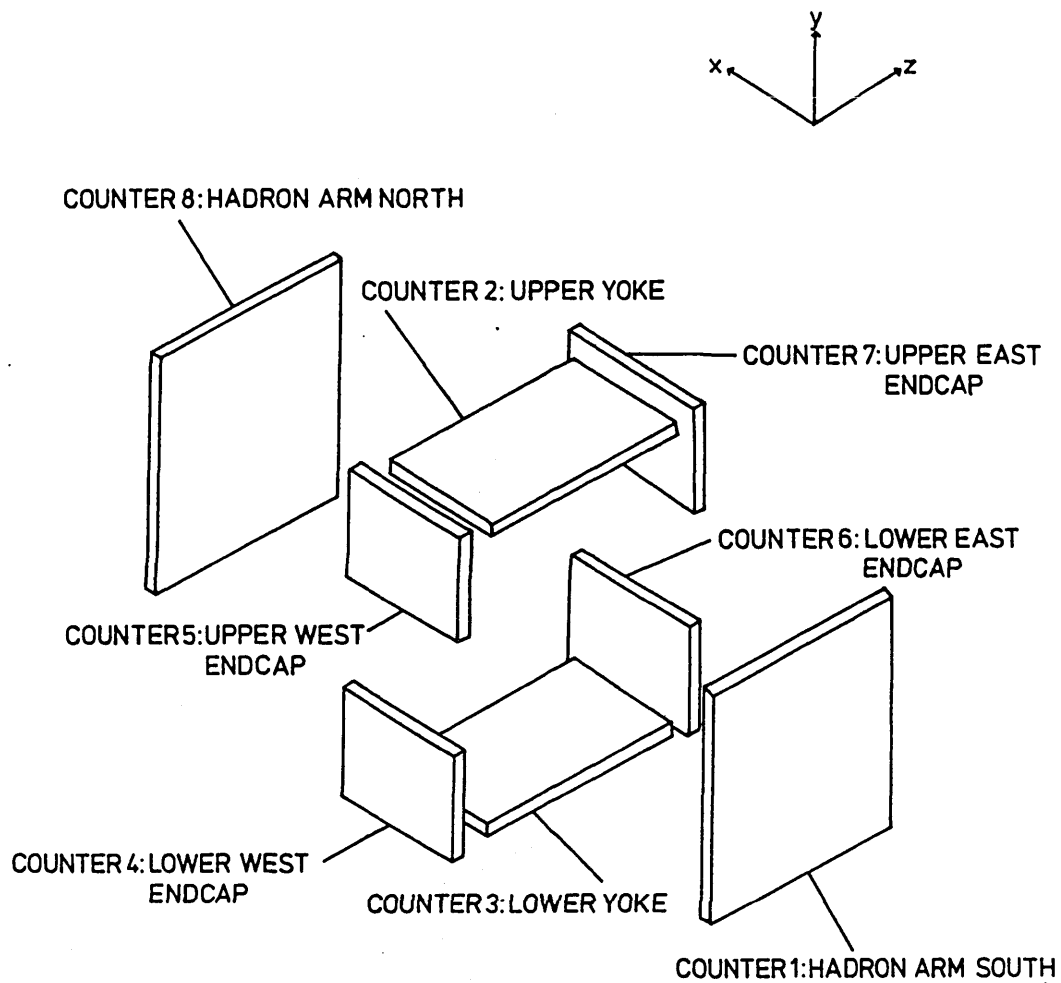
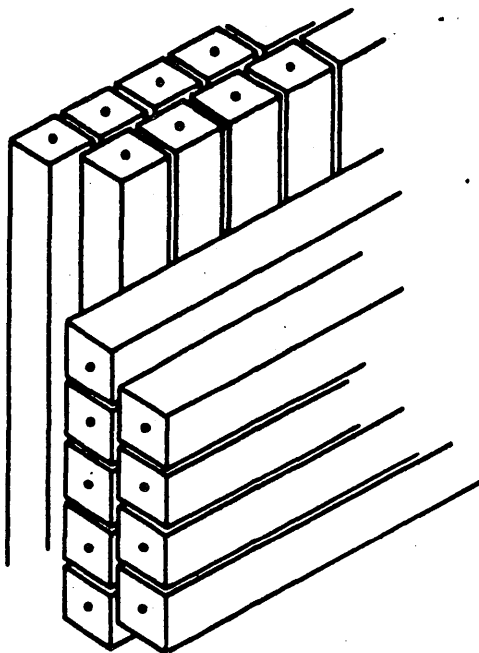


Figure 16: Layout of The Muon Chambers



Proportional tubes

Figure 17: Detail of The Muon Chambers

3.3.4 The Forward Detector - Luminosity Measurement

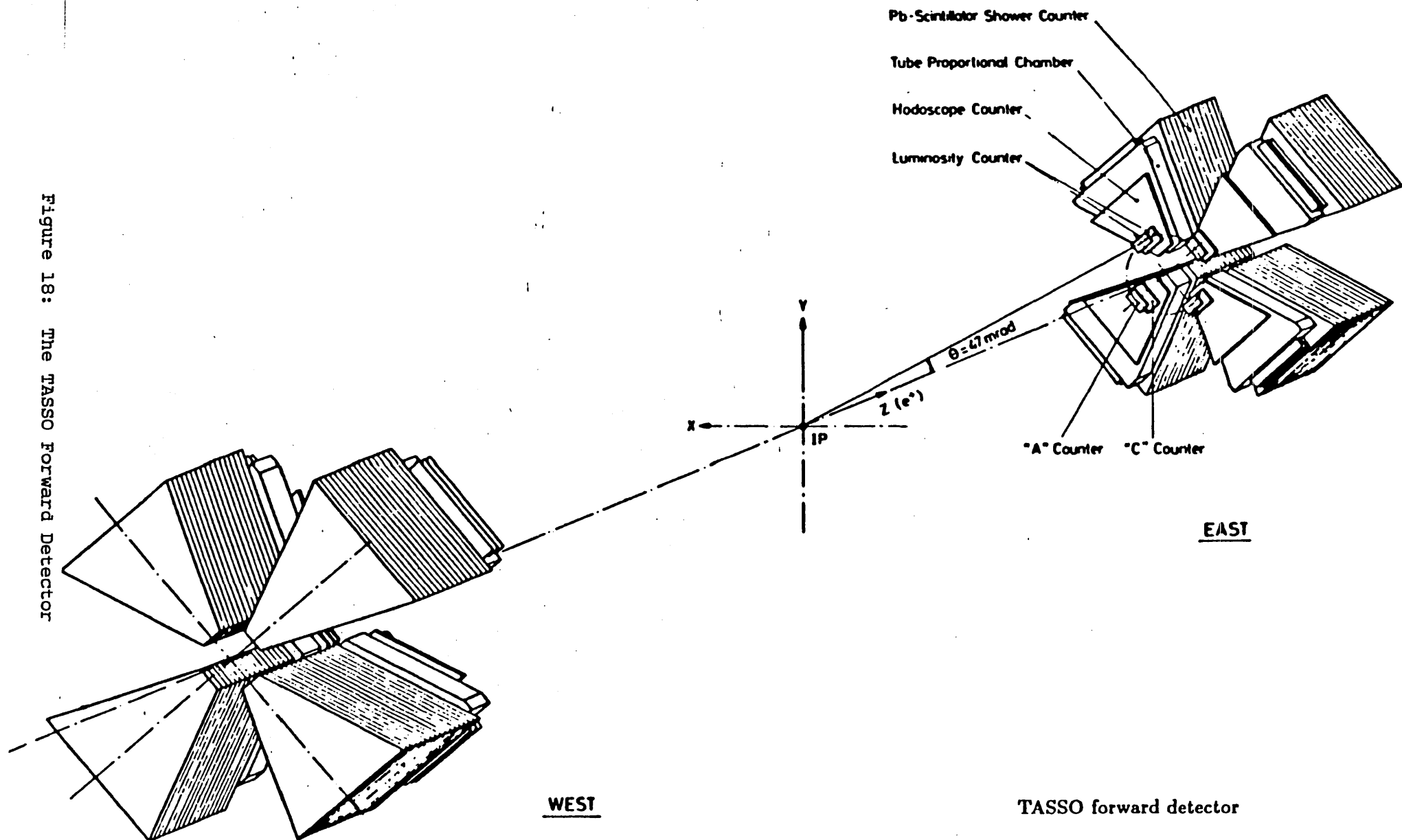
[21]. The complete forward detector in use since May 1982 is shown in Fig. 18, it consisted of eight identical modules, four on each side of the interaction point at $z \sim \pm 3.5$ m. The Luminosity was measured by the rate of small angle bhabha scattering which is well calculated from QED. To detect these events the Luminosity Monitor was used, each of its modules consisted of two small plastic counters A and C, subtending the angle $25 \text{ mrad} < \theta < 115 \text{ mrad}$, situated in front of the proportional chambers and lead scintillator shower counters of the main forward detector. The number of coincidences in diagonally opposite counters, coupled with minimum energy deposits in both shower counters were counted. The acceptance of the luminosity monitors were well known and could be expressed in terms of the bhabha cross section. For example at a beam energy of 20.5 GeV. the cross section of the A counter was $\sigma = 11.3 \text{ nb}$ (8.65 nb) before (after) July 1983, (The counter positions were changed slightly in July 1983). Using these cross sections for an integrated luminosity of 50 nb^{-1} , (which was the typical luminosity taken at each energy during scanning), 2260 (1765) independent bhabha coincidences were expected, this shows that the statistical error in the forward luminosity was negligible.

There were various sources of systematic error including accidental coincidences in the counters, and the effect of material between the interaction point and the counters. The

radiative corrections to the bhabha cross section calculation were only included up to order α^3 when really all orders should be used, so this approximation also introduced a systematic uncertainty. The total systematic error on the forward luminosity amounted to some 4%.

The Luminosity was also measured using the number of wide angle bhabhas in the LABC and using the number of bhabhas into the liquid argon endcaps. These were independent measurements which normally agreed with each other and with the forward luminosity, so they were combined to give the final luminosity used in TASSO data analyses.

Figure 18: The TASSO Forward Detector



3.4 DATA TAKING

3.4.1 The Trigger

Because of the nature of making a search for new phenomena, the ultimate limitation on what one can hope to find is set by the trigger, as this determines which of the interactions are recorded for further analysis. In TASSO there were a number of triggers optimised for different event types, they can be divided into two broad classes. a) Triggers demanding only tracks in the central detector and b) triggers demanding an energy deposit in the calorimeters greater than some minimum value, or a combination of tracks and energy deposits.

3.4.1.1 Neutral Triggers

The energy deposited in the calorimeters was calculated from the signals produced in each element, summations over certain elements were then calculated for the purposes of the trigger.

These were set for the Liquid Argon Barrel to be :

- a) Zero tracks in the central detector and either ≥ 2 GeV in part of a submodule or ≥ 1.5 GeV in a whole submodule.
- b) If there is one track in the central detector then only 0.8 GeV in a submodule was required. a and b were independent.

For the Hadron arm shower counters :

- a) Zero tracks and ≥ 2 GeV in each arm summed over all counters in the arm.
- b) One central detector track and ≥ 1 GeV in one arm.

These energy thresholds were such that a sufficiently low trigger rate (≤ 0.1 Hz) occurred. If they had been set to lower values, noise would have produced spurious triggers not associated with e^+e^- interactions, [22].

The importance of these neutral triggers for this experiment were in the detection of events where a small number of tracks were produced on one side, balanced by neutral energy on the other side.

3.4.1.2 Track Triggers

The track triggers used the drift chamber and CPC processors. A track existed if the drift chamber had a track segment, together with a signal which indicated that the CPC processor had found a track segment in the corresponding ϕ sector, and there was also a signal from the corresponding Time of Flight counter.

The usual requirement at beam energies above 20 GeV was for at least 5 such tracks, (at lower energies only 4 were required). This trigger was the main one for obtaining events of the multi-hadron type.

For low multiplicity events there were the 2 prong triggers :

i) Coarse Topology

The coarse topology trigger required the presence of two tracks back to back in ϕ in the Drift Chamber, it accepted tracks down to the lowest momentum allowed by the processor (320 MeV/c transverse to the beam axis) and back to back to within 3 time of flight counters. This gave an acceptance for events with

accoplanarity less than 20° . This trigger was able to record low multiplicity, low momentum two photon events.

ii) Fine Topology

The fine topology trigger also required the presence of two tracks back to back in the Drift chamber, but in this case they had to be in the two highest transverse momentum bins and back to back to ± 1 time of flight counter. This gave an effective acceptance only for tracks with a transverse momentum greater than 600 MeV/c and coplanar to 5° or less. This trigger was the main one for recording bhabha events.

iii) CPC Cathodes

Each layer of the CPC cathodes had 120 strips. Signals from the 4 layers on the outside of each shell were fed to the cathode hardware processor. They were OR'ed in pairs and then by performing calculations equivalent to rotations of the hit patterns in the 3 outer layers with respect to the innermost one, the Z position of a track was determined. This procedure is fully described in Ref. 23. The Z position was made into 5 bins each 30 cm in length. N_i being the number of 'tracks' found in each Z bin counted as the quantity; 3 folds + 3 x (number of 4 folds); a 3 fold is three hits out of the four layers, a four fold is hits in all layers. A simple algorithm was then used to produce a trigger :

$$N_3 > 1/2(N_1 + N_2) \text{ .AND. } N_3 > 1/2(N_4 + N_5)$$

3.4.2 The Online System

The e^+e^- bunches crossed in TASSO at a rate of 250 Khz. Although an e^+e^- interaction could occur on any of these crossings, in most of the crossings there was nothing of interest present, so that it was therefore necessary to have a trigger which examined every beam crossing in the $4\ \mu\text{s}$ available between them. If some preset combination of track and/or energy deposits occurred, (as described above), a valid trigger was indicated by one or more of the components. In this case the Strobe Interrupt and Gate Handler (SIGH) box prevented further triggers being received until the information in the detector was read out. A signal was sent to the Nord 10 computer and readout via the CAMAC system took place, on average some 1000 to 2000 words of data, each 32 bits long were read out, constituting an event record. The readout took up to several hundred milliseconds to perform. The data were transferred first to a local disk (66 MB), from where they were read into a 168E emulator. The emulator was an IBM type processor which had a fast track reconstruction algorithm, (FOREST) [24] running in it. The program acted on the pattern of drift chamber hits in the event record using a tree and branch type algorithm to locate track patterns. It added the information on these patterns to the raw data from the detector then sent the record via a link to a disk (100 MB), attached to the main DESY IBM computer. When this disk at the IBM was full, its contents were copied to a 6250 bpi tape (dumtape) [25].

The system was monitored using a Nord 100 computer connected to the Nord 10, The Nord 100 looked at a proportion of the events passing through the latter, It histogrammed the hits in the detector components and allowed selected events to be viewed on colour TV monitors. The configuration of the online system is shown in Fig. 19.

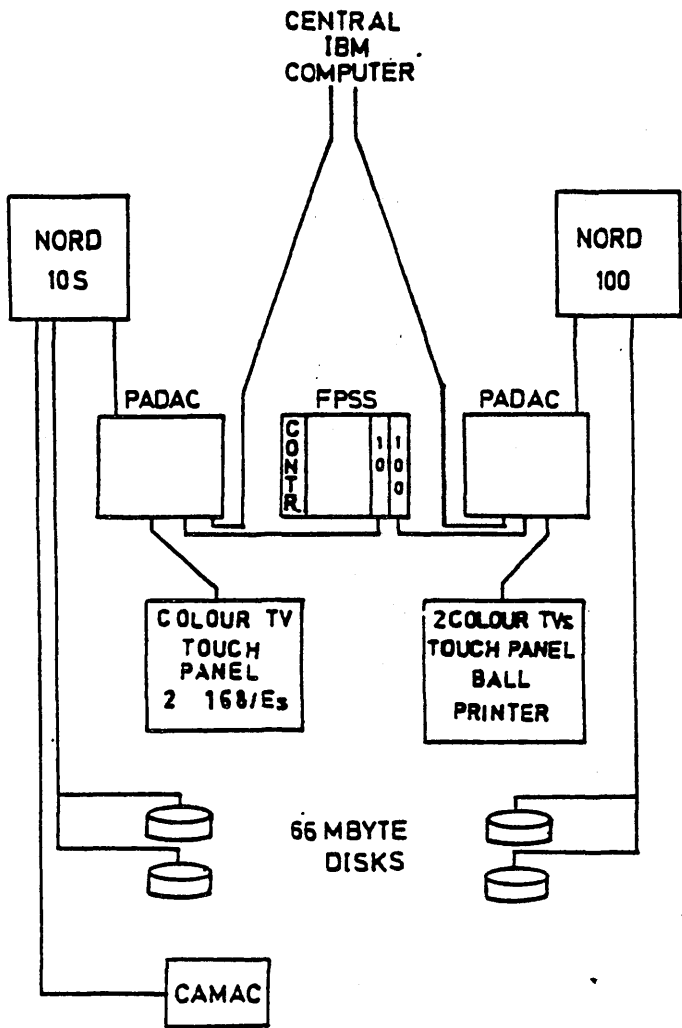


Figure 19: The Online System

3.5 OFFLINE DATA REDUCTION

3.5.1 From the Dumptape to the PASS 3 selection

As the data used in this thesis were primarily that taken in 1983 and 1984, the data reduction chain during these periods will be fully described. The data reduction cuts for the earlier lower energy data differed in some respects so these differences will be indicated. [26].

A dumptape contained around 13000 raw triggers. The majority of these were from background processes such as beam gas scattering or beam pipe interactions and therefore needed to be rejected, although one hoped to keep any new and interesting events. There were four steps in the data reduction chain leading to selection of the one gamma annihilation events. Because of changes in the data reduction scheme, the periods from 1981 to 1983 and 1984 are considered separately, see Fig. 20.

3.5.1.1 Data Reduction 1981 to 1983

PASS 1. All events from the dumptape were copied and a check was made that the FOREST track finding program has been run on all of them during their passage through the 168E emulator. If FOREST had not been run on a particular event then it was run during this copying.

PASS 2. Events were selected from Pass 1 with :

1. At least 1 track fully reconstructed in 3 dimensions with $|d_0| \leq 2.5$ cm and $|z_0| \leq 15$ cm. (See Appendix A for a definition of these quantities). These requirements

removed a lot of the beam pipe and beam gas events not associated with e^+e^- interactions.

Also all of the following triggers were selected because their rates were such that they did not occupy a large amount of space on the tape and almost all of them were interesting.

2. Liquid argon barrel 0 track and 1 track.
3. Liquid argon endcap 0 track and 1 track triggers, (similar criteria to the barrel triggers).
4. Hadron arm shower counter 0 track and 1 track.

The zero track triggers selected events where there were no tracks present, such as in the process $e^+e^- \rightarrow \gamma\gamma$. The one track with neutral triggers selected events where there were tracks and neutral energy, such as in bhabhas and radiative events.

5. Luminosity monitor small angle Bhabha triggers used for luminosity measurement offline.
6. Cosmic rays recorded during running, these mainly came in on the 2 prong triggers but had a time of flight difference of 9 ns between opposite counters and did not usually pass through the centre of the TASSO detector.

PASS 3. Events were selected with at least 3 tracks reconstructed in 2 dimensions (r, ϕ) with $|d_0| \leq 2.5$ cm, and 2 of these fully reconstructed in 3 dimensions with $|d_x, d_y| \leq 2.5$ cm, and $|z_0| \leq 15$ cm.

PR 2. This was a low multiplicity selection from PASS 2. Events were selected with 2 to 4 tracks in r, ϕ with $|d_0| \leq 2.5$ cm and at least one of these to be reconstructed in 3 dimensions with $|z_0| \leq 15$ cm.

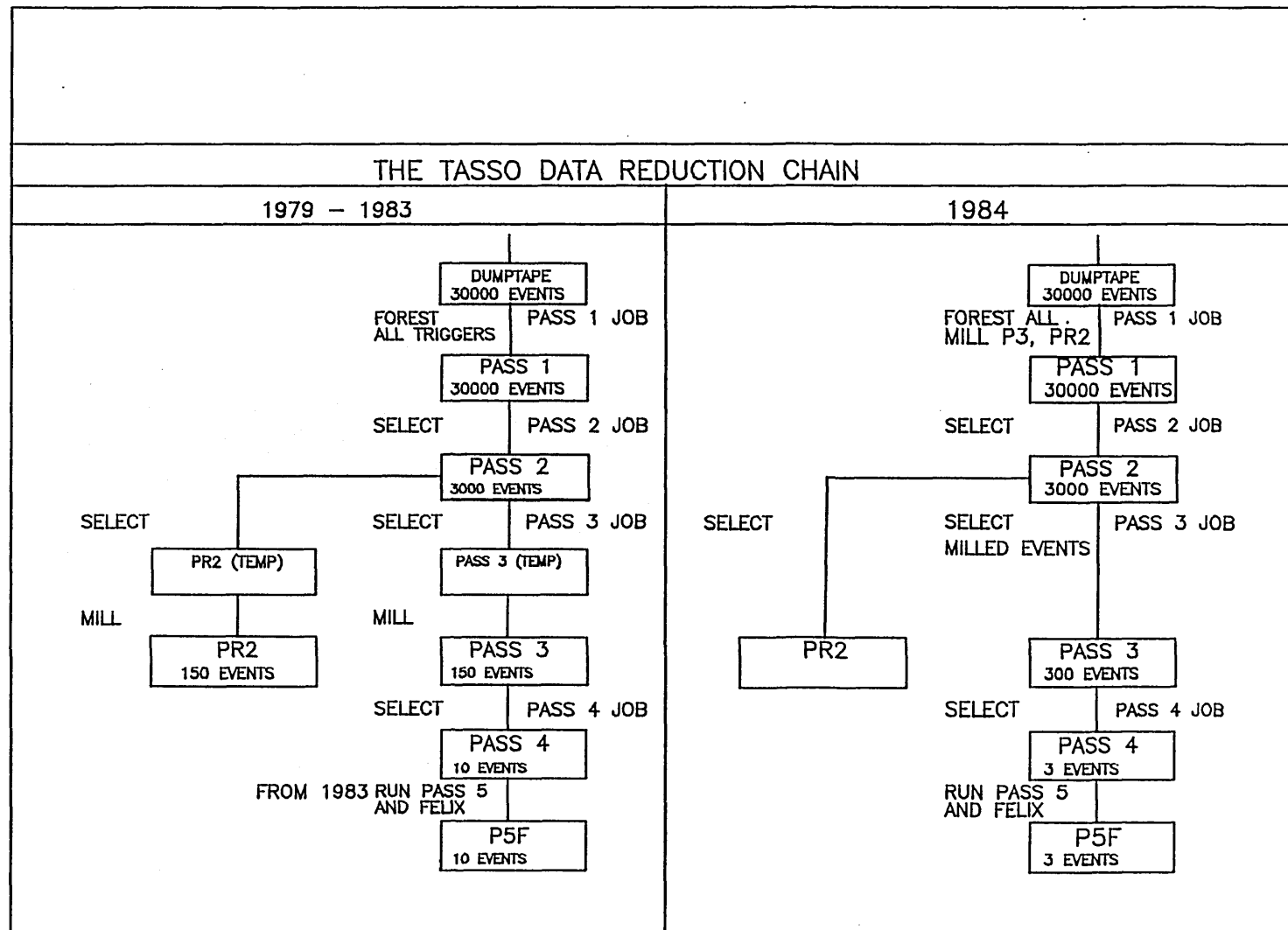
A more thorough track finding program known as MILL was run on the PASS 3 and PR 2 selections, the process of using this program being referred to as milling. MILL used a road type algorithm which is more efficient, whereas FOREST used only a simple tree and branch type. Mill also made use of the CPC anode hits as well as the drift chamber hits, used non-linear space drifttime corrections for the drift chamber and corrected for the entrance angle of the track into the drift cell.

The PASS 3 tape contains all the one γ annihilation events and a lot of the two γ scattering events. A further selection is made to separate the former.

3.5.1.2 Data Reduction in 1984

In 1984 the data reduction was changed to save tapes and CPU time. In PASS 1 the selections as described above for PASS 3 and PR 2 were made, (Except the $|z_0|$ cut was tightened to 8 cm). These events were flagged and trackfinding using the MILL program was performed. For PASS 2, the events which had tracks found by MILL were taken from the PASS 1 tapes, as well as all the others passing the criteria described previously. For PASS 3 only the events with MILL tracks were selected. PR 2 tapes were no longer made, as the data they previously contained was now found on the PASS 2 tapes.

Figure 20: Offline Data Reduction



3.5.2 Hadronic Event Selection - PASS 4

The class of events used in the majority of TASSO analysis were the one photon annihilation events which produce hadron jets. To select these events particular criteria were used which are described below.

First the number of good tracks in an event was counted where the criteria used to define a good track were :

- a) reconstructed in 3 dimensions, b) well fitted,
- c) $|d_0| < 5 \text{ cm}$, d) $p > 0.1 \text{ GeV/c}$,
- e) $|\cos\theta| < 0.87$, f) $|z_0 - \langle z_0 \rangle| < 20 \text{ cm}$

where $\langle z_0 \rangle$ is the average Z for tracks satisfying cuts a to e.

An event then had to have the following requirements :

1. ≥ 5 tracks.
2. To remove events due to Tau pair production, the event was divided into two hemispheres by a plane perpendicular to the sphericity axis, (see Appendix B for a definition). If $W \leq 16 \text{ GeV}$ ($> 16 \text{ GeV}$) and there were three tracks in one hemisphere and one (three) in the other, the mass of the three prong system had to be $\geq 1.78 \text{ GeV}/c^2$, which is the mass of the Tau.
3. At least one track in each forward backward hemisphere, mainly to remove two photon events
4. The z of the event vertex had to lie within $\pm 6 \text{ cm}$ of the interaction region, mainly to remove events due to beam gas interactions.
5. $\Sigma p \geq 0.265 W$, to remove 2 photon events.

6. The sum of the charges of the good tracks (Σq) had to be < 4 , mainly to remove events due to interactions in the beam wall.

It is clear that these selection criteria were ones which would reject many events due to the hypothetical new particles described in this work. Therefore it was necessary to go back to a stage earlier in the data reduction, PASS 3 when making the searches.

3.5.3 Incorporation of The Vertex Detector Information

Up to PASS 4 the Vertex Detector information had not been included in the data reduction. To make use of this information a further track finding algorithm had to be run on the events. There were two approaches to doing this; PASS 5 [27] and FELIX [28].

3.5.3.1 PASS 5

Tracks that had already been found in the drift chamber and CPC by MILL were extended back into the vertex detector by taking a road around where the track entered and trying to fit the vertex hits found within this. The program PASS 5 did this. Because the distance between the innermost and outermost layers of the vertex detector was only 6.8 cm, the tracks in the vertex detector were virtually straight lines which reduced the error in extrapolating tracks into the detector from the drift chamber.

The major advantages of this method were that one was able to start with the best drift chamber tracks, and after refitting find which VXD hits these used, then later trying worse tracks using only those VXD hits which remained. The program was also computationally reasonably fast and tied in with the already well tried and tested MILL program. The disadvantages were that tracks which came from decays outside the vertex detector could be backtracked falsely if there were hits due to noise in the VXD, conversely tracks which existed only in the VXD would not be found, although the latter point could also be an advantage under noisy conditions.

3.5.3.2 FELIX

The other approach was to start again with trackfinding in the complete inner detector, DC, CPC and VXD. By considering the central detector as a complete unit it overcame the problems of doing the track finding in two stages. It also became possible to find tracks at small angles to the beam, which MILL was unable to find because they had insufficient drift chamber hits but which did have hits in the vertex detector. FELIX was also able to reconstruct tracks using the vertex detector only.

The major disadvantage here was the slowness introduced by the greater number of wire layers and the consequent increase in the number of permutations involved. It took around 7 times longer than MILL to process an average multi-hadron event.

Chapter IV

MODELLING SOME NEW PHYSICS

4.1 INTRODUCTION

To determine what it would be possible to detect with the TASSO detector it was necessary to construct 'monte carlo' simulations of events. There were two distinct stages to doing this. First one had the event generator which contained the physics of the e^+e^- reaction of interest. In the generator decisions were made on what particles were produced and how they subsequently interacted with each other and decayed. A list of all the products of the reaction were stored with information on momenta, mass, charge, parents and daughters. In the second stage these were passed through a simulation of the detector and from the known performance of the components appropriate signals in the various detectors were calculated. The final event was stored in a format identical to that of real events and could be passed through the same selection programs as used for real events. It was then possible to determine the acceptance for a particular reaction or particle type and see if a new physical process looked distinct from others.

In this chapter the structure of the generators simulating the production and decay of i) neutral lepton pairs and ii) singly produced heavy neutral leptons (the objects referred to as E^0 s in

chapter 2) will be described. The search was a general one but these two choices were such that they showed the main distinct features of the new particles being searched for without being too restrictive. The generators were written in such a way that parameters such as the mass and angular distribution of the particles being generated could easily be varied.

4.2 NEUTRAL LEPTON PRODUCTION

The assumption was made that the L^0 and E^0 were spin $1/2$, which had consequences for the angular distribution at the production point. For the production of a pair of neutrinos occurring via the Z^0 the differential cross section has the form

$$d\sigma/d\Omega = A(1+\cos^2\theta) + B \cos\theta$$

In Ref. 8, A/B is given as 3.15

For $E^0\nu$ production the case is a little simpler as a neutrino can conventionally only have one helicity so the E^0 helicity is constrained. The angular distribution for left handed couplings is of the form :

$$A(1 + \cos\theta)^2 + B \sin^2\theta$$

For right handed couplings there is no θ dependence. Full calculations in Ref. 10 give for an E^0 of mass M :

$$\frac{d\sigma}{d\Omega}_l = \frac{G^2}{32\pi^2} \left[1 - \frac{M^2}{s}\right]^2 \left[2s(1 + \cos\theta) - (s - M^2)\sin^2\theta\right] \left[1 - \frac{t}{M^2}\right]^{-2}$$

$$\frac{d\sigma}{d\Omega}_r = \frac{G^2}{32\pi^2} \left[1 - \frac{M^2}{s}\right]^2 (4s) \left[1 - \frac{t}{M^2}\right]^{-2}$$

W

where $t = -1/2 (s - M^2)(1 - \cos\theta)$

These differential cross sections are shown in Fig. 21, for an E^0 mass of $3 \text{ GeV}/c^2$.

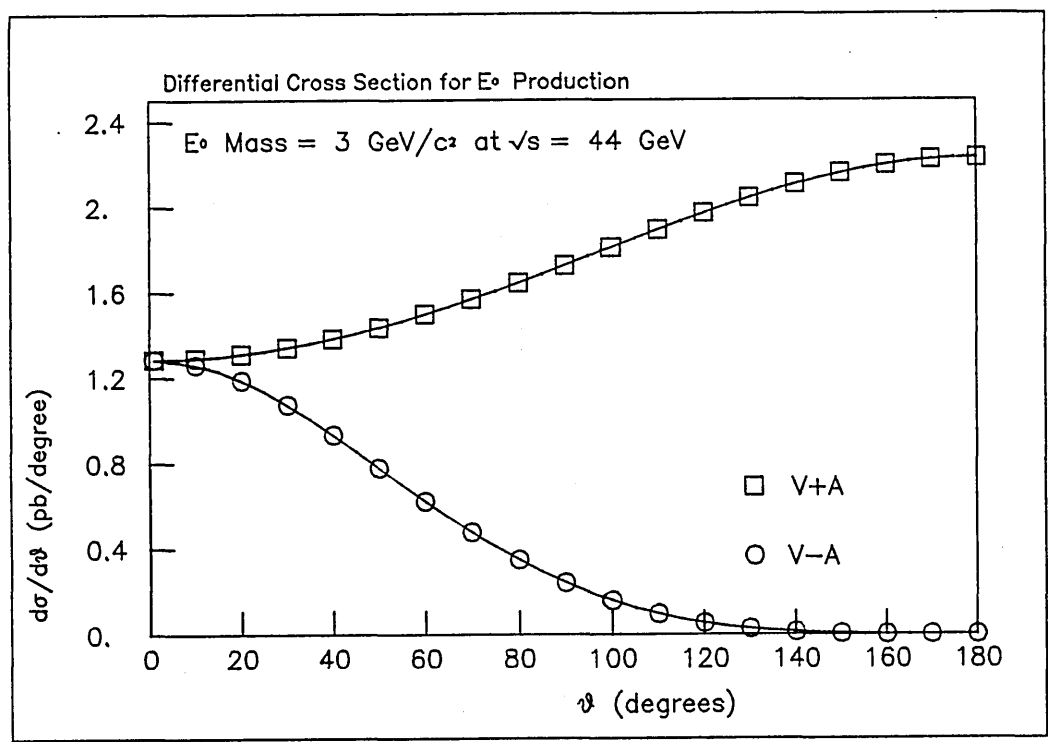


Figure 21: Differential Cross section for $3 \text{ GeV}/c^2$ E^0 's

4.3 DECAYS

4.3.1 The Decay Products

Initially the assumption was made that the L^0 decays to the most massive conventional charged lepton allowed, (ie. with a mass less than the L^0), plus a virtual W .

Four possibilities were considered :

	Mass	1st lepton	Allowed in W decay
a)	$M < M_\mu$	$0.1 \text{ GeV}/c^2$ Electron	e
b)	$M_\mu < M < M_\tau$	$1.0 \text{ GeV}/c^2$ Muon	$e \mu u d s$
c)	$M_\tau < M < 2M_\tau$	$3.0 \text{ GeV}/c^2$ Tau	$e \mu u d s$
d)	$M > 2M_\tau$	$8.0 \text{ GeV}/c^2$ Tau	$e \mu \tau u d c s$

Later the case was considered where the first decay lepton need not be the most massive conventional lepton, for example where the $8 \text{ GeV}/c^2$ L^0 decayed equally to e , μ and τ . The W decayed to either a lepton pair or a quark pair with the branching fractions shown in table 3. These have been calculated for L^0 masses a , b and c which were such that threshold production effects were neglected and all allowed lepton/quark pairs were equally weighted. In the case of quarks there were three colours to be taken into account and mixing which means that $u\bar{d}$, $c\bar{d}$ will be produced proportional to $\cos \theta_c$, and $u\bar{s}$, $c\bar{s}$ proportional to $\sin \theta_c$, where θ_c is the Cabibbo mixing angle and the value $\cos \theta_c = 0.986$ was used [29]. Note that the tables show branching ratios in terms of quarks, but in the simulation it was only possible to perform fragmentation of quarks (using the independent jet scheme) if the W recoil (quark pair) invariant mass was greater than $1.1 \text{ GeV}/c^2$ for $u\bar{d}$, $u\bar{s}$ and $2.0 \text{ GeV}/c^2$ for $c\bar{d}$, $c\bar{s}$. To avoid this problem and get the required overall branching ratios a proportion of the W 's were turned straight into single hadrons, this was 60 % for the both the $1 \text{ GeV}/c^2$ and $3 \text{ GeV}/c^2$ mass L^0 's (ie. all the quark decays) and 8 % for the $8 \text{ GeV}/c^2$ decay. The branching ratios to each hadron type are given in table 4 as a fraction of these percentages. These single hadron branching fractions have been taken from Ref. 30. The calculations in this were done before the discovery of the τ and refer to charged sequential leptons but were appropriate here because only the virtual W is being considered

TABLE 3

Predicted Heavy Neutral Lepton Decay Branching Ratios

Mass Range	L^0	$\bar{L}^0$	Branching Fraction (%)
$M_{L^0} < M_\mu$	e^-e^+	e^+e^-	100
$M_\mu < M_{L^0} < M_\tau$	μ^-e^+	μ^+e^-	4
	μ^-e^+	$\mu^+\mu^-$	4
	$\mu^-\mu^+$	μ^+e^-	4
	$\mu^-\mu^+$	$\mu^+\mu^-$	4
	μ^-e^+	$\mu^+(u\bar{d}/u\bar{s})$	12
	$\mu^-\mu^+$	$\mu^+(u\bar{d}/u\bar{s})$	12
	$\mu^-(\text{quarks})$	$\mu^+(\text{leptons})$	24
	$\mu^-(\text{quarks})$	$\mu^+(\text{quarks})$	36
$M_\tau < M_{L^0} < 2M_\tau$	As above replacing the first μ by τ		
$M_{L^0} \gg 2M_\tau$	τ^-e^+	$\tau^+ (e^-, \mu^-, \tau^-)$	11
	$\tau^-\mu^+$	"	11
	$\tau^-\tau^+$	"	11
	$\tau^-(\text{leptons})$	$\tau^+ (u\bar{d}/c\bar{s}, c\bar{d}/c\bar{s})$	22
	$\tau^-(\text{quarks})$	$\tau^+ (\text{leptons})$	22
	$\tau^-(\text{quarks})$	$\tau^+(\text{quarks})$	44 (4/9)

TABLE 4			
Predicted Single Hadron branching Fractions			
L^0 Mass $\rightarrow$ (GeV/c ²)	1	3	8
Hadron			
π	0.510	0.296	0.161
K	0.025	0.018	0.013
ρ	0.465	0.625	0.551
K*	-	0.041	0.040
A ₁	-	0.020	0.216
Ω	-	-	0.019

4.3.2 The Kinematics of The Decays

The decay of a massive neutral lepton is shown in Fig. 22.

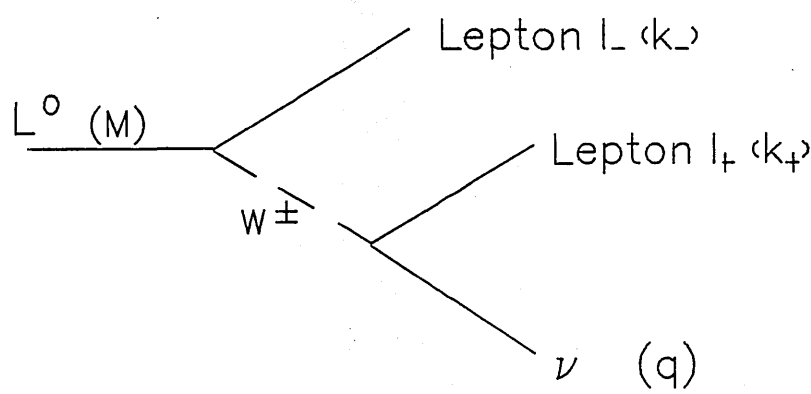


Figure 22: Heavy Neutral Lepton Decay

When considered in the rest frame of the decaying particle, the two leptons in leptonic decays have energies E_- and E_+ and four momenta k_- and k_+ , the neutrino has energy q . In the case of quark decays the energy of the recoiling W is $M - E_-$. The constraints on E_- and E_+ can easily be calculated. If it is

assumed that the lepton l_- is at rest, then the minimum energy of l_+ is m_+ and the maximum is given from :

$$M = m_- + E_+ + q \quad \text{given} \quad q = |k_+| = \sqrt{E_+^2 - m_+^2}$$

Solving for E_+ gives :

$$m_- \leq E_+ \leq \{(M - m_-)^2 + m_+^2\} / 2(M - m_-)$$

To obtain the limits on E_- consider the two limiting cases :

- i) The lepton l_- moves opposite to the lepton l_+ and to the neutrino so has its maximum possible momentum.

$$\begin{array}{c} \longrightarrow l_+ \\ l_- \longleftarrow \qquad |k_-| = |q| + |k_+| \\ \longrightarrow \nu \end{array}$$

- ii) The lepton l_- moves in the same direction as l_+ so has its minimum possible momentum.

$$\begin{array}{c} l_+ \longleftarrow \\ \longrightarrow \nu \\ l_- \longleftarrow \end{array} \quad |k_-| = |q| - |k_+|$$

In both these cases $M = E_+ + E_- + q$ so solving for E_- gives :

$$\frac{(M - E_+ - |k_+|)^2 + m_-^2}{2(M - E_+ - |k_+|)} \leq E_- \leq \frac{(M - E_+ + |k_+|)^2 + m_-^2}{2(M - E_+ + |k_+|)}$$

The limits given here were used to generate the plots in Fig. 23 and were used in the monte carlo generator.

The differential cross section was derived from Ref. 31. Modifications had to be made to the calculation, so that the mass of the first decay lepton was included. These involved two momentum products which, (using their notation) became :

$$k_- \cdot p = 1/2 (M^2 + m_+^2 - m_-^2 - 2ME_+)$$

$$k_- \cdot k_+ = 1/2 (2M(E_+ + E_-) - M^2 - m_+^2 - m_-^2)$$

The final form of the $E_- E_+$ distribution is :

$$\frac{d\Gamma}{dE_- dE_+} = A |g_1|^2 \{ |g_0|^2 E_+ (M^2 + m_1^2 - m_2^2 - 2ME_+) + |g_0|^2 (M - E_+ - E_-) (2M(E_+ + E_-) - M^2 + m_1^2 - m_2^2) \}$$

This was used to select the lepton decay energies, within the constraints given above.

4.4 THE STRUCTURE OF THE MONTE CARLO

The structure of the monte carlo will be described in this section. A set of routines were written to perform the first stage generator section as explained at the start of the chapter, then when an event had been generated, the "SIMPLE" package [32]. was used for the detector simulation. "SIMPLE" was a set of programs designed to simulate the passage of the particles from the generator through the elements of the TASSO detector including many of the effects expected for real data such as interactions, resolution effects and trackfinding efficiencies. The properties of the generated particles were contained in certain data banks, these were the input to "SIMPLE", which then output further banks containing the simulated detector information in identical format to the banks used in the real data.

The structure of the routines making up the generator were such that unnecessary duplication of code was avoided, most of the routines were able to handle either an L^0 , an $\bar{L}^0$ or a single E^0 , hence references in the following to L^0 should be taken to refer also to an $\bar{L}^0$ or an E^0 .

There was a steering routine for the generator that kept track of the particles as they were generated. Variables in common blocks were filled with particle momenta, mass, energy, charge and the information on parents and daughters.

The starting point of the generator was a routine which simulated a pair of particles back to back with either the centre of mass energy of the e^+e^- , or if initial state radiative corrections were applied, the energy remaining after these. A particular angular distribution could be specified at this stage, or the distribution could be uniform. The pair generated were an $L^0\bar{L}^0$, or an $E^0 \nu$. In the case of the $L^0\bar{L}^0$ both were allowed to decay, in the case of the E^0 reaction only the E^0 decayed (and these were treated like the L^0 in subsequent routines), the primary neutrino does not decay so was not considered further.

The L^0 was then decayed. Using a random number one of the possible decay modes was chosen but also keeping within the overall branching fractions. These decay modes were set up in a common block where the initial lepton and the other decay products, which could be either another lepton, a quark pair or a single hadron, were specified.

For pure leptonic decays the momenta and directions of both leptons were calculated and then both were boosted to the L^0 rest frame. This calculation was done in a separate routine which used the relevant distributions for the differential cross section to obtain the energies, E_1 of the first lepton and E_2 of the recoil. At the start of a job to generate some events a plot was made

representing the density of all allowed $E_- E_+$ states in the E_-, E_+ plane. For each event generated the actual energies were selected randomly from the values in this density plot, see Fig. 23. The formulae discussed above in section 4.3.2 were then used to obtain the angles between the decay products.

In the semi-leptonic decays the 1st lepton vector and the recoil mass were calculated. If the recoil mass was sufficient, as discussed above in section 4.3.1, it was considered as a quark pair and routines to perform fragmentation into hadrons were called. The independent jet fragmentation scheme was used because it was the most appropriate for fragmentation to the single jets present in these events. In the circumstance of insufficient recoil mass a single hadron was produced. All particles were then boosted to the L^0 rest frame.

Some of the procedures mentioned above were done in separate subroutines. There was a routine which for two randomly chosen energies calculated $d\Gamma/dE_-dE_+$ and the E_+ limits. Another routine made the choice of the energies in the decay for an event using a random number generator and made sure they lay within the allowed kinematic range. Lorentz transformations, used to boost decay products from rest frame of parent to laboratory frame were also done separately.

To handle the decay of Tau's a package of routines derived from a tau pair monte carlo generator was used. It was also necessary to write a special routine to handle decays of the A_1 because it is not included in the standard set of routines available to decay unstable secondary particles.

This chapter now continues with a more detailed discussion of the characteristics of the two event classes generated.

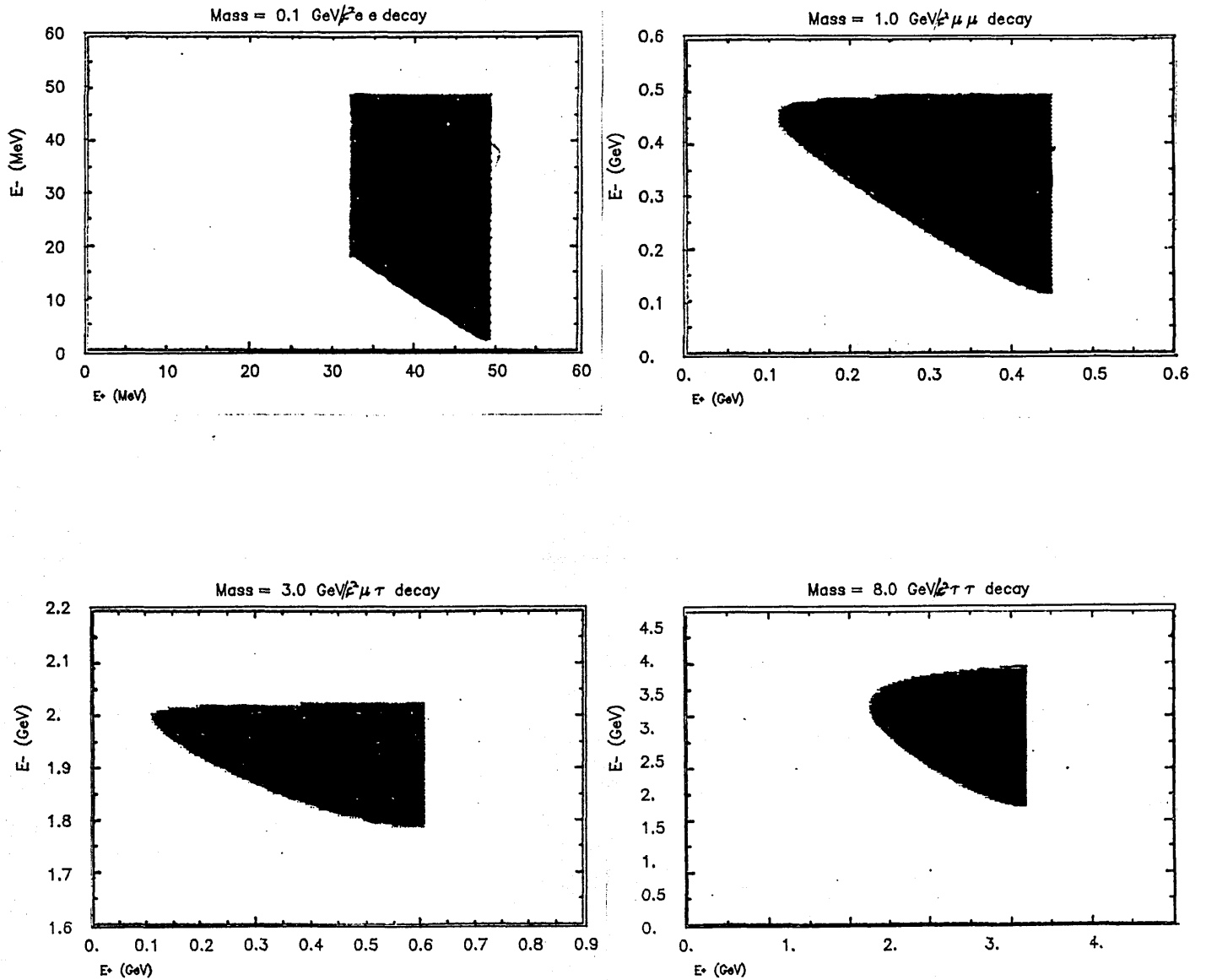


Figure 23: Heavy Neutral Lepton Allowed Decay Energies

4.5 ANALYSIS OF $E^0 \nu$ MONTE CARLO EVENTS

The events from the $E^0 \nu$ process were asymmetric, the degree of asymmetry decreasing as the mass of the E^0 increases. The E^0 and ν were produced back-to-back with equal and opposite momenta. If the E^0 had a mass substantially less than the beam energy it went in the opposite direction to the ν and its decay products were confined entirely to one hemisphere by virtue of the strong Lorentz boost. However if the E^0 mass was in the region of the beam energy or larger, the E^0 was not boosted strongly into the hemisphere opposite to the ν and the decay products were not confined to one hemisphere, but were spread out making the event look more spherical instead of jet like. This asymmetry was measured using the acoplanarity angle of an event which was defined as shown in Fig. 24.

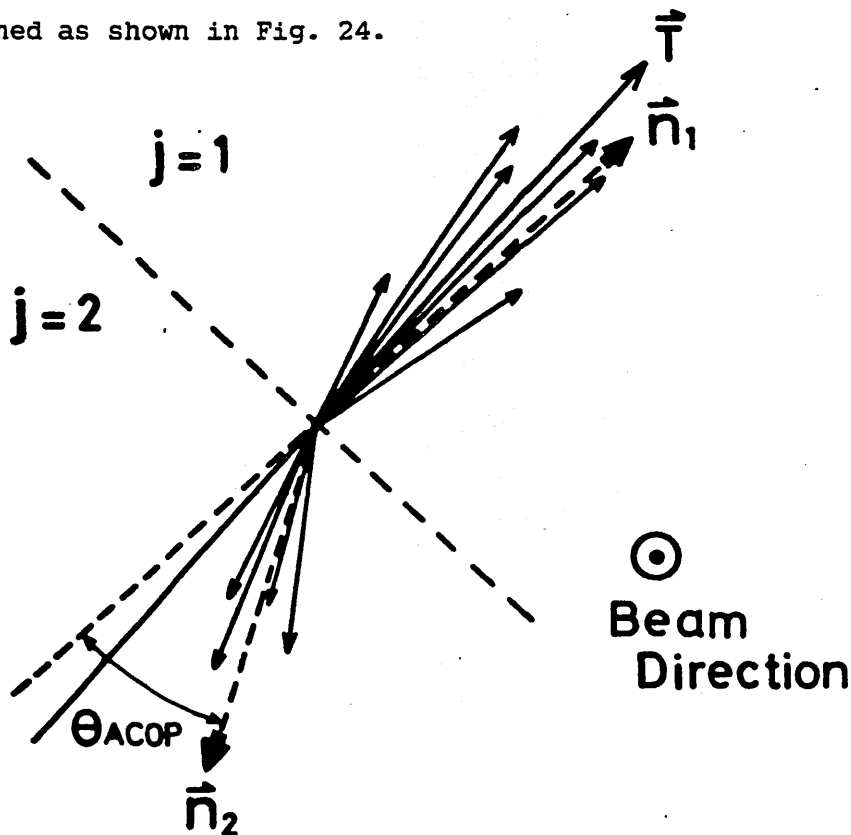


Figure 24: Definition of Acoplanarity

The event was divided into two hemispheres using a plane perpendicular to the Thrust axis (T), (see Appendix B for a definition). $\underline{n}_1$ and $\underline{n}_2$ are the unit vectors in the directions of the resultant momenta of the tracks in these two hemispheres, $\underline{z}$ is the unit vector along the beam direction.

$$\cos \theta = \frac{(\underline{n}_1 \cdot \underline{z})(\underline{n}_2 \cdot \underline{z})}{(|\underline{n}_1 \cdot \underline{z}| |\underline{n}_2 \cdot \underline{z}|)}$$

If all tracks are in one hemisphere $\theta = 180^\circ$.

Because the E^0 was produced with a ν there were no visible neutrals from the recoil. This immediately raised a very important problem because the radiation of an energetic photon in an $e^+e^- \rightarrow$ hadron interaction can produce an event which looks like this if the photon is not detected. This very important background process is considered in the following chapter. In looking at the data one therefore must be able to reject events where a single jet is seen with neutrals opposite to it. This could only be done if the recoil was in the region of the TASSO calorimeters. For the E^0 monte carlo events, with the production angular distributions previously given, the proportion of events where the E^0 enters a calorimeter, were:

Left	LABC = 27%	HASC = 10%	Total = 37%
Right	LABC = 22%	HASC = 20%	Total = 42%

These numbers were calculated using the simple geometrical coverage of the calorimeters, they were slightly lower if allowance was made for the fiducial coverage only.

The figures above were given as a proportion of all events generated. If one made the trigger and PASS 1 2 3 selections, leaving a smaller number of events and then looked at the events in this sample which entered the calorimeters, the proportions of these smaller numbers were larger than those above. This was because those events which were lost at the trigger stage were mainly the ones where the E^0 was produced at low θ , the region not covered by calorimeters.

To examine $E^0\nu$ events, samples of events were generated at a beam energy of 23.285 GeV (The highest reached by PETRA) with E^0 masses from 10 to 30 GeV/c². 4000 events were generated at each mass, and were passed through the full detector simulation. The highly acoplanar events were first selected and then from these the ones where the thrust axis pointed to the calorimeters were chosen.

The results are shown in table 5. as a percentage of the number generated. The acceptance for one jet events where the thrust axis pointed into the calorimeters is plotted as a function of the E^0 mass in Fig. 25.

It was noted when viewing some of these events with the TASSO interactive display program that in many cases the single jet was accompanied by a single track isolated from the main jet. As this track had a momentum higher than the average momentum of the other tracks, it was expected to be the lepton from the E^0 decay. The main jet was made up of the fragmentation products originating from the recoiling W. This effect was investigated by

looking at the number of events with an electron track, (as electron type E^0 's were being used) having a momentum greater than 2 GeV and no other track within 20° . The final row of table 5 shows that, the proportion of events with this isolated electron signature increased as the generated E^0 mass increased, and as the one jet proportion fell.

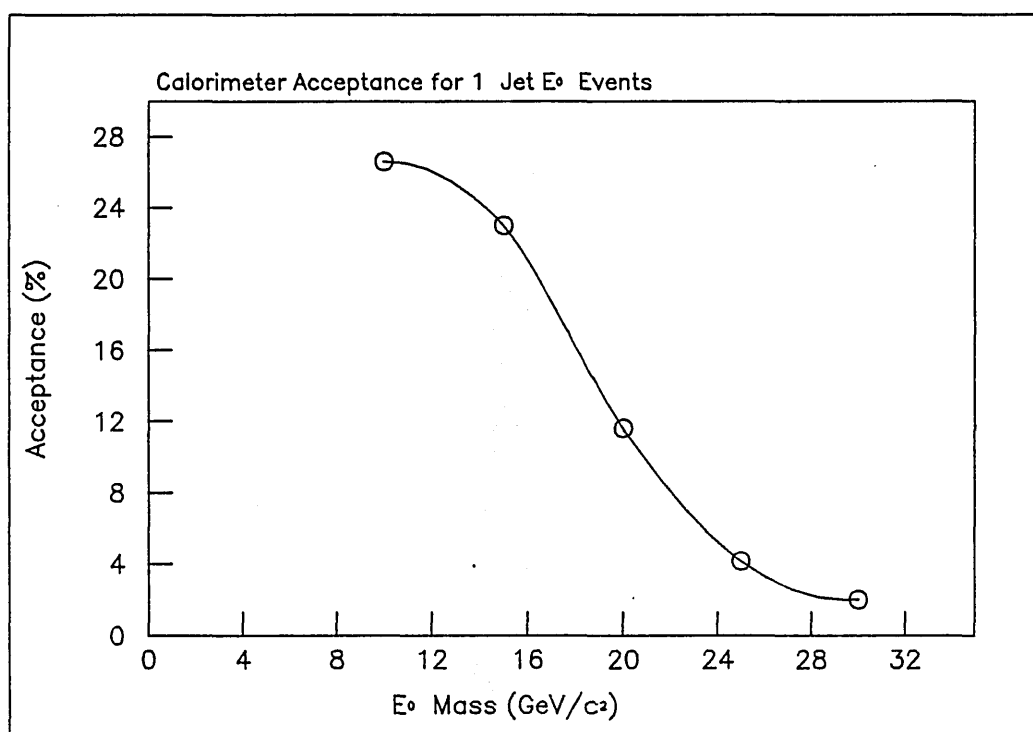


Figure 25: Proportion of 1 jet E^0 with Thrust axis pointing into calorimeters

TABLE 5

Effect of cuts on E^0 Monte Carlo Events

4000 Monte carlo events used					
E^0 Mass (GeV/c^2)	10.0	15.0	20.0	25.0	30.0
$M_{E^0 b} / E_b$	0.43	0.65	0.86	1.07	1.29
Cuts	Percentage of events				
Generated	100.0	100.0	100.0	100.0	100.0
Pass SIMPLE Trigger	72.8	83.5	88.3	87.2	88.2
1) 4 or more tracks	47.5	60.4	70.2	72.1	74.2
2) Sum $E > 8 \text{ GeV}$	36.2	44.0	53.1	58.3	62.4
3) Acoplanarity > 45 Deg.	35.5	38.9	37.9	32.8	23.5
4) All tracks on One Side	32.9	27.8	13.6	5.2	3.0
Thrust axis pointing into Calorimeters					
3i) Events with Acoplanarity > 45°	28.1	30.2	25.4	19.9	13.9
4i) 1 jet events	26.6	23.0	11.6	4.2	2.0
Isolated Electrons					
After cut 1	8.7		18.5		27.3

4.6 ANALYSIS OF $L^0\bar{L}^0$ MONTE CARLO EVENTS

4.6.1 Zero Lifetime Studies

4.6.1.1 General Characteristics

The masses of L^0 chosen to be generated were 0.1, 1.0, 3.0 and 8.0 GeV/c² as discussed in section 4.3.1. Approximately 4000 events were generated in^{each} case at a beam energy of 23.285 GeV. In the case of the 8 GeV/c² mass, sets of events was generated where the first decay lepton was a) a tau and b) an electron. These all had zero lifetime.

General observations. For a low mass L^0 the events had low multiplicity. The 0.1 and 1 GeV/c² masses had a predicted multiplicity of 4 tracks, in the form of a 2 against 2 topology. Due to the large Lorentz boost the pairs were back to back and the tracks in each pair close together. (In some cases so close together that the trackfinder was unable to separate them.) Fig. 26 shows a typical event from the 1 GeV/c² sample.

As the the L^0 mass was increased to that of the tau and then above the multiplicities increased. This increase was due to the greater energy available to the virtual W and hence for the fragmentation of quark antiquark pairs. Fig. 27 shows a typical event from the 8 GeV/c² sample. The Tau decayed in 85% of cases to only one charged particle, so the decay products of the tau did not have a significantly direct effect on the event multiplicity, in fact when in the 8 GeV/c² case case the electron replaced the tau, the mean multiplicities were slightly increased because the virtual W had more energy to give to the rest of the

decay products. It was observed that the events started to look more like two jet hadronic events and this was a limiting factor on the L^0 mass which could be detected.

The multiplicity and visible charged energy values are shown in table 6a. and in the final row are the values for hadronic events (at $\langle W \rangle = 44.6$ GeV) for comparison, [37].

4.6.1.2 Event Selection Criteria

The most distinct signature of L^0 production was found to be events with two isolated tracks in one hemisphere. This observation was made mainly by looking at monte carlo events with the TASSO interactive display program. A systematic set of selections were then applied to the events, as discussed here. The fraction surviving each selection is shown in Table 6b. (Also shown, as the last line of this table, is the fraction of the events which at the trigger simulation stage, had four good tracks).

1. Events had to have at least four good tracks. This was because a neutral object could only decay to an even number of tracks, so four was the smallest multiplicity to be expected from an $L^0 \bar{L}^0$ decay. The effect of this requirement on the monte carlo was to remove events where a track pair had not been distinguished by the track finder, which occurred most often for the $0.1 \text{ GeV}/c^2$ L^0 mass.

2. Events had to have the total momentum of charged tracks greater than 4 GeV/c. The L^0 masses under consideration were well below the beam energy, so even after allowing for energy carried away by unseen neutrinos, the charged tracks were energetic, therefore this requirement had no effect on the low mass L^0 's and only a small effect on the 8 GeV/c² mass.
3. Events had to have only two tracks in one hemisphere, this being the most distinct signature in the low mass case. For the higher mass 8 GeV/c² L^0 's where jets had been produced from quark fragmentation, events were lost by this requirement but they were ones which could not be distinguished from hadronic events.
4. Both members of the isolated track pair had to have opposite charge. In TASSO, charge measurement was accurate up to the highest momenta tracks of greater than 20 GeV/c. Such tracks are found in the muon pair events, where very few events were rejected due to both the tracks having the same charge. In the L^0 monte carlo no effect was observed on the high momentum pairs, but a small removal of events occurred where the pairs were really part of a hadronic jet, and not the complete products of the L^0 decay.
5. Both members of the track pair had to have a momentum greater than 500 MeV/c. For an L^0 of any mass decaying to two bodies a simple calculation shows that the track

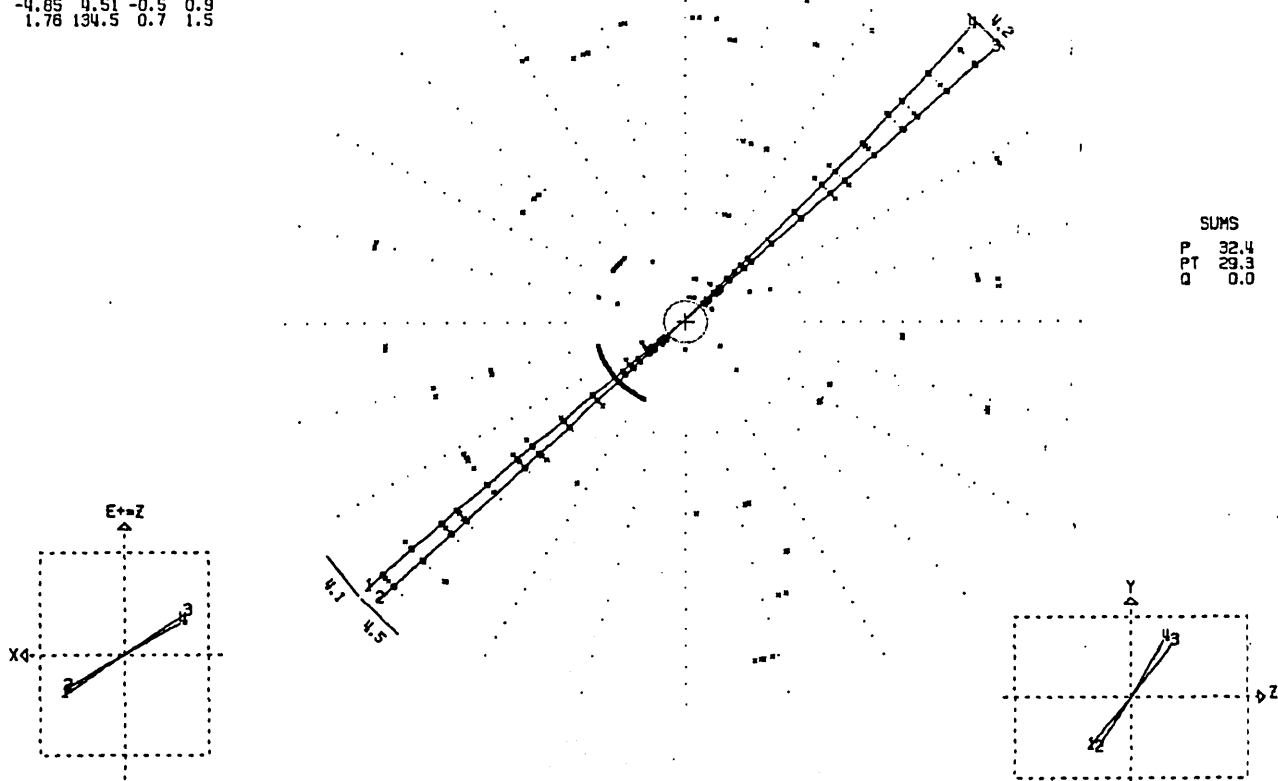
momenta will always be well above 500 MeV/c, so this requirement only removed events where, i) one track in a pair was of very low momentum (possible because of the structure of the monte carlo), or ii) the pair were not the complete decay products of the heavy lepton.

6. The sum of the momenta of the track pair had to lie between 4.5 and 30 GeV/c and the separation of the pair had to be less than 60° . These had little effect on the number of monte carlo events when applied after the other cuts. The purpose was to test the selection of events with two energetic tracks which could be used in vertex fitting.

TR	P	PT	Q0	Z0
CDTR	PZ	PHIO	CHI1	CHI2
1	-8.46	5.69	0.5	0.9
2	-3.08	319.8	1.6	1.7
3	11.58	10.60	-0.5	0.1
4	-4.66	316.0	1.1	1.5
5	9.49	8.45	0.5	-0.1
6	4.30	137.1	1.0	0.6
7	-4.85	4.51	-0.5	0.9
8	1.76	134.5	0.7	1.5

RUN 6101 EVENT 7 EBEAM= 23.28 GEV TRIGGER= 000000100010000

SIMPLE



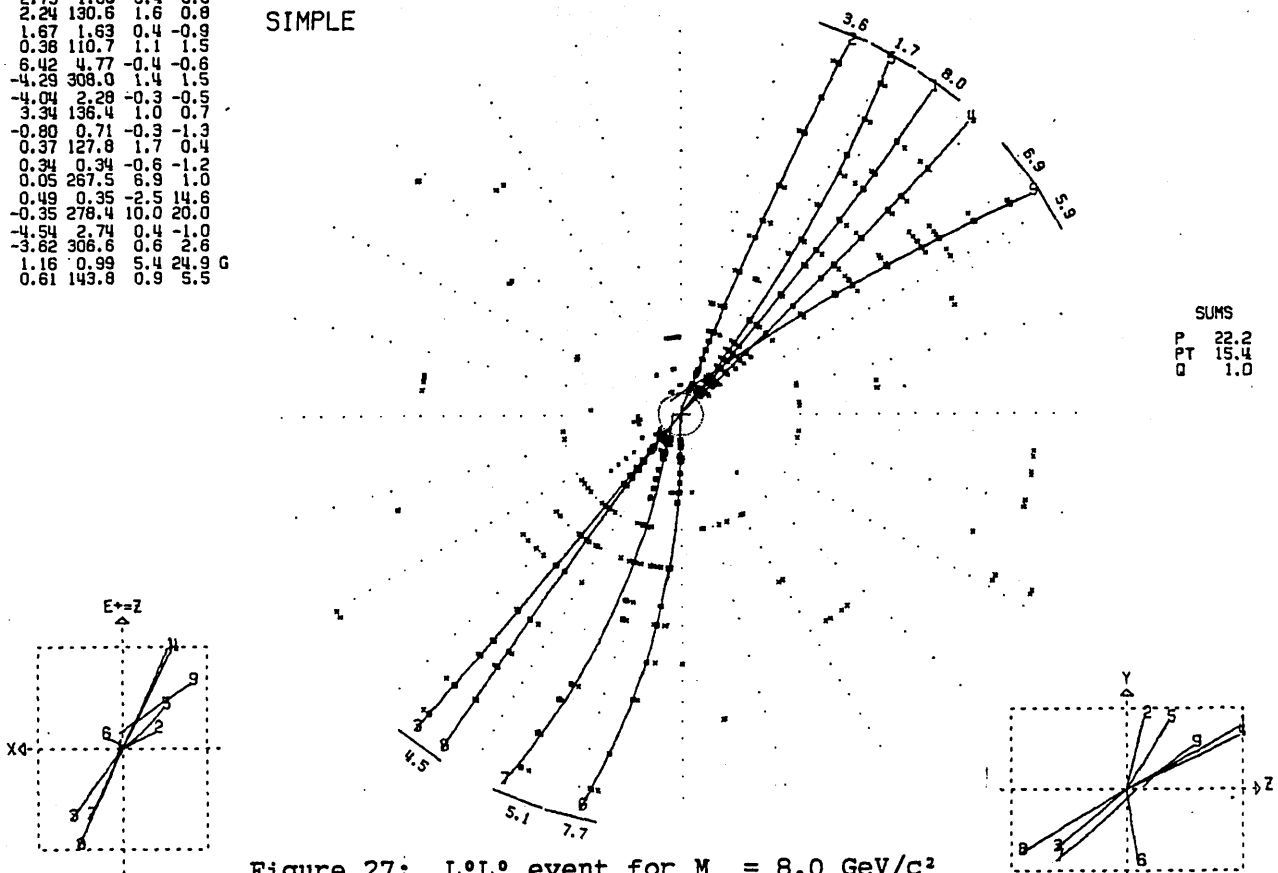
SUMS
P 32.4
PT 29.3
Q 0.0

Figure 26: L^0L^0 event for $M = 1.0 \text{ GeV}/c^2$

TR	P	PT	Q0	Z0
CDTR	PZ	PHIO	CHI1	CHI2
1	-2.75	1.60	-0.4	-0.8
2	2.24	130.6	1.6	0.8
3	1.67	1.63	0.4	-0.9
4	0.38	110.7	1.1	1.5
5	6.42	4.77	-0.4	-0.6
6	-4.29	308.0	1.4	1.5
7	-4.04	2.28	-0.3	-0.5
8	3.34	136.4	1.0	0.7
9	-0.80	0.71	-0.3	-1.3
10	0.37	127.8	1.7	0.4
11	0.34	0.34	-0.6	-1.2
12	0.05	267.5	6.9	1.0
13	0.49	0.35	-2.5	14.6
14	-0.35	278.4	10.0	20.0
15	-4.54	2.74	0.4	-1.0
16	-3.62	306.6	0.6	2.6
17	1.16	0.99	5.4	24.9
18	0.61	143.8	0.9	5.5

RUN 6101 EVENT 6 EBEAM= 23.28 GEV TRIGGER= 000010100010000

SIMPLE



SUMS
P 22.2
PT 15.4
Q 1.0

Figure 27: L^0L^0 event for $M = 8.0 \text{ GeV}/c^2$

TABLE 6

L⁰ Monte Carlo Event Properties

Approximately 4000 Monte carlo events used

a) Multiplicity and Energy

M L ⁰ (GeV/c ²)	Mean charged Multiplicity	Mean visible Energy in Charged Tracks (GeV/c ²)
0.1	3.29 ± 0.02	1.01 ± 0.01
1.0	3.57 ± 0.02	1.42 ± 0.01
3.0	4.63 ± 0.03	0.97 ± 0.01
8.0 (τ dec)	5.83 ± 0.03	1.07 ± 0.01
8.0 (e dec)	6.36 ± 0.02	0.89 ± 0.01
[Hadrons	12.73 ± 0.06	1.05 ± 0.01]

b) Effect of cuts

L ⁰ Mass (GeV/c ²)	0.1	1.0	3.0	8.0 (τ dec)	8.0 (e dec)
Cuts	Percentage of events				
Generated	100.0	100.0	100.0	100.0	100.0
Pass SIMPLE Trigger	61.2	63.3	66.2	79.7	86.6
1) 4 or more tracks	29.3	40.6	54.6	65.1	71.3
2) $\Sigma p > 4$ GeV/c	29.3	40.6	54.6	63.8	68.4
3) Isolated pair	29.1	39.9	45.3	40.8	35.6
4) Pair opp charge	29.0	39.7	43.7	39.2	33.2
5) Pair $p > 500$ MeV/c	26.2	38.6	40.6	38.0	30.8
6) Σp (pair) & sep	24.1	36.9	36.8	35.5	24.1
4 prongs	45.3	58.4	36.3	21.4	18.1

4.6.2 Putting in an L^0 Lifetime

At the end of the generator section an L^0 mean lifetime was specified (actually in the form of a length $c\tau$, The actual decay length in the detector was given by $l = \gamma c\tau$). The correct distribution of decay distances was produced and all the decay products of the L^0 were moved to its decay point.

It was expected that only events where the decay occurs within the vertex detector could be investigated. Event samples were generated each with 500 events and a range of decay lengths from 2 cm to 50 cm. The $1 \text{ GeV}/c^2$ mass was chosen as representative of low multiplicity events and the $8 \text{ GeV}/c^2$ mass as representative of high multiplicity jet type events. Table 7 shows the numbers, passing the standard data reduction procedures, and passing the selections discussed in the previous section, where these were grouped as :

- i) $\Sigma p > 4 \text{ GeV}/c$ and 2 isolated oppositely charged tracks
each with $p > 500 \text{ MeV}/c$.
- ii) i and $4.5 \leq \Sigma p(\text{pair}) \leq 30 \text{ GeV}/c$ and separation of
the pair $< 60^\circ$.

A study of the lower mass L^0 events showed that for event samples with mean decay lengths up to 10 cm an acceptance of around 60% was obtained at PASS 3 and 35% after further selections i and ii. For longer lengths the acceptance dropped as the events failed to satisfy the trigger requirements. For the higher mass L^0 the acceptance at PASS 3 was over 70% for mean

TABLE 7

L⁰ Detection Efficiency vs Decay Length

500 Monte carlo events used

percentage of events

M	l	Generated	Trigger	Reach	selections	
L ⁰	(cm)			PASS 3	i	ii
(GeV/c ²)						
1.0	2.0	100.0	63.4	63.4	39.2	37.6
	5.0	100.0	64.5	64.5	39.5	36.0
	10.0	100.0	60.6	60.4	35.6	33.0
	20.0	100.0	44.2	44.0	22.0	20.6
	50.0	100.0	25.2	25.0	9.8	9.4
8.0	2.0	100.0	85.0	83.8	27.0	19.2
	5.0	100.0	84.6	83.0	21.2	16.6
	10.0	100.0	78.4	72.8	25.4	18.2
	20.0	100.0	74.0	66.8	22.0	16.2
	50.0	100.0	42.6	32.6	7.6	5.6

decay lengths up to 10 cm, but the further selections had a much lower efficiency as they had been specifically geared to the selection of low multiplicity events.

Chapter V

THE SEARCH FOR A SINGLY PRODUCED NEUTRAL PARTICLE

5.1 INTRODUCTION

5.1.1 The Data Available

For the search described here the data amounting to a luminosity 25.0 pb^{-1} taken in 1983 and 1984 was used, (almost all at centre of mass energies above 40 GeV). This was approximately 2×10^7 triggers on 2210 PASS 1 tapes and reduced to 35 PASS 3 tapes containing 400394 events. These were the starting point for the further selections described here.

5.1.2 The Operational Efficiency of the Calorimeters

For the single production search the vertex detector information was not used but the calorimeters were used. Therefore the time for which the calorimeters were fully operational was important. It was determined that there was no liquid argon information in 1777 events (9.1 %), however there were very few occasions when any part of the liquid argon was off. There was no hadron arm shower counter information in 4934 events (25.3 %), however the shower counter high voltage was never normally turned off during datataking. These events were ones where no energy entered the counters, which is reasonable in view of their limited angular coverage.

5.2 DATA SELECTION

5.2.1 The Initial Selection

An event had to have at least four good tracks (as defined in section 3.5.2), and the momentum sum of all charged tracks had to be $> 4 \text{ GeV}/c$.

On the high energy data this gave 19479 events,

On the lower energy data this gave 54515 events.

The four track requirement was the lowest requirement for an even number of tracks which it was possible to have on PASS 3. The 4 GeV requirement removed very soft two photon events.

5.2.2 Acoplanarity as a signature of E^0 Production

To show the significance of acoplanarity as a signature for E^0 type events, a sample of 4000 events with an E^0 mass of $25.0 \text{ GeV}/c^2$, generated at a beam energy of 23.285 GeV , was used to obtain the acoplanarity distribution as shown in Fig. 28. The acoplanarity distribution of all the PASS 4 hadronic events is overlaid for comparison. They are very different. This plot showed that in the region where the acoplanarity was greater than 45° an E^0 signal would have the smallest background due to hadronic events.

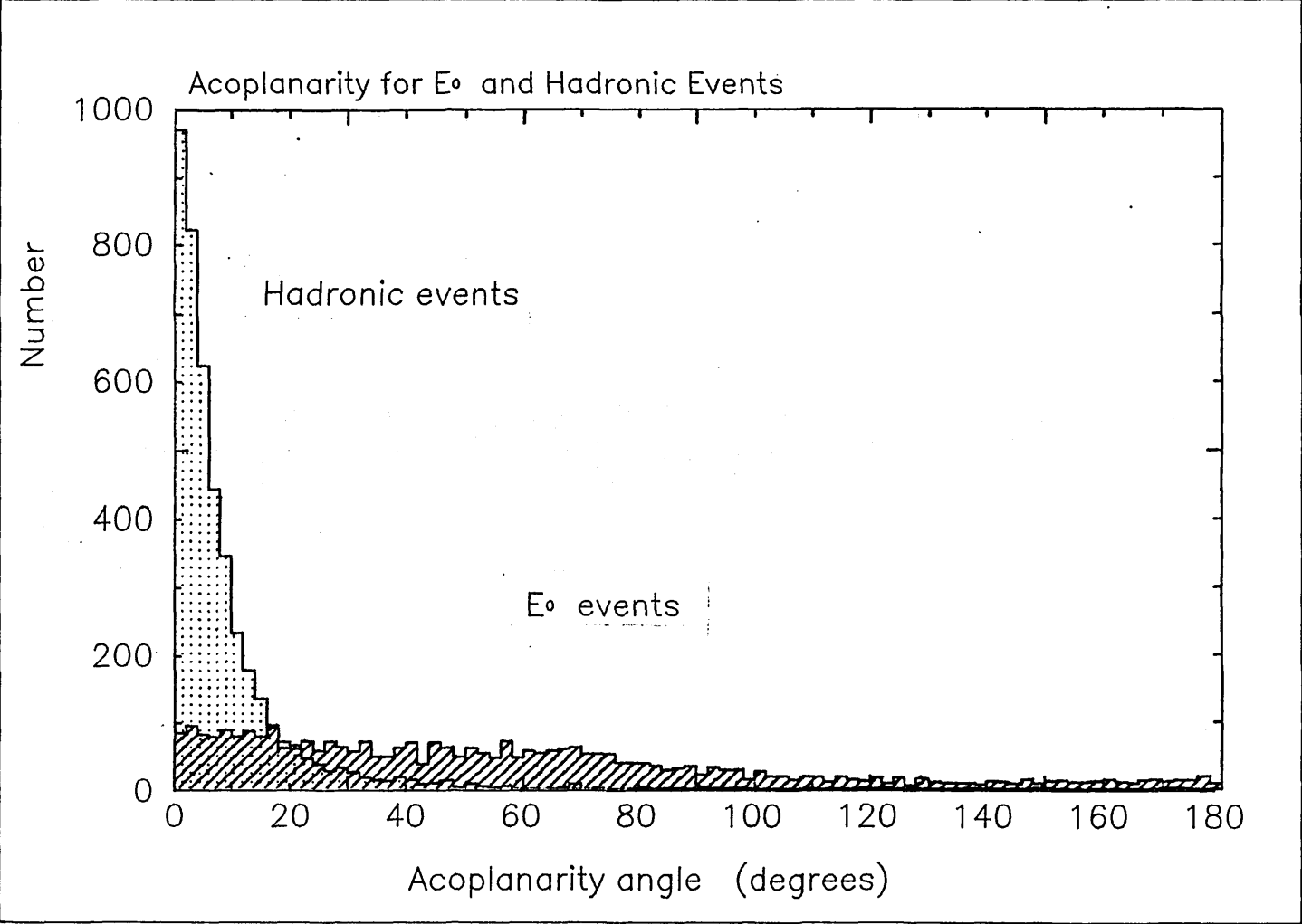


Figure 28: Acoplanarity of E^0 and Hadronic Events

5.2.3 Further Selection of Acoplanar Events

A systematic selection of events was made where the momentum sum from charged tracks had to be $> 8 \text{ GeV}/c$ and the acoplanarity had to be $> 45^\circ$, this yielded a sample of 729 events, of which 269 were one jet events (with acoplanarity = 180°). These selections are summarised in Table 8.

TABLE 8
Data Selection

Selection Criteria	Number of Events
1) ≥ 4 Tracks	19479
2) Sum E $> 8 \text{ GeV}$	7170
3) Acoplanarity $> 45^\circ$	729
4) One Jet	269
Thrust axis pointing into calorimeters	
4a) One Jet	104
Less than 500 MeV in one hemisphere	
3b) Acoplanarity $> 45^\circ$	466

In these it was possible to look unambiguously for neutrals opposite the jet in the cases where the jet entered the calorimeters. Using the thrust axis to define the jet direction there were 66 events where the jet axis pointed into the LABC and 38 events where it pointed into the HASC, a total of 104 all of

which were scanned. After taking a cone of half angle 30° around the thrust axis, on the opposite side to the jet, it was found that 56 of the 104 events had less than 200 MeV of energy deposited by neutral particles within this cone.

TABLE 9			
Classification from Scanning Events			
Classification	< 200 Mev Neutrals	> 200 Mev Neutrals	Total
1) Junk	40	18	58
2) Hard Photon + Jet	2	29	31
3) Others	14	1	15
Total	56	48	104

5.2.4 Visual Scanning of Events

The 104 events were separated without problem into three classes as shown in Table 9 and discussed here.

1. Junk : These were events where the inner chambers contained many noise hits and several tracks had been found of which most were flagged as bad. 58 events were of this type and in general looked a mess. 40 of these had less than 200 MeV deposited by neutrals in the 30° cone opposite the jet.

2. Hard photon opposite a jet : A clear jet containing four or more tracks with a neutral energy cluster of greater than 10 GeV in a calorimeter opposite. 31 events were of this type, (20 in the LABC and 11 in the HASC). Notice that in two cases the large neutral deposit was outside the 30° cone.
3. Others : The remaining 15 events needed more careful consideration as they had a single jet containing good tracks and no large single neutral energy cluster opposite. Seven had a high probability of being due to two photon scattering, they were strongly boosted in the direction of the e^+e^- beams and had low visible momenta (less than 10 GeV/c). Two were bhabha scattering events where radiated photons produced unusual topologies, (one had some neutrals opposite the jet but not in the form of a single hard photon). One had evidence of hits forming a track opposite to the jet so was rejected. Two were due to stray electrons, seen as high momentum tracks which had interacted in the beam pipe. Three could not be classified into known categories and are described individually here.

These three events are shown in Figures 29(A), 30(B) and 31(C).

A). This event had six good tracks forming a jet which enters the LABC. Two features were however significant; i) There were time of flight counters set on the opposite side to the jet. ii) The tracks in the jet had not deposited any energy in the LABC, despite the fact that the event had only been recorded because

trigger two which requires LABC energy was set. It therefore appeared that the LABC information for this event had not been recorded so it was not considered as an E^0 candidate.

B). This event had around ten tracks but its total momentum was only 10 GeV/c, there were lots of hits in the central chambers not associated with tracks and the event vertex was not very clear. It was retained as a candidate event because there was no significant amount of neutral energy deposited in the LABC on the side opposite to the jet.

C). This event had six good tracks but the total momentum was only 8.7 GeV/c of which 4.7 GeV/c was in one track. There were also a number of hits not associated with tracks. Like event B), it is retained as a candidate because of the absence of significant neutral energy opposite to the jet.

These two candidates are used in section 5.4 where limits are calculated. However the low total momenta made these events rather unlikely to be due to the production of a new particle.

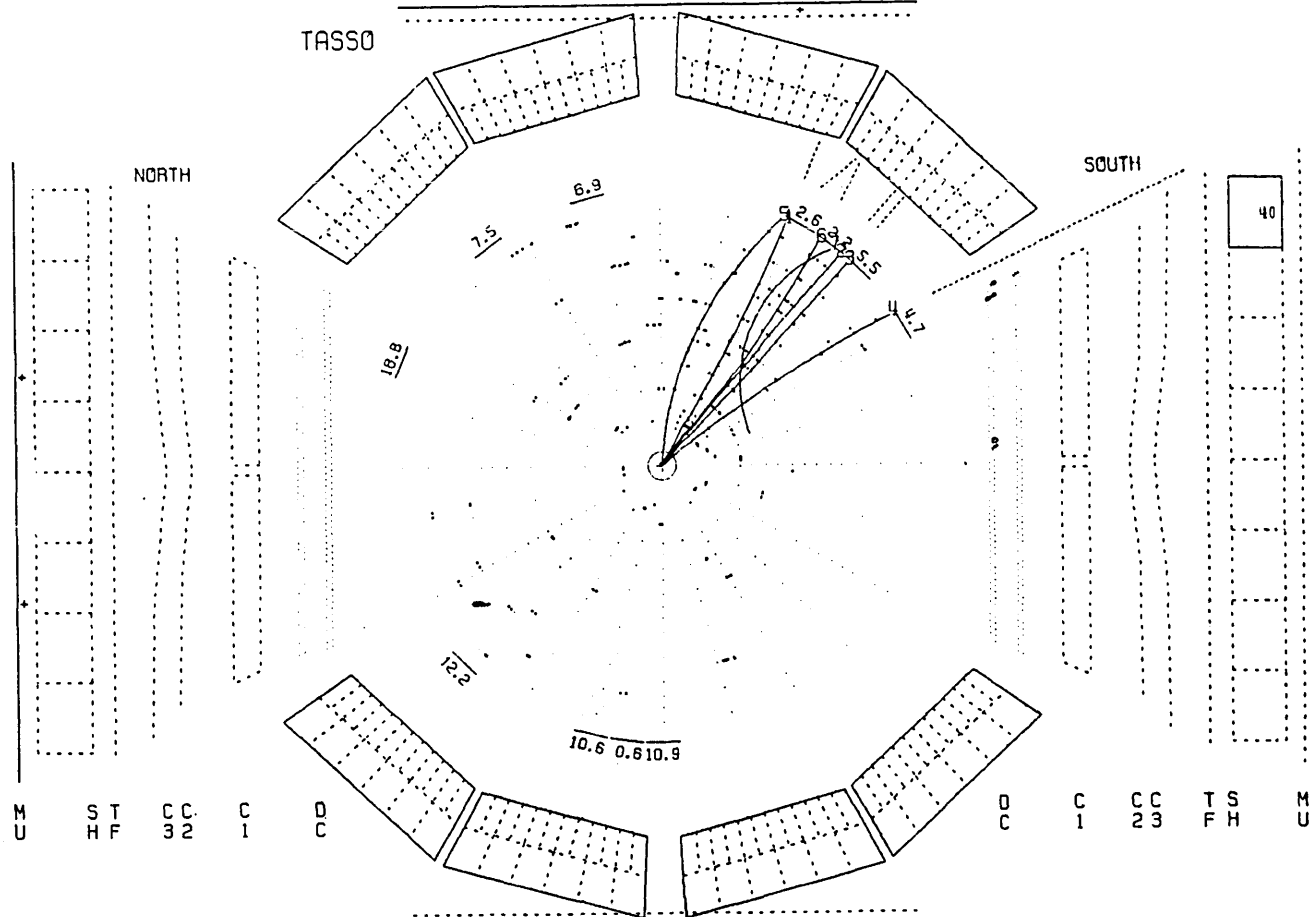


Figure 29: E° Candidate event A

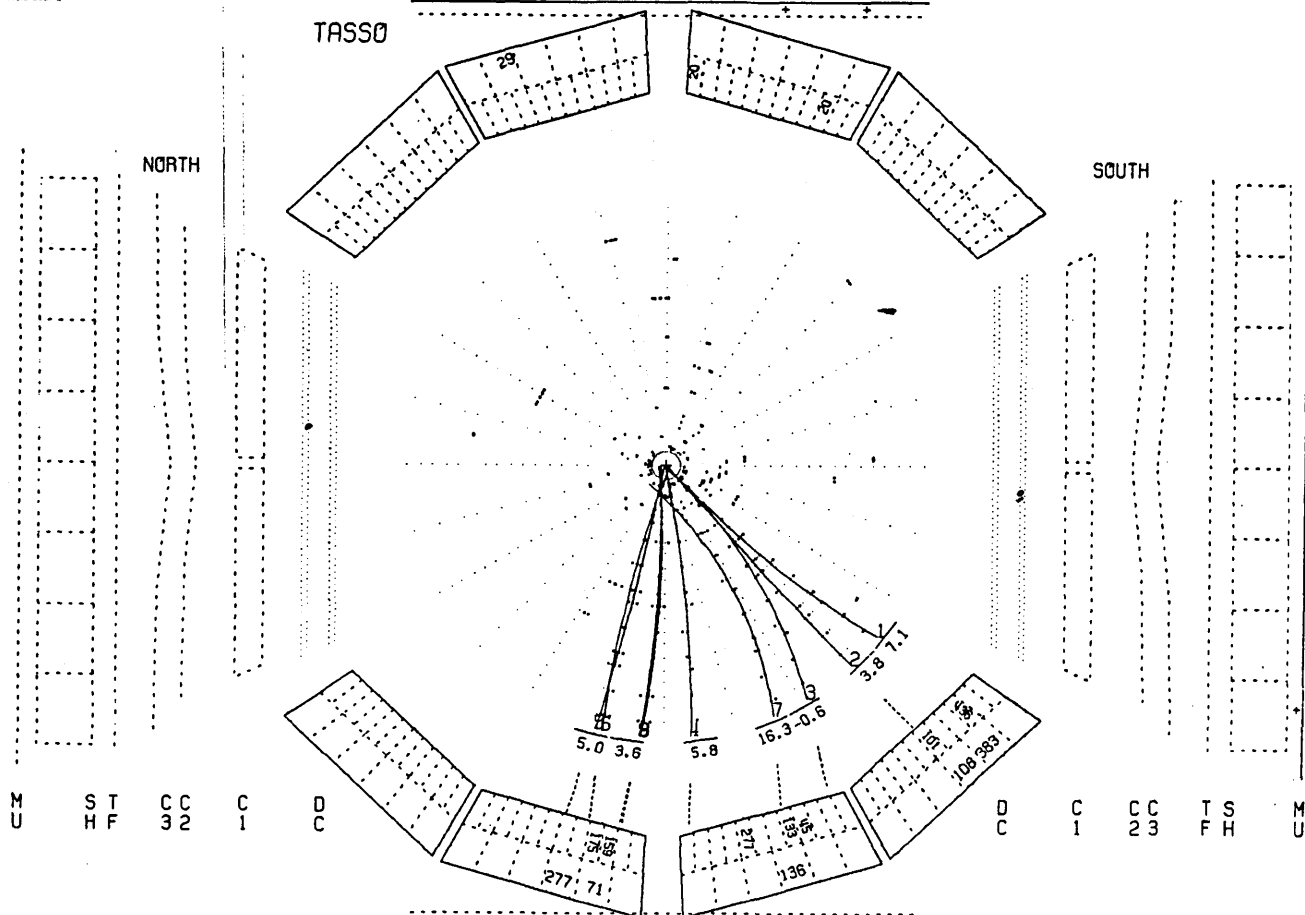


Figure 30: E° Candidate event B

5.3 BACKGROUNDS

The background from radiative $e^+e^- \rightarrow$ hadron events where the photon is energetic was the most significant process which had to be considered in the search for a singly produced heavy neutral particle

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this reason it was only necessary to consider initial state radiation.

The events of the type γ + hadrons were distinguished by a jet balanced by visible neutral energy on the other side. They were identified in TASSO by looking for events containing isolated high energy neutral clusters in the LABC or HASC calorimeters as well as hadronic jets. Two typical events are shown in Figures 32 and 33. Unfortunately the coverage of these calorimeters was incomplete so it was possible for events of this type to appear as single jet events if the photons escaped through gaps in the calorimetry. Because initial state radiation can be calculated in QED and is already incorporated in the simulation program for hadronic event production, (hadron monte carlo), such a program was used here to do two things.

- i) To compare the number of γ hadron events found in the data to the QED prediction.
- ii) To determine the extent to which misidentification of these events in TASSO by not seeing the photon, gave an E^0 like signal.

By using a hadron monte carlo only the hadronic contribution to radiative events was being considered. Other final states such as two photon events or pure leptonic processes had initial state radiation associated with them. The justification for only taking the numbers of hadronic events containing a hard photon, is that the other processes had low multiplicities so were rejected by the demand that the multiplicity of the hadronic jet should be greater than four tracks in the events selected.

The events were selected according to two criteria, each of which allows a different comparison between hadronic data and monte carlo to be made.

The selections referred to as criteria 1 were :

1. The event had to have a certain minimum amount of energy in charged tracks, 8 GeV was initially chosen as this removed the very low Q^2 two photon events.
2. At least one isolated neutral cluster with energy greater than E_c and no charged tracks having a momentum greater than p within a cone of half angle θ_i . Values for these chosen were, for E_c in the range from 4 to 12 GeV, p of 0.4 GeV/c and for θ_i in the range 40° to 80° .

The results are shown in Table 10 where the data and monte carlo numbers of events and the mean photon energies are shown side by side. The numbers of events with photons detected by the LABC and HASC calorimeters are also shown separately. They show that there was good agreement between monte carlo and data.

The selections referred to as criteria 2 were :

1. The charged track momentum sum had to be > 8 GeV
2. The Acoplanarity had to be $> 45^\circ$
3. The event was divided into hemispheres using the Thrust axis, The momentum sum of all charged tracks in each hemisphere was calculated and this sum was required to be < 500 MeV in one of the hemispheres.

Table 11 shows the comparison numbers where the number of monte carlo events has been normalized to the actual number of hadronic

events. They show that the data and monte carlo were in good agreement when selecting events purely on topology using information only from the TASSO central detector.

The Acceptance For Hard Photons

In the hadron monte carlo the real direction and energy of the initial state hard photons generated was known. The TASSO detector simulation calculated whether they would enter the calorimeters, and if they did, what direction and energy would be measured. By making a comparison as shown in Table 12, it was found that the acceptance for detecting the photons in these events was around 40%. Such events therefore appeared to give a large background to any 'monojet' or E^0 signal but it must be noted that the photons were not detected when they went at small angles to the e^+e^- beam. The search described earlier was restricted to looking at events with single jets which pointed into the calorimeters, thus avoiding this background problem.

TR	P	ICUT	LC	FLAG	MC
1	-2.9	110100	1110	0	0
2	3.1	110101	1110	0	0
3	1.2	111101	1000	0	0
5	1.2	110101	1110	0	0

RUN 8477 EVENT 12081 EBEAM= 23.34 GEV TRIGGER= 010000010000000

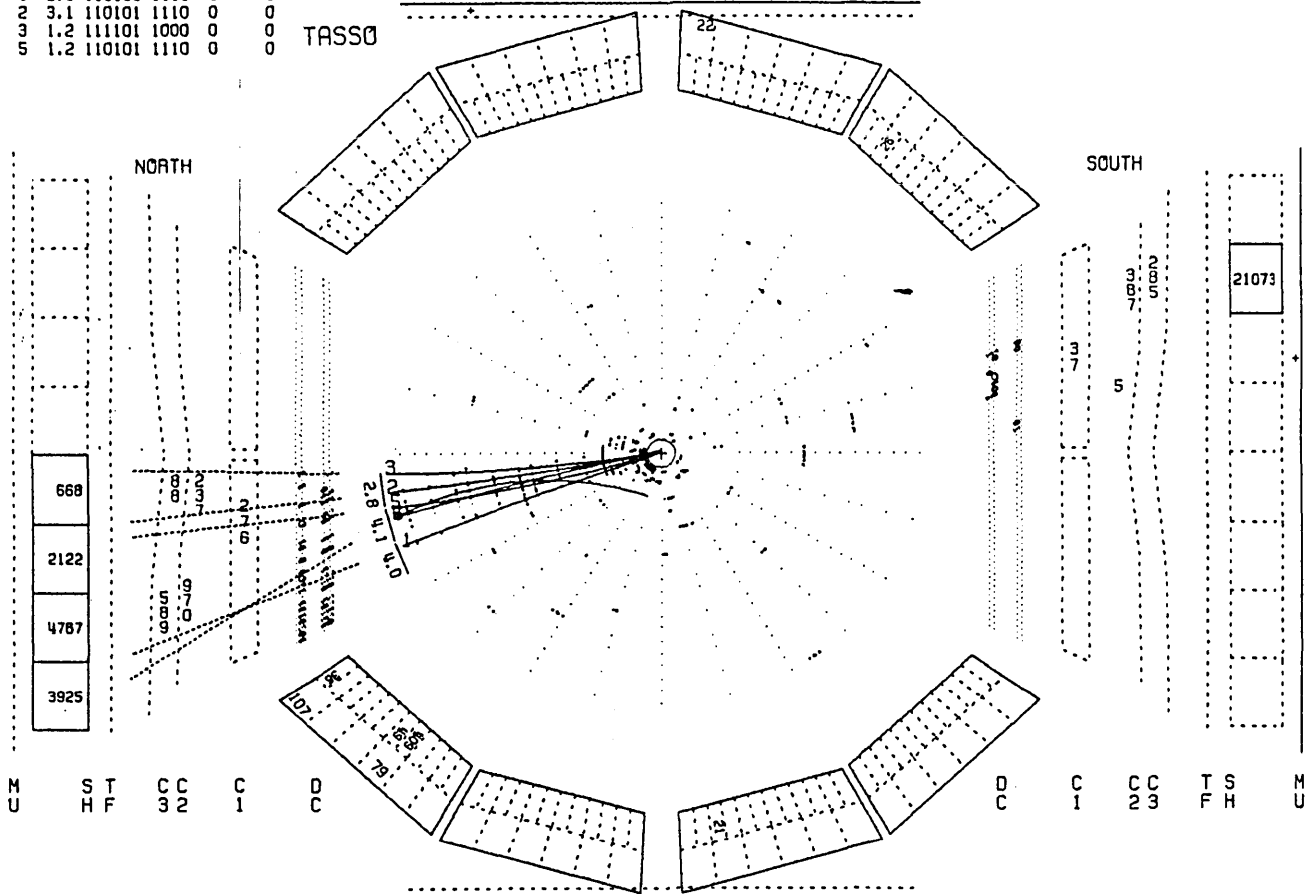


Figure 32: Hadronic Event with Hard Photon A

TR	P	ICUT	LC	FLAG	MC
1	-0.7	101111	XXXXXX	0	0

RUN 8703 EVENT 12644 EBEAM= 21.93 GEV TRIGGER= 000011000000010

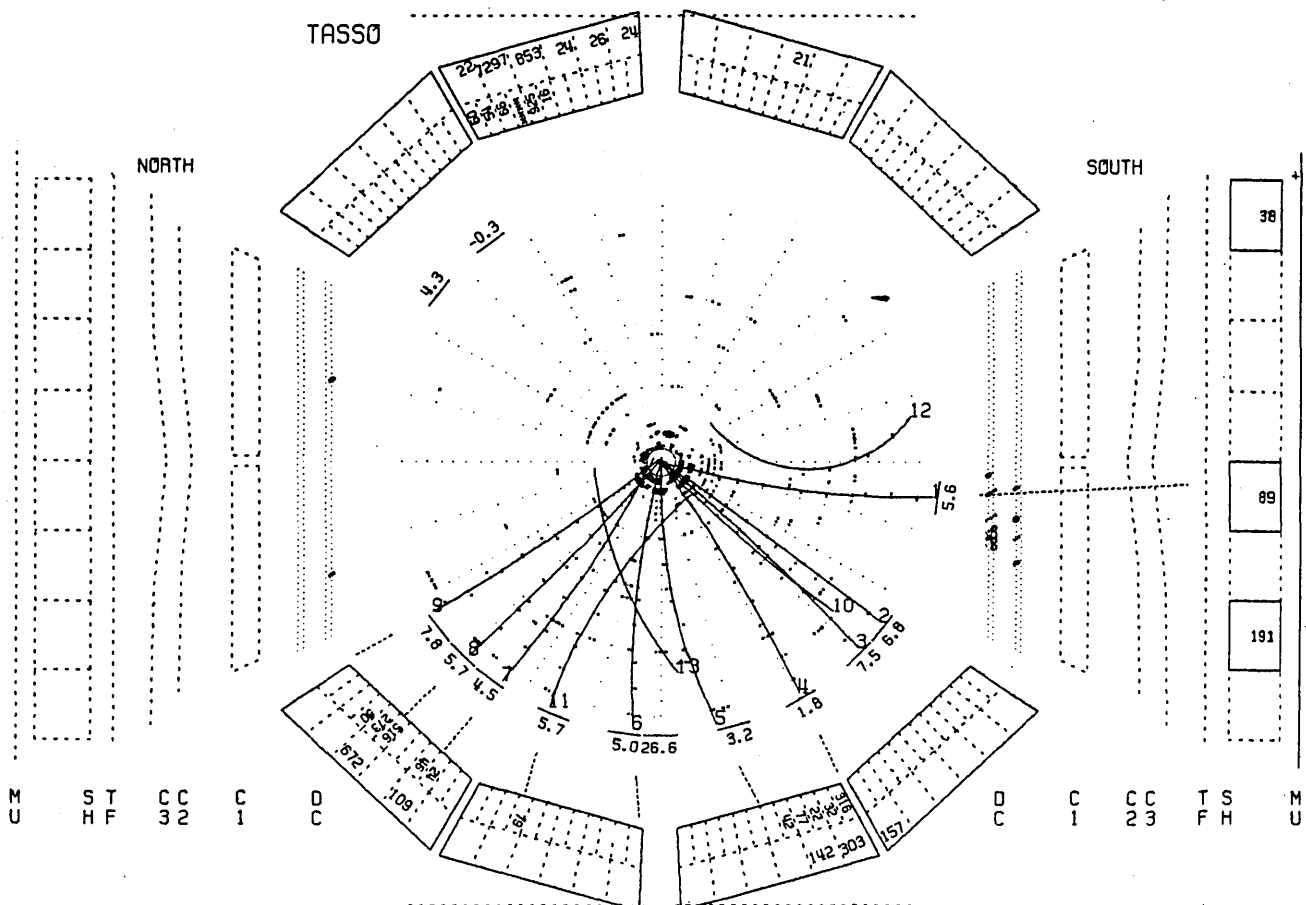


Figure 33: Hadronic Event with Hard Photon B

TABLE 10

Neutral Energy Clusters in Hadronic Events - Comparison of
Data and Monte Carlo

N = Number of Events

E = Mean Cluster Energy in GeV

LABC and HASC Combined

Cuts		Data		Monte Carlo	
E clus	θ_i	N	E (GeV)	N	E (GeV)
4	40°	51	10.9	71	11.7
4	60°	36	12.3	42	14.0
4	80°	23	13.5	25	17.9
6	40°	41	12.5	51	14.4
8	40°	32	14.4	36	17.3
LABC Only					
4	40°	34	11.3	46	12.9
4	60°	27	12.3	26	15.7
4	80°	19	12.9	19	17.4
6	40°	27	12.8	37	14.9
8	40°	22	14.3	28	17.5
HASC Only					
4	40°	17	10.2	25	9.4
4	60°	9	12.3	16	11.3
4	80°	4	16.1	6	19.4
6	40°	14	12.0	14	13.1
8	40°	10	14.5	8	16.6

TABLE 11

Comparison of Hadronic Data and Monte Carlo

Selection Criteria	Number of Events	
	Data	Monte Carlo
MC Generated		6447
Pass Trigger		6014
Reach Pass 3	400394	5981
1) ≥ 4 Tracks	4429	4429
2) Sum E > 8 GeV	4429	4429
3) Acoplanarity > 45°	159	107
4) One Jet	40	31
Thrust axis pointing into calorimeters		
3a) Acoplanarity > 45°	64	59
4a) One Jet	15	18
Less than 500 MeV in one hemisphere		
3b) Acoplanarity > 45°	59	43

TABLE 12

Hard Photon Acceptance From Monte Carlo

Events with a hard initial state photon of energy > 10 GeV

	PASS 3	PASS 4
Generated photons	91	36
Photons seen in LABC	<u>22</u>	<u>12</u>
Photons seen in HASC	10	6
Total photons seen	<u>32</u>	<u>18</u>
Photons not seen	59	18

5.3.2 Two Photon Events

Using a two photon monte carlo generator a sample of 20000 events representing a luminosity of 11.25 pb^{-1} at a centre of mass energy $W = 45 \text{ GeV}$ were generated. The numbers of events passing the selection criteria were multiplied by 2.22 to normalize to the amount of data used, (25.0 pb^{-1}).

18.4 % passed trigger stage, 14.6 % reached Pass 3,

3.86% had ≥ 4 tracks,

0.17% (76 events) had $\Sigma E > 8 \text{ GeV}$,

0.04% (18 events) had acoplanarity $> 45^\circ$,

0.02% (9 events) had all tracks on one side.

None of these events with one jet had their thrust axis entering the calorimeters. Had it done so there would have been an event of the type one jet and no neutrals opposite. It was fortunate

that the strong boost of $\gamma\gamma$ events in the direction of the e^+e^- beams enabled them to be identified and hence eliminated.

5.4 CALCULATION OF LIMITS

The limited acceptance for the one jet topology, the trigger and analysis chain efficiencies and estimates of the backgrounds are used in the determination of a limit on E^0 production and on monojet production given particular theoretical predictions. A model independent cross section limit will be given using the number of events found having one isolated jet and no neutral energy in the recoil.

5.4.1 A Model Independent Limit

After scanning, two events remained which were difficult to interpret as due to some known background process. If one assumed these two events were really from some new process, which is an unlikely assumption, then the 95% confidence level (c.l.) expectation was to see 6.3 events, which gave a cross section limit, after correcting for the geometrical coverage of the calorimeters (namely 54% of the solid angle) of $\sigma < 0.46$ pb at 95% confidence level.

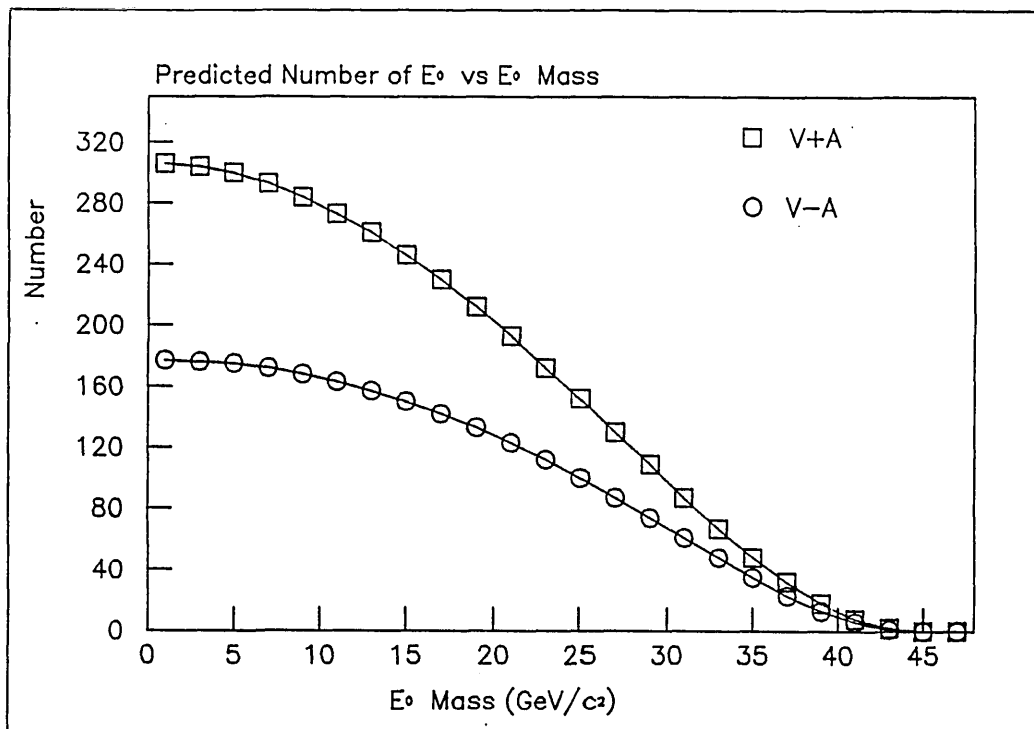


Figure 34: Predicted number of E° events produced vs E° Mass

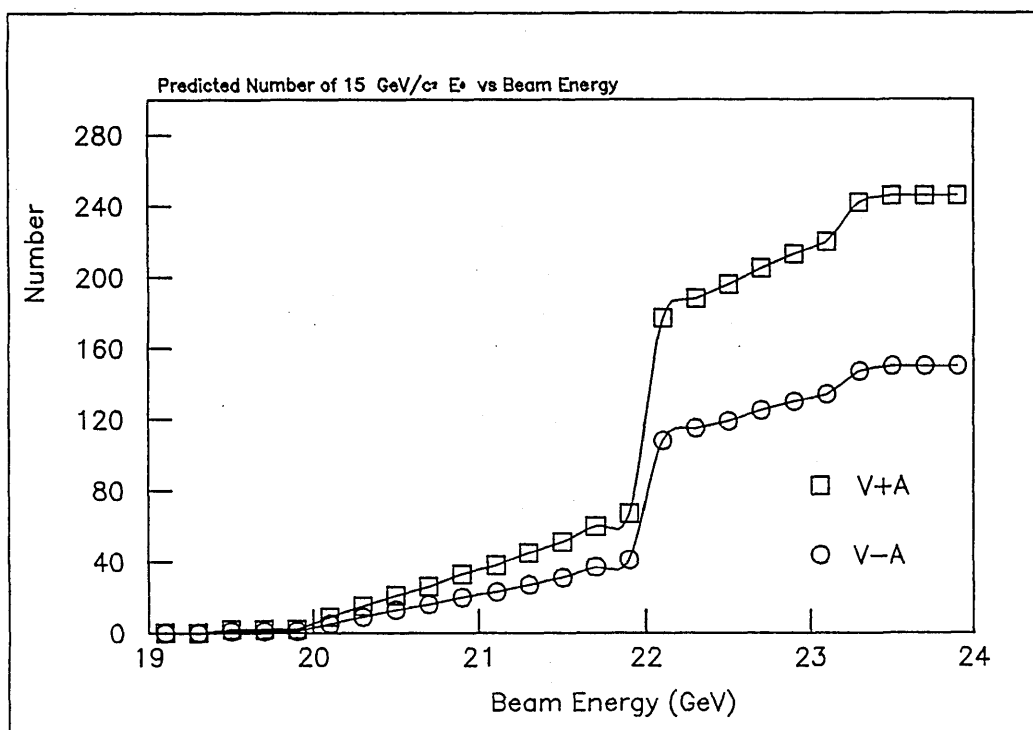


Figure 35: Predicted number of 15 GeV/c² E° events vs Beam energy

5.4.2 A Limit on E^0 Production

Using the production cross section given in chapter two and the luminosity profile of the TASSO data the expected number of E^0 events produced as a function of E^0 mass was calculated and is shown in Fig. 34. The number expected as a function of beam energy over the scan period was also calculated for an E^0 mass of 15 GeV/c² and is shown in Fig. 35.

The acceptance, determined from monte carlo studies described in the previous chapter, was found to be in the range from 25% to 2%. These figures, which were model dependent, were then used to give the number of events expected to be seen, as shown in table 13 and Fig. 36 as a function of E^0 mass.

No events have been observed in the data which could definitely be interpreted as due to E^0 production. There were however two events which could not be identified as due to a particular background process, although they were unlikely to be due to any new physics. Therefore 95 % confidence level limits on the E^0 mass are quoted both for the case where no events have been observed and for the case where the two events are interpreted as due to E^0 production although such an interpretation is unlikely. These limits are, as shown by the hatched lines in Fig. 36 :

V-A E^0 Mass $\geq$ 26.0 GeV/c² (no events observed) or

V-A E^0 Mass $\geq$ 23.0 GeV/c² (assuming 2 events observed)

V+A E^0 Mass $\geq$ 28.0 GeV/c² (no events observed) or

V+A E^0 Mass $\geq$ 25.0 GeV/c² (assuming 2 events observed)

These limits can be compared to those quoted previously by the JADE experiment [11]., who gave :

$$V-A \quad E^0 \quad \text{Mass} \geq 22.5 \text{ GeV}/c^2$$

$$V+A \quad E^0 \quad \text{Mass} \geq 24.5 \text{ GeV}/c^2$$

To conclude: There is no evidence from this or from other experiments for the production of neutral electron type heavy leptons.

TABLE 13

Number of E^0 Events Expected

M E^0	# E^0 Produced		Acceptance (1 jet into Calorimeters)	# Expected	
	(V-A)	(V+A)		(V-A)	(V+A)
1.0	177	306			
5.0	175	300	0.30	53	90
10.0	165	279	0.266	44	74
15.0	150	246	0.230	35	57
20.0	128	202	0.116	15	23
25.0	100	152	0.042	4	6
30.0	68	98	0.020	1	2
35.0	35	48	0.01	<1	1

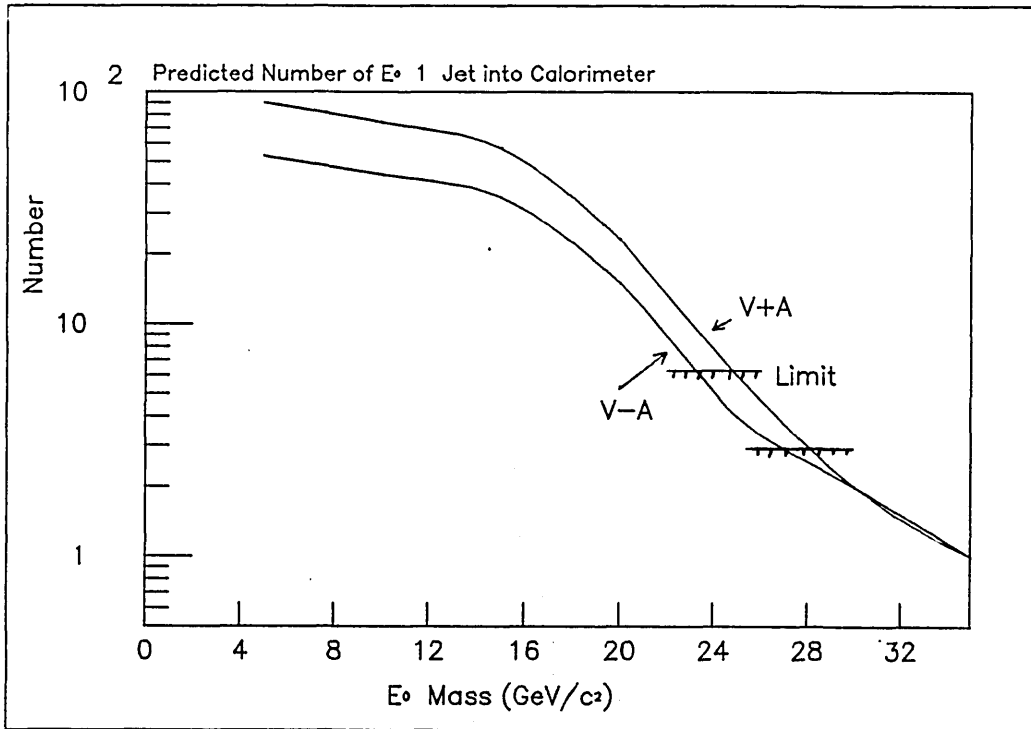


Figure 36: Predicted number of E° 1 jet type events which enter the calorimeters

5.4.3 A Limit on Monojet Production

5.4.3.1 From This Search

To determine a limit on monojet production, a model was required which predicted their production cross section and hence the number of events expected for the amount of data used in this search. The model used considered Z° decay to two particles of very different lifetimes, where the second particle of mass m_2 is the short lived one producing the monojet. There were two variants of this model, in one the pair known as $\chi_1\chi_2$ are the supersymmetric partners of gauge bosons, in the other the pair known as h_1h_2 are a scalar and a pseudoscalar.

The cross sections were taken to be independent of mass m_2 . The acceptance as a function of m_2 was assumed to be the same as that for E^0 's. The number of events expected to be seen was then determined as shown in table 14 and Fig. 37 as a function of m_2 for the $\chi_1\chi_2$ and for the h_1h_2 cases.

TABLE 14					
Number of Monojet Events Expected					
m_2	# Produced		Acceptance (1 jet into calorimeters)	# Expected	
	$\chi_1\chi_2$	h_1h_2		$\chi_1\chi_2$	h_1h_2
1.0	50	12			
5.0	50	12	0.30	15.0	3.6
10.0	50	12	0.266	13.3	3.2
15.0	50	12	0.230	11.5	2.8
20.0	50	12	0.116	5.8	1.4
25.0	50	12	0.042	2.1	0.5
30.0	50	12	0.020	1.0	0.2
35.0	50	12	0.01	0.5	0.1

No events have been observed in the data which could be definitely classed as due to monojet production. There are two events which could be interpreted as monojets although this is unlikely. The 95 % confidence level limits on the mass m_2 are quoted both for the case where no events were seen and for the case where two events were seen. These limits are, as shown by the hatched lines in Fig. 37 :

$$\chi_1\chi_2 \quad m_2 \geq 23.0 \text{ GeV}/c^2 \text{ (no events observed) or}$$

$$\chi_1\chi_2 \quad m_2 \geq 19.0 \text{ GeV}/c^2 \text{ (assuming 2 events observed)}$$

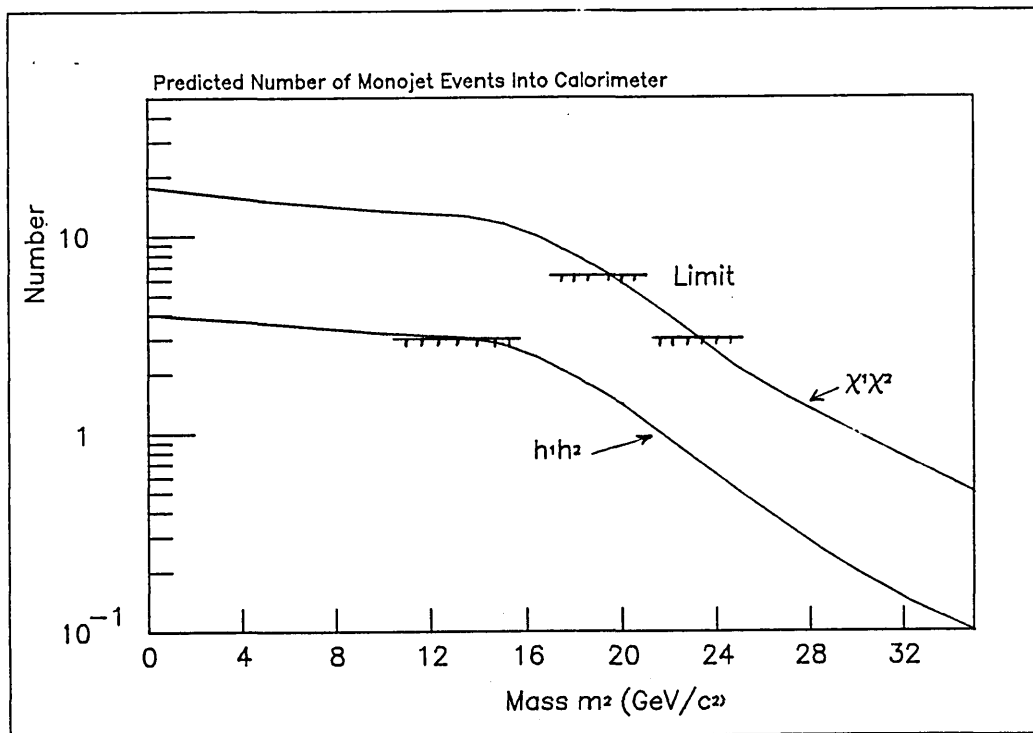


Figure 37: Predicted number of monojet events which enter the calorimeters

$h_1 h_2$, $m_2 \geq 14.0 \text{ GeV}/c^2$ (no events observed) or

$h_1 h_2$, No limit can be given in the case where 2 events were assumed to be observed.

5.4.3.2 Comparison With Other Experiments

To facilitate comparison with the results from other experiments, the results here are expressed as an upper limit on the cross section for the production of $\chi_1 \chi_2$, where the χ_2 mass is less than $20 \text{ GeV}/c^2$.

Taking the case where no events which could be positively identified as due to monojet production have been seen, which

implies 2.3 events at 90 % c.l. then the upper limit on the cross section which is mass dependent is 0.35 pb and 0.75 pb at 10 and 20 GeV/c² respectively.

If the two events which were difficult to attribute to any particular background process were interpreted as being due to monojet production, then the 90 % c.l. upper limit on the cross section would be a factor of 2.3 greater than above.

Other groups have produced limits on the production of monojets in e⁺e⁻ annihilation, HRS, MAC, MK II and JADE, [34]. The first three groups results were all using data taken at a centre of mass energy of 29 GeV at PEP, with luminosities of around 200 pb⁻¹ each. They quote cross section limits using zero or one candidate event seen, for χ_2 masses in the range from 2 to 10 GeV/c² of 0.02 pb to 0.10 pb. The fourth result is from JADE at PETRA, using luminosity taken at 27 to 37 GeV and at 38 to 46.7 GeV centre of mass energies, they have seen no candidates.

5.5 CONCLUSION TO THIS SEARCH

All experiments exclude the interpretation of the UA 1 monojets as being due to the production and decay of a pair of neutral particles of unlike lifetimes resulting from Z⁰ decay.

There is no evidence for monojet production in this experiment and this supports the conclusions from searches made by other experiments. The results from the PEP experiments at a centre of mass energy of 29 GeV, but using higher luminosity are complementary to those from the PETRA experiments working at a higher centre of mass energy.

Chapter VI

THE SEARCH FOR A DOUBLY PRODUCED NEUTRAL PARTICLE

6.1 INTRODUCTION

In this chapter two search strategies will be described.

The first used the ability of the TASSO calorimeters to identify electrons and the muon chambers muons. The monte carlo studies showed that the pair produced neutral leptons would have large branching ratios to electrons and muons and that unusual combinations could result.

The second approach used the TASSO vertex detector to look for events with short decay distances. The very high precision obtainable made this a unique tool for such an undertaking. It should be stressed that there were a number of known event classes which did have finite decay distances, notably the production and decay of T aus, b and c quarks and K^0 's but these had other features which distinguished them from possible neutral particle decays. See the section on backgrounds.

6.2 THE L⁰ SEARCH USING LEPTONS

6.2.1 Lepton Identification in TASSO

6.2.1.1 Identifying Electrons

Electrons entering the liquid argon or the lead scintillator shower counters interact with the atoms and lose energy by the radiation of bremsstrahlung photons. These photons are able to convert into electron positron pairs which then radiate further photons, hence creating a shower.

Various properties of these showers were used to distinguish those due to electrons from those due to primary photons, hadrons, or hadrons with nearby photons. The exact criteria used in the Liquid Argon Barrel, and in the Hadron Arm Shower Counters, are described here. (A further discussion can be found in Ref. 35).

The LABC

1. Only tracks with momentum $p \geq 2 \text{ GeV/c}$ were considered. This was because the efficiency was low for lower momenta, and low momentum tracks were not able to deposit energy over the whole depth of the calorimeter, which was necessary to distinguish electrons.
2. Tracks had to enter the fiducial volume which was defined to be at least 5 cm from the module edges, this was so that the complete energy deposited by the track was recorded.
3. The tracks and neutral clusters had to be closely associated, by requiring the track to be within 3° of the

centre of the neutral cluster, which was 9.22 cm at the LABC. Note that the LABC front tower plates were 7 cm square and the strips were 2 cm wide.

4. The structure of the shower had to be consistent with an electron. The longitudinal development (depth) of the shower was such that, at lower momenta more energy was deposited in the front towers than in the back towers, while at higher momenta the shower centre moved back. Hence the ratio, $r = \text{Front tower energy} / \text{Back tower energy}$ had to be in the range $1/(0.65+0.1p) \leq r \leq 10$, where $1/(0.65+0.1p)$ decreased from 1.18 at $p = 2 \text{ GeV/c}$ to 0.38 at $p = 20 \text{ GeV/c}$.
5. The width of electron showers was such that, at least 4 (5) strips had to have fired for energy deposits < 5 (> 5) GeV.
6. Showers due to hadrons tended to have an energy less than the track momentum causing them, hence the energy deposited in the shower had to agree with the momentum of the track to within 2.5∇ , where

$$\nabla = \sqrt{(\sigma^2 + (0.017p^2)^2)}$$

$$\sigma = 0.16\sqrt{E} + 0.031E \text{ for } p < 4.1 \text{ GeV/c}$$

$$\sigma = 0.11E \text{ for } p > 4.1 \text{ GeV/c}$$

The numbers are related to the energy resolution of the counters, given in section 3.3.1.

The efficiency for identifying electrons with these criteria was $82\% \pm 2\%$ for momenta up to 5 GeV/c (Determined using two photon

events of the type $e^+e^- \rightarrow e^+e^-e^+e^-$). The background due to hadrons had been estimated to be $15\% \pm 2\%$. Furthermore in jets 1% of all hadrons with momentum $p > 2 \text{ GeV}/c$ and transverse momentum (with respect to the thrust axis) $p > 1 \text{ GeV}/c$, passed the electron selection criteria [36].

The HASC

Similar considerations applied to electron identification in the Hadron Arm Shower Counters, as applied in the liquid argon counters.

1. Only tracks with momentum greater than $2 \text{ GeV}/c$ were considered.
2. Tracks had to enter the fiducial volume which is defined to be at least 2 cm from the module edges.
3. The track had to be within 7° of the centre of the neutral cluster, this is around 35 cm at the HASC. Note that each counter module measured $100 \text{ cm} \times 70 \text{ cm}$.
4. At least 750 MeV of energy had to be deposited, which was to reject clusters due to noise, but was made redundant anyway by 5.
5. The energy deposited in the shower had to agree with the momentum of the track to within 2.5∇ , where

$$\nabla = \sqrt{(0.29^2 E + (0.017 p^2)^2)} \quad \text{for } p < 3.74 \text{ GeV}/c$$

$$\nabla = \sqrt{(0.20^2 E^2 + (0.017 p^2)^2)} \quad \text{for } p > 3.74 \text{ GeV}/c$$

The efficiency for identifying electrons was 77% [36].

6.2.1.2 Identifying Muons

Tracks were projected into the region of the muon chambers at a position (x,y) with error (σ_x, σ_y) . The area $(x \pm 10\sigma_x, y \pm 10\sigma_y)$ was searched for hits and the track was assigned a muon quality as defined in Table 15, [26].

TABLE 15		
Definition of Muon Quality		
Quality	Configuration	Description
-1		Track missed muon counter by >100 cm
0	or —	Zero or one wire inside the search area
1	+	Two wires, one in each coordinate
2	≡ or ≡	Three wires, at least one in each coordinate
3	≡	Two wires in each coordinate

For muon quality ≥ 1 the deviation of the actual hit from the projected position δ was determined. A confidence level was then calculated for the hit :

$$CL = \exp(-\chi^2/2),$$

where the χ^2 had two degrees of freedom which were δ and the error ellipse. The criteria used for accepting tracks as muons are described here.

1. The track momentum p had to be $> 2 \text{ GeV}/c$, because for lower momenta the background due to hadron punchthrough was larger, and the interest here is in high momentum muons.
2. Only yoke and hadron arm Muon Chambers were considered because the endcap chambers were affected by noise which produced spurious hits, especially during the poor beam conditions associated with scanning.
3. The quality had to be ≥ 2 , to reduce the effect of random hit coincidences.
4. The confidence level had to be > 0.01 , which meant that the hit was within 2.5 standard deviations of the track.

The muon identification probability, (found using events of the type $e^+e^- \rightarrow \mu^+\mu^-$) was determined to be $96\% \pm 2\%$ for data taken in 1983/84 [37].

6.2.1.3 Lepton Identification in TASSO - 1979 to 1982

Although data was taken between 1979 and 1982 corresponding to a luminosity of 84.0 pb^{-1} , the liquid argon barrel was only fully installed from January 1981. (Before this date parts of the barrel area were filled by shower counter modules later moved into the hadron arms). Leptons have therefore only been identified in the data taken after this time, corresponding to a luminosity of 55 pb^{-1} which excludes the 14 or 22 GeV data. The data corresponding to the 55 pb^{-1} occupied 21 PASS 3 tapes which contained 220667 events.

6.2.2 Selection of Events With leptons

As the search was for a new neutral particle, events needed to be considered where there was an even number of tracks in a pair. The two track against two topology was the one to investigate thoroughly as events with four tracks on each side were confined to the hadronic event sample, (66 from 4429). It was shown using the monte carlo simulations of neutral lepton pairs that the number of events with eight tracks was zero for the 0.1 and 1 GeV/c² masses, 2% in the 3 GeV/c² case and 7% in the 8 GeV/c² case. Therefore in view of the small production cross sections expected and the hadronic background, using these events in a search would not be fruitful.

The sample selected as in section 5.2.1 was used as input and the further selections described below in table 16 were made in increasing order of severity. The numbers of events surviving after each selection and the number of these with one identified lepton in the track pair are shown at each stage, for both the high energy and lower energy data.

6.2.2.1 The Higher Energy Data

The 40 events in category 1a in table 16 were scanned and were divided into:

- i) 18 events with 2 tracks against a jet of ≥ 5 tracks,
- ii) 5 events with 2 tracks against 3 tracks,
(at least one track must be undetected),
- iii) 1 event with 2 tracks against 4 tracks and
- iv) 4 events which were noisy and badly fitted so were

TABLE 16

Data Selections for L^0 Search

	Higher Energy	Lower Energy
≥ 4 tracks and sum $p > 4$ Gev		
1) Two Isolated tracks in one hemisphere any number in the other	4229	9052
a) 1 track of pair in 1) a lepton	40	97
2) The pair have opposite charge	2028	5762
a) 1 track of pair in 2) a lepton	30	66
3) Each track of pair has $p > 500$ MeV/c	750	3238
a) 1 track of pair in 3) a lepton	21	43
4) 2 tracks vs 2 tracks	110	571
a) 1 track of a pair in 4) a lepton	11	14

not considered.

v) The remaining 12 events were of the type two track

against two track. Of these, 3 events were lost by cuts 2) and 3) leaving 9 events. (The 11 in the table include 2 classed as junk.) These remaining two track against two track events were categorised into radiative leptonic type events as follows :

1) $\mu\mu\gamma$ (2 events), In one event only one muon was identified, but the full centre of mass energy was present and the pair of tracks not containing the μ were close together and both were

electrons (from the converted hard γ). In the other event both muons were identified.

2) $ee\gamma$, Cases where photons were radiated off the initial or final state electrons in the process $e^+e^- \rightarrow e^+e^-e^+e^-$.

2a) (3 events) If two moderately soft photons (up to a few GeV) were emitted and converted, but one of the conversion pair was not seen in each case, then an event was observed with 2 track pairs each containing a high momentum and a much lower momentum track.

2b) (1 event) If one lepton emitted a hard photon (over 10 GeV) which converted, an event with a well separated pair, (the initial leptons) and a close pair, (the conversion) was seen.

2c) (3 events) A combination of a and b, A hard photon from one lepton had converted to a pair, the lepton was not seen, while the other lepton radiated a soft photon and it was seen accompanied by a low momentum track.

Trying to fit the pair on each side to a common point (see later), produced results which supported the conclusions given above. Where the track pair were believed to originate from a converting photon, the vertex fit had a large χ^2 per degree of freedom (dof) (>5) and/or the number of iterations to the convergence of the fit was 10 (the maximum allowed). No event produced two well fitted vertices where the χ^2 and the number of iterations was small in both the fits.

6.2.2.2 The Lower Energy Data

In the 2 vs 2 track category, (cut 4 in table 16) there were 571 events from the whole of the lower energy data, 14 of these events had leptons and these were examined. They could be classified, as above into :

1) ($\mu\mu\gamma$) 5 events, 2a) 2 events, 2b) 2 events, 2c) 3 events, one junk event, and one event which was boosted forward and looked like a two photon scattering event. In these events recorded before the installation of the vertex detector, fitting has not been performed so only the small subsample of leptonic events have been investigated.

6.2.3 Conclusion to Search using Leptons

All the possible candidates for low mass neutral particles decaying to produce leptons have been classified as being due to known QED processes. No spectacular events were observed which it would have been impossible to explain in terms of conventional processes.

The limitations on lepton identification in the TASSO detector make any calculation of limits highly dependent on the model chosen for the neutral particle decays, therefore production limits are discussed later in the context of the search using the vertex detector.

6.3 THE L^0 SEARCH USING THE VERTEX DETECTOR

6.3.1 Lifetime Measurement With the VXD

The Tasso vertex detector had already shown that it was capable of measuring the flight path of decaying τ 's [38], and of measuring the impact parameters of bottom hadrons [39], to an accuracy of 200 μm .

The approach used here was to measure a flight path for any new particle which decayed to two charged particles, as it had been speculated that a new heavy neutral particle could have a measurable decay length. To do this one needed to know the interaction point of the e^+e^- , where the particle was produced, and the decay point where it ended.

There now follows a discussion on the selection of events suitable for fitting, and of some problems encountered when performing track finding in the vertex detector using the FELIX program.

6.3.2 Event Selection

The monte carlo studies showed that the products of the decay of a neutral particle were close together for masses up to 10 GeV, and the momentum sum of the pair was substantial. Therefore further cuts A) and B) were applied to the 750 events as selected in table 16 - criteria 3, These were :

A) i) That the momentum sum of the track pair should lie in the range from 4.5 to 30 GeV/c. The lower limit had the effect of eliminating low momentum events mainly resulting from two photon

processes. The upper limit removed events where tracks had been reconstructed with absurdly high momenta due to the incorrect association of hits.

ii) That the opening angle between the tracks in the pair should be less than 60° . The monte carlo studies showed that this requirement would not affect the acceptance for low multiplicity neutral heavy lepton events.

After selection i) $4.5 < \Sigma P \text{ (pair)} < 30 \text{ GeV/c}$, 207 events remained and after ii) opening angle $< 60^\circ$, 177 events remained, this was using tracks found by the MILL trackfinder.

B) A requirement that the events had only two good tracks in each hemisphere, which reduced the number of acceptable events to 110.

6.3.3 Vertex Detector Information

6.3.3.1 | The Operational Efficiency of the Chamber

Because of the vital role of the vertex detector it was necessary to know the proportion of the time it was fully operational. In each event the status of all the chamber high voltage sectors at that instant was recorded. It was found that in the high energy selected sample of nearly twenty thousand events the vertex detector was on for 17525 events (90.5 %) and off for 1854 events (9.5 %). The majority of the events in which the detector was off fell into two periods, in one of these periods excess current was drawn by the chamber, in the other there were technical problems with the gas supply.

6.3.3.2 Running The FELIX Trackfinder

It was decided that the vertex detector information would be incorporated in the events under investigation by using the trackfinder FELIX (see section 3.5.3.2). Under normal circumstances the FELIX program is only run on the final events selected as multi-hadrons (PASS 4), therefore as the selections being used in this search came from PASS 3 it had to be run by the author. The program needed a significant amount of computer time to process each event, with the further consideration that as the numbers of hits in the tracking chambers increased so must the number of possible track permutations and hence the computation time. The time required would have been difficult to obtain on the DESY laboratory central IBM computer. Fortunately the FELIX program had been implemented on a 370E IBM emulator processor connected to this central machine. This emulator was used to process the events which were stored on the disks attached to the central computer [40].

Even with the emulator available to provide the extra time required, the whole sample of around 20000 events, (from section 5.2.1) with ≥ 4 tracks and charged track momentum sum > 4 GeV/c could not have been processed using the FELIX program, (a process referred to as FELIXing). Therefore preselection of events, using the MILL tracks, was necessary before FELIXing. The selections were the same as in the search using leptons, namely: Two good tracks in one hemisphere, with any number in the other and then that the isolated pair should have opposite charge. This

produced 2028 events (see table 16). These were FELIXed in batches of approximately 250 events. Each batch required about four hours on the 370E.

TABLE 17		
Data Selections for The L^0 Search, Comparison of MILL and FELIX		
	Number of events	
	MILL	FELIX
1) 4 or more tracks	--	1849
2) Sum p > 4 GeV/c	--	1384
3) 2 isolated tracks	--	1001
4) Pair have opposite charge	2029	941
5) Pair both p > 500 MeV/c	750	429
6) $4.5 < \Sigma p \text{ pair} < 30 \text{ GeV/c}$	207	132
7) Opening angle < 60°	177	115

Imposed on the whole 2029 event sample		
Sum p > 8 GeV/c	462	388

6.3.3.3 Comparison of MILL and FELIX Trackfinders

To compare the performance of the two trackfinders, the selection criteria originally used with the MILL tracks were applied but this time using the tracks found by FELIX. The results of this are shown in table 17, the left hand column gives the numbers of

events selected using MILL tracks which is only meaningful in this context after cut 4, the right hand column shows FELIX selection. The differences were significant and required further investigation. It should be pointed out that in the hadronic event sample the number of tracks and the total momentum in an event found by the two trackfinders was not significantly different [41].

It was found that when a momentum sum requirement of 8 GeV/c was made, using MILL tracks 462 events were selected (from 2029), using FELIX tracks 388 Events were selected. This indicated that the differences lay more with the low momentum events.

To make a qualitative judgement as to why events passing selections using MILL tracks failed using FELIX, some events were scanned using the TASSO interactive display program.

The ≥ 4 track requirement, The events failing were not sensible in either case. The chambers were full of hits spread randomly and many spurious not accepted tracks resulted. The accepted tracks arose by chance, other possibilities using their hits could have been made. These events were classed as junk.

The ≥ 4 GeV requirement. The events failing here with FELIX were classed into approximately 30% junk, the rest were those which in MILL, had a momentum only just greater than 4 GeV/c, in most cases they looked like two photon events as they were strongly boosted into one hemisphere.

The two isolated track requirement. The classification was again into junk and into borderline events where minor

differences between the trackfinders had caused the event to be rejected. FELIX often found extra tracks not having many drift chamber hits, or conversely it failed to find one of the MILL pair.

The point about the differences between the trackfinders is raised again later where it is used in a positive way to reject events. The comments made here justify this use.

6.3.4 The Elements Used in Vertex Fitting

6.3.4.1 Finding The Beam Spot Position

The interaction point must be inside the beam spot envelope which had an rms size of 0.1 cm horizontally by 0.01 cm vertically. (This vertical size was below the resolution of measurement). The position of the beam spot was determined using events which had tracks which came from the beam, at least 50 such tracks being required to give a position. The beam spot was found for each run if this was possible, but if the run contained too few events it was found for a group of runs. Events were taken from the PR 2 tapes on which the PASS 5 trackfinder had been used to locate tracks in the vertex detector. The selection criteria for these events were :

i) No tracks with $|z_0| > 15$ cm. This was to eliminate events which contained noise and might not have been due to an e^+e^- interaction, for example beam gas or beam wall events, which by chance also had tracks originating from the origin.

ii) At least 2 tracks in the event having $|d_0| < 7$ cm and an sz fit, (s is the distance travelled along the particle trajectory in the xy plane). This ensured the event had a very high probability of being due to an e^+e^- interaction, and that a reasonable track fit had been performed.

For all possible pairs of tracks in an event the position of the intersection in the xy plane $r = \sqrt{x^2+y^2}$ was calculated. if r was < 2 cm the tracks were assumed to come from the interaction point and the average r was found, taken over all the events in the sample. The errors on the position obtained were of the order of $100 \mu\text{m}$.

In the period when the data used here were being recorded it was found that the maximum variation in the beam position was 0.5 cm in x and 0.16 cm in y

6.3.4.2 Description of the Fitting Programs

The decay point of a particle was determined by fitting the tracks believed to come from the decay to a common point. The fitting programs used here were written by D H Saxon, see Ref. 42. They used an iterative procedure, the basic aim of which was to find a point where the best fit was obtained, measured by the reduction in the χ^2 for the tracks when fitted to a vertex, compared to the χ^2 before fitting.

$$\forall \chi^2 = \chi^2 (\text{vertex fit}) - \sum \chi^2 (\text{track fits})$$

At each iteration the new track vector was $V_{n+1} = V_n - G^{-1}g$, where g is the first derivative and G the second derivative of the χ^2 for

the track. The χ^2 was a sum over all the measurements of the track. Fits could be performed in two dimensions or in three, the number of constraints being :

$$\begin{aligned} N &= 2 \times (\text{number of tracks}) - 3 \text{ for a 3 D fit} \\ N &= \text{number of tracks} - 2 \text{ for a 2 D fit} \end{aligned}$$

A two track fit was constrained in three dimensions but not in two. When fitting two tracks a three dimensional fit was first attempted, if this failed then a two dimensional fit was made. A $\chi^2 \geq 4$ was considered as indicating a good fit after visually scanning the fitted events.

In TASSO the CPC represented 3.3 % radiation lengths (r.l.) of material and the vertex detector 2.71 % r.l. This material caused scattering of tracks, which was parameterised in the vertex fits as the effect of a single plane of material of 6 % r.l. situated at a radius of 16 cm.

6.3.4.3 Finding a Decay Length

The decay length was calculated, given a beam spot position with an error matrix and a fitted vertex with an error matrix, using the formula [43] :

$$l = \frac{x \sigma_{22} t_1 + y \sigma_{11} t_2 - \sigma_{12} (x t_2 + y t_1)}{t_1^2 \sigma_{22} - 2\sigma_{12} t_2 t_1 + \sigma_{11} t_2^2}$$

where x and y are the vertex coordinates,

$\sigma = \sigma_{ij}$ vertex beam Is the sum of vertex and beam spot error matrices, and,

t_1, t_2 are the direction cosines of the decay, (the direction of the sum of the momentum vectors of the fitted tracks).

The error on the decay length was given by :

$$(\nabla_1)^2 = \frac{\sigma_{11}\sigma_{22} - \sigma_{12}^2}{t_1^2 \sigma_{22} - 2\sigma_{12}t_2t_1 + \sigma_{11}t_2^2}$$

Because in a search of this kind one wanted to be sensitive to a wide range of mass of the decaying particle, limits on the decay length only will be given. The lifetime is $\tau = 1/\gamma c$ so unless this was known, (which it would not be for any new particle found) the decay length could not be used to obtain the mass.

6.3.5 Examining and Fitting The Selected Data

6.3.5.1 Introduction

At this stage there were two event samples selected as described in section 6.3.2. The first sample was the 115 events analysed with the FELIX program which passed cut 7 in table 17. The second sample was the 110 two track versus two track events passing cut 5 in table 17, (this time using the MILL tracks), The further examination and classification of the two event samples and the conclusions from the fitting are discussed below. First some general comments are made.

Because the fitter was being used in a way which it was not originally intended it should be, some events failed. This was indicated by the number of iterations being returned as the maximum allowed (10), a very large χ^2/dof . and in most cases also a position for the vertex which was a large distance (>20 cm) from the origin. It should be stressed that a very big vertex distance must not in itself be taken as an indication of something being wrong.

The invariant mass distributions of the pairs, in both the above event samples are shown in Figs. 38 and 39 over the range from 0 to 2 GeV/c². In Fig. 38, 14 events had invariant masses greater than 2 GeV/c², in Fig. 39 the number is 25 track pairs. The assumption that the tracks were pions has been made, which is why the lower cutoff values on the invariant mass lie at 270 MeV/c². These plots using pion masses were used to look for any peak at the K⁰ mass, (498 MeV/c²). There were no such peaks in either plot.

6.3.5.2 Examining and Fitting 2 vs Any Events

The 115 events of the two track versus any number type were examined. (The any number of tracks included two tracks, there were 16 events of this type). Increasing the momentum sum requirement from 4 GeV/c to 8 GeV/c removed 4 events which on examination were characteristic of two photon processes. There were 70 events with 7 tracks or more, such events normally fell into the hadronic event class, the isolated pairs in these events could in some cases be identified as electron-positron pairs resulting from hard photon conversions.

There were 30 events with 4 or 5 tracks which would normally be attributed mainly to QED processes, (of the type discussed earlier when looking at events containing leptons).

All 115 events were passed through the fitting program where the isolated track pair was fitted to a vertex. A decay length was calculated for the 73 events where the $\chi^2/\text{dof.}$ was ≤ 4 after

fitting the pair. (The number of degrees of freedom was typically 30). The $\chi^2/\text{dof.}$ cut was at the point shown in the distribution in Fig. 40.

The distribution of decay distances is shown in Fig. 41. The mean was -0.12 ± 0.10 which showed no significant deviation from zero, however there were a number of events with absolute decay distances in the range greater than 0.6 cm. and there were slightly more events with large negative decay distances than with large positive ones.

The 16 events with fitted decay distances $|l|$ greater than 0.6 cm were examined to determine if the long decay length showed some interesting phenomenon or if the events had other peculiarities. They were divided as follows :

1. Eight events had multiplicities of 7 or greater so were not distinguishable from hadron events.
2. Four events had multiplicities of five. One event had a very long decay length but the track pair looked as if it resulted from the conversion of a photon to an e^+e^- pair. One event was most likely due to two photon scattering or an interaction with the beam wall. Two events were found to be actually three prong versus three prong topologies where the third track had been flagged as bad because it was at low z and had few drift chamber hits. This topology is consistent with τ pair production.
3. The remaining four events had four tracks, so fall into the two track versus two track sample dealt with below.

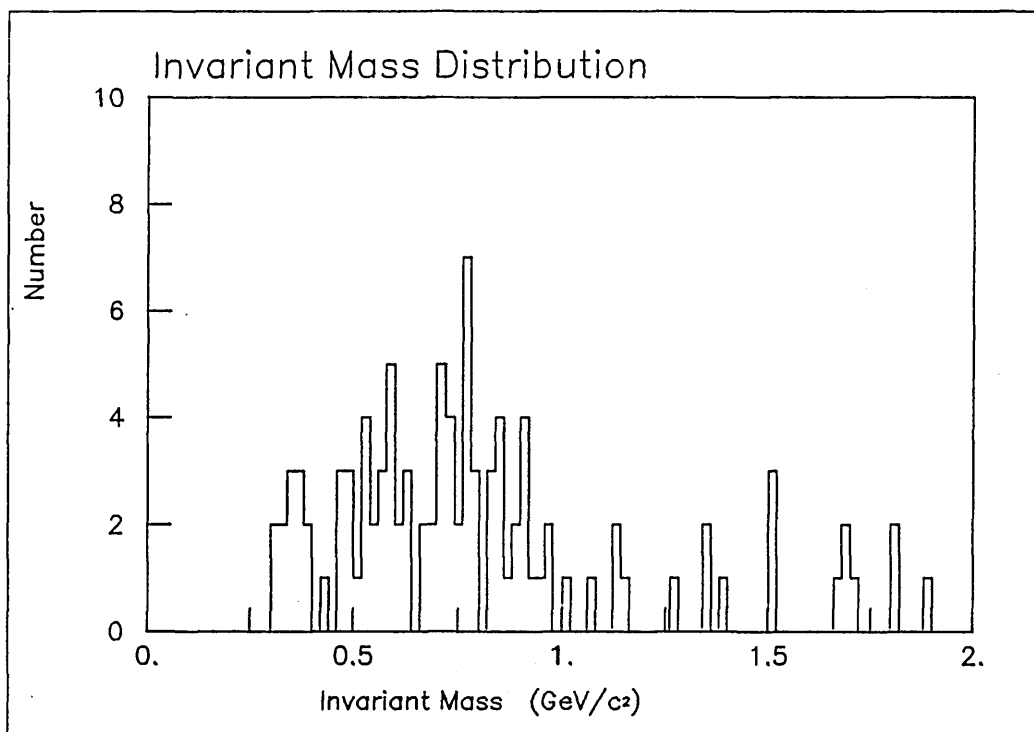


Figure 38: Invariant Mass of Pairs in 2 vs Any Events

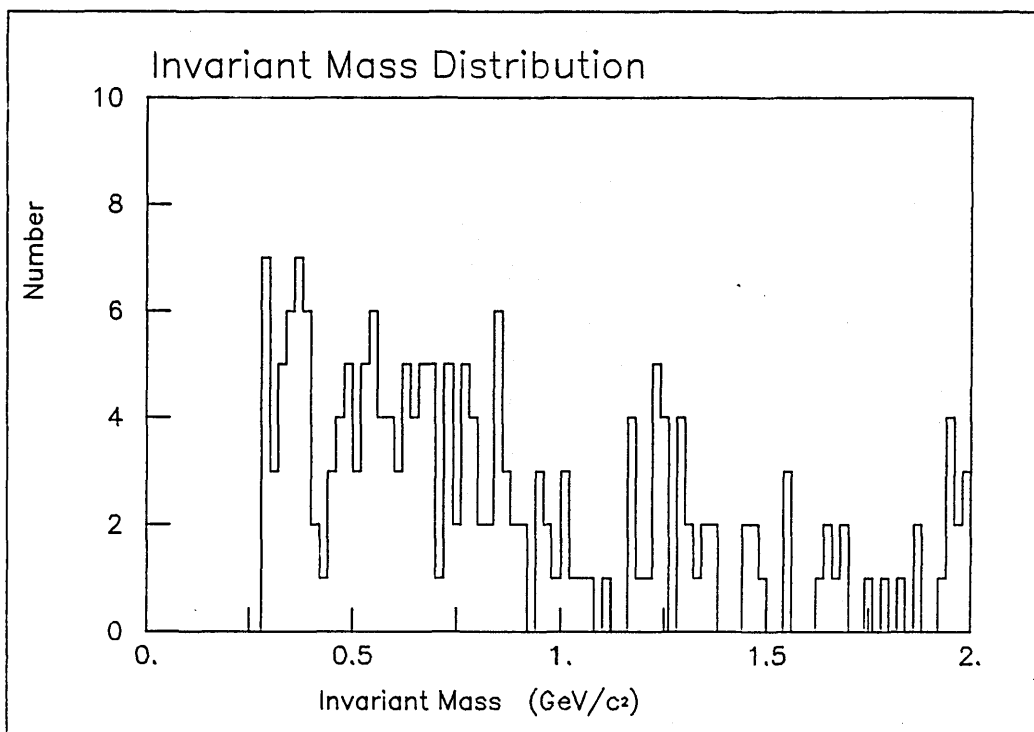


Figure 39: Invariant Mass of Pairs in 2 vs 2 Events

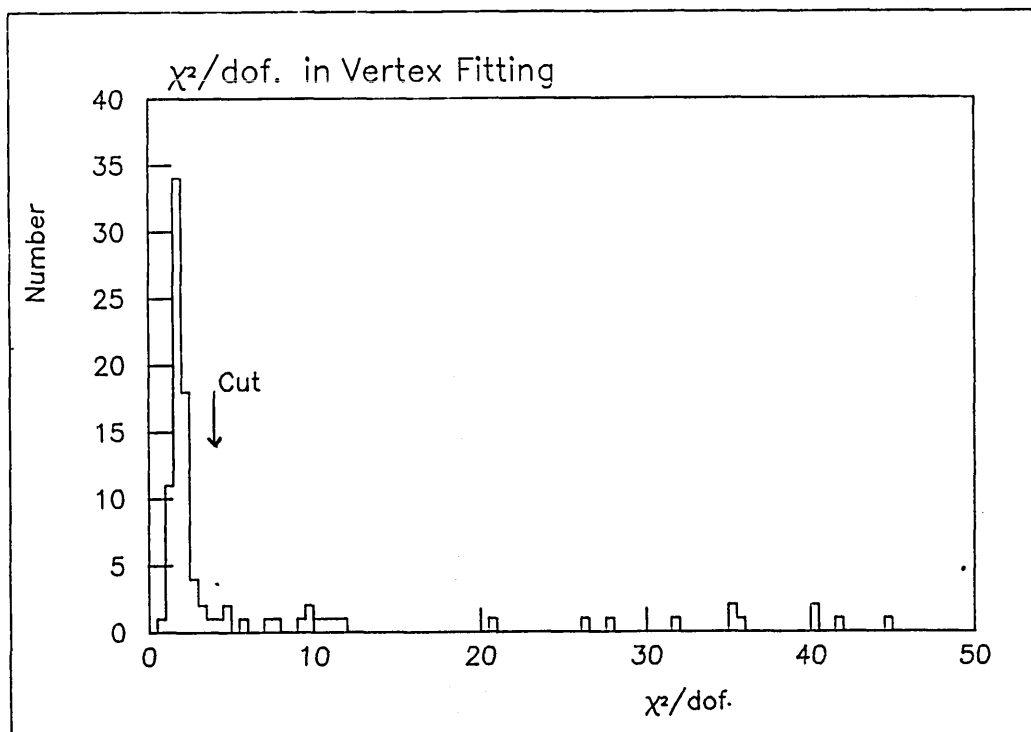


Figure 40: $\chi^2/\text{dof.}$ Distribution of Fitted 2 vs Any Events

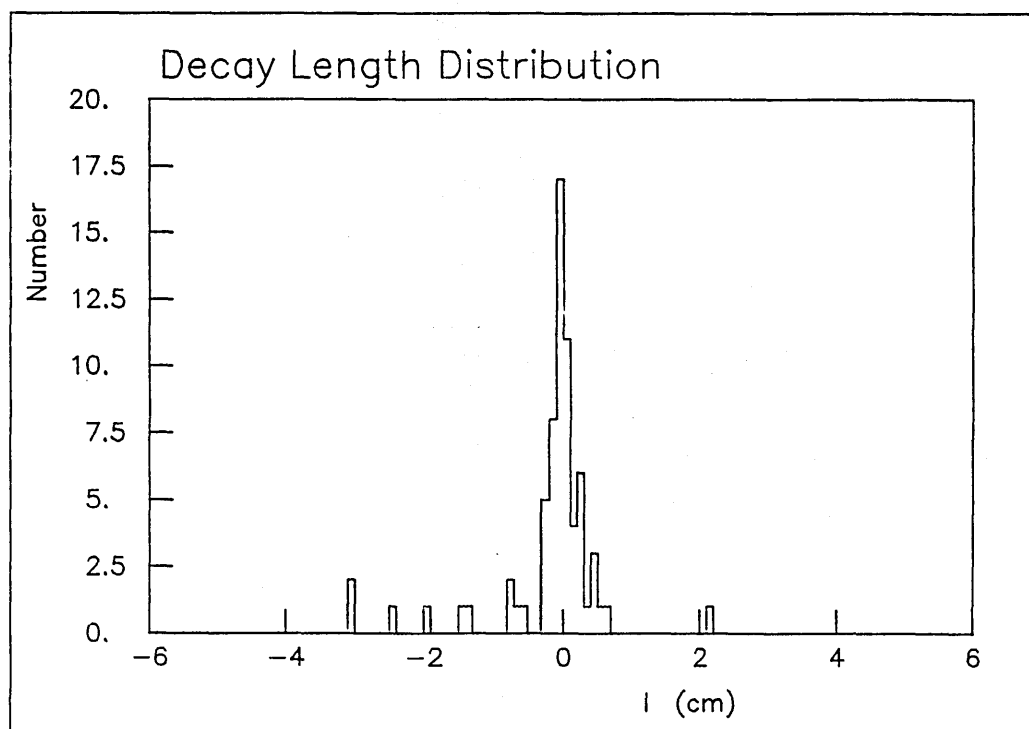


Figure 41: Decay Lengths of Fitted 2 vs Any Events

6.3.5.3 Examination and Fitting 2 vs 2 Events

There were 110 two track versus two track events selected using tracks found by MILL. The criteria used to select these (in table 17) were re-applied using the tracks found by the FELIX trackfinder, the results are shown in table 18. Only 57 events out of the 110 reached cut 5. This large difference was not unexpected but prompted a careful examination of the 110 events using the TASSO display program. The following criteria were then used when attempting to classify events.

TABLE 18

Reselection of 2 vs 2 Track Events Using FELIX Tracks

Events Input	Number of events
	110
1) 4 or more tracks	70
2) $\sum p > 4 \text{ GeV/c}$	64
3) 2 isolated tracks	62
4) pair have opposite charge	58
5) pair both $p > 500 \text{ MeV/c}$	57

Events characteristic of two photon processes were distinguished by : Having a momentum sum ~~xxx~~ between 4 and 6 GeV/c. Having a separation between the pairs of greater than

15°. Being forward boosted into one z hemisphere and often having significant numbers of hits in the tracking chambers associated with bad tracks or not associated with tracks at all.

Events characteristic of conversion pairs from photons typically had the momentum sum greater than 10 GeV/c. The events contained pairs where the track separation in the pair was less than 10° and often there was a difference of many GeV/c between the momenta of the pair.

The first observation from scanning was that the total momentum requirement of 4 GeV/c included many events due to two photon scattering and a number of triggers due purely to noise hits in the chambers. When the total momentum requirement was increased to 8 GeV/c, 42 events remained. A further 8 of these were eliminated as due to noise leaving 34, (of which 15 were contained in the FELIX sample.)

It was then observed that the 19 events NOT considered as 2 vs 2 by FELIX, (out of this 34) were ones where the track pairs looked as if they came from a photon conversion. The tracks forming the pair were close together and in the Vertex detector and CPC could not be separated, hence these events presented a particular problem for FELIX.

To identify radiative events in a quantitative way, the two tracks in a pair were both considered to be electrons and the invariant mass was calculated. The requirement was then made that if either pair in an event had an invariant mass less than 0.2 GeV/c² the event was rejected.

Out of 34 events, 19 events were rejected including 17 which looked like conversions. This left 15 events selected using MILL tracks. 10 of these were contained in the sample selected using FELIX tracks. These selections are summarised in table 19. The final 10 events are discussed again after vertex fitting.

TABLE 19

2 Track versus 2 Track - Further Selections

	Number of Events Using Tracks Found by	
	MILL	FELIX
2 vs 2 events	110	57
With Sum Momentum $> 8 \text{ GeV}/c$	42	
After rejection of Noise	34	15
After rejection if one pair has Inv. Mass $< 0.2 \text{ GeV}/c^2$	15	10
With $ 1 > 5 \text{ cm}$	6	2

Despite the previous remarks, the 110 events represented a sample selected using well defined criteria, free from any bias or uncertainty of interpretation introduced by scanning. They were all passed through the fitter. A decay length was calculated if the $\chi^2/\text{dof.}$ was ≤ 10 for either vertex after fitting both pairs. (This cut was at the point indicated in the distribution shown in Fig. 42. It was a looser requirement than

that made when fitting the other data sample and it included many vertices where the number of iterations was 10, the maximum.) 153 vertices in 96 events satisfied this. The distribution of decay distances is shown in Fig. 43. The mean was 0.13 ± 0.16 , again showing no significant deviation from zero but the distribution had more pronounced tails than that for the other data sample.

The 33 events with long decay lengths where long meant $|l|$ greater than 5 cm were examined. They contained :

1. 15 events characteristic of two photon processes.
2. 4 events due to chance combinations of noise which were rejected.
3. 12 events with pairs characteristic of conversion pairs from photons.
4. The remaining two events were ones where the pairs had a long decay distances and the topology was such that they could not immediately be classified as due to photon conversions. These two are also the only events contained in the sample of 10 selected without using decay length criteria. The long decay lengths were however an artifact of the trackfinding, as when the other trackfinders tracks were used in the fitting, the decay lengths were significantly different as shown in Table 20. The invariant mass of the pairs, assuming each track to be an electron, are also given here. These two events are shown in Figs. 44 and 45 and are discussed below.

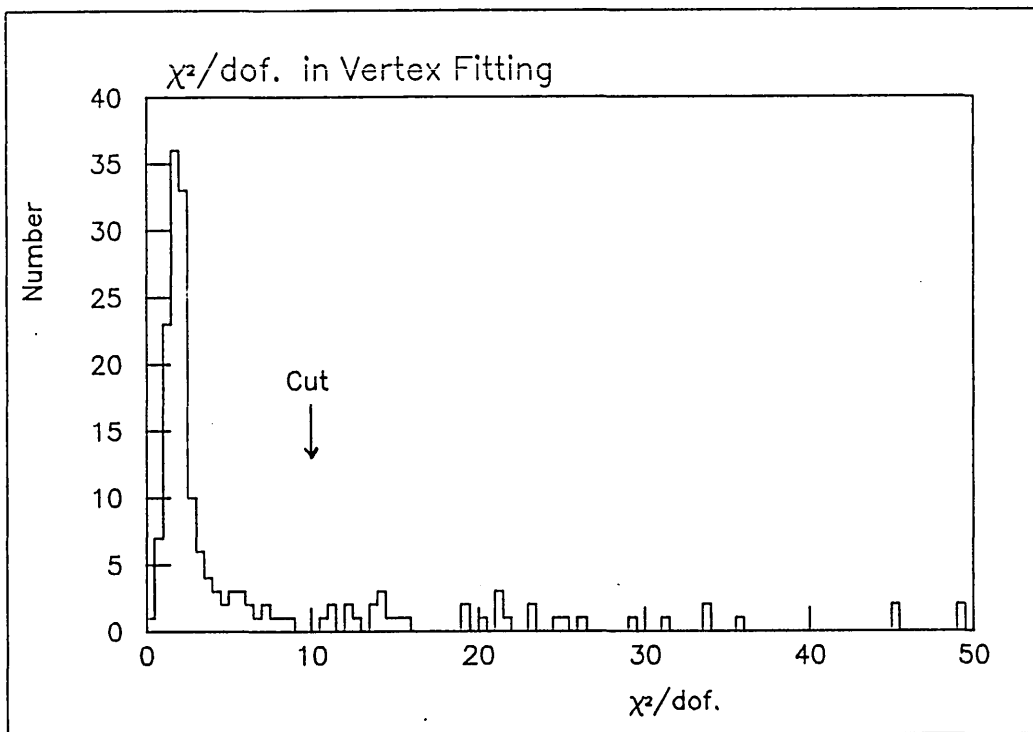


Figure 42: $\chi^2/\text{dof.}$ Distribution of Fitted 2 vs 2 Events

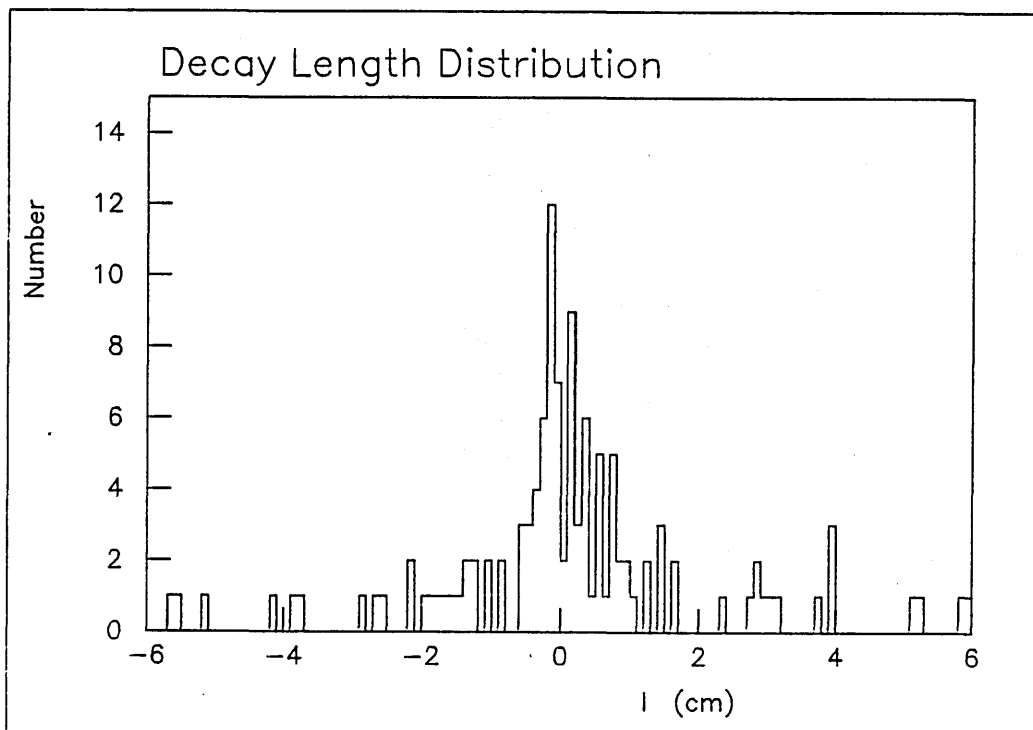


Figure 43: Decay Lengths of Fitted 2 vs 2 Events

TABLE 20

Comparison of MILL and FELIX tracks

Event	Tracks in fit	l (cm)		Invariant Mass GeV/c ²
		MILL	FELIX	
7042	1,2	-0.04	0.00	17.44
	3,4	-77.1	-0.02	1.48
7732	1,2	6.3	1.09	0.76
	3,4	-0.53	0.01	1.00

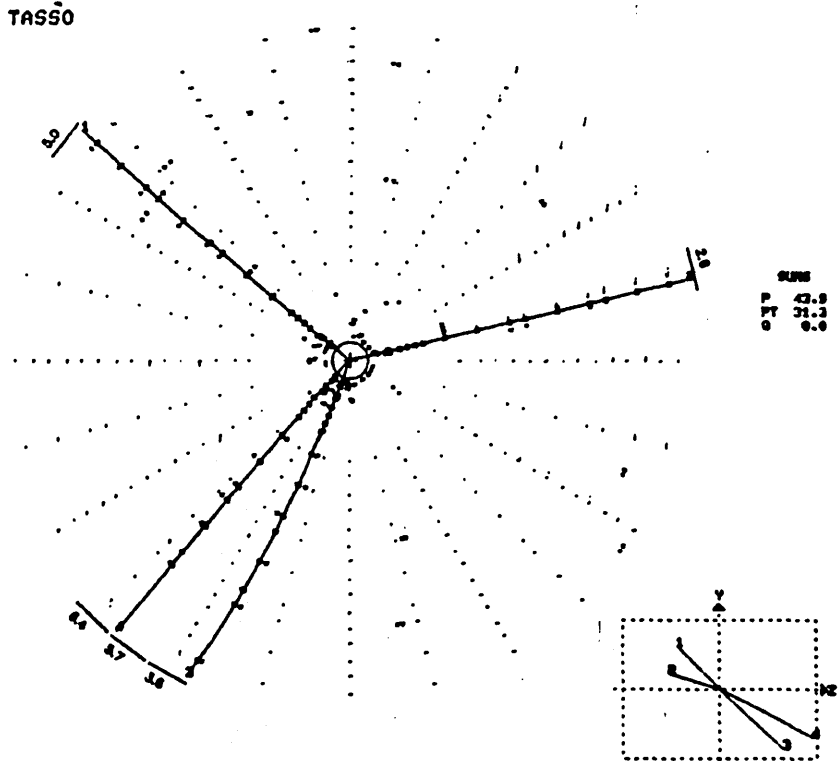
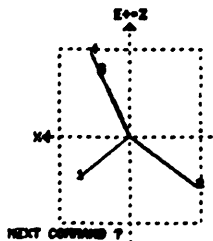
The 10 events will now be considered using both their topology and their general properties, as well as the results of the fitting. Two events were ones containing a pair of muons accompanied by a pair characteristic of a photon conversion. These events had a total momentum close to $\sqrt{s}$. A further event had a pair where one track was identified as a muon, the other track unfortunately did not point to any muon chamber, the other pair in this event was a conversion type. Three other events were of a similar topology to these $\mu\mu\gamma$ types, including event 7042 shown in Fig. 44.

This particular event is unlikely to be due to a neutral particle because of the great difference in the invariant mass of the two pairs and because the whole available e^+e^- energy has appeared in tracks, not allowing any energy to be carried off by neutrinos.

TR	P	PT	SO	20	REN	7042	EVENT	3438	ESSEN	20.00	GEV
1	0.73	7.23	0.2	1.2	2						
2	-4.67	30.8	0.3	0.1							
3	-10.05	12.01	-0.2	1.2							
4	-9.08	157.0	0.3	0.4							
5	0.98	0.89	-0.4	0.8							
6	0.95	228.8	0.3	0.9							
7	-19.00	10.30	0.6	0.5							
8	14.04	311.0	0.3	0.3							

TRIGGER= 010010000000010

TASSO



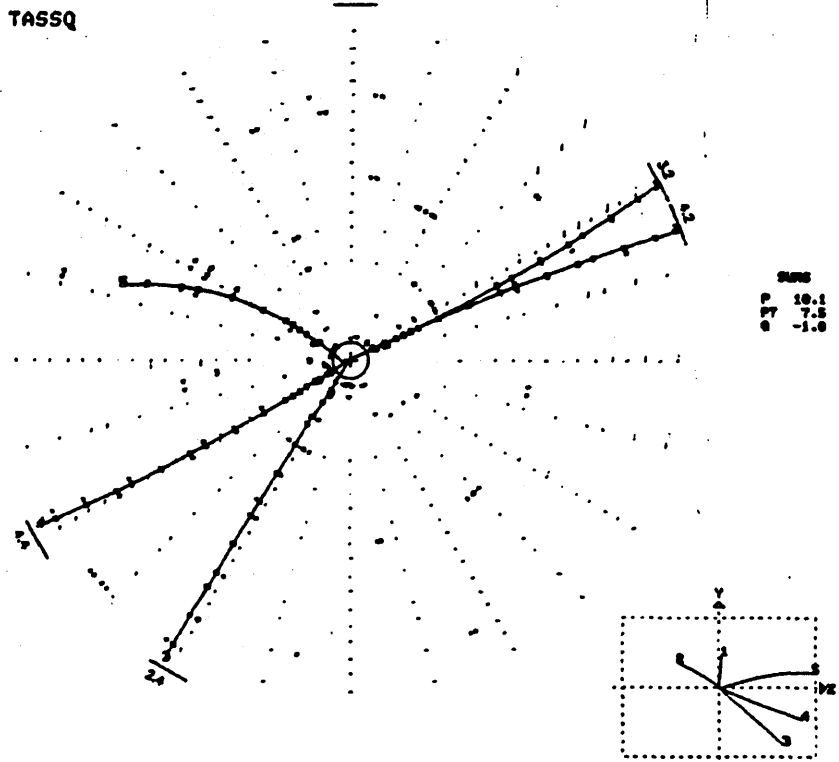
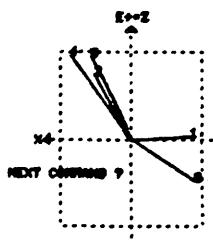
SUMS
P 43.8
PT 31.3
Q 0.0

Figure 44: Event 7042 - 3438

TR	P	PT	SO	20	REN	7732	EVENT	9762	ESSEN	22.10	GEV
1	-0.04	0.04	-0.4	-0.2							
2	1.41	1.19	0.2	0.2							
3	-0.75	153.9	0.7	1.0							
4	-5.00	4.17	0.4	-1.2							
5	4.03	302.7	0.4	1.0							
6	1.00	1.00	-0.4	-1.0							
7	1.00	302.4	0.6	1.4							
8	-0.33	0.18	-0.8	0.4							
9	0.30	44.1	1.3	0.5							

TRIGGER= 010000100000000

TASSQ



SUMS
P 10.1
PT 7.5
Q -1.0

Figure 45: Event 7732 - 9762

One event looked like a 2 jet hadronic event, it had a multiplicity of 4 good tracks of course, but the other tracks found made it impossible to consider this event as due to production of two neutral particles.

Two events had momenta sums of 8 GeV/c and 13 GeV/c. Both contained 4 bad tracks and a lot of noise hits, for this reason they were unlikely to be neutral lepton decays.

The remaining event is event 7732 shown in Fig. 45, with a momentum sum of 10 GeV/c. It was also unlikely to be due to a neutral particle decay because of the low momentum and the presence of an extra track which had been poorly tracked by being at a small angle to the z axis.

6.3.6 Backgrounds

There were two classes of background. The first were events which did not have inherent finite decay lengths, but mimicked the event shapes expected from heavy neutral particle decays and/or had apparent decay lengths due to detector effects. This type of background was mainly two photon and radiative events, (which have been discussed above when classifying events passing various cuts), so it was possible to make a quantitative estimate of these backgrounds using Monte Carlo simulations.

The second class of background was because other particles produced in e^+e^- annihilation at PETRA had finite decay distances. However the resulting events had other distinguishing features allowing them to be identified and eliminated.

6.3.6.1 Two Photon Events

The same monte carlo sample was used as in section 5.3.2. All the numbers quoted have been normalized to the luminosity of 25 pb^{-1} .

For the two track versus any sample when all cuts in table 17 were applied, 9 events survived. When the momentum sum requirement was increased from 4 GeV/c to 8 GeV/c, 7 events survived. These were consistent with the numbers of events in the data sample.

There were zero events with two tracks versus two tracks passing all the criteria in table 18 and a momentum sum requirement of greater than 8 GeV/c. This is consistent with an estimate of two events in the data.

6.3.6.2 Radiative Bhabha Events

A bhabha monte carlo generator [32], which had radiative corrections up to order α , was used to generate a sample of 50000 events at a centre of mass energy of 44 GeV. These corresponded to a total integrated luminosity of 4.96 pb^{-1} , hence to normalize the results to the data, the numbers extracted from the monte carlo events had to be multiplied by five.

For the two track versus any sample, when all cuts in table 17 were applied, 15 events survived.

There were 20 two track versus two track events passing all the criteria in table 18.

These numbers are consistent with the numbers of events found in the data. Scanning the monte carlo events showed that events occurred which looked like the one in Fig. 44. This indicated that the approach of using both the event topology and fitting information was a sensible one.

6.3.6.3 Tau Pair Production

Taus have a mean decay length of 1.05mm [36], but decay to one, three or five prongs. The three prong decay has been a problem in that if one track is not reconstructed or is reconstructed poorly then it mimics a two prong. Two events from the sample with long decay lengths (discussed above) were of this type.

6.3.6.4 Heavy Quark Decays

Heavy quarks produced high multiplicity decays and had typical decay distances of a few hundred microns at PETRA energies. They would place a lower limit on the detectable heavy lepton lifetime if a search strategy using high multiplicity events was followed. The occurrence of high multiplicity jet type hadronic events also placed an upper limit on the mass of any neutral heavy lepton which could have been detected, as shown by the monte carlo studies in chapter four. However, because the search strategy in this work was concentrated on low multiplicity events, heavy quark decays were not a source of background.

6.3.6.5 K^0 Production

$K^0 \rightarrow \pi^+\pi^-$ was another possible source of background as $c\tau = 2.67$ cm, but the pions had the invariant mass of the parent (498 MeV/c²) so a calculation of the pair invariant mass allowed K^0 's to be identified and rejected. It turned out that the invariant mass distribution for the track pairs showed no peak at the K^0 mass, as stated earlier.

6.4 CALCULATION OF LIMITS ON L^0 PRODUCTION

6.4.1 In This Search

Fig. 8 in chapter 2 showed the predicted mean decay length l_0 , as a function of mass for a heavy neutrino with mixing parameter ϵ between 0.01 and 1.0. In the mass range considered, the predicted cross section for pair production of heavy neutrinos was 0.8 pb, (approximately independent of mass) so the number of events expected with the TASSO luminosity was $N_0 = 20$. The monte carlo studies in chapter four showed that an acceptance of around 35 % was obtained for L^0 events with decay lengths up to 10 cm, so 7 of these events could have been observed.

With no candidates seen in the decay length range from $l = 1$ mm to $l = 10$ cm, the 95 % confidence level expectation would be to see $N(1) = 3$ events, which could have any measured decay length of l in this range. The L^0 's would decay exponentially where :

$$N(l) = N_0 \exp(-l/l_0)$$

This is used to obtain the mean decay length l , where the 3 events are assumed to all be measured first at $l = 1$ mm, which gives the higher mass limit and then at $l = 10$ cm which gives the lower mass limit. The conversion from decay length to mass depends on ϵ . These limits are shown in table 21 and are used to draw an excluded region in the mass - decay length plane as shown in Fig. 46. This excluded region is quite small but it is stressed that it is model dependent.

6.4.2 Comparison With Other Experiments

To allow comparison with other experiments: If B is the topological branching ratio for L^0 decay to two charged particles and any number of neutrinos, then the 90 % c.l. upper limit on $\sigma.B$ is 0.26 pb for masses less than 8 GeV/c².

Other searches with negative results have been performed at PEP, at a centre of mass energy of 29 GeV.

HRS [44], looked for the production of pairs of neutral particles decaying to an electron and a minimum ionising particle. The events they found could all be interpreted as background giving a limit on $\sigma.B$ depending on mass and lifetime which was in the range from 0.08 to 0.2 pb.

MK II [45], have looked for particles with long decay lengths. They did not find any with decay lengths in the range from 1 to 20 cm and with heavy neutrino masses from 1 to 13 GeV/c².

The present search is complementary to these searches because of the higher energy of PETRA compared to that at PEP.

TABLE 21			
Mean Decay Length and Corresponding Mass			
l (measured) cm	l ₀ cm	L ⁰ Mass (GeV/c ²)	
		ε = 1.0	ε = 0.01
0.1	0.053	2.07	4.42
10.0	5.3	1.0	2.07

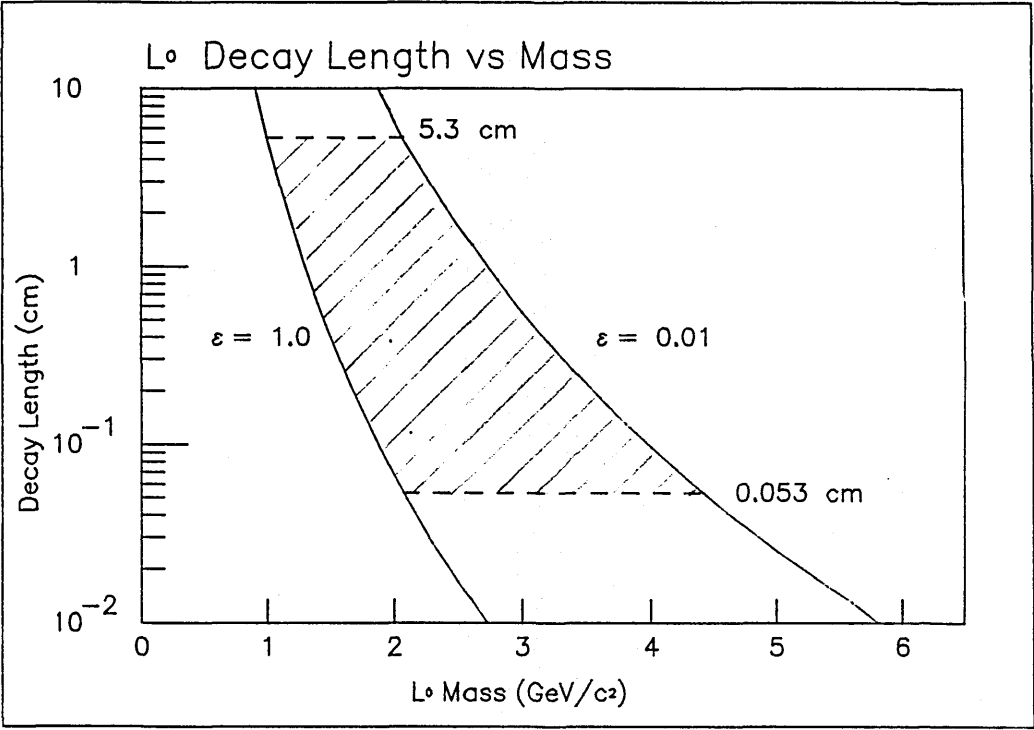


Figure 46: Heavy Neutrino Production Limits

6.5 CONCLUSION TO THIS SEARCH

The decay length region from around 1 mm to 10 cm has been investigated for a neutral particle decaying to two charged particles. The events found could be explained by background processes. There is presently no evidence for the production of heavy neutral particles in e^+e^- annihilation at centre of mass energies up to 45 GeV.

6.6 GENERAL CONCLUSION

There is no evidence for any new neutral particles, from this experiment, or from other experiments studying e^+e^- annihilation.

If new particles had been observed here then they could have been incorporated into the theoretical framework and perhaps would have opened a new window on some of the unanswered questions in the standard model. These questions, at least in terms of what the neutral particle sector can say about them, will have to wait for other experiments using different probes or, in the case of e^+e^- , higher energies.

It now appears that the unusual events seen in the early proton-antiproton collider runs have not been confirmed by subsequent running, which supports the lack of evidence for monojets from e^+e^- experiments.

These conclusions should not however be taken as too depressing because they point to the strength of the standard model in its ability to describe all the phenomena we have so far observed.

Appendix A

THE TASSO COORDINATE SYSTEM

The TASSO coordinate system is shown in Fig. 47. The axes were defined such that the x axis points towards the centre of the PETRA ring, the y axis points vertically upwards and the z axis is in the direction of the positron beam.

The track projection in the x-y plane shown in Fig. 48. has the parameters :

d_0 is the distance of closest approach of the track to the origin in the x-y plane.

z_0 is the distance from the track to the origin in the z direction at the point where d_0 was measured.

ϕ_0 is the angle between the x axis and the tangent to the circle at the point where d_0 was measured.

r_0 is the radius of the track circle.

θ is the angle between the track and the z axis.

Q is the charge of the track (± 1).

p is the track momentum.

p_t is the track momentum component in the x-y plane.

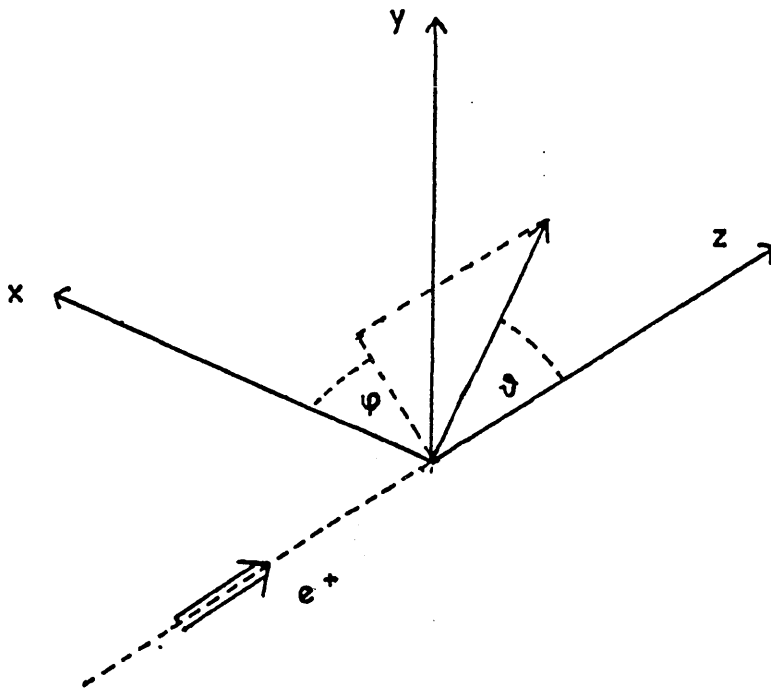


Figure 47: TASSO Coordinate system

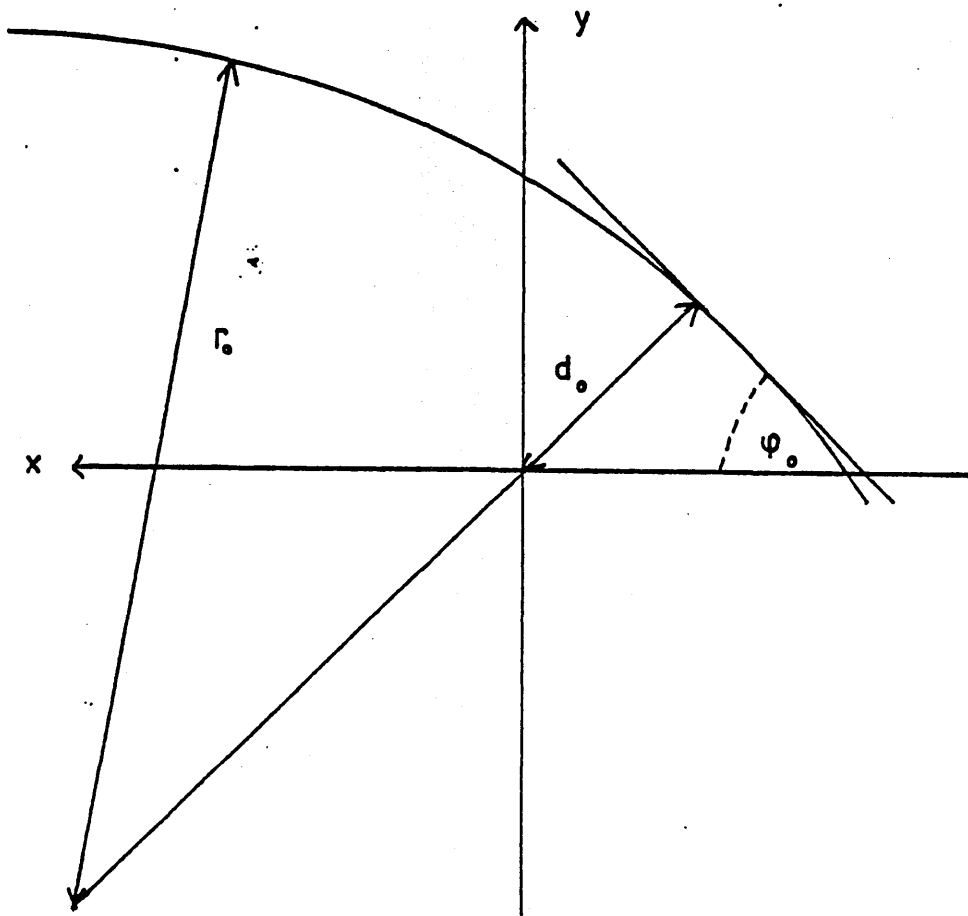


Figure 48: Track projection in x-y plane

Appendix B

JET VARIABLES

The Sphericity S is defined as :

$$S = \frac{3}{2} \text{Min} \frac{\sum (P_{Ti})^2}{\sum |P_i|^2} \quad 0 \leq S \leq 1$$

The Thrust T is defined as :

$$T = \text{Max} \frac{\sum |P_{Li}|}{\sum |P_i|} \quad 0.5 \leq T \leq 1$$

where P_{Li} and P_{Ti} are the longitudinal and transverse momentum components of a charged particle with respect to the jet axis.

The sphericity axis is defined from the eigenvector of a momentum tensor :

$$M_{a\beta} = \sum_{j=1, N} P_{ja} P_{j\beta} \quad a, \beta = x, y, z$$

P_{ja} are the momentum components of the N charged tracks in the event.

The normalized eigenvector corresponding to the largest eigenvalue of this tensor is the sphericity axis.

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