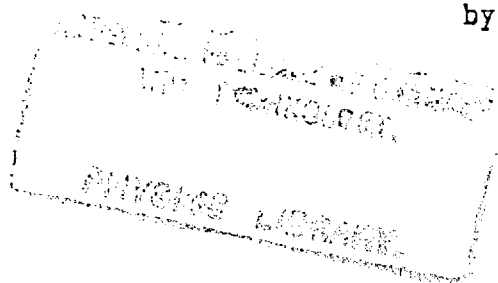


J/ψ PRODUCTION BY 175 GEV/C π^- Be COLLISIONS

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ABSTRACT

J/ψ production in 175 GeV/c π^- beryllium collisions.

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This thesis describes the dilepton experiment WA11, carried out using a large acceptance spectrometer at the CERN Super Proton Synchrotron. The apparatus, triggering techniques, and on-line monitoring are discussed and the data processing described.

An appraisal of the data taken with a $2e$ trigger is described. The 2μ data is used to study mechanisms of hadronic J/ψ production. The possibility of associated production of charm is investigated by analysing additional leptons, and found to be negligible. A search for χ states is carried out using information from the photon position detector and calorimeter and a large fraction of J/ψ 's are found to be formed via intermediate χ states.

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Chapter_1

Introduction

1.1 Quark - Parton Model

In the early 1960's the number of observed elementary particles rose to such a level that it was seriously questioned whether or not they were indeed "elementary". The natural approach to a more simplified scheme was to categorise them into separate groups of particles with similar properties, such as spin and parity, in a manner similar to Mendeleev's Table of the Elements. The idea of looking for regularities in such a fashion proved so successful, that, just as new elements were predicted and found as a result of gaps in the Periodic Table, so new particles were found.

Taking the parallel still further, Gell-Mann (Ref 1) and Zweig (Ref 2) proposed that each "elementary" particle had yet simpler constituents, which they called quarks. At the time three different types, or flavours were sufficient to construct all known hadrons, baryons consisting of 3 quarks, and mesons of quark-antiquark pairs. However, their somewhat unusual fractional quantum numbers, especially that of electric charge, together with their non-observation in free state led to a scepticism lasting some years. Their credibility was further worsened by the notion of requiring 3 "colour" degrees of freedom as well as 3 flavour degrees

of freedom, i.e. each flavour of quark can exist in any of 3 different colour states, as long as the overall hadron colour factor cancels out (the hadron is "colourless"). This was initially introduced to make quarks comply with Fermi spin statistics, but was later endorsed by the partial width of the decay $\pi^0 \rightarrow \gamma\gamma$, and the total annihilation cross-section of e^+e^- into hadrons.

These difficulties were not conceptually prohibitive however, and the trend was a widespread movement towards accepting the existence of quarks. Fractional quantum numbers were not a big problem, half-integral spin for example, being naturally predicted by quantum mechanics. The fact that free quarks had not been observed was then explained by very large quark masses and potential wells, such that the accelerators then available could supply sufficient energy neither to create quarks, nor overcome the binding energy between them.

In 1969 Feynman (Ref 3) deduced that nucleons might have hard, point-like constituents, which he called partons. This work was primarily to explain the phenomenon of Bjorken scaling (Ref 4) in deep-inelastic scattering, which essentially expresses the differential cross-section at high energy and 4-momentum transfer in terms of dimensionless quantities only. The absence of a fixed dimensional parameter indicates that deep-inelastic scattering is independent of any basic scale length, i.e. the interaction is between point-like entities. This provided an explanation for the anomaly of the high

differential cross-section found at large transverse momenta in e - p , μ - p and π - p scattering (Ref 5) by likening it with Rutherford's observations of the scattering of α -particles on gold nuclei. Thus, the naive parton model considers a high energy hadron to be a collection of free, point-like partons.

A study of high energy inclusive lepton-hadron scattering has since deduced several properties of partons, which strongly suggested that they are the quarks proposed by Gell-Mann and Zweig. By comparison with Dirac scattering, one can deduce the Callan-Gross relation (Ref 6) as borne out by experiment. This confirms partons to have spin $1/2$, an almost mandatory property for the satisfactory explanation of hadron spectroscopy. Further theoretical study predicted there to be an infinite number of partons inside the nucleon. This is consistent with the belief that hadrons consist of 2 or 3 valence quarks, together with an infinite sea of virtual quark-antiquark pairs.

Further investigation of deep-inelastic lepton scattering indicated a breakdown of the naive parton-quark model with the discovery both of scaling-violation, and that half the nucleon momentum is carried by particles other than charged partons. These defects were reconciled by quantum chromodynamics (usually known as QCD). This theory is an extension of the quark model along the lines of quantum electrodynamics, or QED, the extremely accurate theory of electro-magnetic interactions. The major difference is that the strong quantum, the gluon, carries

(colour) charge, whereas the photon carries no (electric) charge, and as a result the gluons are able to couple to themselves as well as to quarks. This makes the theory very complex, but yields the "asymptotic freedom" of the parton model, in which the coupling between quarks tends logarithmically to zero as their separation tends to zero. It is hoped that it will also lead to "confinement", the name given to the rise of coupling constant with increasing distance. This explains why free quarks are not seen. QCD, as a quantum theory of coloured quarks and gluon fields has now been sufficiently developed to emerge as the leading candidate to provide the means of a global description of hadron dynamics.

1.2 The Effect of the ψ

Evidence also existed however, which indicated that 3 flavours of quarks might be insufficient to explain weak interactions. Aside from the aesthetically pleasing lepton-quark symmetry an additional flavour would create, it was needed so that Gauge Theories could comply with the experimental observation of decays showing an absence of strangeness changing neutral currents, eg $K^0 \rightarrow \mu^+ \mu^-$. These decays were predicted to proceed several orders of magnitude faster than they were measured. A new flavour would cancel the unwanted neutral currents and $|\Delta S|=2$ transitions via the GIM mechanism (Ref 7) and so it was labelled "charm" in analogy with the way that a magical charm protects against or cancels evil.

Thus, the discovery of the heavy, long lived ψ states by BNL and SLAC in 1974 (Ref 8) initiated an era of "New Physics", their existence being satisfactorily explained as a bound state of this fourth quark together with its antiparticle. From this a whole field of charm spectroscopy ensued, and a family of other stable states consisting of a charm quark bound with u, d or s quarks was predicted, and subsequently found. Later still, experimental evidence for another quark, the bottom quark, was produced by the discovery of the Υ meson. Whether or not the number of flavours of quarks will be further extended is as yet unknown.

1.3 ψ Production Mechanisms

There are many mechanisms which can be constructed to produce a ψ in hadronic collisions, the most favoured having been in dispute and confusion. Some of these mechanisms are described below. As a result of considerable experimental work a much clearer picture of the processes involved has developed, and it is now realised that no one process can dominate at all energies for all possible beam particles.

An important feature regarding which $c\bar{c}$ state (ψ or χ) is formed is the C-parity of the gluon, -1. Since the colourless ψ also has negative C-parity it can only couple to an odd number of gluons, and since the gluons are colour charged, the lowest order process is a 3 gluon coupling. The χ , on the other hand, has positive C-parity, and so couples to an even number of gluons, subsequently cascading

down to a ψ with the emission of a photon.

1.3.1 Electro-magnetic Production

At the time of the discovery of the ψ work was being carried out on the study of the production of lepton pairs in hadronic collisions. This was believed to occur via the Drell-Yan mechanism (Ref 9) Fig 1.1a, whereby a quark and an anti-quark annihilate producing a virtual photon which then couples directly to a lepton pair. It was a plausible suggestion that the ψ might be simply a resonant form of this process in a manner shown in Fig 1.1b. This was disproved quite quickly by comparing the ψ 's produced hadronically with those produced electro-magnetically in e^+e^- colliding beams, Fig 1.1c.

The ratio of signal to background at m_ψ in electro-magnetic production (R_{ee}) and hadronic production ($R_{p\pi}$) have both been measured experimentally. If electro-magnetic production is important in hadronic collisions, one would expect $R_{ee}=R_{p\pi}$. Since $R_{p\pi} \sim 100 R_{ee}$ (Ref 10) the evidence is fairly conclusive that electro-magnetic processes are not a major contribution to the hadronic cross-section.

1.3.2 Charm Quark Fusion

This is the fusion of a charm quark with a charm anti-quark, both from the sea, to form a ψ , Fig 1.1d. If there are no final state cancellations, this must result in the

production of associated charmed hadrons as the spectator charm quarks dress themselves to form the final colourless states. However, since the charm sea quark momentum distributions are suppressed with respect to light sea quarks and valence quarks, it is believed that this mechanism of producing a high mass $c\bar{c}$ state may be unimportant. This is consistent with the experimental non-observation of these charmed hadrons in their expected leptonic decay channels (Ref 11).

1.3.3 Light Quark Fusion

Basically, this involves the annihilation of a light quark and antiquark into gluons. The q and $\bar{q}$ can originate from either valence quarks or sea quarks, with the obvious exception that, in baryons, $\bar{q}$ are only found in the sea. The direct production of a ψ via a 3 gluon exchange is shown in Fig 1.2a. This process has 6 quark-gluon vertices, each with an associated coupling of $\alpha_s=0.2$, and so is strongly suppressed. Less suppressed diagrams can be drawn where the intermediate $c\bar{c}$ state couples to only 2 or 1 gluons (Fig 1.2b, 1.2c) shedding its excess colour by soft gluon Bremsstrahlung. Fig 1.2d shows the production of a χ state by a similar mechanism, radiating a photon in turn to form a ψ . It is argued that the kinematics of the final state depend mainly on the properties of the fusing quarks, and are smeared out only a little by the radiated soft gluons and photons (Ref 12).

At one time, this mechanism was highly favoured. One of

the reasons was derived from observations that the X_F distribution of the ψ 's produced with meson beams peaked at positive values of around 0.15 (Ref 10). This was explained by the valence quarks in the meson carrying on average an equal share of momentum, i.e. $1/2$ the meson momentum each in the centre of mass system (CMS). Quarks from the nucleon however, carry only $1/3$ of the nucleon momentum each, resulting in an X_F distribution which peaks at the difference between these values, i.e. $1/6$. Consistent with this belief was the observation of the ψ X_F distribution for nucleon-nucleon collisions being symmetrical about zero. Contrarily, the sea and glue were expected to be the same for all hadrons, and hence should show no such effect. It was later proposed, however, that each individual quark has its own gluon field, together with an associated sea which arises from the polarisation of this field. This invalidated the distinction between mechanisms in this fashion.

Another convincing result in support of this mechanism comes from experiments carried out comparing cross-sections for the ψ produced by p (with no valence antiquarks) and $\bar{p}$, and finding a ratio of $\frac{\sigma(pp \rightarrow \psi X)}{\sigma(\bar{p}p \rightarrow \psi X)} = 0.15$ (Ref 13). This is best explained by valence quark fusion, assuming that the glue and sea are the same for p and $\bar{p}$. Theoretical calculations would expect a ratio of one for gluon fusion. However valence quark fusion is now understood to be dependent on $\sqrt{s}$, and of considerably less importance at higher energies.

1.3.4 Gluon Fusion

This mechanism involves each of the incoming hadrons (in CMS) emitting a gluon which then couple together. Although 2 gluons can only couple to a positive C-parity state, a ψ can still be produced "directly" if the intermediate state is colour charged (Fig 1.3a, 1.3b). The colour is then removed by gluon bremsstrahlung. The ψ can also be produced via intermediate χ states by very similar processes, such as is shown in Fig 1.3c, where a χ is formed directly as a result of gluon fusion. Fig 1.3d shows a 3 gluon self-coupling, followed by a $c\bar{c}$ creation from the single gluon. The χ state then emerges after the colour has "evaporated" by the emission of a soft gluon. Other, higher order diagrams can of course be added. Consideration of the momentum distribution functions of the various partons inside hadrons results in the prediction that gluon fusion should become the dominant process at high energies for all possible types of beams and targets. It is also expected to dominate at low energies for N and K^+ beams, as they have no valence $\bar{u}$ or $\bar{d}$ quarks which can annihilate with the valence quarks of the target.

1.4 Experimental Detection of the ψ

The decay mode of the ψ which led to its discovery - into lepton pairs - is frequently used by high energy physics experiments to detect the ψ because of its relatively clear signature. At the time of the proposal of

the WA11 experiment, which of the 3 mechanisms above were the most important in producing the ψ was in dispute. One method of investigation would be to study the kinematic parameters of the di-leptons, such as X_F , differential cross-sections and decay angle distributions, and compare them with the results predicted by QCD. This is the method used by "beam dump" experiments, which place a large amount of material of high atomic number a metre or so downstream of the target (to enable separation of interactions in the target from those in the absorber) and analyse the particles which emerge in some form of spectrometer. This results in :

a) a very clean trigger. The only particles seen are prompt μ 's and μ 's arising from decays upstream of the absorber. All particles other than μ 's then interact either electro-magnetically or hadronically with the absorber before they have had time to decay, and as a result they are eventually stopped inside the material.

b) a high luminosity. Any interactions which do not produce prompt μ 's will not fire the trigger, so with such a low background, an intense beam can be used before the event rate becomes too large for the apparatus to handle.

c) a very poor resolution. The μ 's suffer severe multiple scattering in the filter before entering the spectrometer and as a result, it is difficult to know the position of the vertex and the opening angle - required for reconstructing the 2μ mass. Particle measurement between the target and the μ filter, and hence improvement of the

vertex measurement, is not possible because of the high luminosity - the interaction rate is so high that the electronic equipment would not have enough time to recover between consecutive events. This is not an unsurmountable handicap due to the high statistics which result from the increased luminosity, although it does usually exclude the possibility of separating the ψ from the ψ' .

d) the detection of associated particles is made very difficult. Although conjoint production of charm is possible through a search for additional μ 's, a complete study is not feasible, as no other particles are detected.

Given the above limitations of beam dumps, the need for experiments which measure the final states was clear. The characteristics of these experiments are quite different from those of beam dumps :

a) as the apparatus needs to be very long (several metres) in order to have good particle identification, there is sufficient time for hadrons such as π and K mesons to decay in flight. This provides additional leptons to the background, and results in a high trigger rate.

b) since each interaction results in particles entering the apparatus, only a limited luminosity can be used before confusion between consecutive events occurs. This requires that the apparatus used has a high geometric acceptance.

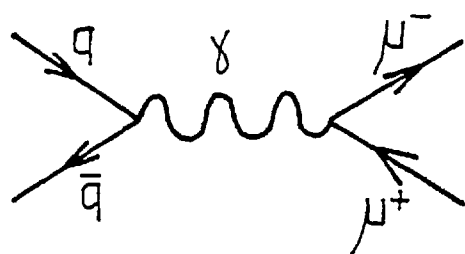
c) a very good resolution is obtained, as the leptons can be accurately tracked through the spectrometer. Despite the lower statistics this clean signal allows an easy study of

both the ψ and the ψ' , there being no overlap between the two states.

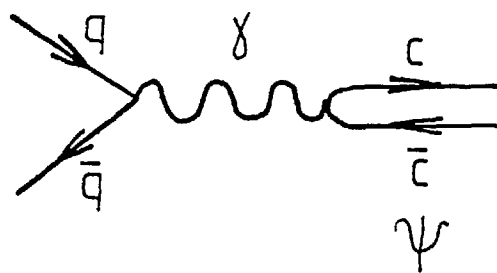
d) The particle identification enables a more detailed analysis of the final states. Thus a search for photons or additional leptons produced in association with the ψ can be a useful tool for discrimination between the various processes.

It should also be mentioned that ψ production as a result of very high energy pp collisions can be studied using the CERN Intersecting Storage Rings (ISR). Although the luminosity is somewhat low, this facility provides a means of studying interactions at CMS energies unavailable to current beam-target experiments. The apparatus used is in many respects similar to those of the non-beam-dump (or "open") experiments described above.

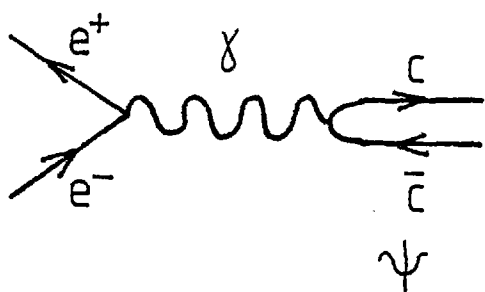
The experiment reported here (the WA11 experiment) was of the "open" type and was designed to be able to study not only the ψ , but also the particles produced with it. This thesis reports the search for χ states by detecting them via their photonic decay to the ψ , and the conjoint production of charm by studying the μ 's and e's found in the final state with the ψ .



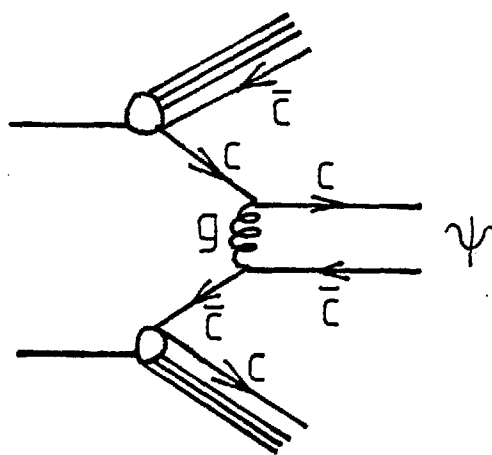
(a) Drell-Yan process



(b) e.m. ψ production

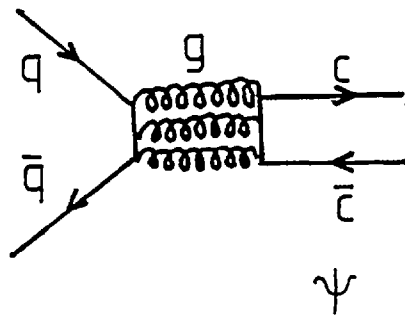


(c) e^+e^- ψ production

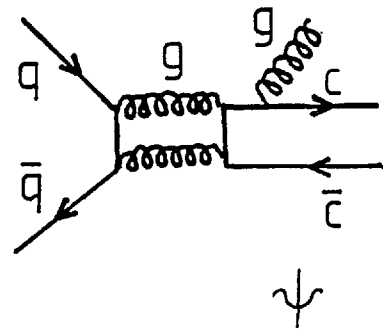


(d) $c\bar{c}$ fusion

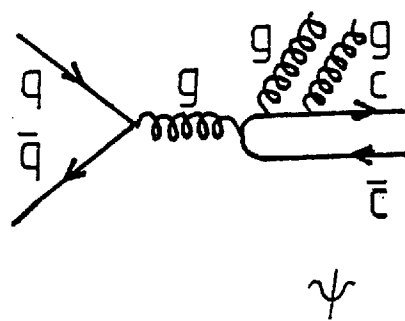
Fig 1.1



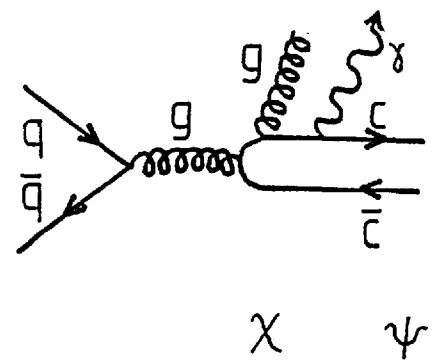
(a)



(b)

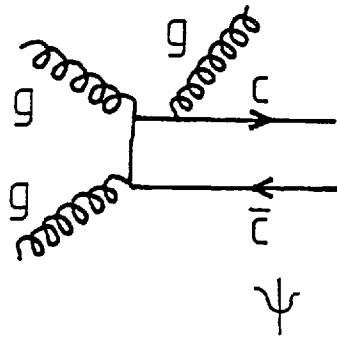


(c)

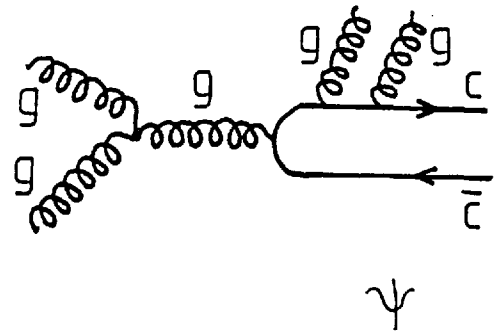


(d)

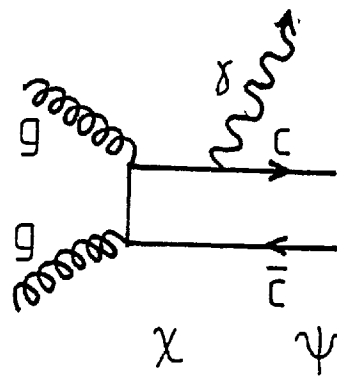
Fig 1.2: Valence Quark Fusion



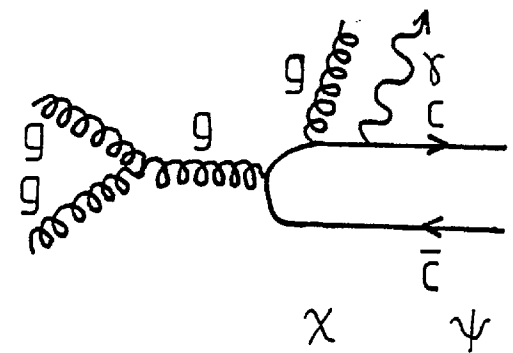
(a)



(b)



(c)



(d)

Fig 1.3 : Gluon Fusion

Chapter 2

The WA 11 Experiment

2.1 Apparatus

The more salient features of the experiment will be briefly presented in this chapter. The calorimeter and trigger technique will be described in more detail in chapter 3. The apparatus (Fig 2.1) was originally designed to study the ψ by triggering on its 2μ decay mode and consisted of a spectrometer with hodoscope and cerenkov counters. Imperial College later joined the collaboration by providing an electro-magnetic calorimeter as a means of identifying associated electrons and photons. The intention was also to form a $2e$ trigger operating in parallel with the 2μ trigger at a later date. This, it was hoped, would be able to double the number of ψ events obtained.

2.1.1 Beam

The apparatus was situated in the high energy, high intensity H3 beam produced from target T5 during the slow spill of the CERN SPS (Ref 14). The data were taken from September 1977 until the summer shutdown in 1980 at π^- beam energies of 140, 150, 175, 185 and 192.5 GeV, with a $\pm 2\%$ momentum acceptance. The yield was $6 \cdot 10^6 \pi^-$ per $10^{12} p$, leading to a typical π^- intensity, "Pinc", of $4 \cdot 10^6 \pi^-$ per burst. The K^- and $\bar{p}$ contamination was $4 \cdot 10^{-3}$ and $5 \cdot 10^{-4}$

respectively. The incident beam trajectory was measured by a hodoscope formed by the horizontal (T0) and vertical (T1) scintillators situated 10m and 1m upstream of the targets respectively. The useful beam area was defined to be 1.2cm^2 by scintillators S1.

2.1.2 Target

The experiment was proposed using a 1 metre long liquid hydrogen target ($\rho=7\text{ gm/cm}^3$) but this was rejected in favour of beryllium targets of density, $\rho = 16.4\text{ gm/cm}^3$ to increase the ψ production rate. In order to reduce photon conversions and other secondary interactions, the target was chosen to be fragmented into 3 pieces positioned 271.4cm, 230.0cm and 181.7cm upstream of the centre of the magnet.

The nucleon density, D , of the targets is related to ρ by the atomic number of the target, A , and Avagadro's number N_A

$$D = \rho \cdot N_A / A \cdot A = 16.4 \cdot 6 \cdot 10^{23} = 10^{25} / \text{cm}^2$$

The resultant event rate, R , for a process of cross-section σ per nucleon is given by

$$R = P_{\text{inc}} \cdot D \cdot \sigma \text{ per burst} = 4 \cdot 10^6 \cdot 10^{25} \cdot \sigma = 4 \cdot 10^{31} / \text{burst}$$

The event rate per cross-section (R/σ) can be called the luminosity, L .

2.1.3 Spectrometer

The central part of the apparatus was the Goliath magnet, so named due to its size, having an aperture 2m wide by 1m high and providing a field of 1.5 Tesla. The large acceptance spectrometer (described fully in Ref 15) consisted of 13 multi-wire proportional chambers (MWPC's). Situated inside the fringe field zone of Goliath, and downstream of the targets were chambers F1 and F2. These had 3 sense planes of area 23 by 61 cm, with 2 planes of pitch 2mm and 1 of 1mm. Centered inside the magnetic field followed 9 MWPC's (D3 - D11) having 4 sense planes of 2mm pitch and useful area 1.8m by 0.74m. These were responsible for the accurate momentum resolution.

Downstream of the magnetic field was a 2.5m lever arm, comprising 2 large MWPC's (D2 and D1) of 3.2m by 2.2m. Each chamber had 4 sense planes of 3mm pitch. This played an important role in calculating roughly the charged particle trajectories without having to perform tracking in the magnetic field. It could also be used to estimate the invariant mass of the trigger particles in the software analysis. Sandwiched between the 2 lever arm chambers was a 28 celled cerenkov counter, filled with carbon dioxide at atmospheric pressure. This provided limited p, K and π separation at threshold energies of 33, 17 and 5 GeV.

2.1.4 Calorimeter

The calorimeter is described in detail in Ref 16, but

briefly, consisted of 7 planes of detectors arranged in a criss-cross array as shown in Fig 2.2. The most important part was the Pb-scintillator sandwich type shower counters, B and D, arranged in vertical modules of 25cm width. The B counters each contained 3.8 radiation lengths of material in the form of 7 Pb sheets interleaved with 6 sheets of scintillator. The D counters contained 9 Pb sheets of total thickness 9.6 radiation lengths, with 9 sheets of scintillator. These counters provided a measurement of shower energies, together with a crude estimate of the y coordinate.

The four planes of counters H1H, A, C and E, formed a hodoscope of horizontal strips, giving information on the shower z coordinate. The A counter consisted of 2 strips of scintillator, joined at the photomultiplier end, interleaved with a Pb sheet of thickness 1.1 radiation lengths. 1.7 radiation lengths of Pb was placed immediately in front of the A counters to initialise shower development. The C counters were placed between B and D, 6.6 radiation lengths after the targets, intentionally at a position of maximum shower intensity. Following the D counters was a Pb wall making a total of 32.5 radiation lengths of material upstream of the E counters. The strip width of each plane differed slightly such that the edges pointed back in the vertical sense to the central target. A typical width, that of the C counters, was 12.5cm.

To allow the beam to pass through the apparatus, a hole was made at the centre of the calorimeter. This was done

by withdrawing the innermost B counter of each quadrant by 12.5cm (the width of a single C counter) and the innermost C counter of each quadrant by 25cm (the width of a single B counter) giving a hole 50cm by 25cm.

A large MWPC, D0, identical to those employed in the lever arm, was situated after the A counters, and was essential for locating electro-magnetic showers, in particular photons, a task which could not be carried out by the spectrometer. This had the disadvantage of reducing the effective width of the calorimeter to 3m, as the steel frame intercepted some of the electrons in the outer two B counters of each quadrant, giving rise to very unreliable energy measurements. This affected 7% of all tracks, equivalent to a loss of calorimeter information on 10% of otherwise good tracks.

In addition, 5 scintillator sheets, called "Trou" counters, were set up in the beam-line itself at the very end of the calorimeter in an effort to measure the energy escaping detection due to particles lost in the hole. Unfortunately, their resolution was too poor to be of much use.

2.1.5 Muon Hodoscopes

The μ hodoscopes consisted of 3 planes of scintillator strips. The 2 horizontal arrays H1H and H3H were positioned either side of 2380 gm/cm² of iron which acted as a hadron and electro-magnetic absorber. The scintillators

had slightly different strip widths, and were arranged such that the edges of corresponding counters projected back to the central target in a similar fashion to the calorimeter hodoscope. The vertical array, H3V, was positioned downstream of the iron wall, and together with H1H and H3H located the μ position to within a cell 6cm by 6cm.

It was the μ hodoscopes which limited the angular acceptance for the ψ subtended by the apparatus (± 160 mrad vertically by ± 250 mrad horizontally).

2.2 Di-lepton Triggers

For 175 GeV π -Be collisions the mean multiplicity is of order 10, comprised mostly of π mesons, some of which decay in the 8m necessary for their identification between the targets and the iron shield, producing a considerable background. The number of decay leptons decreases with increasing parent momentum, and they are mainly emitted at low p_T . Use is made of this to help reject them at the trigger level. The effective mass, m_{12} , of two particles is related to their momenta (p_1 and p_2) and opening angle (θ_{12}) roughly by the expression

$$m_{12}^2 \sim p_1 p_2 \theta_{12}^2$$

Since the background "mass" is small with respect to the ψ mass, they can be rejected by the following conditions:

- a) large lepton momentum is obtained by the magnetic

field of Goliath, which sweeps out of the trigger system most particles with momentum less than 5 GeV/c. Fig 2.3b shows the momentum distribution of all tracks with $p > 1$ GeV/c produced at the target. Fig 2.3a displays the momentum distribution of the decay leptons of the ψ , as calculated by Monte Carlo technique. A comparison of the two shows that a 5 GeV/c momentum cut rejects 42% of background tracks, yet only 20% of the ψ 's.

b) large di-lepton opening angles are demanded by having no contribution to the trigger from horizontal scintillator strips at or near the horizontal median plane. This formation of a vertical gap could not be performed in the horizontal sense due to the magnetic deviation of the tracks.

c) opposite charged leptons were demanded by triggering on diagonally opposite quadrants. Although this cut lowers the ψ acceptance it was required to reduce the trigger rate to an acceptable rate as it suppressed the background in preference to the signal. Figs 2.4a and 2.4b show plots of the position of positive and negative tracks at the calorimeter. It can be seen that asking the two trigger particles to be in opposite "left-right" halves will cut down background from particles of the same signed electric charge considerably. Similarly, the initial p_T of the decay leptons in the vertical sense implies that they will tend to be located in opposite "up-down" halves. The combination of these two effects results in a coincidence between diagonally opposite quadrants. Monte Carlo

calculations show that the requirement of opposite quadrants resulted in the loss of 1/3 of otherwise accepted ψ 's. This led to an overall geometric acceptance of 22%.

Once the di-lepton trigger was formed, a coincidence with the event trigger, as defined by several interaction counters about the targets (Fig 2.5) was demanded. The event also needed to satisfy what was called the past and future protection deadtime. This system vetoed any event either during or within 50 ns of the previous or following interaction in the target. This ensured that the outputs of the chambers and counters were due to a single interaction only.

2.2.1 2μ Trigger

The 2μ trigger was formed entirely by the μ hodoscopes. The μ signature was taken as a coincidence of 2 corresponding counters in H1H and H3H, ORed with each of the H3V counters in the same quadrant. A coincidence between 2 single μ 's in opposite quadrants then provided the 2μ trigger.

The background for this trigger came mainly from the μ halo associated with the beam, and the π and K decays in flight. The μ halo was largely removed by the veto counters V1 and V2 and by insisting that the corresponding counters in H1H and H3H point back at the target. Low mass background, coming from, eg, $\pi\pi \rightarrow \mu\mu$, was suppressed by the 20 mrad vertical gap.

The resultant final 2μ trigger rate was $3 \cdot 10^{-6}$ pinc, or equivalently, 12 per burst.

2.2.2 2e Trigger

The main problem of the 2e trigger was the huge background from photon conversions, and misidentified hadrons, hence a sophisticated trigger was required in order to reduce the event rate to an acceptable level.

The signal for a single electron was defined as a coincidence of corresponding horizontal counters H1H,A,C CRed with the vertical B counters in the same quadrant, in a similar manner to the 2μ trigger. In addition, appropriate signals from the cerenkov counters were included to help cut down the background. The 2e signature was then a coincidence between single electrons in diagonally opposite quadrants. The central C counter of each quadrant was removed from the trigger, providing a 30mrad vertical gap.

The 2e trigger rate was eventually reduced to twice the 2μ trigger rate by a series of cuts which reduced the acceptance of ψ 's in this decay mode from 22% mentioned earlier to approximately half the 2μ acceptance of 15%. The method by which this was achieved is described in detail in section 3.5.

2.3 Data Acquisition

When an event was selected by the hardware trigger, the

states of all the counters and chambers were read via a CAMAC interface into the on-line PDP 11/45 computer, which read information into its buffers either when the burst had finished, or its buffers were full. Initially, it was programmed to write to magnetic tape after the burst had ended, but this meant that the amount of data taken was limited by the size of the computer buffers to about 50 events per burst. This was subsequently modified to allow writing during the burst so that up to 100 events could be logged per burst.

During a run, which normally spanned a whole tape, statistics were kept of various counting rates, such as number of incident beam particles, trigger rates, etc, together with other monitor information, and were printed out at the end of the run for immediate study as well as reference purposes. The statistics were also available during the run, together with counter histograms and an event display, so that any anomaly or fault could be checked or corrected as soon as possible.

The bulk of the calorimeter on-line monitoring was performed by a Hewlett Packard 64MX computer, which could operate either via a link with the PDP during data taking, or in a "stand-alone" mode, in which case the calorimeter information could not be passed on to the data tape. This latter option was used mainly during the setting up of the 2e trigger, and for calorimeter calibration runs.

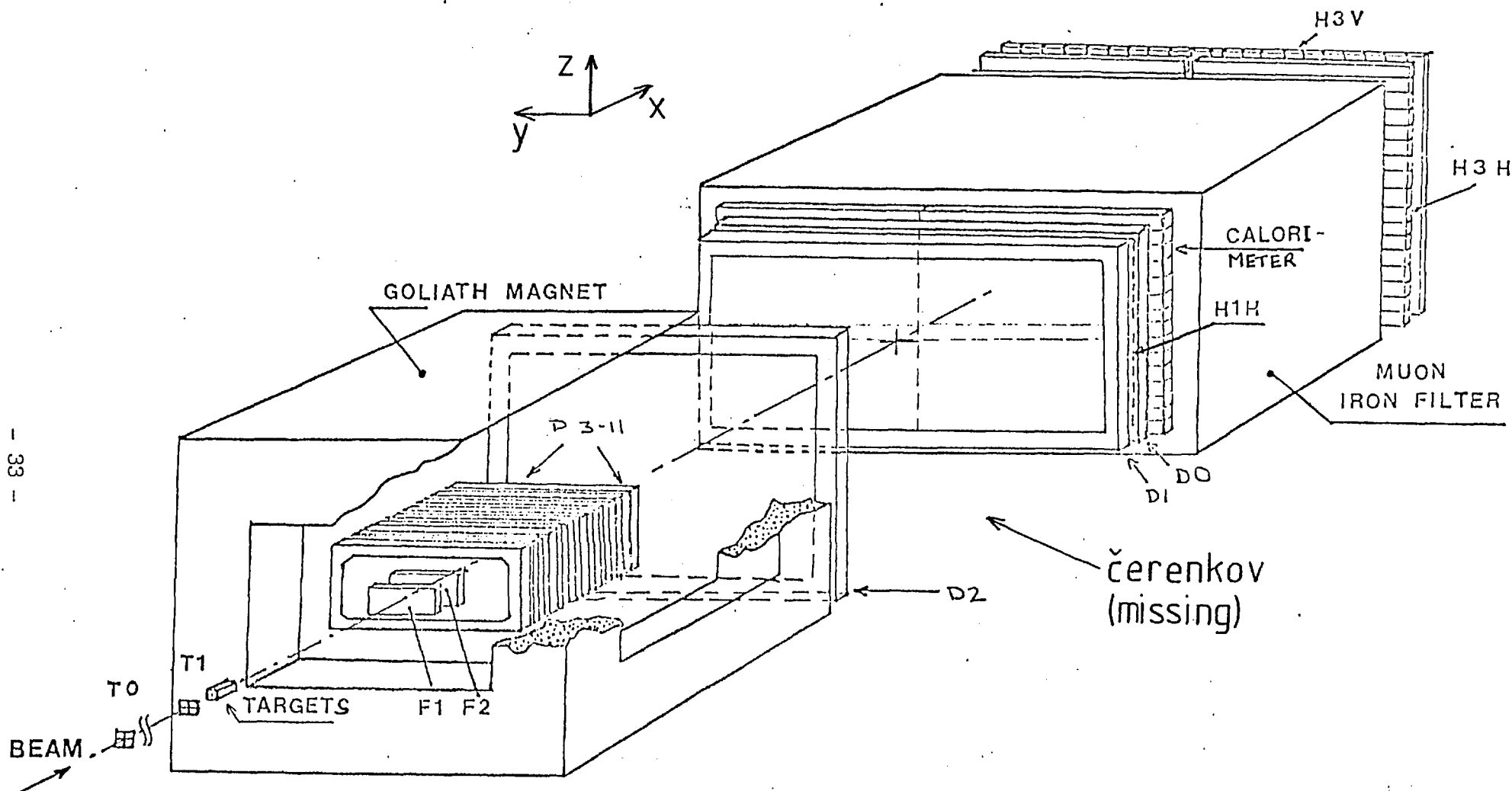
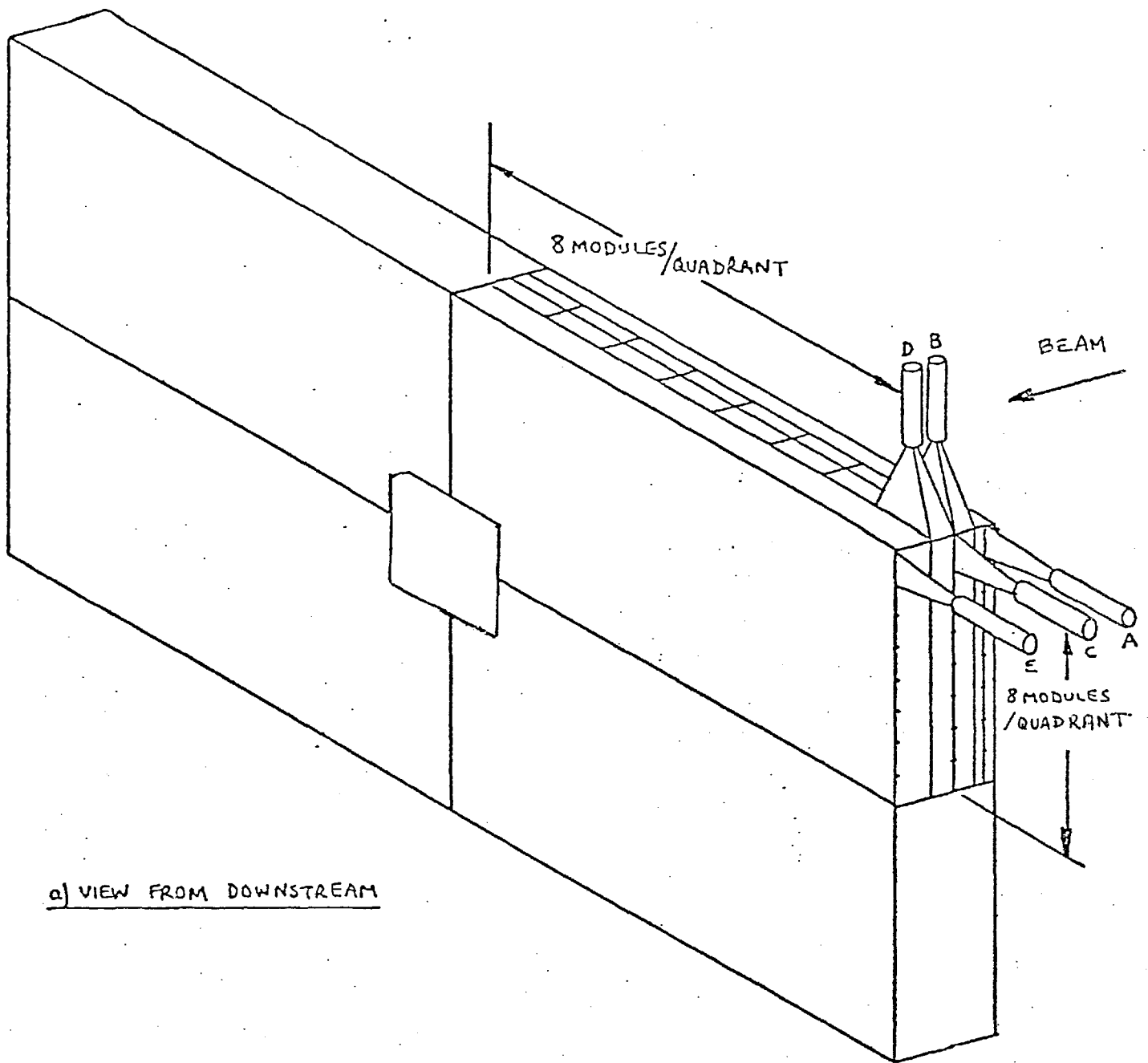


Fig 2.1: Experimental Layout



a) VIEW FROM DOWNSTREAM

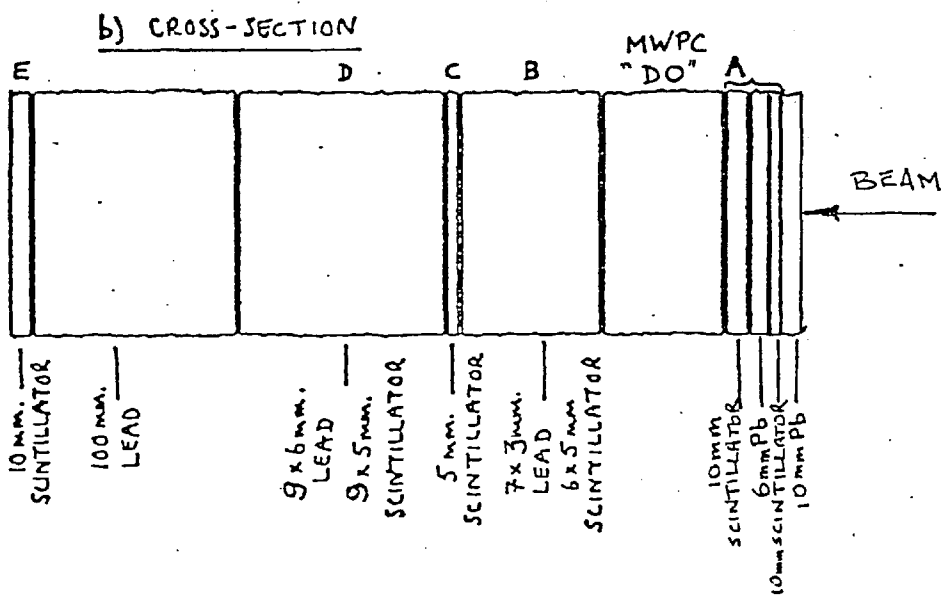


Fig 2.2: Detail of Calorimeter

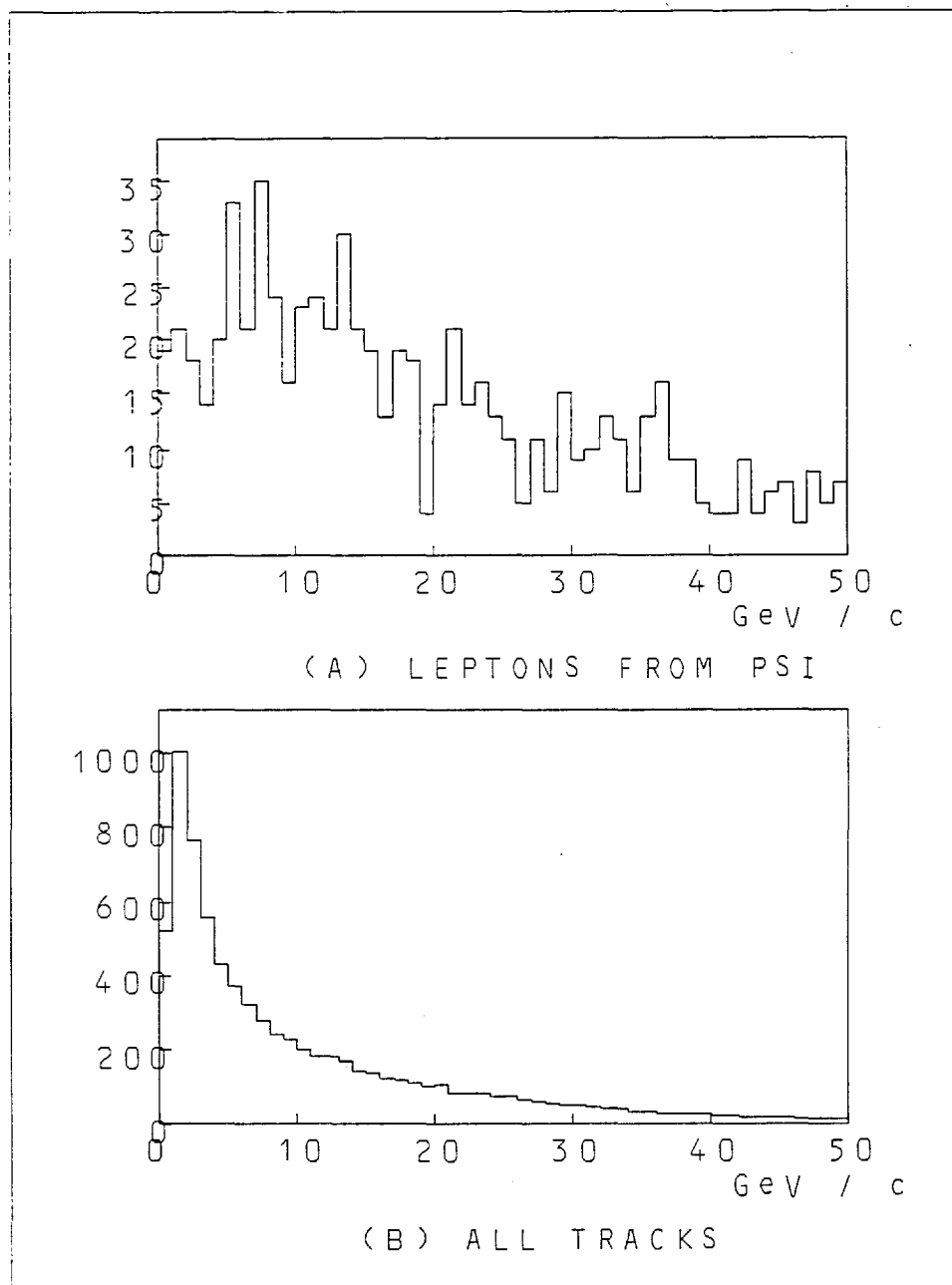


Fig 2.3: Momentum Spectra

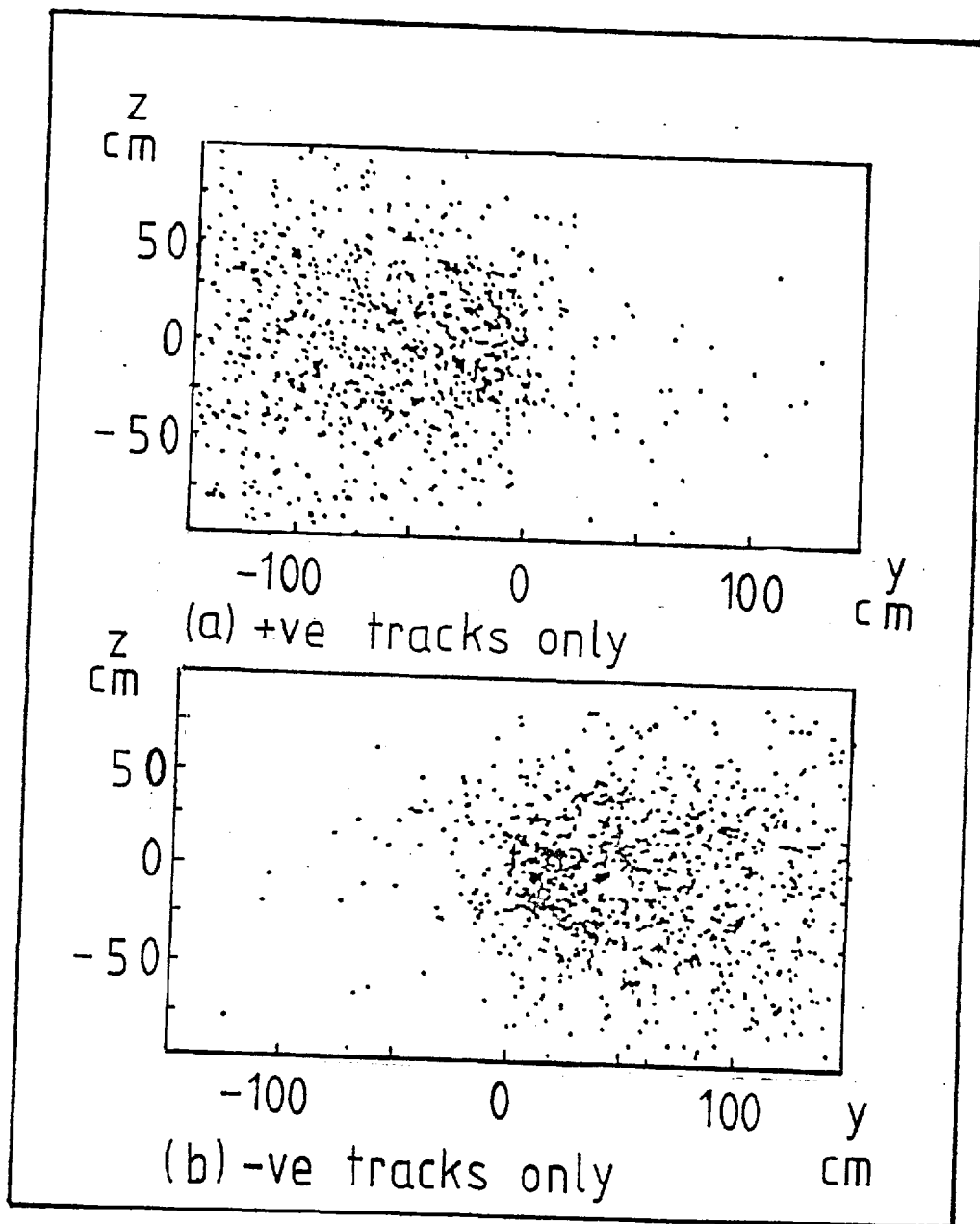
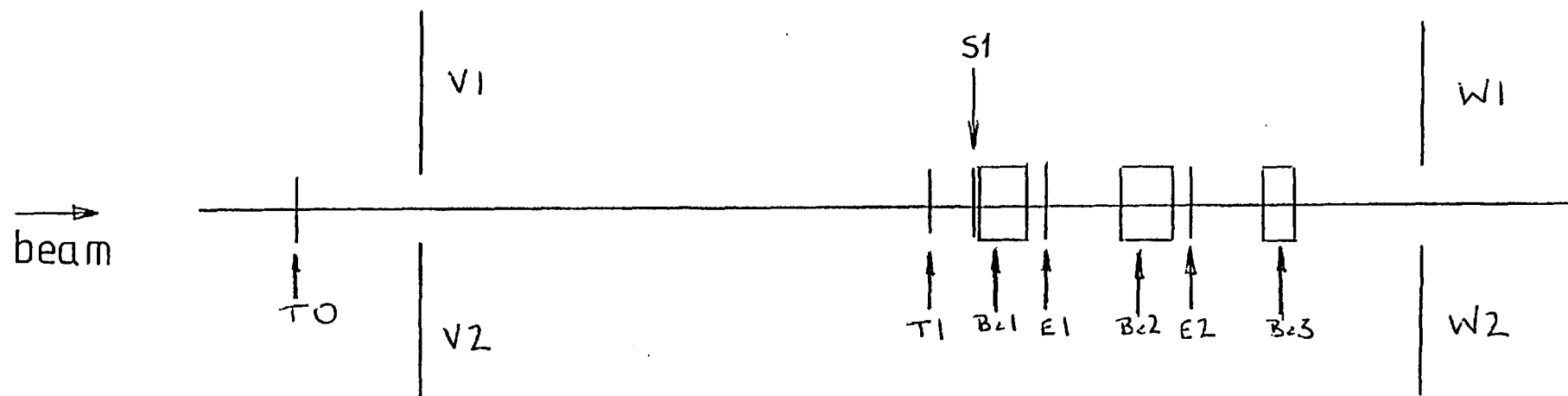


Fig 2.4: Hits in D0



$$P_{inc} = T0 \cdot T1 \cdot \overline{V1} \cdot \overline{V2} \cdot S1$$

$$Dif = P_{inc} \cdot W1 \cdot W2$$

Fig 2.5: Event Trigger

Chapter 3

The Calorimeter

3.1 Design Criteria and Construction

As stated earlier, it was intended that the calorimeter should provide detection of electrons and photons (in particular those of a few GeV) associated with the 2μ trigger, and a trigger for the $2e$ decay mode of the ψ . To satisfy the first condition a good shower energy and position measurement was required, with its identification as an electron, photon or hadron. This could be obtained using information from the MWPC (D0) and calorimeter planes B and D alone. The provision of a $2e$ trigger at a rate comparable to that of the 2μ trigger made more stringent demands on the calorimeter design. This needed reasonable energy and position measurement, and hadron rejection on-line. It was with this in mind that the calorimeter was constructed consisting of several planes, each containing many identical detectors.

The chosen design was not an ideal one, as it was determined not only by physics arguments, but also by economic ones. Because a large solid angle was to be subtended (the array was of approximate area 4m by 2m) a Pb-scintillator sandwich type shower counter was preferable to other designs such as those using Pb glass or liquid argon because of its substantially lower cost. "Plexipop"

was chosen as the scintillator, despite its low light output and short attenuation length as compared with other scintillating materials. A MWPC was chosen for the purpose of detecting shower positions in preference to an array of narrow scintillator strips, partly due to reasons of availability, since two similar chambers were already under construction for use in the lever arm, but also because of its lower cost. Consequently, a complex pattern recognition process was required to determine the shower position offline.

The attempt at forming a 2e trigger was so unsuccessful that it was eventually abandoned, since its presence excluded potential 2μ events by the dead-time it created when events were read into the computer buffers. This is attributed to the necessity of raising the counter thresholds to such a high level in order to obtain a tolerable trigger rate that the acceptance fell considerably. The problem was further aggravated by the presence of more material in the beam than was originally proposed, resulting in bremsstrahlung processes which reduced the acceptance by a further 40%. The 2e trigger is discussed more completely in chapter 4.

3.2 Electro-magnetic and Hadron Showers

For high energy electron and photons (i.e. those above a critical energy " E_c ", typically a few MeV in solids) the most important form of energy loss is via cascade showers. This process develops from a combination of

bremsstrahlung and pair production, both of which result in an increased population of electrons and photons in the shower, and consequently a decrease in the mean energy per particle. Thus, the electron-photon population grows to a maximum and the energy of more and more electrons falls below the critical energy. Eventually, collision processes become more important than radiative processes, and these electrons lose their energy in atomic excitation, resulting in a decrease in the shower population.

The development of a 10 GeV electron shower in the calorimeter is shown in Fig 3.1 (taken from Ref 17). The electron population of the shower is seen to rise to a maximum at a depth of about 6 radiation lengths (X_0 's) and then fall almost to zero at a depth equivalent to the end of the D counters. (For a definition and discussion of radiation length, see Appendix A). The position of shower maximum increases only logarithmically with the primary electron or photon energy, and so a large fraction of the shower profile will be "contained" in the calorimeter for a wide range of energies. Work simulating shower development has shown that energetic electrons (of 30 GeV) have 7% of their energy escape detection by "leaking" out of the back of the calorimeter. The "total integral track length" (the area under the curve) can be shown to be proportional to the energy of the initial electron or photon (Ref 18). If the shower is completely contained in the calorimeter, the entire energy of the primary particle is deposited in the calorimeter in the form of atomic excitation.

Hadrons also produce showers when passing through matter, although their shower "length" is dependent on the nuclear collision length (L_{coll}) rather than the radiation length which characterises electro-magnetic showers. For lead $L_{coll}/X_0 = 17.5$, so hadron showers develop much more slowly than electro-magnetic showers, and are not usually contained in the calorimeter. This gives rise to a smaller light output from the counters, and enables discrimination between electrons and hadrons in the calorimeter, although complications occur when hadrons produce π^0 's, whose daughter photons will then start an electro-magnetic shower.

The parameterisation of counter outputs with shower energy (calibration) and type (hadron rejection) is discussed in the following sections.

3.3 Calibration and Resolution

A sandwich type electro-magnetic calorimeter makes use of the proportional relationship between the primary energy and total integral track length. Since the light output from a piece of scintillator of fixed thickness is a function of the number of tracks passing through it, it can be placed in an absorber to count the number of charged particles at a given depth. By alternating sheets of scintillator and absorber, the number of charged tracks at various depths can be sampled, and an estimation made of the total integral track length. The energy, E , of an electron can then be represented by a weighted sum of the pulse-heights of each

of the counters it passes through in the planes A to E, plus a correction, $K(E)$, to allow for the part of the shower not contained in the calorimeter, viz

$$E = \alpha_1 A + \alpha_2 B + \alpha_3 C + \alpha_4 D + \alpha_5 E + K(E)$$

where A is the pulse-height in the A counter, etc. $K(E)$ represents the energy lost out of the back of the calorimeter.

The calibration thus entailed setting up the apparatus in an electron beam of known momentum and recording the pulse-heights in each of the counters. This was performed in the South Hall using the CERN PS primarily for the B and D counters, as they were considered to be far more important in measuring particle energies. Later, a computer program adjusting the values of α in the expression above in order to minimise the resolution found that the inclusion of the A, C and E counters made an improvement of only 3%. Hence their use in energy measurement was not considered worthwhile, in view of the difficulty of maintaining their gains at a stable, known value. Thus the energy - pulseheight relation was greatly simplified and took the form

$$E = \frac{B}{\beta} + \frac{D}{\delta}$$

This was used when studying data taken with a 10 GeV π^-p charge exchange trigger. A π^0 peak was found at roughly the correct mass and resolution in the 2γ effective mass spectrum, hence justifying the simplification.

Due to the statistical fluctuations in shower starting position, the relative amounts of energy deposited in B and D vary for a given shower energy. A scatter plot of B versus D therefore yields a straight line fit of gradient $-\frac{\delta}{\beta}$ and intercept E/β . The width of the line gives the counter's resolution, which turned out to be disappointingly poor, ranging from $\frac{44\%}{\sqrt{E}}$ to $\frac{56\%}{\sqrt{E}}$ over the 32 modules. Thus, before being set up in the West Hall each B and D pair was calibrated using 6 GeV/c electrons, identified by 3 threshold Cerenkov counters. Electron beams of energy 2, 4, 8 and 10 GeV were also used to study the accuracy of the calibration procedure. A plot of $\frac{B}{\beta} + \frac{D}{\delta}$ versus beam energy gave a good straight line, indicating the method to be satisfactory, i.e. the parameters β , δ and $K(E)$ were not very strongly dependent on energy.

Other studies carried out at 6 GeV included that of shower overlap between counters, the results indicating that electrons striking more than approximately 3 cm from the edge of a module deposited less than 5% of their energy in the neighbouring counters. A summation of the energy deposited in each individual module, however, gave a good estimate of the true momentum for the 25% of the electrons affected. The surface response of the counters was also scrutinised, and found to be represented fairly well by an attenuation length of approximately 1.5m.

Were the counter gains to have remained perfectly stable, this is all the calibration that would have been needed. However, this was never the case, especially before

experience with the calorimeter had been obtained, so provision was made for a means of checking for drifts in gain. To act as a reference for the gains, something was required which could faithfully give standard results under easily reproducible conditions. Ideally, one would like to have been able to steer an electron beam of known energy, checked in the spectrometer, into each counter in turn and measure the pulse-height. Clearly this method would have been far too clumsy and time-consuming to use except in the initial setting-up procedure, so instead the halo μ 's were used as an absolute reference. These had the property of producing much the same ionisation irrespective of their momentum, and being in plentiful supply. Because they do not shower, μ 's did not give rise to a large amount of light in passing through B or D counters. To remedy this problem of photon statistics, a large block of high quality scintillating material, known as the calibration scintillator, was placed at the junction of the light guides and the photo-tubes, giving a large pulse on irradiation with μ 's. Thus, future gains were determined by comparing the μ pulse height in these scintillators with those at the time of calibration. The positioning of the calibration scintillator was later considered ill-advised in that although the photomultiplier could be well studied for drifts or ageing effects (such as change in capacity or leakage of the optical coupling) no information was available on changes in the scintillator strips, light guides or glue joints.

When the apparatus was moved to the West Hall for data

taking, the gains were reset so that 40 GeV deposited in a single B or D counter would give a full scale deflection on the ADC's. During further calibration studies, however, a discrepancy was found between South Hall and West Hall data - the ratio of 5 GeV electron pulse height to that of μ 's in the calibration scintillator had changed for some counters. This still awaits a satisfactory explanation, and as a result, all calibration constants for data analysis were taken from a calibration run using a similar 5 GeV/c electron beam at the West Hall.

3.4 Hadron Rejection

Having arrived at a method of calibration for electromagnetic showers it was important to compare the results with the effects of hadrons in the calorimeter. Hadrons (over 90% of which are π mesons in the π Be interactions) are not usually contained in the calorimeter and so deposit little energy in it. A test run, however, showed that 21% of 6 GeV π^- mesons deposited over 50% of their energy. This can be attributed to charge exchange reactions which form π^0 mesons whose decay photons start an electro-magnetic cascade shower. Thus, although the energy deposited in B was small, due to the delayed shower development, the total amount in the calorimeter was not always negligible. Further study showed that 10% of all hadrons striking the calorimeter deposited over 10 GeV in it, and so it can be seen that this posed quite a severe problem for the 2e trigger.

The mean number of hadrons in the calorimeter was 5 per event, and from the point of view of off-line analysis, these could usually be distinguished from an electron by comparing the energy found with the momentum measured by the spectrometer. However, when a hadron struck the same BD module as an electron of comparable momentum, ambiguities arose as to the identity of the particles, leading to increased background problems. The main problem occurred when a hadron struck a module in which a photon was found. Since a mean of 5 (and up to 20) showers per event were identified in the MWPC D0, the probability of a hadron sharing a calorimeter module with one or more photons is considerable. If the hadron deposits a significant amount of energy in the calorimeter an incorrect quantity might then be attributed to the photon, and so events with high photon multiplicity were rejected.

3.5 Trigger

The 2e trigger logic was briefly described in section 2.2 as demanding an electron in two diagonally opposite quadrants, an electron being defined as a coincidence of corresponding H1H, A, B and C counters. D and E counters were not included in the trigger because of their difficulty in distinguishing electrons from hadrons, and the already low acceptance. Originally, a blanket threshold of 3 GeV for each B counter was used. i.e. it was demanded that at least 3 GeV be deposited in the relevant B counter. With these thresholds an initial trigger rate of

order 10^{-3} Pinc was obtained. At the time, Pinc was of order 4.10^6 per burst, and so the hardware logic was accepting 4.10^3 triggers per burst, 2 orders of magnitude above a tolerable level. Even this figure was obtained using only one of the two diagonal pair of quadrants, i.e. half of the calorimeter, so it was clear that an efficient method of reducing the high rate needed to be found if the acceptance was not going to be lowered too much more than the 15% then calculated.

Fig 3.2 shows a histogram of the energy spectrum in calorimeter module BD7 for data taken with a 2μ trigger (which is essentially background for the purposes of $2e$ studies). The distribution approximates fairly well to an exponential. 93% of events give a pulse-height in the BD module corresponding to energies less than 10 GeV, whereas Monte Carlo studies indicate that 7% of electrons produced by ψ decay and accepted by the trigger geometry fall in this category. These background events can be a result of, for example, genuine low energy electrons, produced from photon conversions and light meson decays, or hadrons which deposit only a fraction of their energy in the calorimeter. Thus, had the apparatus been triggered each time the geometry logic was satisfied and a measurable amount of energy was found in the necessary calorimeter cells, the apparatus would have been flooded with events of little or no interest.

The obvious solution of reducing the trigger rate was to raise all the thresholds. This needed to be done in such a

manner as to lose as few ψ 's, yet reject as much background as possible. To do this efficiently it was necessary to make use of the heavy mass of the ψ , which imparts a large p_T to the daughter electrons, hence leading to a greater signal to noise ratio for the outermost counters than the innermost ones. The place to make more stringent cuts, then, was preferentially with the more central counters. Using this information plus the knowledge of different momentum spectra of the ψ events and the background events, a system of "graded thresholds" was set up. Each B counter had the relevant resistors connected to the discriminator to set a high threshold for the central ones, decreasing gradually to a minimum threshold for the outermost, as shown in Fig 3.3. Values for the bottom-right quadrant only are given, as the others can be obtained by symmetry.

The precise value of the thresholds were determined, somewhat arbitrarily, by simply setting them such that an acceptable trigger level was obtained. A similar arrangement was made for the C counters, but due to their poor energy resolution, anything other than very loose cuts would have rejected too many ψ 's. As the proportion of cascade showers contained in the B counter alone decreases with energy, the B counter threshold could correspond to an electron of somewhat greater momentum. Alternatively, several low energy electrons and photons sharing the same module could also cause it to trigger, thus leading to complications in the acceptance calculations (section 4.4). The graded thresholds had the effect of reducing the trigger rate from 10^{-3} Pinc to $5 \cdot 10^{-5}$ Pinc.

Further investigations showed that the central 4 B counters (1 per quadrant) contributed by themselves 50% of the background, yet only 20% of the ψ 's. To make use of this the innermost B of each quadrant was given, in addition to the normal threshold, a "high" one, set at twice the "low" value, to be used when the trigger came exclusively from the central 4 B counters. This halved the trigger rate and rejected about 25% of the ψ 's which would have been accepted without the inclusion of this extra, high threshold.

Bringing the cerenkovs into the trigger and demanding a hit in the relevant cell introduced little, if any, further detection inefficiency, while roughly halving the trigger rate by rejecting spurious coincidences. The cerenkov, however, had 28 cells, 7 by 4, and so it was not straightforward to identify cerenkov cells with calorimeter cells. As can be seen from Fig 3.4, the outer 2 B counters of each quadrant were not related to any cerenkovs, whereas B6 overlapped with 4 cells, Č19, Č20, Č26 and Č27. The quadrants of HAC counters were grouped into inner (HAC 5-8) and outer (HAC 1-5) configurations. Each corresponded to a row of cerenkovs, HAC 5 being common as it intercepted both rows.

To satisfy these last 2 conditions 4 logic boxes were built, 1 per quadrant. These made a solely geometrical demand that the relevant counters had fired. The momentum threshold cuts were applied at the discriminator, placed after a splitter panel. This gave the option of sending either the whole signal to the ADC's, as was necessary for

calibration, or more normally, 1/6 to the ADC's and 5/6 to the discriminator. The logic boxes also had the possibility to act as a photon trigger, since a photon, converting in the A counters, had the same properties as an electron, except that there was no pulse in the Cerenkov or H1H counter. This possibility was investigated but not utilised, due to even more formidable background problems.

Thus the final trigger rate was of order 10^{-5} Pinc, with an acceptance of about 7%. The acceptance is discussed further in section 4.4.

3.6 Monitoring

Once set up at the beginning of data-taking using the calibration scintillator, the apparatus was constantly monitored to check that all the components continued to function well, and especially to ensure that the gains or thresholds did not drift. Throughout the overall data-taking period several methods of monitoring were used, though one principle which was always present was that of symmetry between quadrants, i.e. a histogram of pulse-height distribution or counting rate should have been the same for (say) the outermost counter in the top-right (TR) quadrant, as for its three corresponding counters (partners) in the quadrants top-left (TL) bottom-right (BL) and bottom-right (BR).

3.6.1 The Gains

A first approximation to stabilizing the gains was to maintain the high tension (HT) of each counter constant. This task, amongst many others, was performed by the HP computer, which sampled the HT of each counter in turn at a rate of around 1 per second, thus completing the full calorimeter cycle in approximately 3 minutes. The reading obtained was compared with an array of required values, and when an HT had changed by a preset value (usually around 3 volts) a message was printed out so that it could be corrected. The array basically contained the HT's of the calorimeter after the most recent calibration run adjustments, and was stored on cassette both for reference and so that it could be read into the computer later if required. However, maintaining the HT's constant alone is not sufficient to prevent the gains from drifting, and so when it was found that a counter gain had changed in spite of its voltage surveillance, it was necessary to alter the HT to bring the gain back to the required value. The old value of the HT in the array was replaced with the new one via the computer front panel switches and the terminal keyboard. When a sufficient number of counters had been so modified, the updated array was dumped to a new file on cassette, to act as the most recent reference.

Originally, a multiple-counter histogram display of data was used to compare by eye the 4 partners of a given counter type, and also to ensure a smooth transition from

one counter histogram to the next. When things had changed sufficiently, another μ calibration run was taken, and counters reset accordingly. These events were triggered by a coincidence in horizontal strips of scintillator positioned either side of the calibration scintillator in the shower counters, and after the iron wall. In order to improve the μ flux through the calorimeter the magnetic field was turned off and the beam collimators closed. Such a run still took around an hour, during which time no dilepton data could be collected and so this method needed to be superseded by one which entailed less frequent μ runs. This was done by using the light emitting diodes (LED's) which were attached to the calibration scintillator and flashed at a suitable brightness every 10 bursts. The event was flagged for calibration use only, so that time was not wasted reading out the wire chambers, Cerenkovs and hodoscopes, being unimportant to these events. The mean of the LED pulse height spectrum was taken during the μ calibration run, and used as a reference. Thus a shift in the LED peak was considered as a change in gain, and so when the shift was greater than 10%, the HT was corrected to bring the LED peak back to the reference value. Only after several such alterations had been made was another μ calibration run taken. Due to shortage of computer memory, these reference values were not stored in an array in a similar fashion to the HT's but nevertheless, a continuous monitor was made by the HP by collecting LED data, and printing out useful statistics at preset intervals. Hence, mean values of pulse-height distributions

could be compared with earlier printout to check for stability.

This use of LED's not only soon revealed discrepancies between the two methods of calibration, but also that some counter histograms had double peaks, implying that the gain had suddenly shifted during the run. Further study attributed this latter effect to a change of gain with counting rate, i.e. whether or not the beam was on. Although this was only a 3% effect for most counters, a few differed by as much as 30%. This was disturbing, as μ calibration runs were performed effectively during "beam off" conditions, since the collimators were closed, while the data was collected under the normal, "beam on" conditions. This problem was alleviated by connecting one of the redundant LED's in each counter to a DC level between bursts, thus providing a continual glimmer sufficient to maintain the phototube at "beam on" condition.

Eventually it was decided to use the LED's for monitoring the gains, despite their inherently less trustworthy nature (eg effects such as change of light output with age) in order to alleviate the need for frequent μ calibration runs. Thus a system was developed such that, in between calibration runs, the HT was adjusted whenever the LED pulse-height indicated a gains shift of 10% or more.

3.6.2 The Thresholds

B and C counter thresholds were also monitored by the HP, each counter histogram only being filled if it had a signal out of the discriminator, i.e. had exceeded the threshold. This was performed by a series of bit pattern units, which sent a packed logical word to the computer with each of its bits set to 0 or 1 depending on whether or not a particular counter had fired the discriminator. Thus a roughly exponential distribution was obtained (as in Fig 3.2) with a cut-off at the low energy end, these particles being unable to fire the threshold. The position of the cut-off gave a fairly good measurement of the threshold.

Fig 3.5 shows such a histogram for counter B7 and reveals that the cut-off is not completely sharp, since the threshold function is not a perfect step function, but has a finite spread in its "width". What is observed is a multiplication of this function with an exponential distribution. On-line, the threshold position was manually determined to be the value where the number of entries fell to half the mode, 245 ADC counts in this case. This was easy to judge except for the outer counters where the statistics were poor. An algorithm was later found which could reproduce the values obtained by hand so that the computer could be programmed to print the thresholds automatically at periodic intervals, in a similar manner to the LED information.

Fig 3.6a shows the same pulse-height distribution, but with a superimposed exponential, adjusted to fit at the high

energy tail of the histogram. This reveals the above method of estimating the thresholds to be slightly inaccurate. The true value is the position where the exponential distribution obtained with the counter in the passive mode drops by a factor of two when the threshold is introduced - roughly at the mode for this counter.

A more accurate determination can be made by dividing the pulse-height distribution by the fitted exponential, Fig 3.6b. The threshold, which then corresponds to a value of 50%, is found to be 260 ADC counts. The difference between the method used here, and that used on-line during data-taking amounts to 15 ADC counts (roughly 0.6 GeV/c) for a typical counter such as B7.

The momentum cut imposed by each module was estimated by histogramming a weighted sum of the pulse-heights in B and D rather than B alone. This threshold was found to be typically 50% higher (and somewhat broader) than that imposed by B alone, and so the "effective" thresholds listed in Fig 3.3 were used in the acceptance calculations. However, it was later realised that this overestimates the thresholds because it does not allow for energy deposited in the calorimeter by undetected particles, such as photons, which cause the electron to appear to be more energetic than it really is. A more accurate estimate can be obtained by using information from the spectrometer and plotting the momentum of tracks which enter a calorimeter trigger cell. This has been done, and although the analysis suffered from poor statistics for some counters, it gave

values less than the "effective" thresholds listed in Fig 3.3 by roughly 1 or 2 GeV.

This method could not be used to find the thresholds of the A counters, as they were set to trigger with only 7 minimum ionising tracks passing through a single strip. The 10 to 20% accuracy obtained with oscilloscope measurements was quite adequate, as these counters were much less important than the C counters in forming the trigger.

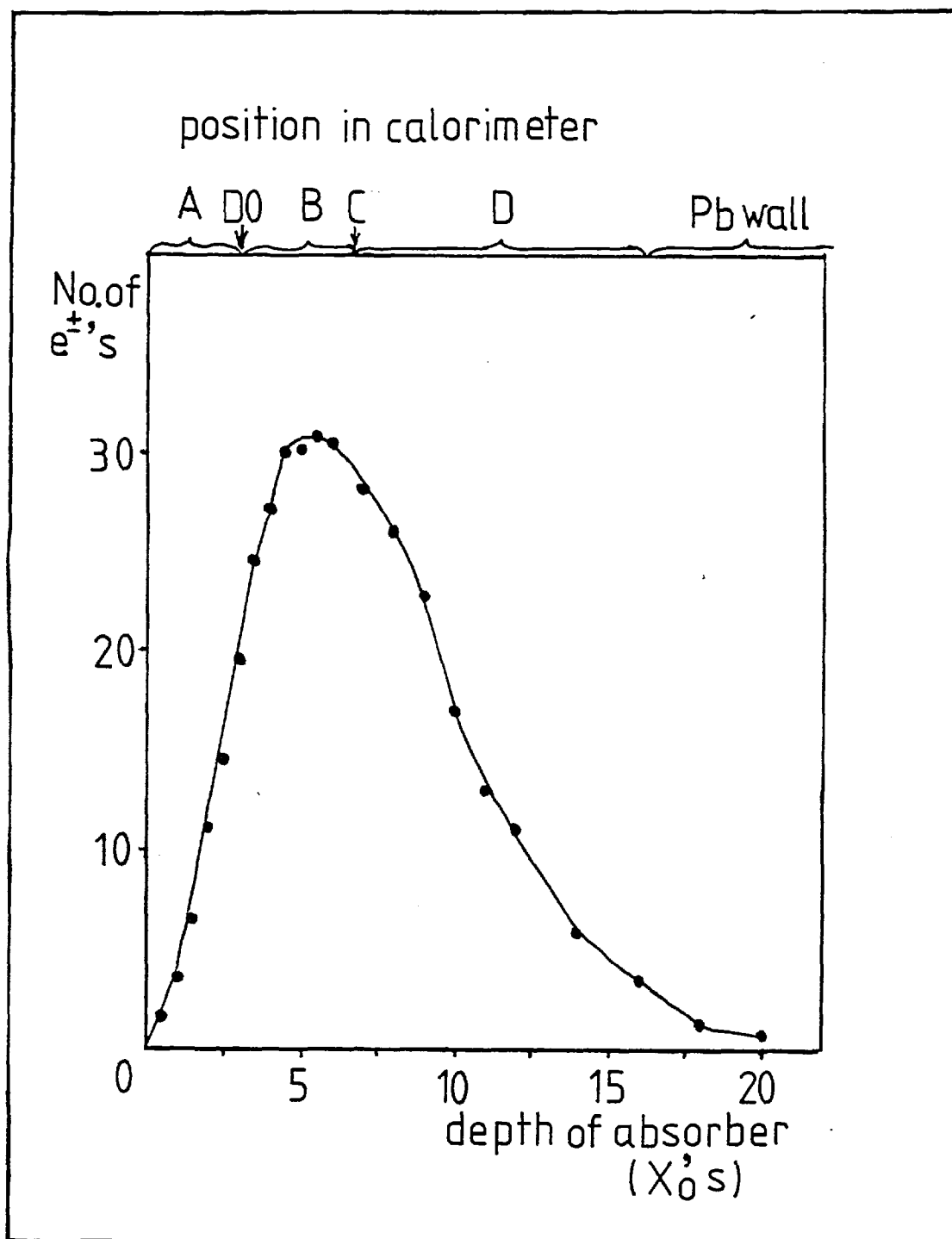


Fig 3.1: Development of 10 GeV Electron Showers

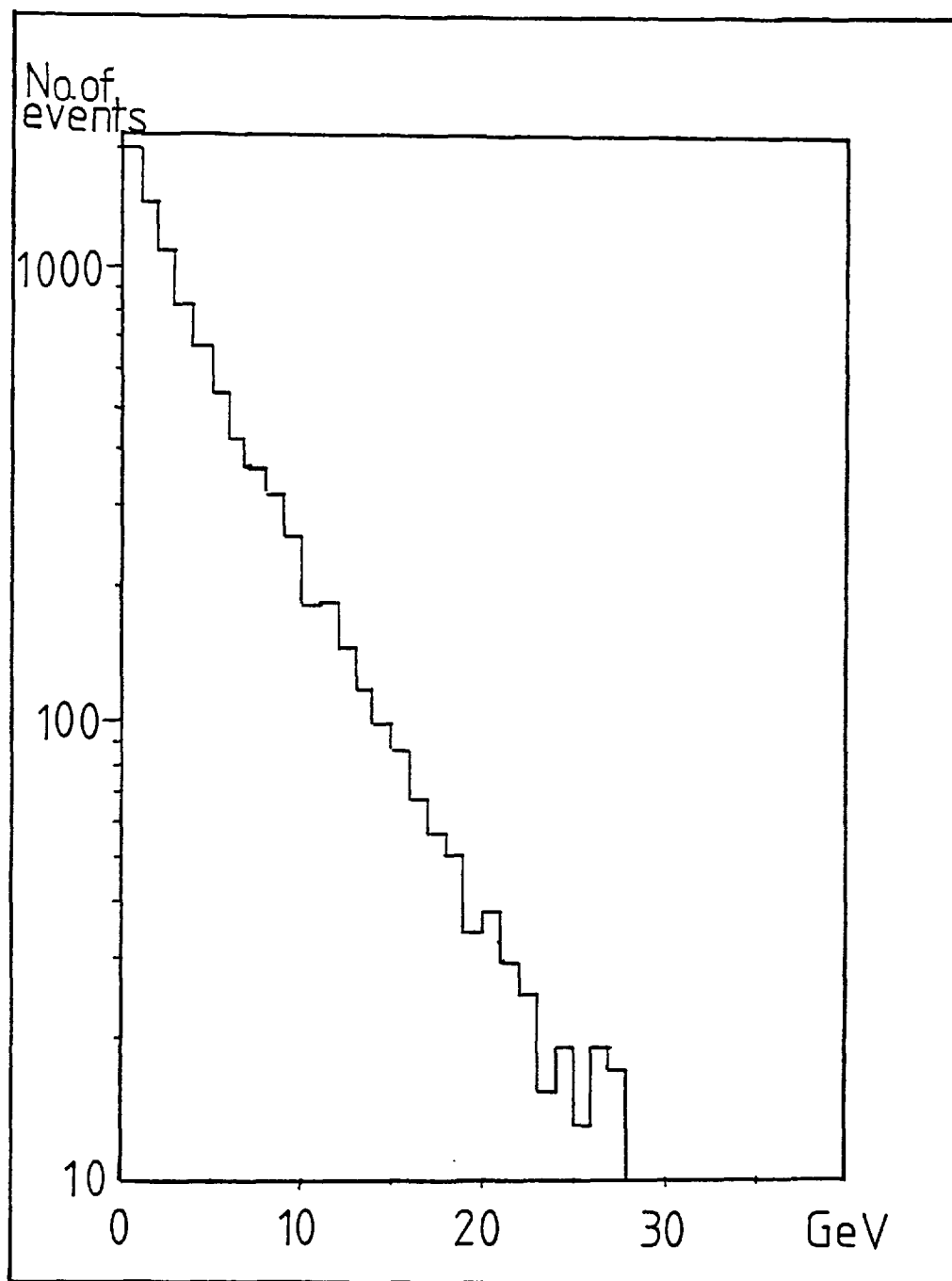


Fig 3.2: Energy Measured by BD7 in 2μ Data

Table of Graded Thresholds

momentum		"effective"		momentum	
counter	threshold	threshold	counter	threshold	
	(GeV/c)	(GeV/c)		(GeV/c)	
B1	4.4	6.8	C1	1.8	
B2	5.6	8.7	C2	2.0	
B3	7.2	11.2	C3	2.4	
B4	8.3	12.9	C4	2.8	
B5	9.5	14.7	C5	3.4	
B6	11.5	17.8	C6	3.9	
B7	12.3	19.1	C7	4.9	
B8	13.7	21.2	C8	∞	

Fig 3.3

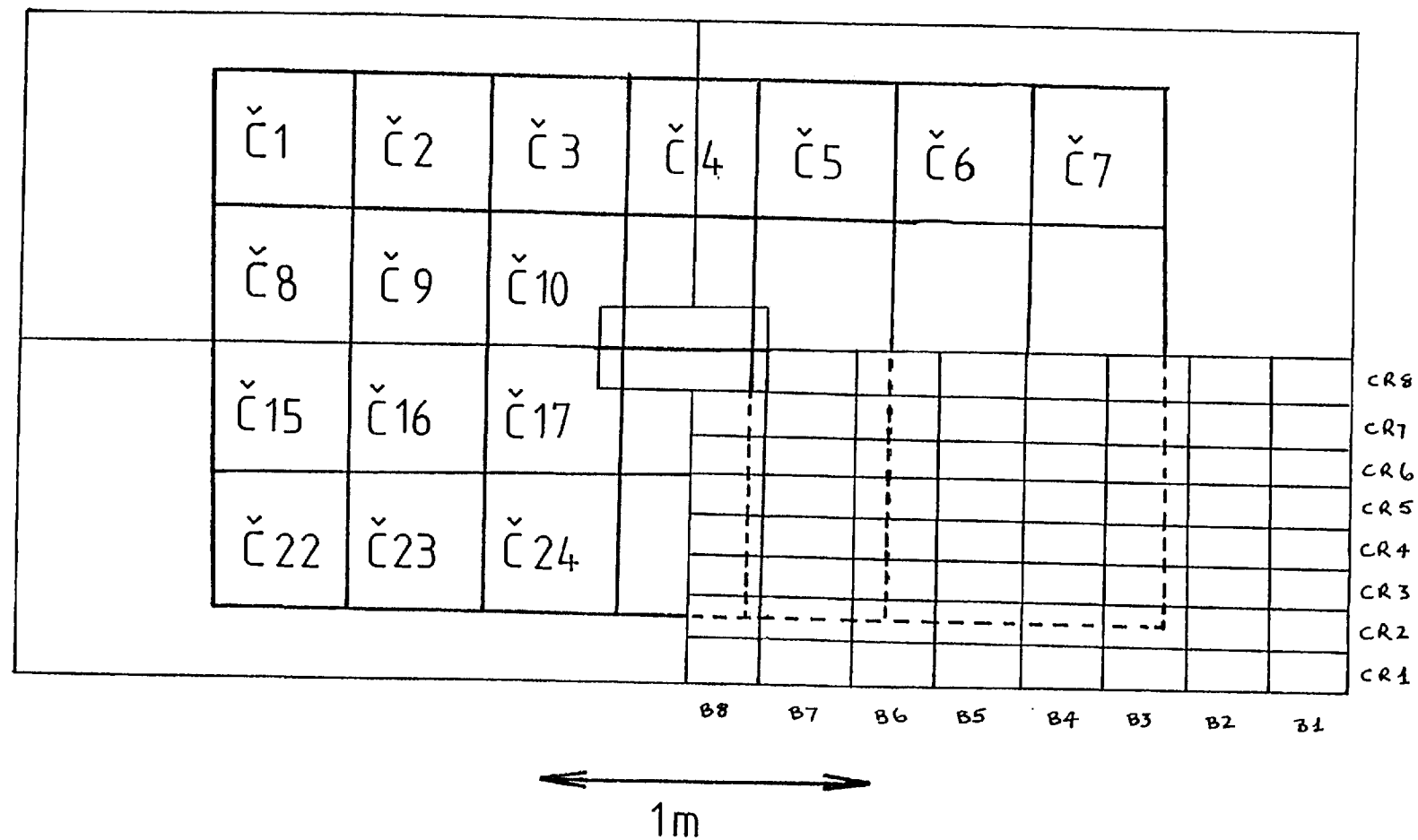


Fig 3.4 : Relative Geometry of Calorimeter and Čerenkov

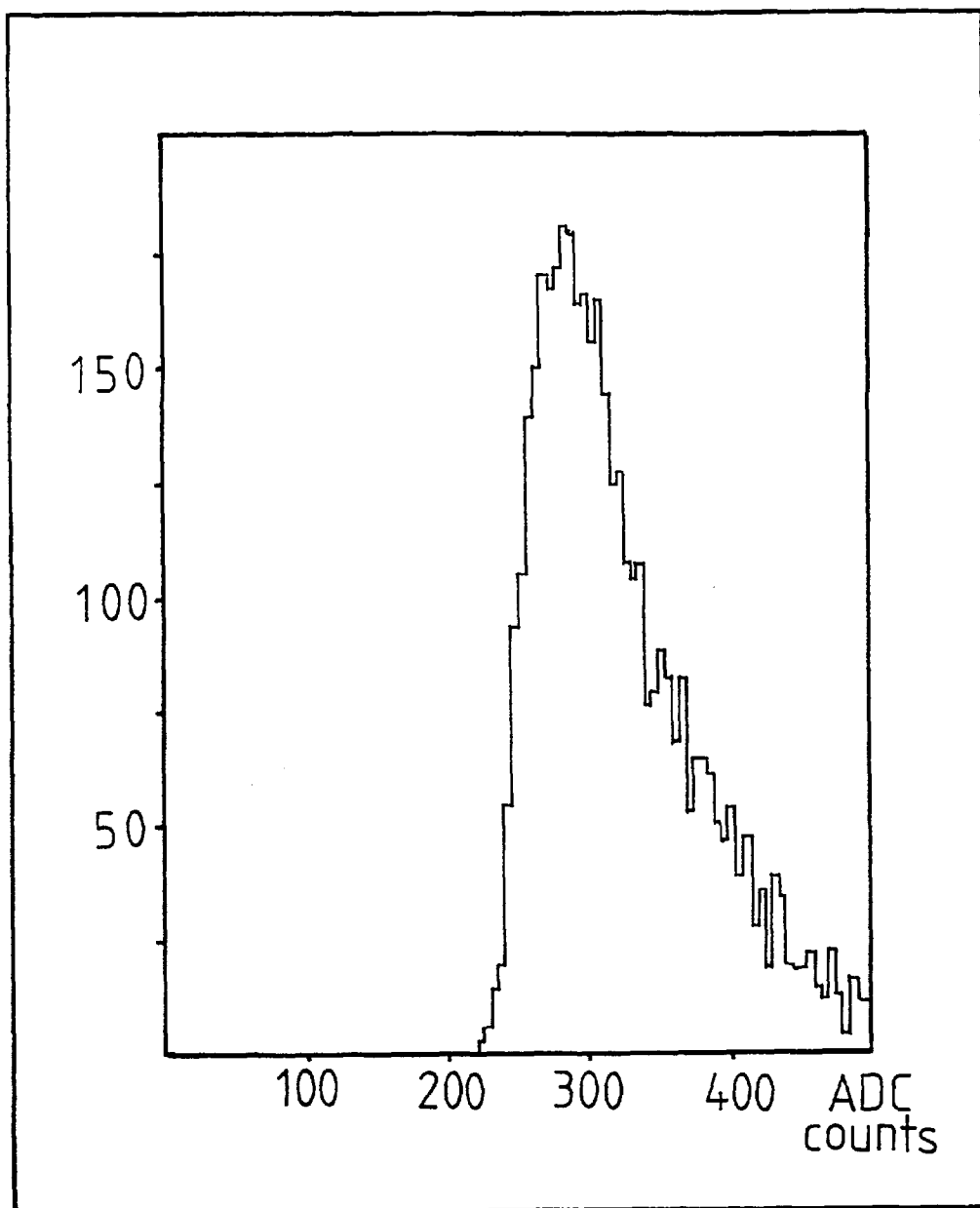


Fig 3.5: Triggered Pulse-Height
Spectrum in B7

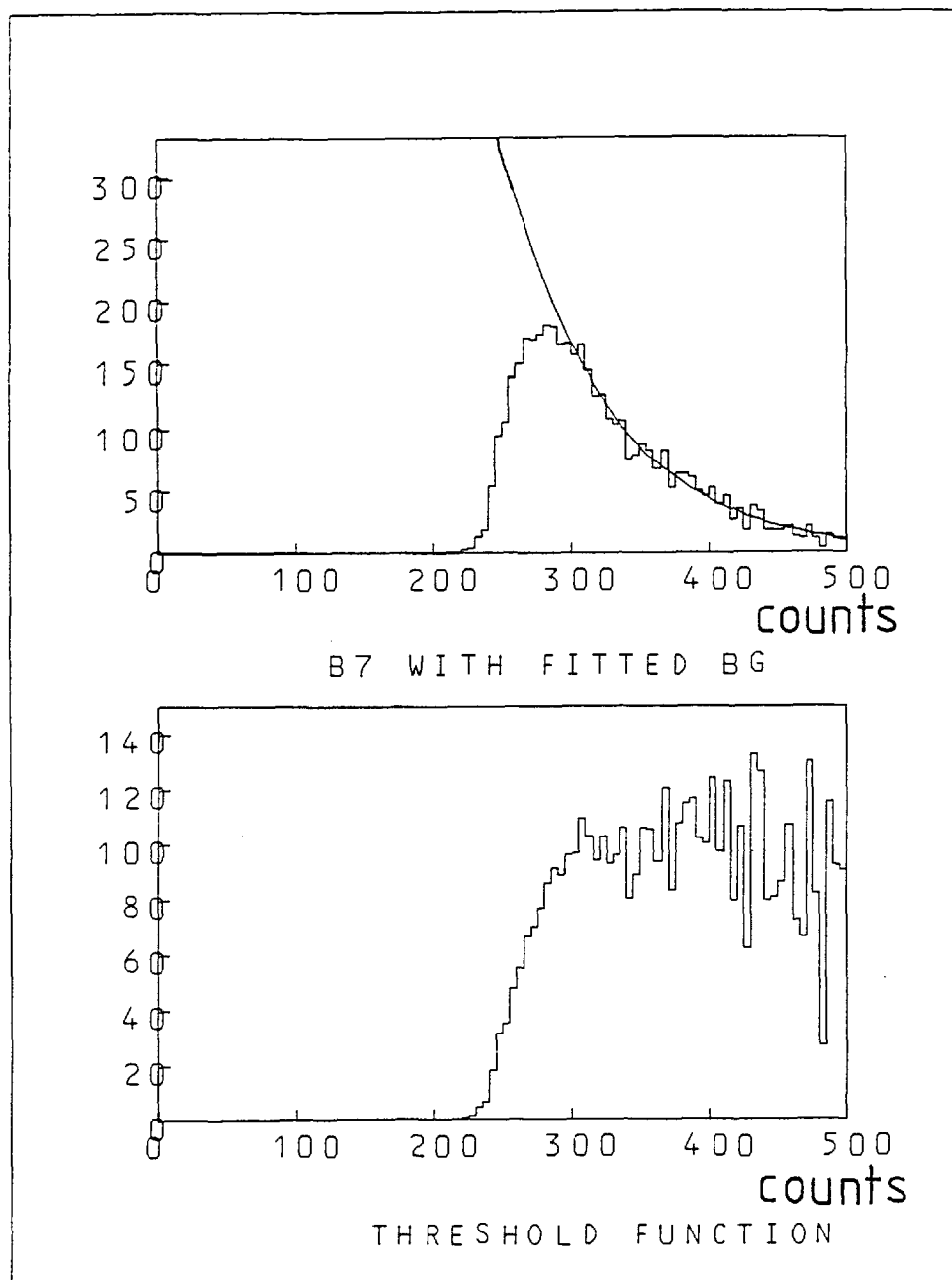


Fig 3.6:Threshold of B7

Chapter 4

Data Reduction and Analysis of the 2e Data

4.1 Data Rates

For the last year of data taking (a period during which the 2μ data analysed in this thesis was taken) the 2μ trigger rate had been reduced to 3 events per 10^6 incident particles, i.e. $3 \cdot 10^{-6}$ Pinc. The 2e data analysed here (SPS runs 1940 to 2136) were taken in April 1978, before the above period, with a mean 2e trigger rate of 10^{-5} Pinc. The 2μ trigger at this time was less sophisticated, with a trigger rate of $6 \cdot 10^{-6}$ Pinc. The incident π flux was $4 \cdot 10^6 \pi$ per burst, and resulted in a dilepton trigger rate of about 60 events per burst. The typical beam cycle was 8 to 10 seconds, and so this amounted to filling a 1600 bits per inch (bpi) magnetic tape with 15000 events in approximately 30 minutes.

4.2 Data Reduction

For a total cross-section for ψ production at $\sqrt{s}=17$ GeV of 95 nb per nucleon, branching ratio to μ 's of 7%, acceptance of 15%, and a luminosity of $4 \cdot 10^{31} / \text{cm}^2$ per burst, the ψ event rate is

$$95 \cdot 10^{-33} \cdot 0.15 \cdot 0.07 \cdot 4 \cdot 10^{31} = 0.04 / \text{burst}$$

To find the effective ψ event rate allowances need to be

made for effects such as software inefficiencies and losses due to the electronic difficulties in measuring the incident beam flux accurately. The resultant ψ event rate was $3.5 \cdot 10^{-9}$ pinc, or about 100 ψ 's per day.

The 2e trigger contributed only an extra 30% to the event rate due to its lower acceptance. The processing chain of both the 2e data, and the 2μ data analysed in chapters 5 and 6 is shown in Fig 4.1, and explained throughout the rest of this chapter.

4.2.1 Fast Filter Program

With such a low ratio of signal to background of less 0.1%, it is too costly in computer time to run a full pattern recognition program on each event, and so the data is first passed through a quick and simple filter program which only accepts events that can possibly be ψ candidates.

To write a tape of such events the program would read a raw data tape, rejecting calibration events, and check the hardware logic. Having found the trigger cells, using either the μ hodoscopes in the case of the 2μ trigger, or the calorimeter in the case of the 2e trigger, it defines two windows in MWPC's D1 and D2 through which the leptons should have passed. The program then "point-finds" in each of these areas. This involves looking for (y,z) position coordinates where there are intersections of wires from more than 1 of the 4 planes, i.e. coordinates which are

common to more than one wire. Ideally, a track passing through a MWPC would "set" a cluster of at least one wire in each of the planes, and in this case a (y,z) coordinate would be shared by wires from each of the 4 planes (a "quadruplet"). However, due to problems such as wire inefficiency and oblique angles of incidence one or more of the clusters may be absent, forming for example only a "triplet" (3 intersecting wires). In order to reject track candidates due to the intersection of randomly set wires the criteria for deciding if a charged lepton is present is normally to insist that not more than one cluster per window be missing, i.e. at least one triplet or quadruplet is demanded in the windows of both D1 and D2. In the case of the $2e$ trigger, a conservative momentum threshold is applied to each track. An estimate, accurate to about 10%, is then made of each of the possible dilepton effective masses. Only if the event satisfies all of the above criteria, and a mass of greater than $2 \text{ GeV}/c^2$ is found is the event output to the summary tape.

This process takes about 20ms per event, and results in an enrichment of the data by a factor of 70 for 2μ triggers, and 30 for $2e$ triggers. with an efficiency of about 6% per track (and hence 12% per ψ).

4.2.2 Pattern Recognition Program (TRIDENT)

TRIDENT (an abbreviation of "track identification") is the name of the pattern recognition program which reads events produced by the above lever arm filter

program, performs full reconstruction (taking about 200ms per event) and writes the results onto an "RGOUT" data summary tape. It was written for a CDC 7600 computer where it requires overlaying because of its size.

For each event TRIDENT creates tracks from the lever arm and follows them through the Goliath chambers to the target. These tracks are then fitted to a primary interaction vertex and a maximum of 3 secondary vertices which would be due to decays of neutral particles. Tracks failing to match up with another track to form a vertex are designated "extra" tracks. The information Trident outputs is formatted into 3 blocks, which can then be easily read by other programs for further analysis :

- a) - a header block, containing accounting information and address pointers

- b) - an electronic block, filled with the contents of the cerenkov and calorimeter counters, and chamber DC

- c) - a geometry block, containing results of the fit, and track parameters.

Because of the complexity which results from the high multiplicity (about 10 charged tracks per event) this process has an efficiency of only 90% per track. The data reduction obtained by this program is a factor of 10 for the 2μ events, and a factor of 6 for the $2e$ events. The overall ψ efficiency (Fast Filter plus TRIDENT) was computed by mixing together Monte Carlo ψ events and experimental data, and found to be 70%.

The RGOUT tape is then passed onto a program which uses the cerenkov information in the second block of each event to identify the particle types. This program uses a Monte Carlo technique to predict the number of photo-electrons expected in the cerenkov cell for each of the hypotheses e, π, K, p . Normalisation is obtained from decays of known tracks (μ 's from ψ decay, π 's from K^0 decay, and e 's from γ conversions). Calibration of the photomultiplier is obtained with LED's. A Poisson probability for each identity is then calculated and appended to the end of the third block.

4.3 2e Trigger Analysis

Only 50 of the 600 tapes containing 2e triggers were put through the full analysis chain because of the limited amount of computer time available. The rest of this chapter describes this analysis and compares the number of ψ 's found with the number predicted by Monte Carlo studies.

4.3.1 Thresholds and Acceptance

The ψ acceptance of the 2e trigger was studied using the Monte Carlo package GEANT (Ref 19). ψ events were generated using the kinematical distributions as measured in the 2μ channel, and loose cuts applied to decide whether it would be possible to reject the event at an early stage. These preliminary cuts involved a minimum momentum of 5 GeV (necessary to escape Gcliath) and a projection in z (where

there was no magnetic bending) to test whether the tracks would miss the calorimeter. Approximately 50% of the ψ events passed these tests, and these e's were then tracked to the calorimeter where they were asked to satisfy the 2e trigger. The successful events could then be written to tape for analysis by Trident.

As mentioned in section 2.2, 20% of the ψ 's were lost because their momentum was too small to escape Goliath. The left-hand column of Fig 4.2 (bremsstrahlung not taken into account) shows that a further 22% are lost as the electrons do not reach the calorimeter. These electrons have low energies, so that they suffer large deviations in Goliath, or large transverse momentum, in which case they might miss the calorimeter even without magnetic bending. At the other extreme, 9% of events are lost due to one of the electrons being sufficiently energetic to follow the beam almost undeflected into the hole at the centre of the apparatus. A fairly large loss of ψ 's was caused by the vertical frames of the MWPCs F1 and F2, which were designed for the slightly smaller geometric acceptance of the 2μ trigger. Similarly, the frame of D1 was positioned in line with the outer two BD modules of each quadrant. Electrons intercepted by these frames would radiate energy before reaching the calorimeter, making information from these outer counters untrustworthy. Thus the useful area of the calorimeter (i.e. allowances made for the hole at the centre and obstruction by MWPC frames) limited the acceptance of the 2e trigger to a maximum of 29%.

In order to reduce the trigger rate further, more cuts were needed. The acceptance was almost halved by insisting that the two electrons lie in diagonally opposite quadrants (to favour opposite charge electron pairs) and removing the central C counter of each quadrant (to favour large e-e opening angles). Imposing the effective thresholds of the B counters (Fig 3.5) reduced the acceptance by a further factor of two. The introduction of the high threshold for the central B counter of each quadrant when these exclusively produced the trigger (the "2B" threshold) led to a final acceptance of 6.5%, to be compared with the 2μ acceptance of 15%.

As noted in section 3.3, the "effective" thresholds used here were an overestimate by 1 or 2 GeV. It was found that if all the graded thresholds were lowered by 2 GeV, the overall acceptance was reduced from 16% to 11%, instead of to 8%. The application of the "2B" threshold led to a final acceptance of 8%.

4.3.2 Bremsstrahlung

There are several processes whereby a charged lepton can interact with the media it is traversing. The amount of material upstream of the calorimeter (which provides the $2e$ trigger) is small compared to the amount of material in the calorimeter and iron wall which are upstream of the H3H and H3V components of the μ hodoscope. Thus, although some processes need to be taken into consideration for the 2μ trigger, they can be neglected in the case of the $2e$

trigger.

Loss of energy by ionisation in the target is only approximately 3 MeV/cm, and can be neglected along with loss by Cerenkov radiation, which is an order of magnitude less important still. Multiple Coulomb scattering affects the trajectory, rather than the energy of a particle, and the scattering angle roughly lies under a Gaussian distribution, with a rms scattering angle, $\theta = 21Z/p$ mrad per radiation length (where Z is the atomic number and p is in GeV/c) (Ref 18). For a 5 GeV/c particle travelling through 5% of a radiation length of beryllium, this angle is calculated to be

$$\theta = 21 \cdot 9 \cdot 0.05 / 5 \sim 2 \text{ mrad}$$

This is equivalent to a displacement of less than 2cm at the calorimeter.

The above mechanisms lead to predictable (and small) modifications. For electrons with energy above a few GeV, bremsstrahlung is the principal form of energy loss. Via this process an electron has a finite probability of radiating up to 100% of its energy while passing through even diffuse media. Thus, rejection of ψ 's can result from reduction of momentum below threshold, deflection out of a geometrically accepted configuration (due to the increased bending by Goliath for tracks with reduced momentum) failure of TRIDENT to reconstruct tracks with bremsstrahlung in the magnetic field, and incorrect effective mass calculation.

Calculating energy losses in materials such as targets, air and the iron wall is fairly straightforward. Other parts, however, obviously require a simplified model - it is not possible to treat each wire individually. Thus, the apparatus is replaced by equivalent blocks of homogeneous media, Fig 4.3. Each medium has its boundaries fixed, and is given a serial number to which the physical properties are associated, for example radiation length, dE/dx , presence or absence of magnetic field. Fig 4.4 describes the distribution of material in the apparatus.

To calculate the effective radiation length, X_0 , of, for example, the MWPCs inside Goliath, the 10 planes of stainless steel cathodes would be smeared out into a sheet of equivalent thickness of iron. The 4 planes of tungsten sense wires are treated similarly and these are both then compounded in inverse with the 2 mylar windows, assigning the relevant statistical weights to each material :

$$\frac{L_{TOT}}{X_0^{eff}} = \frac{L_{Fe}}{X_0^{Fe}} + \frac{L_W}{X_0^W} + \frac{L_{mylar}}{X_0^{mylar}}$$

Bremsstrahlung was simulated by randomly selecting a distance (in radiation lengths, to avoid confusion when crossing from one medium to another) after which a photon should be emitted. When this distance was reached in the track following a bremsstrahlung photon energy was chosen and the electron energy and trajectory were recalculated. The details of how parameters were randomly chosen are discussed in appendix A. The Monte Carlo

allowed no bremsstrahlung downstream of the magnetic field, since for a typical $e-\gamma$ opening angle of 1 mrad (appendix A) the $e-\gamma$ separation at the calorimeter is less than 1 cm. Thus the photon energy will still be measured and attributed to the electron, making the loss ineffectual. Further upstream the electron will be deflected by the magnetic field away from the γ into a different counter, and so the energy given to the photon is irrevocably lost.

To study directly the effect of bremsstrahlung, the track coordinates of each Monte Carlo event was saved so that it could be processed twice - with and without bremsstrahlung. Fig 4.2 reveals the effect on acceptance. There are less electrons actually reaching the calorimeter when bremsstrahlung is applied, but comparing the fraction of ψ 's whose leptons strike the useful area of the calorimeter, these can be ascribed to trajectories which intercept the MWPC frames. 25% of the events which satisfied the 2e trigger at the first pass had an electron which radiated over 10% of its energy as bremsstrahlung at the second pass, causing the event to be rejected. The remaining 75% satisfied the trigger criteria at both passes.

The events with bremsstrahlung that were still accepted by the 2e trigger were then analysed by TRIDENT. The resulting 2e effective mass spectrum (Fig 4.5) shows that the ψ peak is degraded by the electron radiation losses. 6% of the ψ 's are so severely affected that their invariant mass is shifted to below $2 \text{ GeV}/c^2$, and so are rejected by the

fast filter program. 30% of the ψ 's are reconstructed at a mass less than 2.8 GeV/c, and so will be effectively indistinguishable from the background.

4.3.3 The 2e Mass Plot

The 2200 events on the RGCUT summary tape were used to search for the ψ at 3.1 GeV/c² in the invariant mass plot. It is possible to reject background in the 2-body mass plot by insisting that the particles :

- a) are of opposite charge
- b) originate at the primary vertex
- c) hit the calorimeter in a diagonally opposite configuration.

Confidence that the tracks passing these cuts are predominantly electrons can be obtained from a plot of the ratio of energy measured in the calorimeter to the momentum measured by the spectrometer, Fig 4.6. As expected, a broad peak of around 1 is observed indicating the presence of electrons. The structure at very low values is attributed to hadrons which deposit only a small amount of their energy in a module whose threshold was fired due to other effects such as an unidentified photon depositing a large amount of energy in the same module. A minimum limit of $E/p > 0.2$ was set for a track to qualify as an electron.

Fig 4.7 shows the 2-body mass spectrum of these electrons, revealing a ψ peak centred at about 3.18

GeV/c². This is slightly higher than the accepted value, and is assumed to be the result of a statistical fluctuation. An estimation of the number of ψ 's present can be obtained by interpolating from either side of the peak as shown. With this estimate of the background 40 ± 6 ψ 's are counted in the mass range 3.04 to 3.32 GeV/c². This can be compared with the 2500 ψ 's found in the 2μ data. Fig 4.1 shows that the 2e data analysed arise from only 2% as many interactions in the target as the 2μ data. Thus, allowing for the inferior acceptance of the 2e trigger by a factor of two, and the 30% loss due to bremsstrahlung, the number of ψ 's expected in the m_{ee} plot is

$$2500 \cdot 1/50 \cdot 1/2 \cdot 0.7 = 18$$

The difference between the number of ψ 's expected and the number found can be explained by the difficulty in estimating the background in the data under the peak, and the inaccuracies in the data reduction chain shown in Fig 4.1.

Because of the poorer acceptance of the 2e trigger (a consequence mainly of the rather high thresholds required to obtain an acceptably low trigger rate) it was removed from the logic, as its presence was excluding 2μ events due to the dead-time introduced. The 2e triggers on another 550 tapes are so far unanalysed.

Data Reduction

	2μ chain	2e chain
interactions in target	2.10^{12}	4.10^{10}
trigger rate / Pinc	3.10^{-6}	1.10^{-5}
events on tape	6.10^6	4.10^5
fast filter reduction	70:1	30:1
filtered events(pre-TRIDENT)	1.10^5	13.10^3
pattern recognition reduction	10:1	6:1
RGOUT events (post-TRIDENT)	10000	2200
number of ψ 's	2500	40

Fig 4.1

Table of Acceptances

Cuts	2e acceptance (%)	
	without	with
	Bremsstrahlung	Bremsstrahlung
none	100	100
reach calorimeter	58	52
miss hole at centre	49	44
hit useful area	29	28
diagonally opposite		
quadrants	20	19
removal of central		
C counters	16	14
B threshld	8.1	6.2
2E threshld	6.5	4.9

Fig 4.2

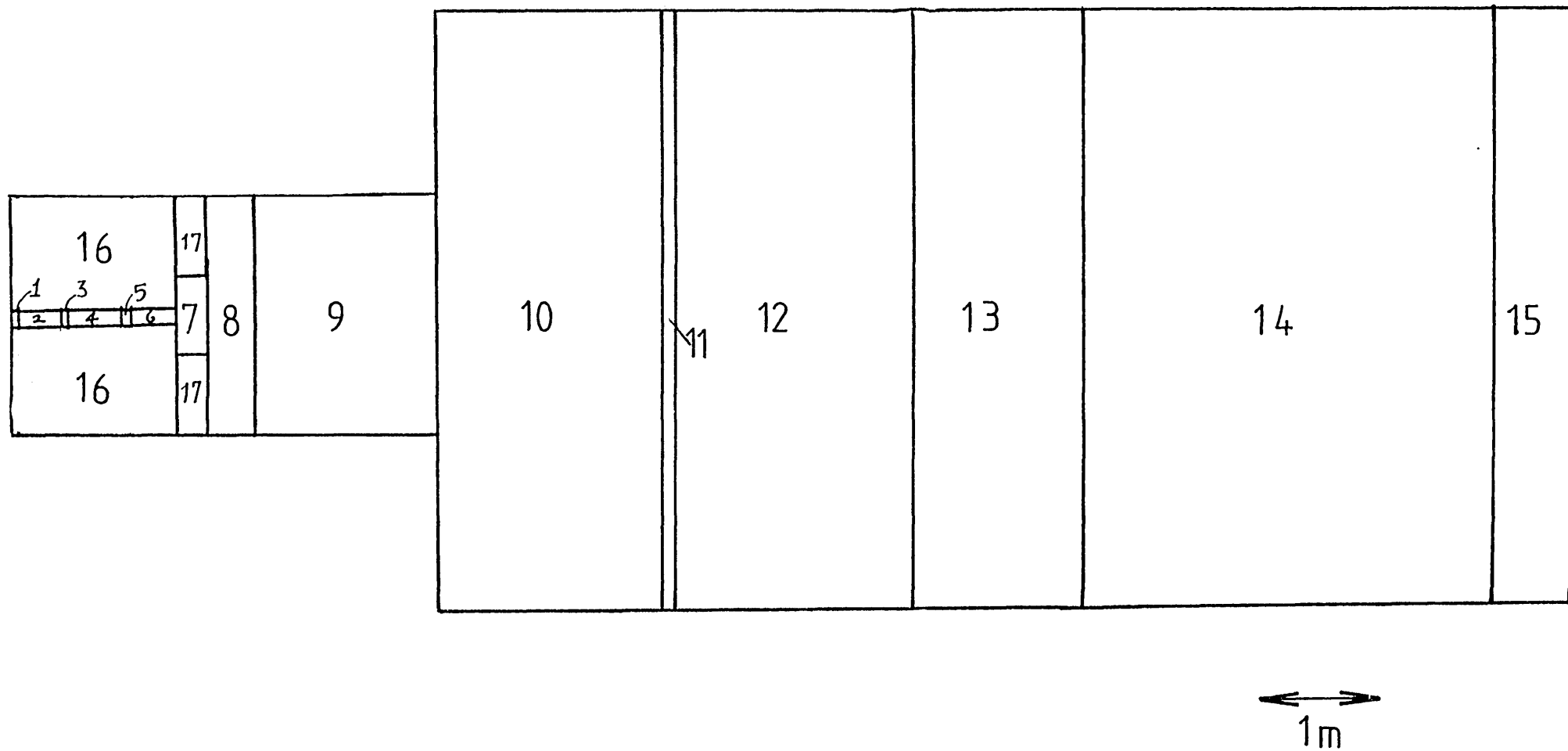


Fig 4.3:Block Diagram of Apparatus

medium number	description	amount of material	
		(g / cm ²)	(Xo's)
1	target 1	7.76	13.0%
2	air	0.05	0.1%
3	target 2	5.96	9.6%
4	air	0.06	0.1%
5	target 3	2.22	4.8%
6	air + Dif counter	0.62	1.6%
7	F1,F2	0.045	0.5%
8	air	0.04	0.1%
9	D3 - D11	0.41	3.0%
10	air	0.20	0.6%
11	D2	0.04	0.3%
12	cerenkov	1.16	4.1%
13	calorimeter	207	32.5
14	iron wall	2380	1170
15	hodooscopes	0.6	1.5%
16	air	0.15	0.4%
17	iron frame of F1,F2	25	2

Fig 4.4 : Distribution of Material in Apparatus

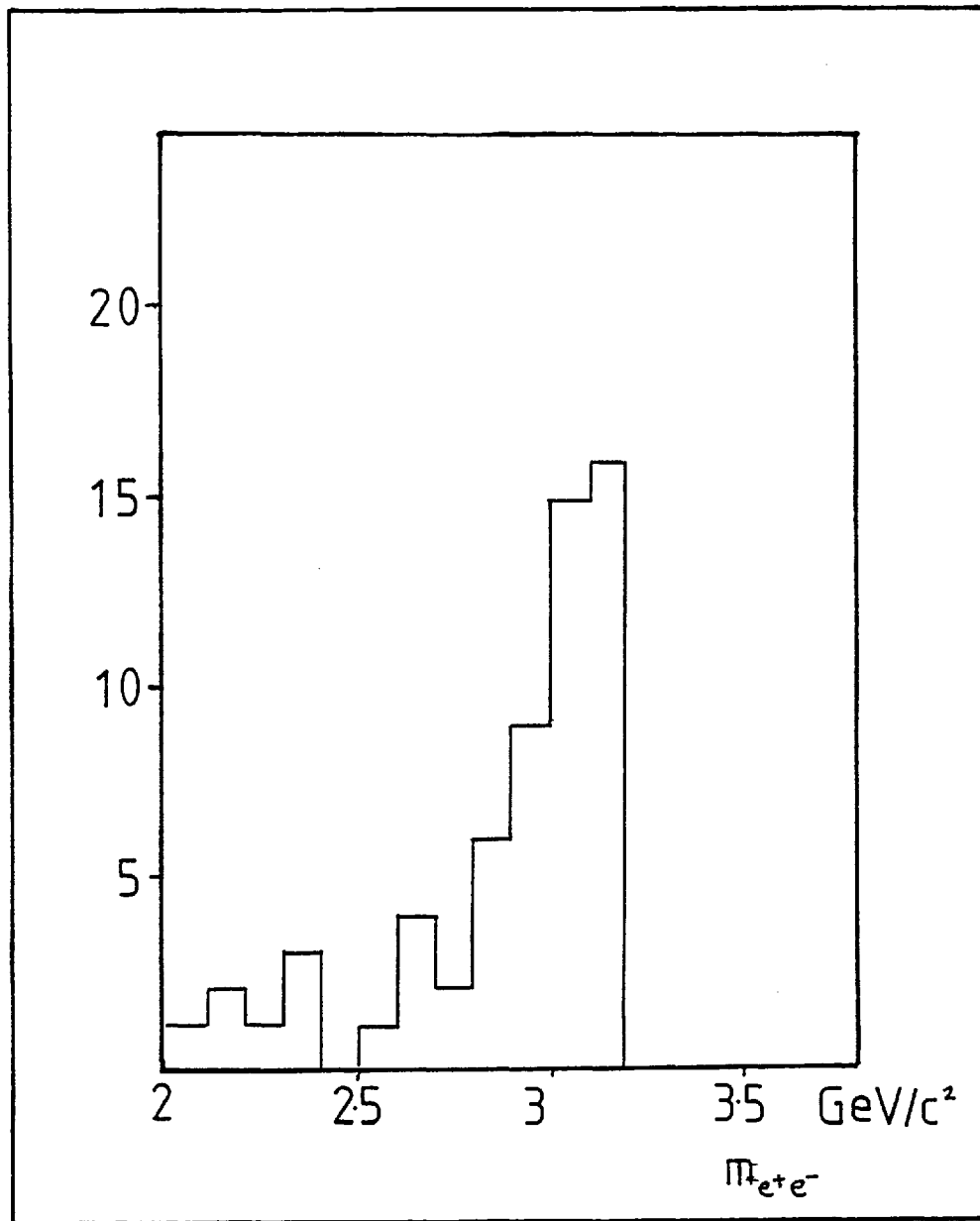


Fig 45: Effect of Bremsstrahlung on
Monte Carlo ψ 's

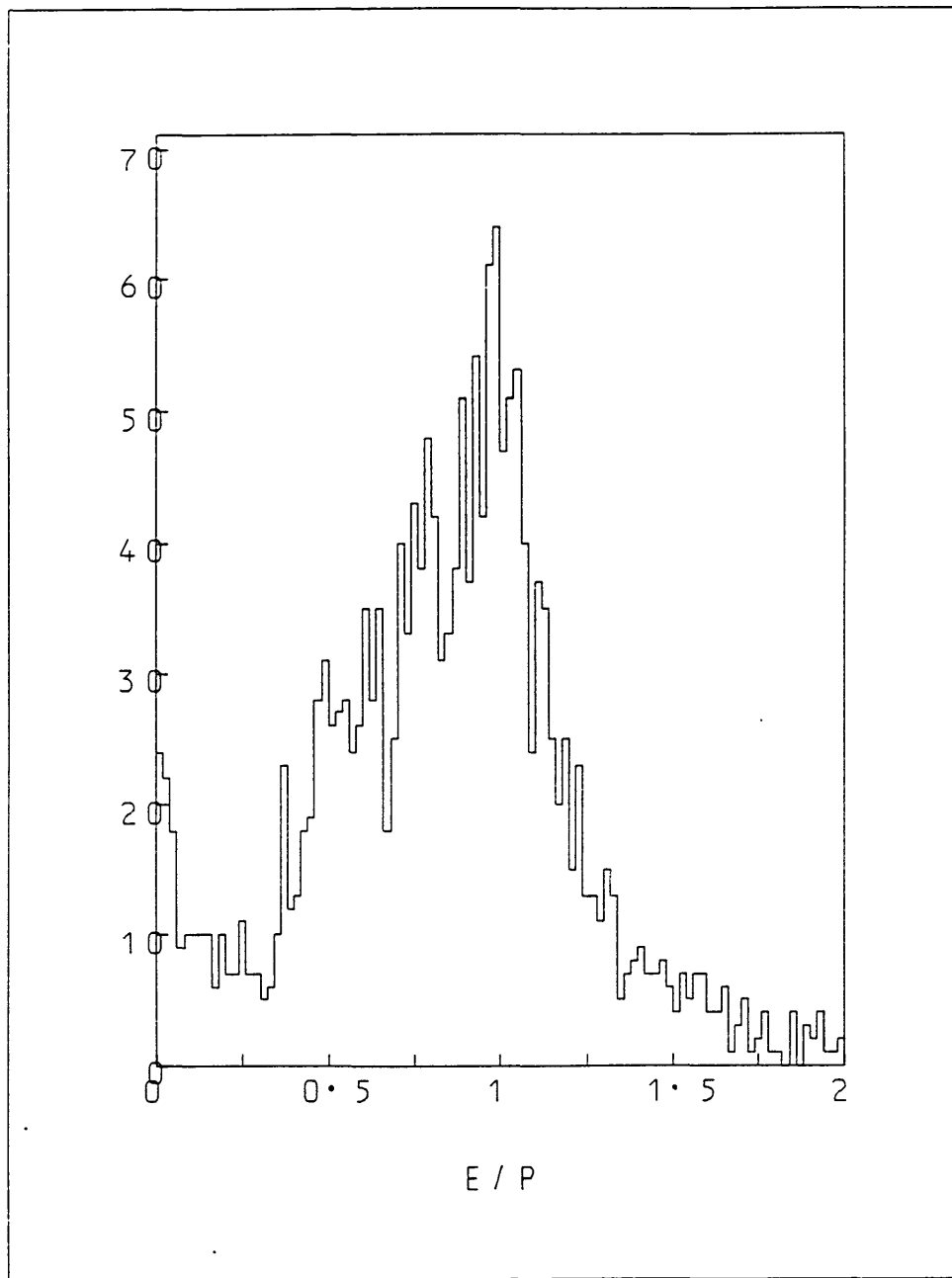


Fig 4.6: Fractional Energy Deposited in
Calorimeter by Electron Candidates

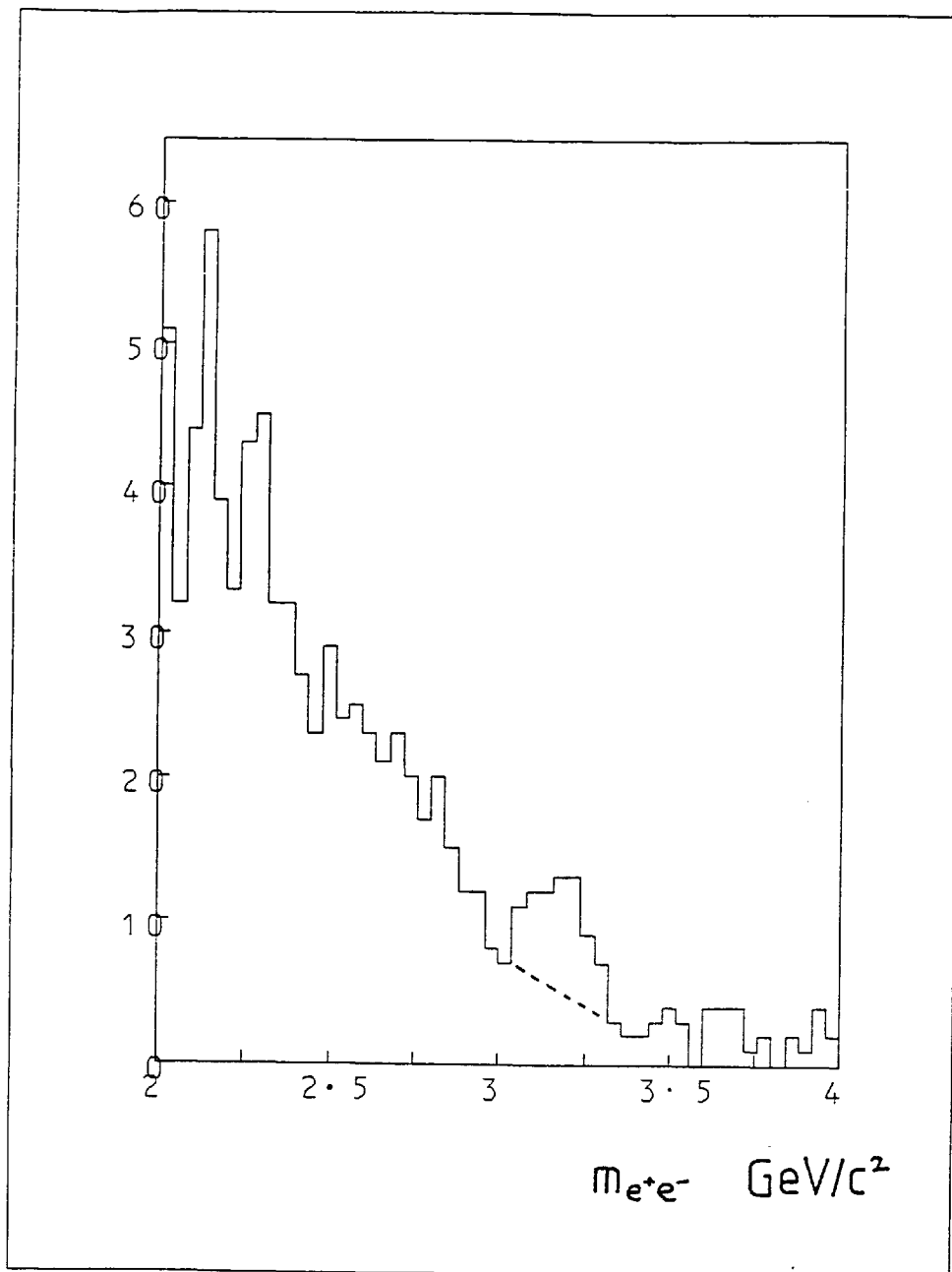


Fig 4.7: e^+e^- Mass Spectrum

Chapter 5

Psi Production and Associated Charm

5.1 Selection of Data for Analysis

The 2μ data used in this thesis was taken after a re-calibration by scanning the calorimeter using a 10 GeV electron beam on 20/3/79, run 11875. By this time the calorimeter was well understood, and could be monitored sufficiently well on-line that the majority of the counter gains remained constant to within $\pm 3\%$, thus removing the need to calculate sets of calibration constants at frequent intervals.

In this sample of 10000 RGOUT 2μ events, 7319 had at least a pair of μ 's :

- a) of opposite charge
- b) in diagonally opposite quadrants
- c) originating at the primary vertex
- d) with effective mass greater than $2 \text{ GeV}/c^2$

The 2μ effective mass plot of the 6859 events in which only 2 μ 's were found is shown in Fig 5.1. To obtain the ψ , the 2479 events in the mass range 3.0 to $3.18 \text{ GeV}/c^2$ were selected and constrained to the correct mass of $3.097 \text{ GeV}/c^2$ by adjusting the μ momenta. By interpolating the continuum from either side of the ψ mass, 171 of these events were

estimated to be background from π and K decays, and the Drell-Yan process.

Although there are more events in the range 2.95 to 3.0 GeV/c² and 3.18 to 3.25 GeV/c², these add only 5% to the number of ψ 's, while the signal to noise ratio in these regions is of order one. Similarly, relaxing the definition of a μ adds considerably more to the background than the number of ψ 's. Thus, only well measured μ 's and ψ 's are used in the analysis so that any effect is not masked by the background contributions.

5.2 Associated Production Search

As described in chapter 1, a candidate ψ production mechanism was that of associated production of charmed mesons or baryons, via charm quark fusion, eg

$$\pi^- N \rightarrow \psi D \bar{D} X$$

where D and $\bar{D}$ are the mesons carrying naked charm. Other charmed hadrons can also be produced, but are unstable, and cascade down to the D states by light meson emission. The D mesons are also unstable, but being the lightest of the charmed particles, can only decay weakly, having a 10% branching ratio to both $K\mu\nu$ and $Ke\nu$ ("prompt lepton emission"). This channel can be used to test if this is an important production mechanism even though the D mass cannot be reconstructed, due to the energy taken away by the undetected ν .

Monte Carlo studies show that the mean geometric

acceptance for prompt leptons arising from the decay of a meson carrying naked charm is about 50% (Ref 20). If the ψ were produced solely via charm quark fusion, the number of leptons found arising from the D meson decay would be

$$100\% \cdot \text{branching ratio} \cdot \text{acceptance}$$

$$= 100\% \cdot 0.1 \cdot 0.5 = 5\%$$

Thus, with 2500 ψ events, 125 prompt μ 's should be observed. In the case of electrons there is a 60% software reconstruction efficiency (see later this chapter) and so the number of ψ events with an associated electron will be only 3% (75 events).

To see if the leptons found in association with the ψ are due to charmed meson decay, they must be compared with the non-prompt leptons. This can be done allowing for any possible kinematical trend introduced by the energy taken away by the μ pair by studying the lepton as a function of the 2μ effective mass.

It is reasonably easy to identify and study the properties of electrons independently of the origin of the μ pair. For a 3μ event however, there is an ambiguity between the possible 2μ combinations, each of which have an associated μ . The decision as to which is the "real" pair for each event is not only arbitrary, but also to some extent meaningless in that most μ 's comprising low mass pairs are from π decays anyhow. Thus, although it is possible to consider the kinematics of both "extra" μ 's for comparison with those found with the ψ , a study of the

"associated fraction" for different pair masses (i.e. the percentage of events of a given $m_{\mu\mu}$ with an extra lepton) will not be performed for extra μ 's.

5.3 Background Processes

The main problem of such a charm search is the large background involved. An order of magnitude consistency check on the number of μ 's and e's anticipated at the primary vertex predicts over 10% per event.

For electrons, the background is mostly due to π^0 's whose photons convert in the target. The mean amount of material to be traversed, averaged over the 3 targets is 4% of a radiation length. The geometric acceptance of electrons resulting from π^0 decay followed by photon conversion was studied using a Monte Carlo computer program (Ref 20) and can be broken down as follows :

- a) 73% of events have 0 electrons in the calorimeter
- b) 16% have 1 electron only in the calorimeter
- c) 11% have both electrons in the calorimeter.

Thus, the number of electrons found in the calorimeter as a result of 1 converted photon is $0.16 + 2 \cdot 0.11 = 0.38$. With a software reconstruction efficiency of 60% the number of extra electrons expected per event is

$$2.7 \cdot 2 \cdot 0.04 \cdot 0.38 \cdot 0.6 = 5\%$$

Of the 7319 2μ events, 140 (2%) had an electron detected

by the calorimeter.

There are very few processes which will give μ 's originating at the primary vertex. The background mainly comes from π decays whose daughters are then identified by the hodoscope, thus tagging the particle as a μ . The mean decay length for a π in its centre of mass is $c\tau = 7.8\text{m}$ (Ref 21). Fig 2.3 gives a mean hadron momentum (and hence energy) of 10 GeV/c, so the decay length in the lab frame is boosted by a factor of

$$\gamma = \langle E_{\pi} \rangle / m_{\pi} = 10 / 0.14 \sim 70$$

As the π and μ have roughly the same mass, the decay is almost colinear, so the efficiency for detecting the μ 's from the 5.4 π 's per event which pass through D0 is of order 100%. The number of π 's per event expected to decay in the 8m between the target and the iron wall is therefore given by :

$$\langle N_{\pi} \rangle = 5.4 / \gamma c\tau = 5.4 \cdot 8 / (70 \cdot 7.8) \sim 8\%$$

K mesons also have a large branching ratio to μ 's, but do not contribute significantly to the background, mainly because their production cross-section, as found from cerenkov studies, is only 5% that of π 's. Assuming a mean energy of K's to be also approximately 10 GeV, the decay length, $c\tau = 3.7\text{m}$ is boosted by a factor of

$$\gamma = \langle E_K \rangle / m_K = 10 / 0.494 \sim 20$$

Thus a similar calculation to that above predicts that the number of K's decaying per event to be

$$\langle N_K \rangle \cdot 8 / \gamma_{c\tau} = .27 \cdot 8 / (20 \cdot 3.7) \sim 3\%$$

Furthermore, some μ 's will not be accepted due to the high p_T given them by the massive K, making the contribution to extra μ 's small in comparison with the π decays.

In fact, of the 7319 events, 460 (6.3%) had more than 2 μ 's, in support of the above estimation.

5.4 Electro-Magnetic Shower Detection

As was described in section 3.1, the choice of a MWPC as position detector was not ideal, nor was its location, which would optimally be set at the position where the e - γ population is at a maximum (6 radiation lengths for the 10 GeV electron shower in Fig 3.1). Nevertheless, even situated after 2.8 radiation lengths of Pb, a large number of wires, of order 100, were struck each event. A typical ψ event is shown in Fig 5.2. These wires are due to either electro-magnetic particles which interact in the Pb to produce a wide shower, to spurious wires firing, or to hadron showers, which usually arise from the production of π^0 's. The nuclear absorption length in Pb is 18.5 cm, so hadron showers are often delayed in developing, and consequently have a smaller lateral spread at D0. Because of the complexity of the events, the normal use of point-finding techniques were too expensive in computer time, and so a special pattern recognition program, "DEETWO", was written by Andrew Wylie. This is fully described in Ref 16, but briefly can be summarised as :

a) reclustering the data so that it was of manageable proportions. This procedure involved discarding very small wire clusters, and simplifying the larger ones by filling in narrow gaps between wires

b) selecting shower candidates from the reclustered data, using the four planes in the MWPC, and the calorimeter

c) rejecting poor candidates according to a list of criteria

d) distributing the energy in the calorimeter between the surviving candidates, allowing for overlap into a neighbouring module, and more than one shower per module

e) discarding all resulting showers with energy less than 1 GeV

f) ignoring events with a shower multiplicity above some threshold, N_{γ}^{max} , these events being too complicated for the software to deal with. This was set at 10 showers per event, effecting 11.5% of the data, thus leaving 6600 events with shower information.

Confirmation that this procedure identified γ 's satisfactorily can be obtained by looking for π^0 's in 2- γ invariant mass spectra. This is most easily done using data taken with an incident 10 GeV π^- beam and a neutral trigger. Fig 5.3 shows the $\gamma\gamma$ mass plot for events containing 2 γ 's only in the final state, with the γ 's taking all of the 10 GeV (± 0.5 GeV). This strongly favours the charge exchange reaction $\pi^- p \rightarrow \pi^0 N$, and shows a clear

π^0 peak at a mass of 145 ± 5 MeV/c². As these data were taken at roughly the same time as the 2μ data, it indicates that the energy calibration was, in fact, incorrect. The π^0 width of 40 MeV/c², FWHM, is consistent with the measured position and energy resolutions (Appendix B).

As the γ 's from 10 GeV π^0 's have similar characteristics to those found in the data taken at 175 GeV/c, the γ software reconstruction efficiency can be estimated by taking events in which a π^0 was identified and superimposing on data taken at normal energies. This was done by ORing the chamber wires together and adding the relevant counter pulse-heights. The events were then rewritten to disk and reprocessed. It was found that a global value of 40% of these known γ 's were missed in the second pass through DEETWO. This is in good agreement with the value of $60 \pm 10\%$ efficiency found by superimposing π^0 events on each other in a similar manner.

When the 6600 2μ RGOUT events with shower information were processed by DEETWC a mean of 4.1 showers per event were found. In order to find out how many of these were due to charged particles, the distance from each track to the nearest shower at D0 was plotted, Fig 5.4. The distribution peaks at small distances and is explained as being the result of electron and/or hadron showers. The position resolution is seen to be 35cm (FWHM). By extrapolation of the background, the number of charged tracks with an associated shower was found to be about 500, compared with a background of 1000 accidentally close

occurrences.

To test which of the charged showers are hadronic and which are electro-magnetic, a similar method was employed to that used in the analysis of the 2e data. Fig 5.5a plots the fractional energy deposited in the calorimeter, showing an excess of events with $E \sim p$. This indicates the presence of electrons in the data. Estimating an exponential fit to the background, there is an excess of about 250 tracks with $0.6 < E/p < 1.4$, and these tracks are considered to be electrons. 30% of the tracks in the 6600 2μ events are either from secondary vertices, or are tracks which could not be fitted to a vertex, and so cannot be due to prompt lepton emission. If only tracks from the primary vertex are considered, and the above is repeated (Fig 5.5b) there is a rough estimate of 140 electrons (2% per event).

5.5 p Dependence

Studying the absolute momenta, p , of the extra leptons, is not the best place to look for D decays. Fig 5.6 shows the momentum of the extra lepton plotted against $m_{\mu\mu} \cdot \mu$'s from ψ decay were previously measured to have a mean momentum $\langle p \rangle = 25 \text{ GeV}/c$, so if leptons from D mesons have a similar energy, then an excess of high p entries would be expected at m_{ψ} .

From projections onto the p axis of selected mass ranges, $\langle p_{\mu} \rangle$ is found to be approximately the same as $\langle p_{had} \rangle$, with $10 \text{ GeV}/c$ for μ 's associated with the ψ , and 10.8

GeV/c for μ 's found with other pairs. $\langle p_e \rangle$ is found to be 9.1 GeV/c and 9.7 GeV/c for $m_{\mu\mu}$ on and off ψ resonance respectively. The conclusion is therefore that there is no observed difference between the momenta of prompt lepton candidates and those which are known to be due to π decays. $\langle p_e \rangle$ is slightly lower than $\langle p_\mu \rangle$ because electrons take a smaller share of their parent π^0 momentum than the μ 's take of their parent charged π momentum.

5.6 p_T Dependence

As the D mesons are massive in comparison with other final state particles, their decay products will be emitted with a large transverse momentum, p_T . Thus, a plot of the p_T of the extra lepton vs $m_{\mu\mu}$ (Fig 5.7) might be expected to show a cluster of high p_T entries at m_ψ .

There is no evidence for this in the case of extra μ 's, Fig 5.7a. Projections onto the p_T axis show that for $m_{\mu\mu} \neq m_\psi$, the extra μ 's have $\langle p_T \rangle = 498$ MeV/c, as compared to $\langle p_T \rangle = 502$ MeV/c for $m_{\mu\mu} = m_\psi$.

To avoid the possibility that any variation in $\langle p_T \rangle$ due to associated charm might be suppressed by the higher population of low p_T entries due to π decay, the proportion of leptons with p_T greater than some nominal value can be studied. If this value is set at $\langle p_T \rangle$ (500 MeV/c) the fraction of μ 's above this "threshold" is found to be 46% and 43% on and off ψ resonance respectively.

Fig 5.7b might appear to suggest an excess of very high

p_{τ} electrons, ($p_{\tau} > 1.2 \text{ GeV}/c$), at $m_{\mu\mu} = m_{\psi}$, although averaging over all relevant entries, $\langle p_{\tau} \rangle$ on and off ψ resonance is 405 and 393 MeV/c, and the proportion of entries above $\langle p_{\tau} \rangle$ (400 MeV/c) is 38% in both cases. As in the case of absolute momentum above, the smaller $\langle p_{\tau} \rangle$ of the electron is due to them having a smaller share in the momentum of the parent π^0 . Thus, once again there is no observed difference between possible prompt leptons and non-prompt leptons.

5.7 The Associated Electron Fraction

As described in section 5.5, a study of the number of extra μ 's associated with a μ pair is hampered by the ambiguity between the different possible mass combinations. However, electrons do not suffer from this problem, and an examination of the frequency with which different pair masses have an associated electron (i.e. a projection of Fig 5.6b or 5.7b onto the mass axis) reveals a plot similar in shape to the $m_{\mu\mu}$ spectrum, Fig 5.8a. This is what would be expected if the existence of an extra lepton were independent of $m_{\mu\mu}$. A more useful plot is the fraction of associated production, as obtained by division of Fig 5.8a by the μ pair mass spectrum, the result of which (Fig 5.8b) is an approximately flat distribution.

Thus, although there may be associated production of charm at some low level, these results are consistent with zero. If the 5 high p_{τ} ($p_{\tau} > 1.2 \text{ GeV}/c$) extra electrons found at $m_{\mu\mu} = m_{\psi}$ were due to $\psi D \bar{D}$ production this would correspond to the process contributing only 5/75 (~7%) of the ψ cross-section.

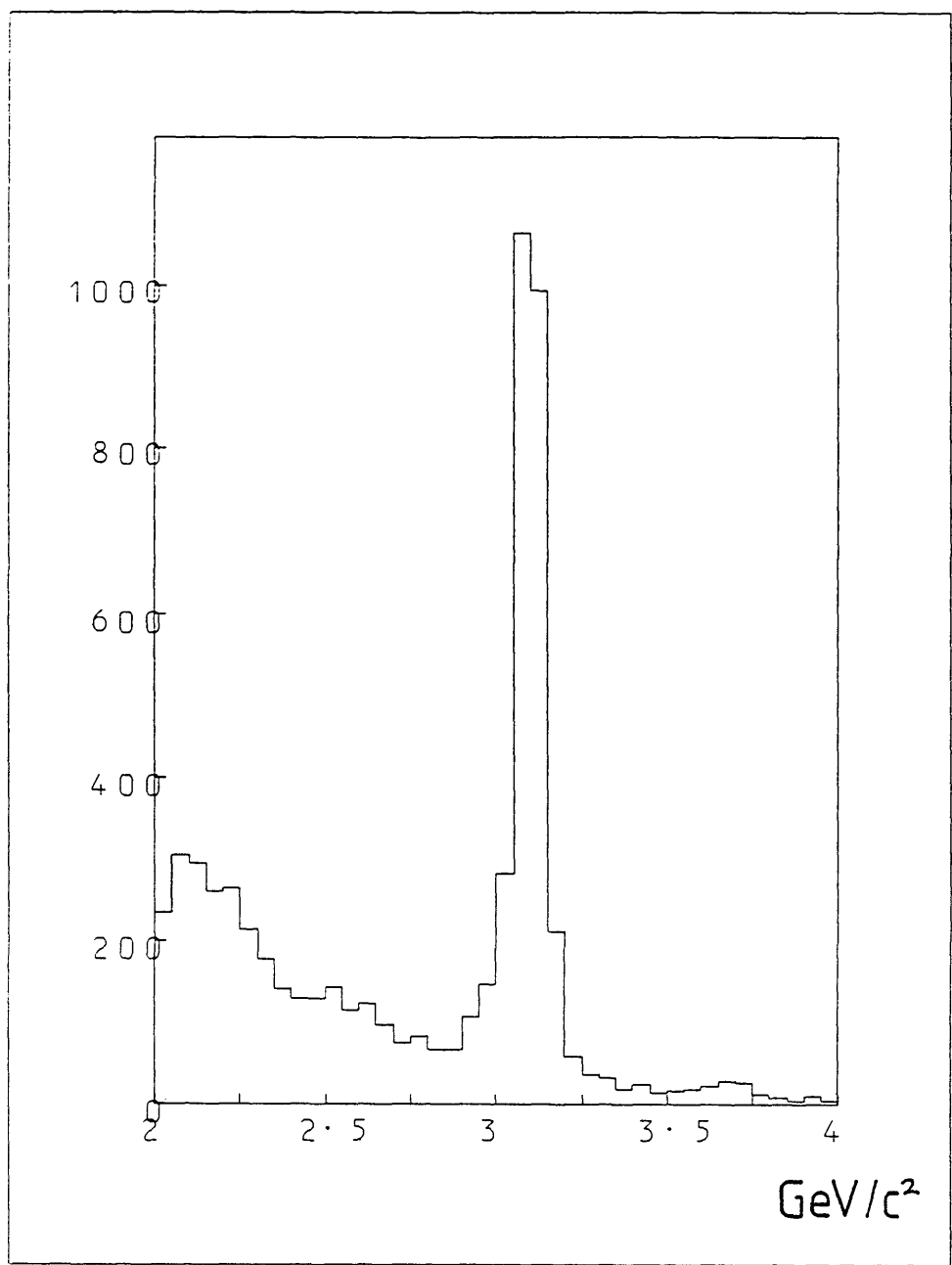


Fig 5.1: 2μ Mass Spectrum

RUN 11334 EVNT 1689 TRIG 2MU
CHAMBER D0

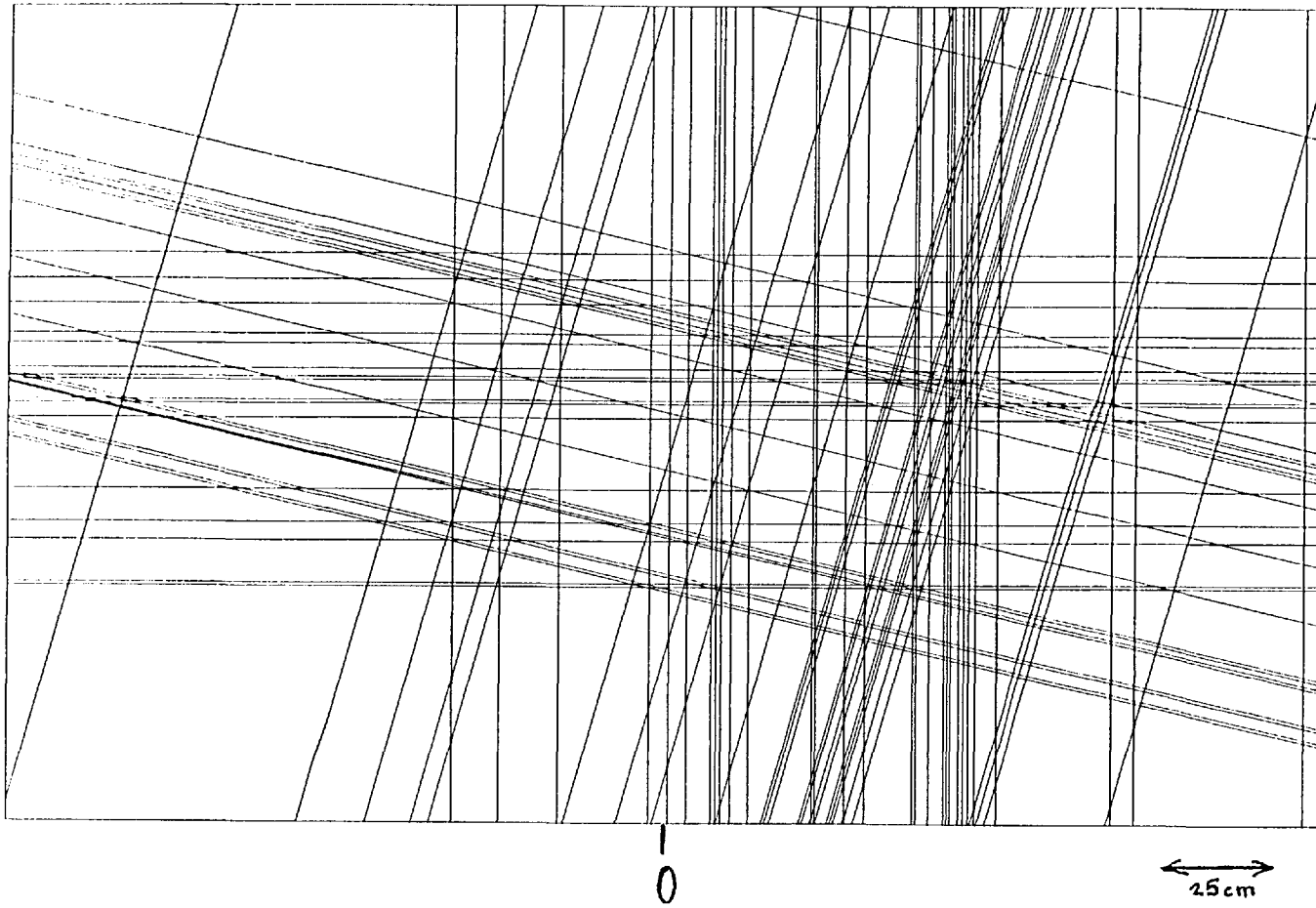


Fig 5.2: D0 Face for ψ Event

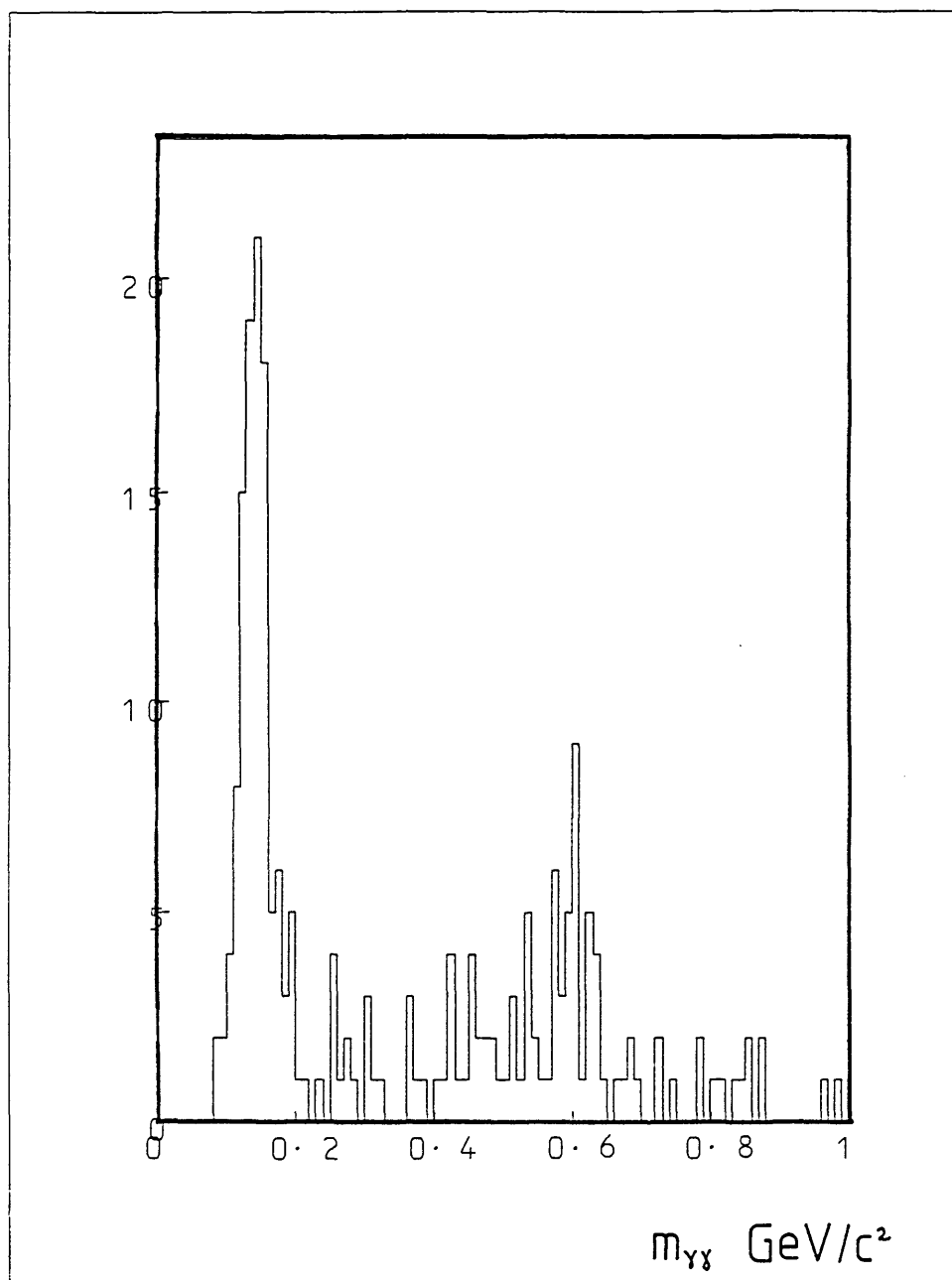


Fig 5.3: γ - γ Mass Plot (Neutral Trigger)

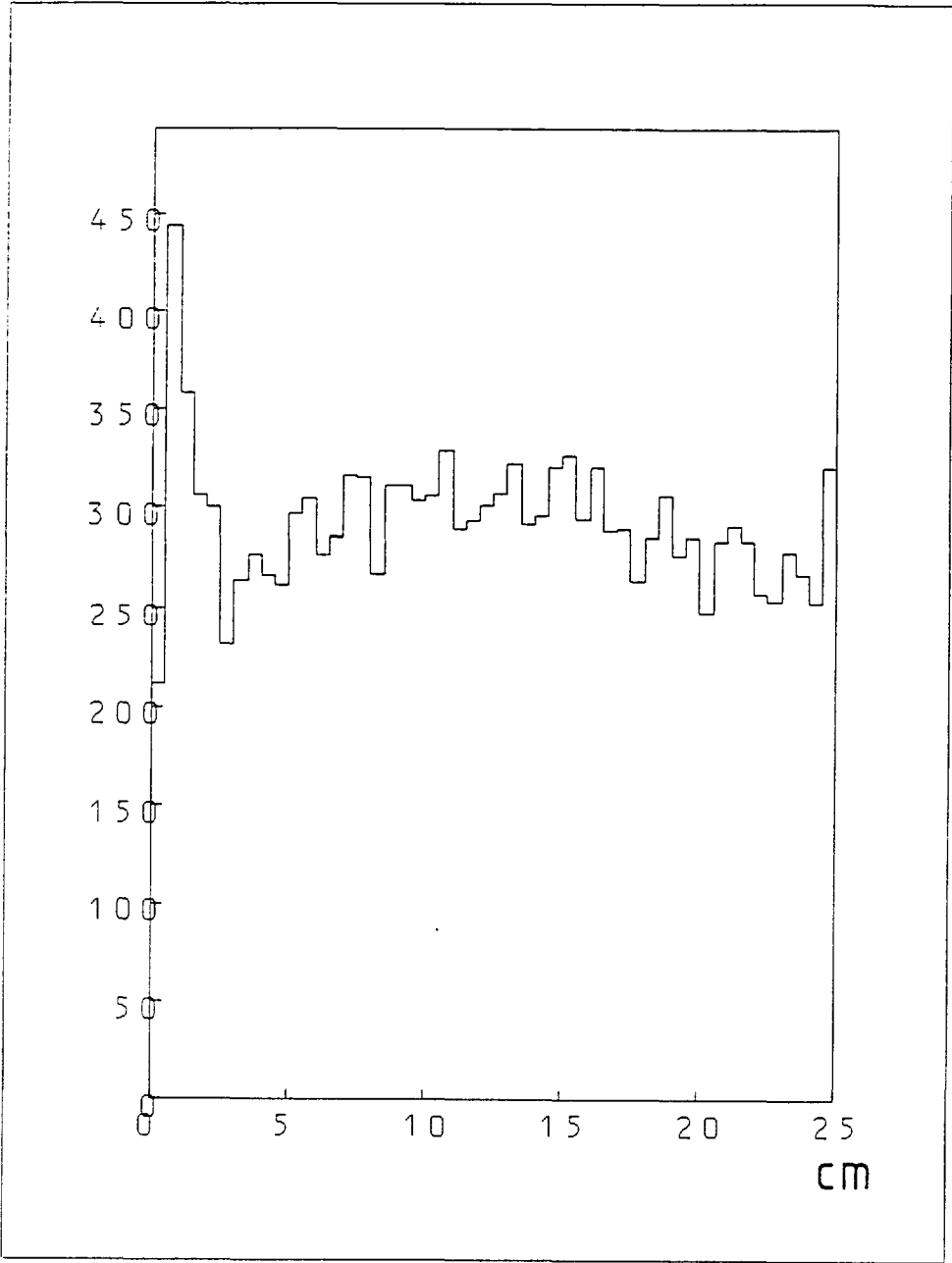


Fig 5.4: Track-Shower Separation at D0

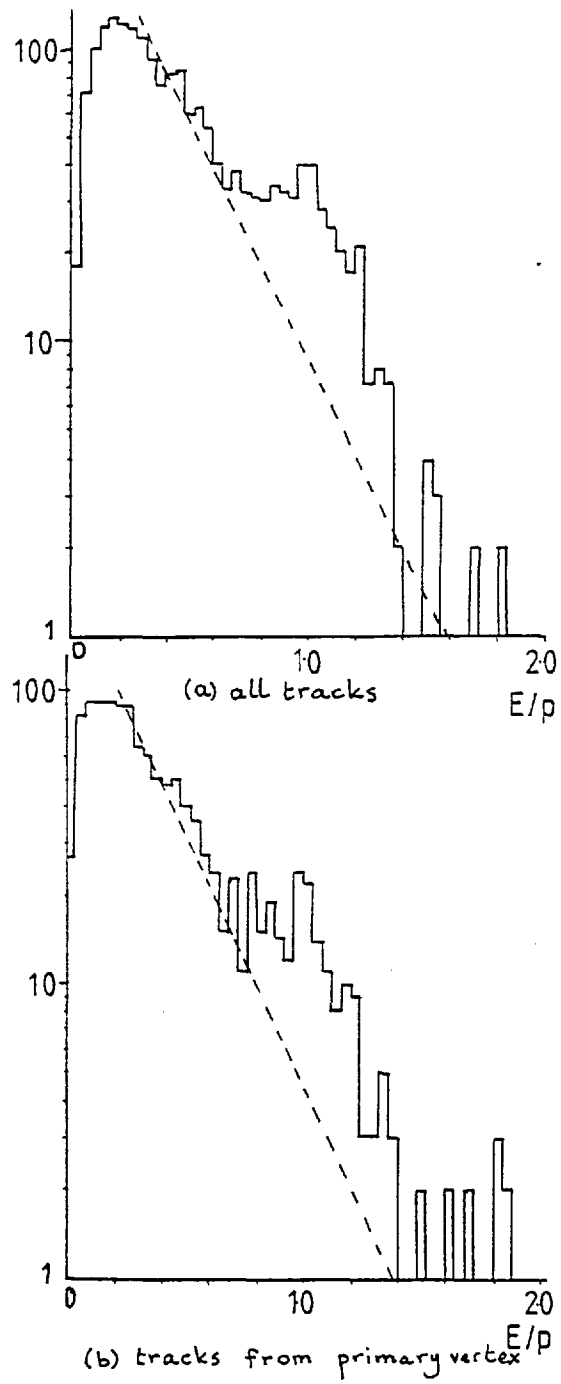


Fig 55: Fraction of Charged Shower Energy
Deposited in Calorimeter

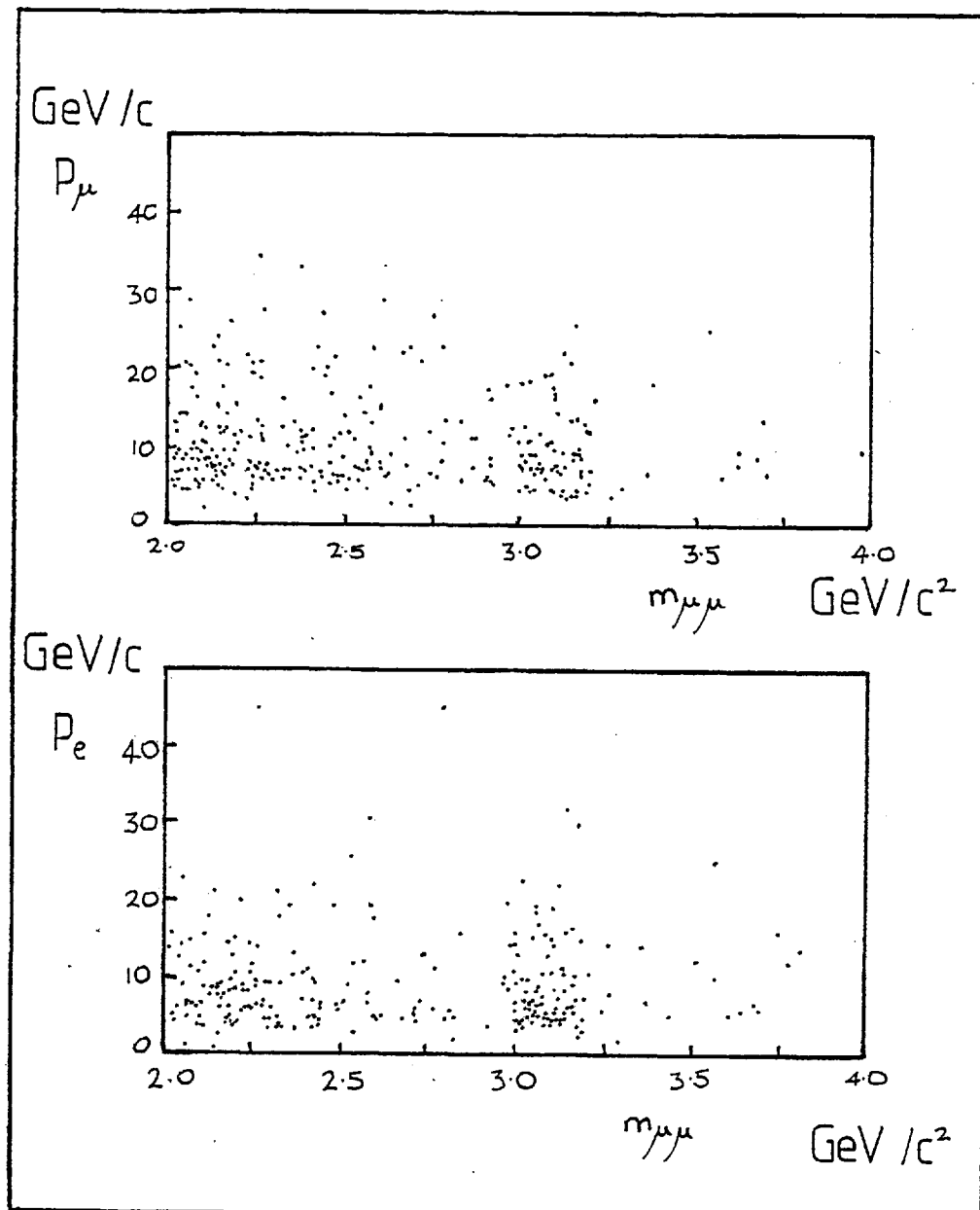


Fig 5.6: p_{lepton} VS $m_{\mu\mu}$

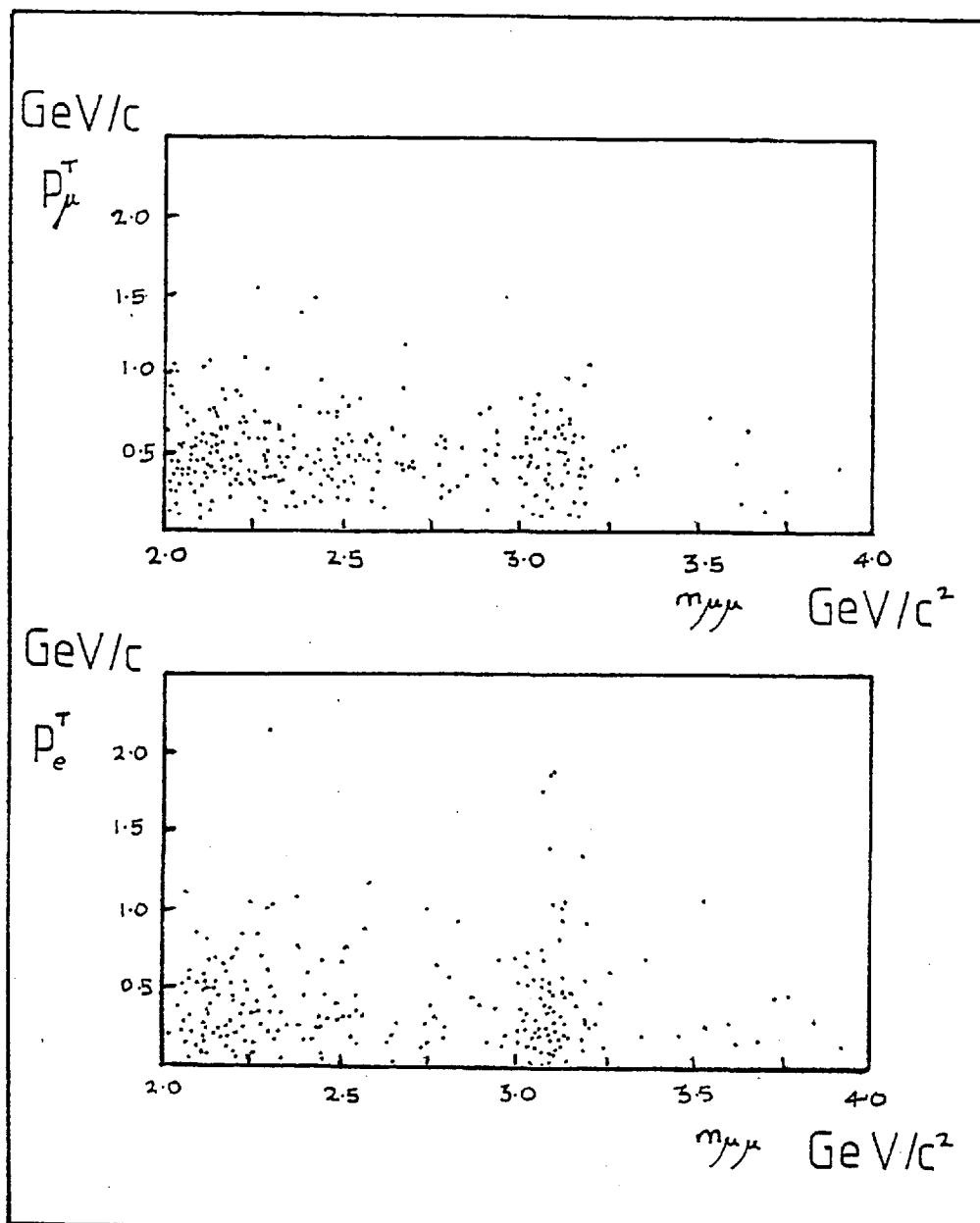


Fig 5.7: p_{lepton}^τ vs $m_{\mu\mu}$

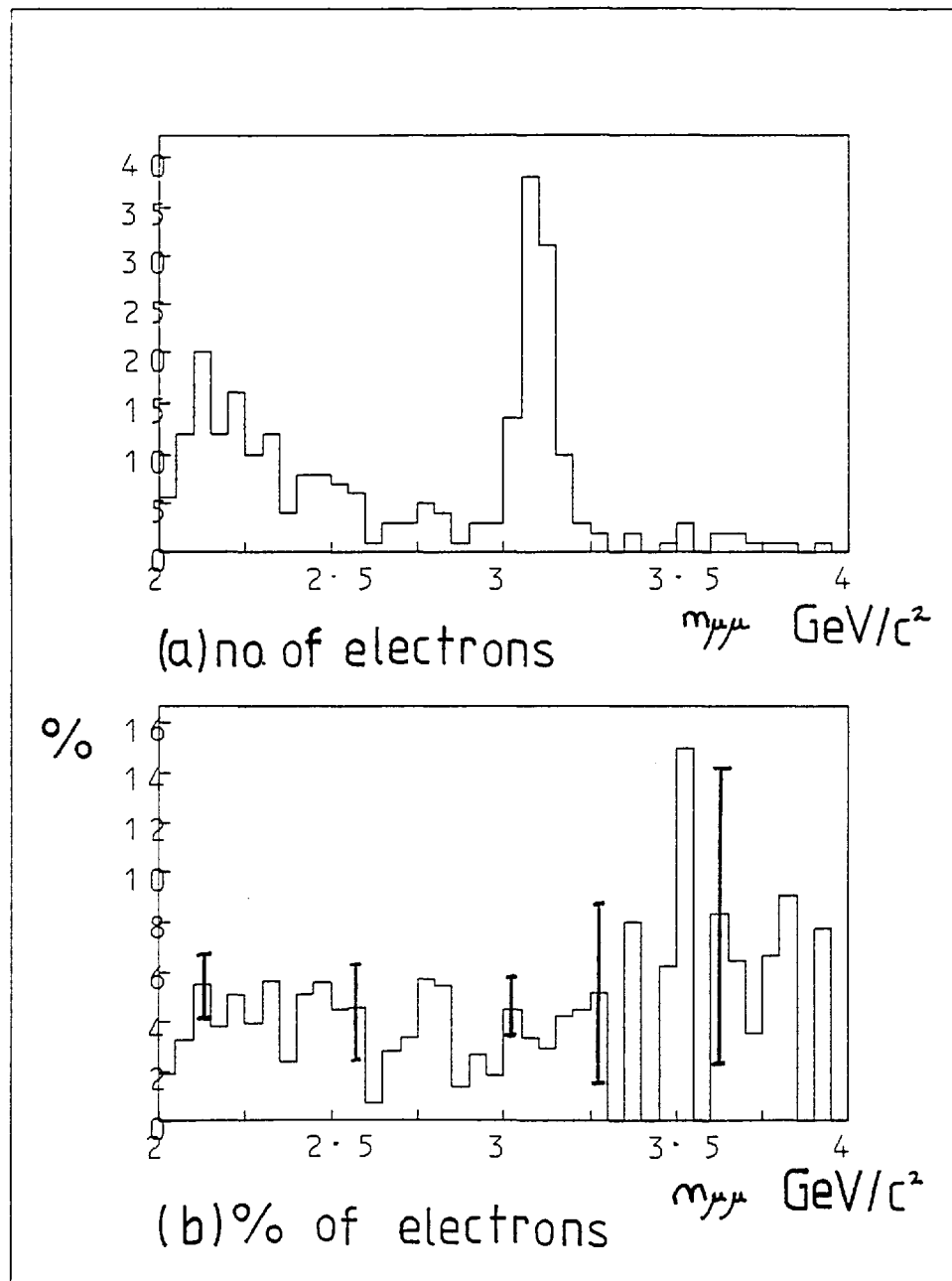


Fig 5.8: Fraction of Associated Electrons

Chapter 6

Chi Production

6.1 Introduction

As discussed in section 1.3, a possible ψ production mechanism is via the photonic decay of intermediate χ states, formed by either gluon fusion or valence quark fusion. If this is an important contribution to the hadronic ψ cross-section then it should be possible to detect these photons and thus study which of the χ states are involved and to what extent they contribute to ψ production. The detection of χ 's by the calorimeter was discussed in section 5.5, and this chapter will use these photons to search for χ states in the data.

6.2 Uncut $M_{\psi\chi}$ Spectrum

Fig 6.1 shows the invariant mass spectrum of the 2267 ψ 's with all correlated χ 's. Little obvious structure can be seen above the large combinatorial background. This background is due to mass combinations of ψ 's with χ 's which are either falsely identified or are from decays of particles such as π^0 's. The background can be fairly well simulated using uncorrelated ψ 's and χ 's, i.e. those from different events. This constructed background plot excludes any possible χ signal, although it does contain structure due to the χ 's from χ decay, whose

kinematical properties differ from those which comprise the background (this is taken into account in section 6.6). Nevertheless, a good first approximation to the real background can be obtained by neglecting this component, and the generated background can be subtracted from the $\psi\chi$ mass plot to make any possible presence of χ states more apparent.

In obtaining the background plot, only ψ events were used, in order to make the same CMS energy available to the χ 's as there would be in the data. Only ψ 's and χ 's originating in the same target were used to avoid miscalculating the χ momentum components. High statistics were obtained by saving the pertinent information from many previous events. Two background plots were made, one using ψ 's saved from the previous 50 events combined with the χ 's of the current event, and the other by using the current ψ with the previous 100 χ 's. These mass spectra are shown in Fig 6.2, and since they agree with each other to within a few per cent, only the background using previous χ 's will be shown hereafter, although the mean of the two results will be used in calculations. The background plot was then normalised to the signal, excluding the mass range 3.48 to 3.68 GeV/c^2 , where the χ signal was to be found, and subtracted, resulting in Fig 6.3. A mean excess of 98 ± 27 events are found in the region 3.54 to 3.64 GeV/c^2 .

Although this 200 MeV/c^2 slice around the χ excluded for normalisation does not contain all of the signal, it is considered a superior method to normalisation using the

high mass tail only because of its increased sensitivity. The effect of the badly measured χ 's is a small underestimate in the number counted in the peak due to the slightly increased background estimated under it as a result of these χ 's. The effect is calculable, and is included in the acceptance in section 6.6.

6.3 Effect of Photon Energy (E_γ) Cuts

To make the existence of χ states more significant it is necessary to reduce the number of background entries in the mass plot preferentially to the signal. This can be done by removing either :

- a) falsely identified or badly measured γ 's, such as those that share the calorimeter module with another γ or hadron
- b) γ 's which result from π^0 decays.

As the shower finding routine had already been tuned to look for γ 's, the effort was concentrated on b). For this purpose a Monte Carlo routine written by A. Duane was used. This generated χ 's with the same kinematical distributions as the ψ , followed by isotropic decay, plus a mean of 2.7 π^0 's per event. The γ 's were then followed to the calorimeter where the shower position and energy deposited in each BD module were smeared out in accordance with the experimental resolutions. The γ parameters were then reassigned allowing for the redistribution of energy in modules with more than 1 γ . One χ per event was

generated - effects which are dependent on the fraction of χ 's produced per event can be allowed for with a suitable scale factor.

Fig 6.4 shows the energy spectrum for χ 's in the calorimeter resulting from π^0 's (hereafter labelled χ_{π^0}) and χ 's (labelled χ_χ) respectively. From this it can be seen that a useful cut might be to include only χ 's in the reconstruction if their energy is above some minimum value other than 1 GeV. $M_{\psi\chi}$ spectra after imposing shower energy cuts of 2,3,4 and 5 GeV are shown in Fig 6.5.

A background can be constructed for each plot using the same energy cuts, and subtracted to give the number of χ 's in each case. In order to see if these numbers are consistent they must be corrected for acceptance. A crude estimate of this can be obtained by taking the fraction of Monte Carlo χ_χ 's with energy above the relevant threshold which hit the calorimeter. In addition to this "geometric acceptance" it is necessary to consider the Monte Carlo $\psi\chi_\chi$ invariant mass plot. Fig 6.6 shows that not all the entries are in the mass range 3.546 to 3.646 GeV/c², where the χ is found in the data. Some effective masses are outside the limits because of the finite energy and position resolutions, and some are shifted considerably due to the χ_χ being in the same BD module as a χ_{π^0} . The energy sharing algorithm may then assign a low energy to the χ_χ , leading to an incorrect invariant mass. Thus, the estimated "effective" acceptance is the fraction of generated events whose mass is reconstructed in the correct range. These

values will be further refined in section 6.5, but serve their purpose here of acting as a consistency check.

Fig 6.7 tabulates for each of the energy cuts, the geometric and effective acceptances, and the number of χ 's found in the data before and after correction which are seen to agree to within $\pm 4\%$. The gradual change in the acceptance with χ energy threshold indicates that the error in the estimated number of χ 's arising from the incorrect energy calibration (as witnessed by the $m_{\chi\chi}$ plot, Fig 5.3) will be less than 1%.

6.4 Removal of π^0

Another way of reducing the background would be to search for π^0 's in the data and remove their γ 's from the sample. However, the 2- γ invariant mass plot, Fig 6.8, shows no evident π^0 peak. As the Monte Carlo finds the geometric acceptance to be only 20%, and the software reconstruction efficiency for both γ 's is about 40%, the number of π^0 's expected is only

$$N_{events} \cdot N(\pi^0/event) \cdot (\text{geom acceptance}) \cdot (\text{software eff})$$

$$= 2500 \cdot 2.7 \cdot 0.2 \cdot 0.4 \sim 500$$

Some of these will have energy less than 10 GeV, and so the π^0 width will be up to 67 MeV/c² (Appendix B) Thus any signal will be swamped by the vast combinatorial background.

Nevertheless, assuming that the π^0 's are indeed present

in the data, an attempt can be made to exclude their χ 's from the $m_{\psi\chi}$ plot by rejecting any χ which will combine with any other χ of the same event to give a low effective mass. An $m_{\chi\chi}$ cut-off of 250 MeV/c² was estimated to remove over 95% of reconstructable π^0 's, as well as some of the soft background χ 's, and when applied, rejected 80% of all χ 's. The resultant $m_{\psi\chi}$ plot is shown in Fig 6.9, and reveals a clear χ peak in roughly the expected region.

The number of χ 's present can be calculated by fitting an exponential plus a Gaussian, leaving all parameters free, to the range 3.3 to 4.3 GeV/c², Fig 6.10. This gives a value of 107 ± 15 χ 's at a mass of 3.586 GeV/c², with a width of 100 MeV/c², FWHM.

This mass needs to be corrected for the systematic error in the calibration of the calorimeter as found from the position of the π^0 peak in the 2χ mass plot shown in Fig 5.3. A Monte Carlo program simulating a 10% error in energy measurement resulted a shift in the peak by 45 MeV/c². The calibration could be improved by studying the fractional energy deposited in each individual calorimeter module by electron shower candidates, as in Fig 5.6, in data taken after the recalibration. This would require the processing of more raw data by the pattern recognition program to obtain better statistics. So far, this has only been done for a limited amount of data taken after the 2μ trigger was removed.

An independent method of calculating the number of χ 's

present is to construct a background using the same technique as that used in section 6.2. When this is done, and subtracted from the signal, Fig 6.11, a mean of 78 ± 16 χ 's are found in the mass range 3.52 to 3.64 GeV/c². The acceptance was also studied in the same manner as used for the uncut data, and it was estimated that the geometric acceptance for χ_χ in the calorimeter and not being rejected as a π^0 was 31%, and that the effective acceptance ($m_{\chi\chi}$ being reconstructed in the correct mass range) was 24%.

To resolve the discrepancy between the 2 methods of counting the number of χ 's in the peak, further refinement of the background construction is needed (affecting also the acceptance calculation slightly) and this will be discussed in section 6.7.

6.5 Sensitivity to Cuts

Despite the necessary refinements mentioned, the methods used are still accurate enough to examine the sensitivity of various cuts both on the acceptance and the number of χ 's counted. The biggest defect of the Monte Carlo is perhaps that it only includes "real" χ 's, finding 3.2 χ 's per event in the calorimeter (this would be reduced to about 2 χ 's per event found in the calorimeter if the 60% software efficiency is taken into consideration). This implies that the data used, with 4.1 showers per event, contains roughly 2 spurious showers per event which are not due to χ 's. It has already been shown that the number of χ 's counted is a fairly stable function of the E_γ

threshold. To check how it varies with the mean multiplicity $\langle N_Y \rangle$ the number of π^0 's generated per event in the Monte Carlo was increased from 2.7 to 3.5 and 4.5. The resulting effective acceptances are plotted in Fig 6.12 for various values of $N_Y^{\max}$, the maximum γ multiplicity allowed per event. Setting a low value of $N_Y^{\max}$ in the uncut data reduces the probability of γ_χ having its energy miscalculated by the energy sharing algorithm due to a γ_{π^0} in the same module. However this is seen to be a negligible effect. For the π^0 removed data a low $N_Y^{\max}$ increases the acceptance by reducing the probability of the γ_χ combining with a γ_{π^0} to form a low invariant mass, thus being rejected. Unfortunately, due to the reduced number of events which could be used it is not possible to capitalise on this and improve the significance of the χ peak in the data.

The number of π^0 's generated per event in the Monte Carlo is seen to have a material effect on the acceptance. In the uncut data the acceptance falls with rising $\langle N_{\pi^0} \rangle$ due to the increased probability of the γ_χ having its energy measurement contaminated by γ_{π^0} 's. As $\langle N_Y \rangle$ in the data is 4.1, the estimate of the effective acceptance could be revised from 38% to $35 \pm 2\%$. The acceptance for the π^0 removed data would also need to be similarly revised down from 24% to $22 \pm 2\%$.

The $\gamma\gamma$ effective mass below which γ 's are discarded in the effort to remove π^0 's is also a parameter in need of study. Fig 6.13 shows the result of choosing $200 \text{ MeV}/c^2$ and $300 \text{ MeV}/c^2$ as well as $250 \text{ MeV}/c^2$ for the cut-off. The yield

of χ 's is found to be insensitive to these cuts.

6.6 Corrections to Background and Acceptance

The background in the $m_{\psi\chi}$ plot is due to mass combinations of ψ 's with χ 's which are either from decays such as π^0 's, or are falsely identified. However, the generated background constructed using ψ 's and χ 's from different events contains not only this but also an extra component due to χ_χ 's from previous events. A Monte Carlo mass plot of ψ 's with only uncorrelated χ_χ 's, Fig 6.14, shows a broad enhancement of width about 400 MeV/c² centered at the χ mass. This component needs to be subtracted from the generated background before normalisation for it to accurately represent the true background. The amount which needs to be subtracted is given by the fraction of χ_χ present in the total χ sample.

If the fitted value of 107 is used as the most reliable estimate for the number of χ 's in the data with the π^0 's removed, a correction needs to be applied to allow for the 23% (0.07/0.31) of geometrically accepted χ 's which although they do not reconstruct at the correct mass, nevertheless contribute to the enhancement. Thus, the number of χ_χ present in the total of 1984 found in the calorimeter is estimated to be 139 (7.0%).

Thus, the Monte Carlo plot, Fig 6.14, must be scaled to 7% of the generated background and subtracted from it. Fig 6.15 shows this resultant background superimposed on the

signal, after normalisation. When this background is subtracted from the signal, the structure on the low mass side of the peak, which results from the effect of the χ background component, is seen to be greatly diminished. The corrected value of 103 χ 's is in good agreement with the value of 107, as found using the exponential plus Gaussian fit. A plot of the variation of the number of χ 's versus the amount of χ background component correction, Fig 6.16a, shows that it is a sensitive parameter.

The same correction can be made to the uncut data. The fraction of Monte Carlo background to be subtracted from the generated background is, as before, given by the fraction of the total χ sample made up by χ . This number can be obtained by multiplying the total number present in the π^0 removed data (139) by the ratio of the geometric acceptances (58%/31%) and is found to be 260. This represents 2.8% of the total number of χ 's (9237) present. A scan of number of χ 's versus amount of Monte Carlo background correction is shown in Fig 6.16b. 2.8% corresponds to an estimate of 140 χ 's in the mass range 3.54 to 3.64 GeV/c².

To obtain the best possible estimate of the acceptance, the Monte Carlo needs to be treated in exactly the same way as the data. This means taking the $m_{\psi\chi}$ plot and constructing two backgrounds, one of ψ 's with all uncorrelated χ 's, and the other of ψ 's with uncorrelated χ only. The relevant fraction of the $m_{\psi\chi}$ background plot is then subtracted from the total generated

background, normalised to the signal (excluding the 200 MeV/c² slice around the χ) and subtracted. The number of χ 's then counted in the same mass range as in the data then gives the "real" acceptance. This was found to be 32% for the uncut data, and 22% for the π^0 removed data.

6.7 The Chi Fraction Obtained

If the 140 ± 39 χ 's counted in the uncut data are corrected for the real acceptance of 32%, and χ software reconstruction efficiency of 60%, the total number of χ 's present in the data sample is calculated to be 729 ± 203 . For the 102 ± 22 χ 's in the π^0 removed data, the software efficiency and 22% acceptance give a value of 795 ± 167 χ 's. These 2 figures are quite consistent given the size of the errors, but the latter is considered more reliable.

When expressed as a fraction of the 2096 ψ 's (corrected for Drell-Yan and background) this gives a value of $38 \pm 8\%$ of ψ 's produced via intermediate χ states.

As discussed in section 6.4 the mass(es) of the χ state(s) involved cannot be determined from the calorimeter information because of its miscalibration. A more reliable estimate can be obtained by analysing χ_x 's which have converted, and whose electrons are measured in the spectrometer. The acceptance for this process is much smaller (1.3%) but has a superior mass resolution of 22 MeV/c², FWHM. If all 42750 ψ 's are used, both the $\chi_{3508}(1^{++})$ and the $\chi_{3554}(2^{++})$ are observed in a ratio of

$\sigma(2++)/\sigma(1++)=1.4\pm0.9$, with the combined fraction of ψ 's coming from χ 's= $31\pm11\%$ (Ref 22). Although the calorimeter is unable to fully resolve these 2 χ 's the experimental width should be broadened to the mass resolution ($100 \text{ MeV}/c^2$ FWHM) plus the separation of the 2 states ($46 \text{ MeV}/c^2$), i.e. to a width of $\sim 150 \text{ MeV}/c^2$ FWHM. As the measured width was only $100 \text{ MeV}/c^2$, further study is warranted to obtain consistency between the 2 results.

6.8 Comparison with Other Experiments

To date there has been 2 other experiments which have published results on the χ fraction. Neither were able to resolve the 2 states $\chi_1(3508)$ and $\chi_2(3554)$, but they both obtained estimates of the fraction of ψ 's produced by χ states compatible with WA11 :

a) At the CERN ISR using pp collisions at $\sqrt{s}=62\text{GeV}$ (Ref 23) $47\pm8\%$ of ψ 's were found to originate from the photonic decay of χ states. This value is in close agreement with the WA11 result, and suggests that valence quark fusion, which cannot occur to any great extent at the ISR is also responsible for ψ production at WA11.

b) An experiment using a $217 \text{ GeV } \pi^-$ beam at FNAL (Ref 24) found that $70\pm28\%$ of their ψ 's came from intermediate χ states. Although this is somewhat higher than the other values, it is still consistent to within one standard deviation because of the large error involved.

6.9 Discussion

The observation that 40% of the ψ 's are produced via χ states in this experiment is not sufficient to completely determine which of the mechanisms described in chapter 1 are dominant. Additional information can be obtained from the x_F distribution of the observed ψ (Ref 25) as this reflects the momentum distribution of the fusing partons. The x_F distribution is found to be centered at a positive value of ~ 0.15 in meson-nucleon collisions, although this does not indicate which of the partons are involved as the momentum distribution of the gluons and sea quarks are believed to be linked to that of the valence quarks. The important feature is the width of the x_F distribution, which is found to be much more narrow than that of the x_F distribution of Drell Yan μ pairs (which are believed to be formed mainly from valence quark-antiquark collisions). Also, a theoretical x_F curve for the ψ can be calculated using the π and nucleon structure functions as found by other experiments, and assuming that ψ 's are produced via valence quark fusion. This is found to be much broader than that obtained experimentally, and is inconsistent with light quark fusion providing a major contribution to the ψ cross-section.

This implies the need for partons with a more restricted momentum distribution, as possessed by c quarks and gluons. These are found predominantly with small momenta and so after fusion would give a narrow x_F distribution as required. Due to the absence of conjoint production of

charmed particles, it can be assumed that gluon fusion is the dominant process at WA11.

Further support for the increasing importance of gluons with $\sqrt{s}$ can be obtained from the ratio $R_\psi = \frac{\sigma(pN \rightarrow \psi X)}{\sigma(\bar{p}N \rightarrow \psi X)}$ at different beam energies (Ref 13,26) :

$$R_\psi(\sqrt{s} = 8.6) = 0.15 ; R_\psi(\sqrt{s} = 13.7) = 0.5 ; R_\psi(\sqrt{s} = 19.4) = 0.7$$

Whereas antiprotons have 3 valence antiquarks, protons only have them in the sea. Hence $q\bar{q}$ fusion is suppressed when using proton beams and the ratio R_ψ is expected to be small (as found at $\sqrt{s}=8.6$). The gluon momentum distributions in protons and antiprotons, however, are identical and so if gluons were wholly responsible for ψ production the ratio R_ψ would be one. Thus, the contribution from gluons to ψ production is seen to increase as the beam energy increases.

Fig 1.3 shows that there are several different proposed mechanisms involving gluon fusion, some of which produce χ 's and some of which produce ψ 's directly. The observed degree of χ production suggests that these are occurring in roughly equal amounts.

It is argued (Ref 27) that further insight of the processes involved can be obtained from the different relative abundances of the different χ states found. Models in which a coloured intermediate $c\bar{c}$ state is formed followed by gluon bremsstrahlung (eg Fig 1.3d) would lead to the relative amounts of each χ state being proportional to the statistical weights $(2J+1)$, i.e.

$$\sigma(\chi_0) : \sigma(\chi_1) : \sigma(\chi_2) = 1 : 3 : 5$$

The branching ratios of these states into $\psi\gamma$ vary considerably (Ref 21) :

$$BR(\chi_0 \rightarrow \psi\gamma) = 2.7\% ; BR(\chi_1 \rightarrow \psi\gamma) = 31.5\% ; BR(\chi_2 \rightarrow \psi\gamma) = 15.4\%$$

This implies that the states observed would be predominantly χ_2 and χ_1 , in a ratio $\frac{\sigma(\chi_2) BR(\chi_2 \rightarrow \psi\gamma)}{\sigma(\chi_1) BR(\chi_1 \rightarrow \psi\gamma)} = 0.8$. Models assuming that only a colour neutral intermediate state can be formed by the fusing gluons (eg Fig 1.3c) forbids the production of the χ_1 state (by conservation of C-parity) and implies an observed dominance of χ_2 states because of their larger branching ratio to $\psi\gamma$.

Hence, although spectrometer measurements of converted photons (with a value of $\frac{\sigma(\chi_2) BR(\chi_2 \rightarrow \psi\gamma)}{\sigma(\chi_1) BR(\chi_1 \rightarrow \psi\gamma)} = 0.6$) appears to allow the existence of coloured intermediate states, a more accurate measurement of the relative χ proportions would be of considerable interest.

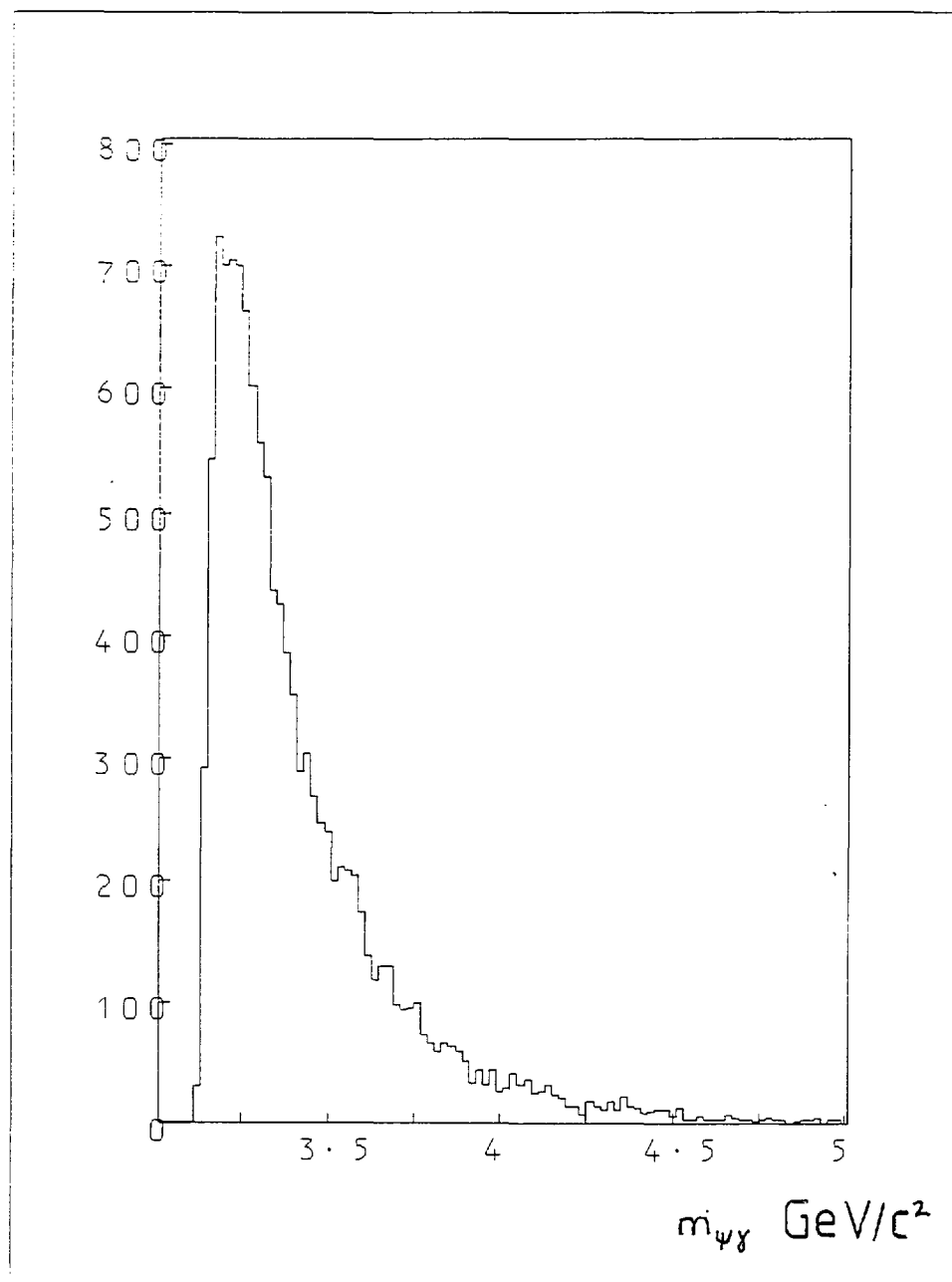


Fig 6.1 :Uncut ψ - γ Mass Plot

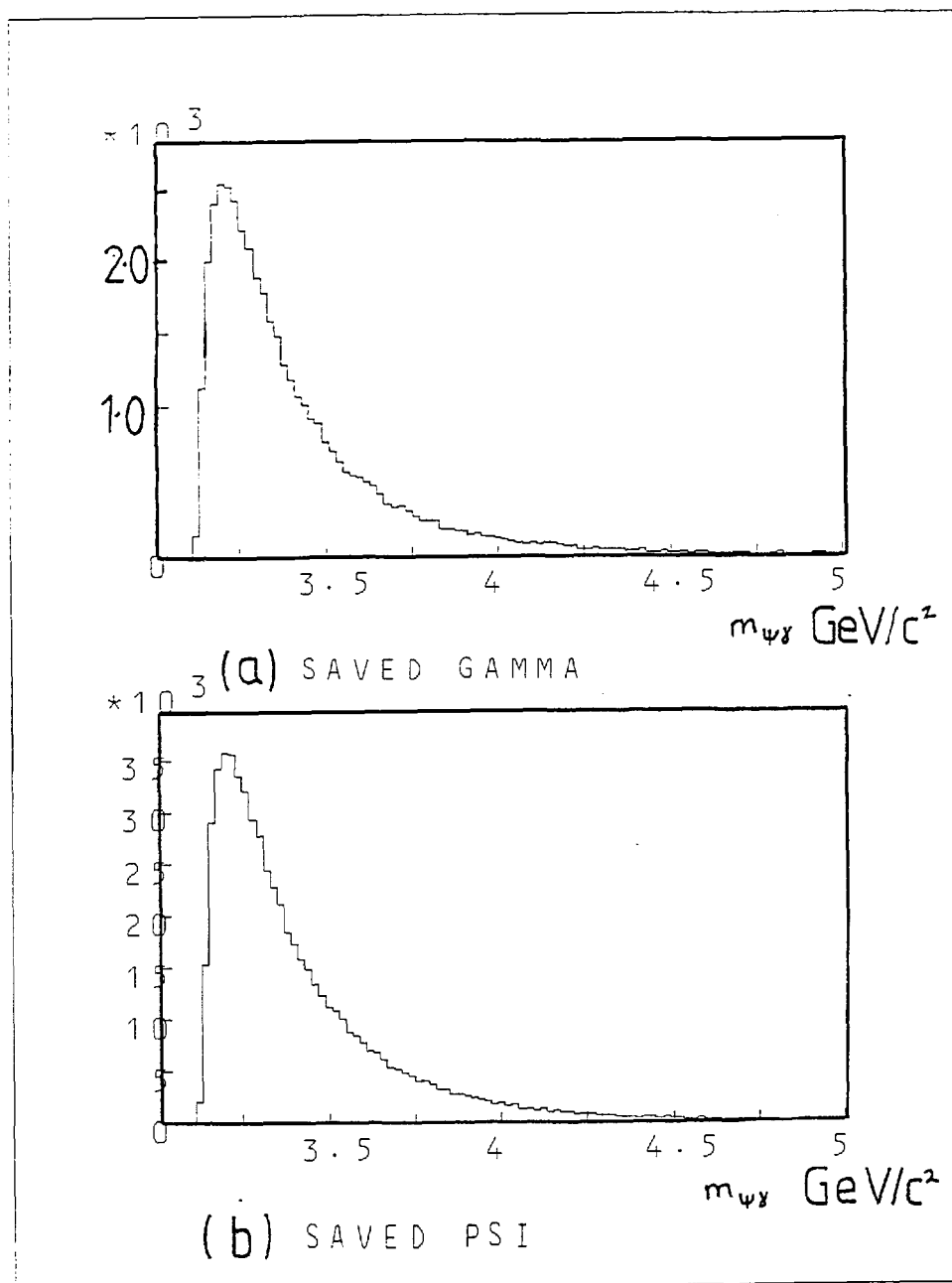


Fig 6.2: Uncut ψ - γ Background Mass Plots

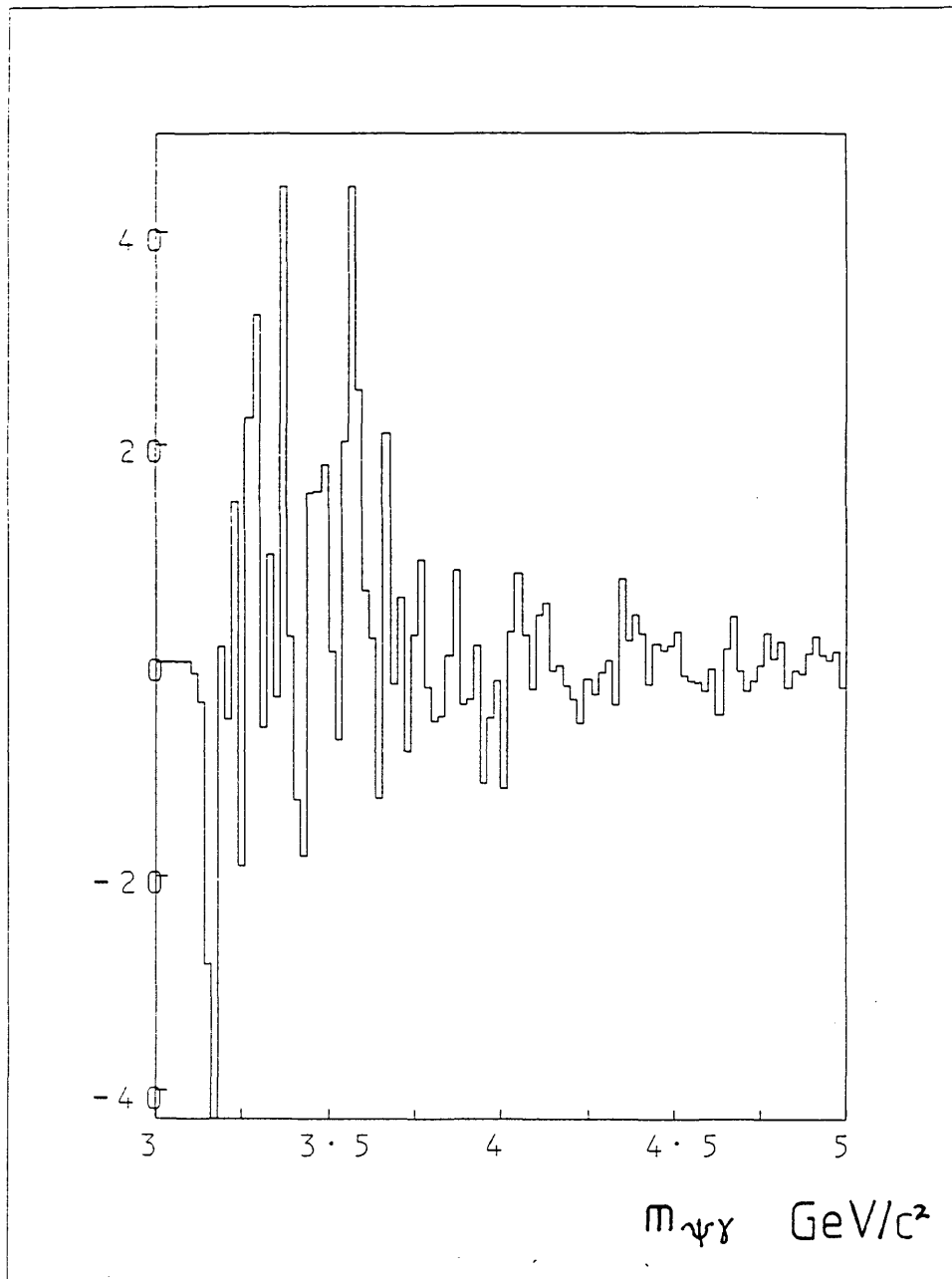


Fig 6.3: Uncut $m_{\psi\gamma}$ Spectrum,
Background Subtracted

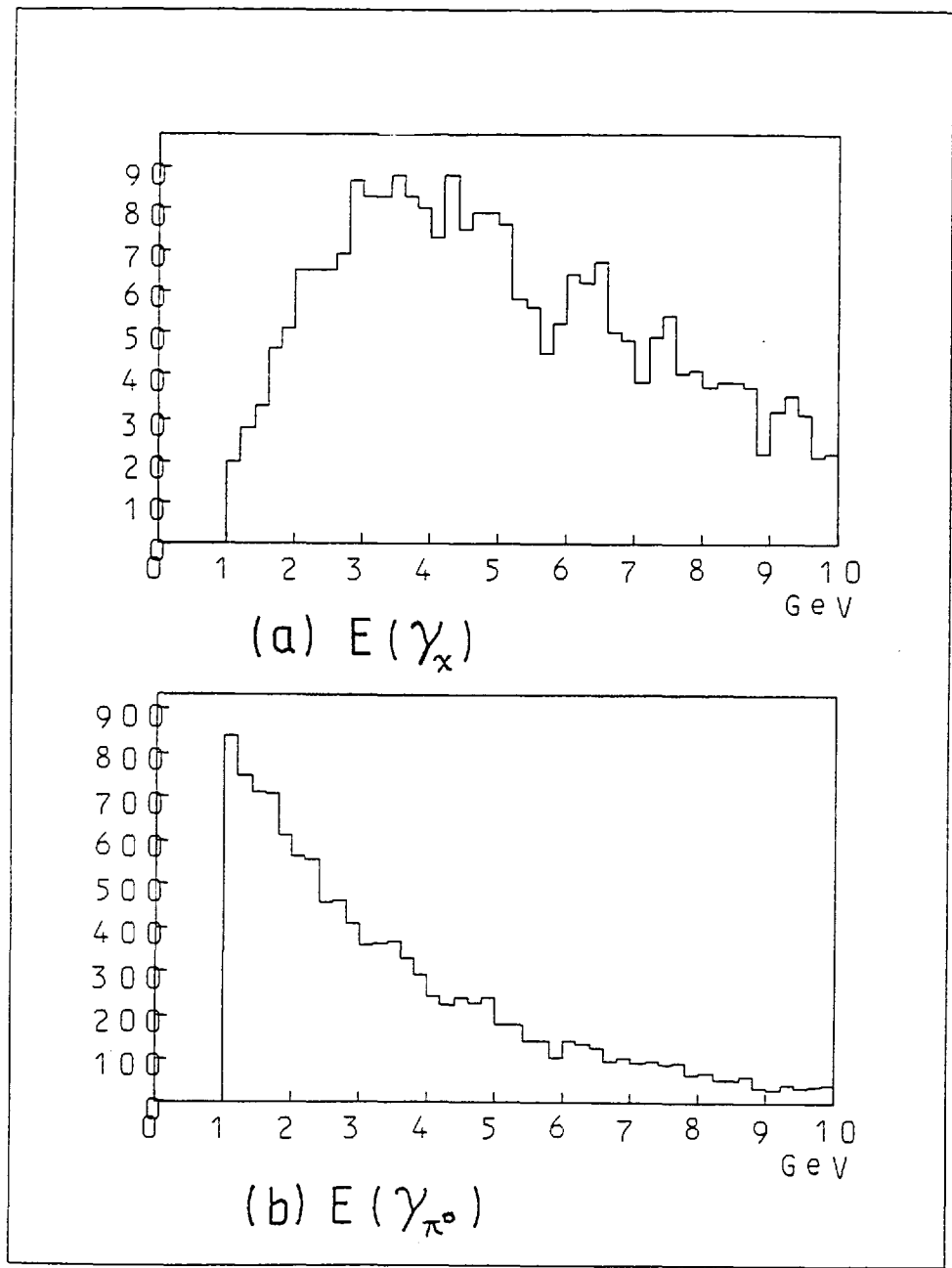


Fig 6.4: Photon Energy Distributions

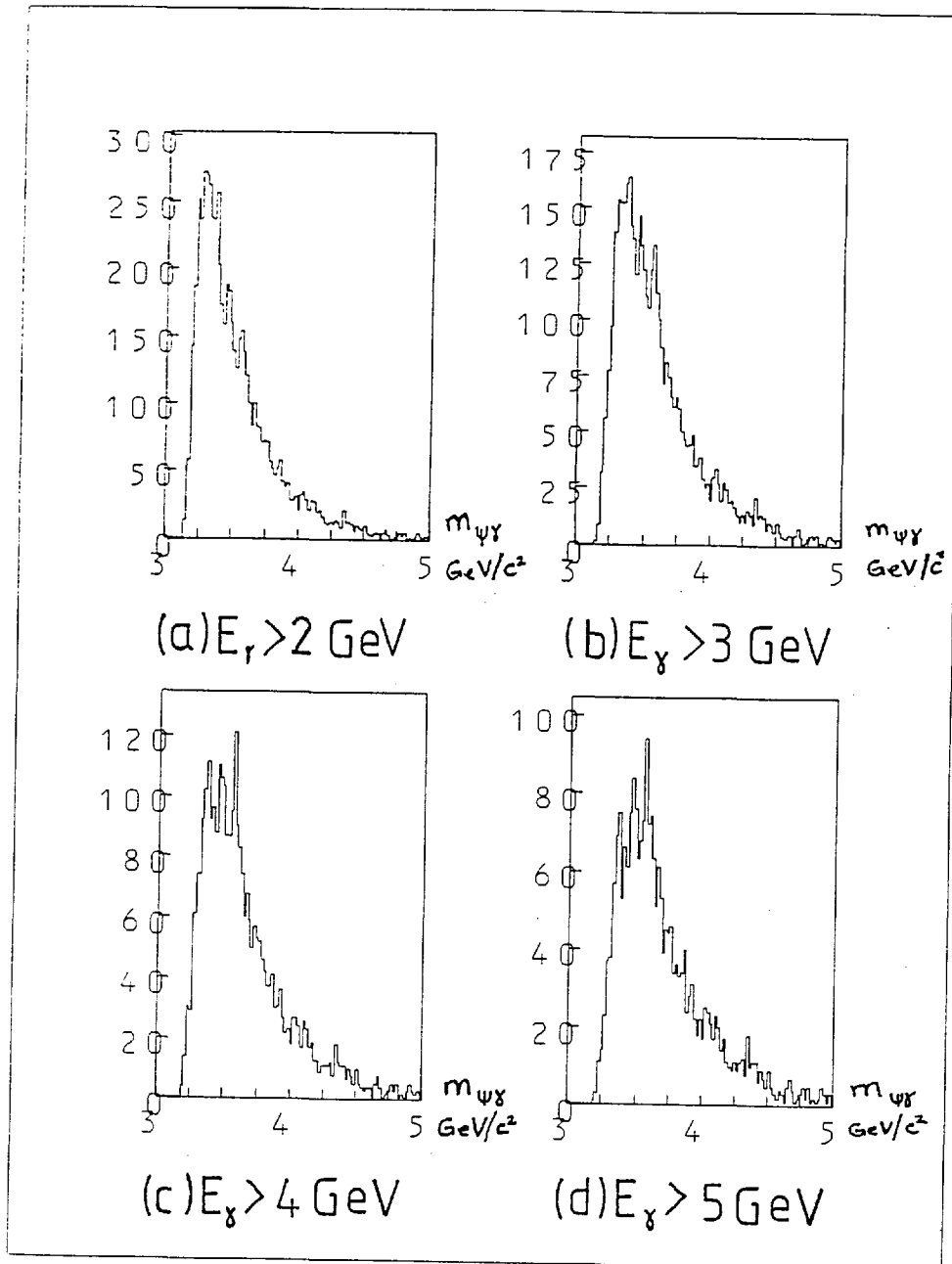


Fig 6.5: $m_{\psi\gamma}$ Spectra with E_γ Cuts

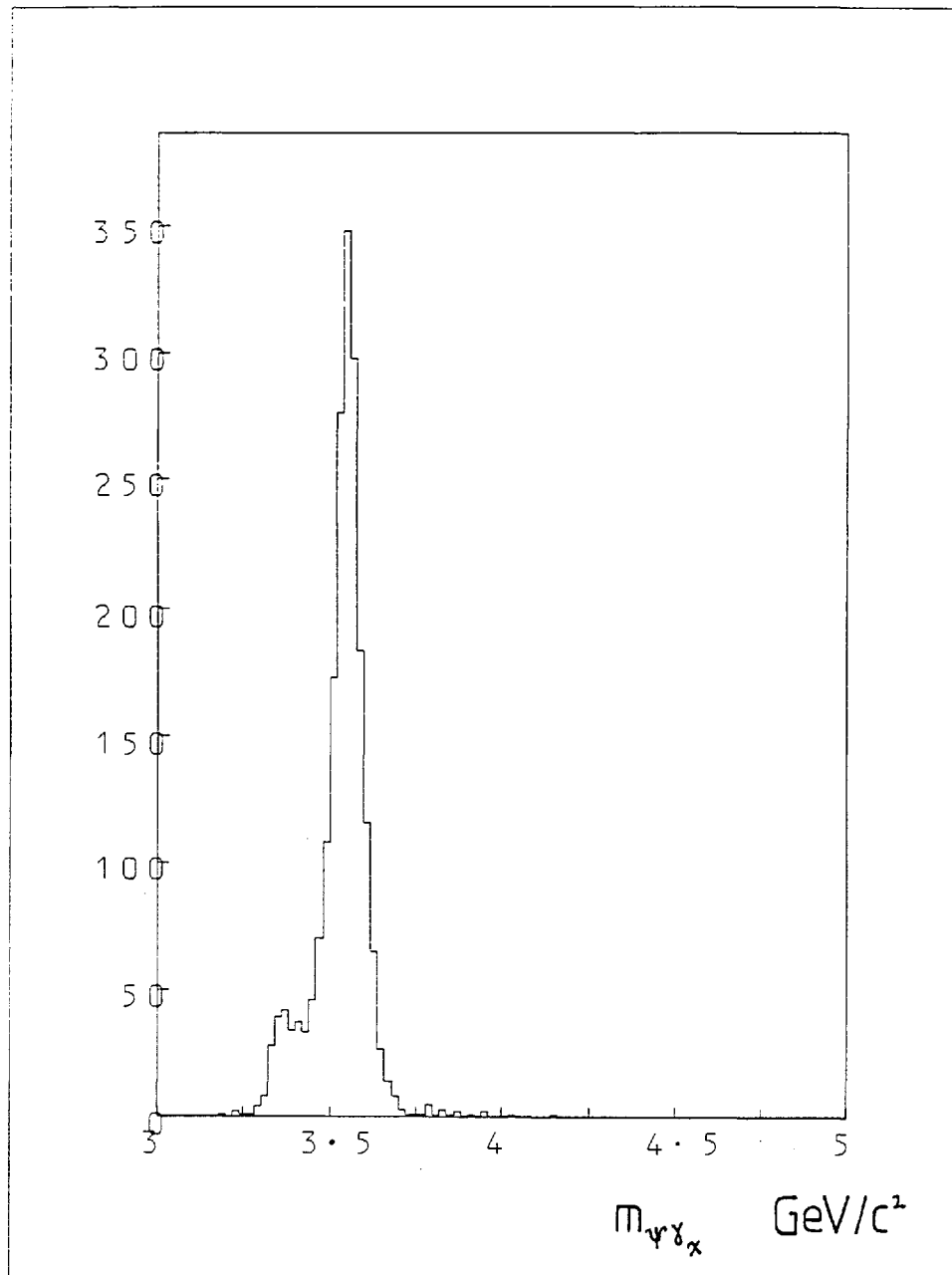


Fig 6.6: Monte Carlo $m_{\psi\gamma_\chi}$ Spectrum

E_γ cut (GeV)	1	2	3	4	5
Geometric Acceptance	58%	55%	49%	41%	33%
Effective Acceptance	38%	37%	35%	30%	26%
No. of χ 's (observed)	98 ± 27	89 ± 25	85 ± 23	79 ± 21	61 ± 19
No. of χ 's (corrected)	258 ± 71	241 ± 68	243 ± 66	263 ± 70	235 ± 73

Fig 6.7: Effect of E_γ Cuts

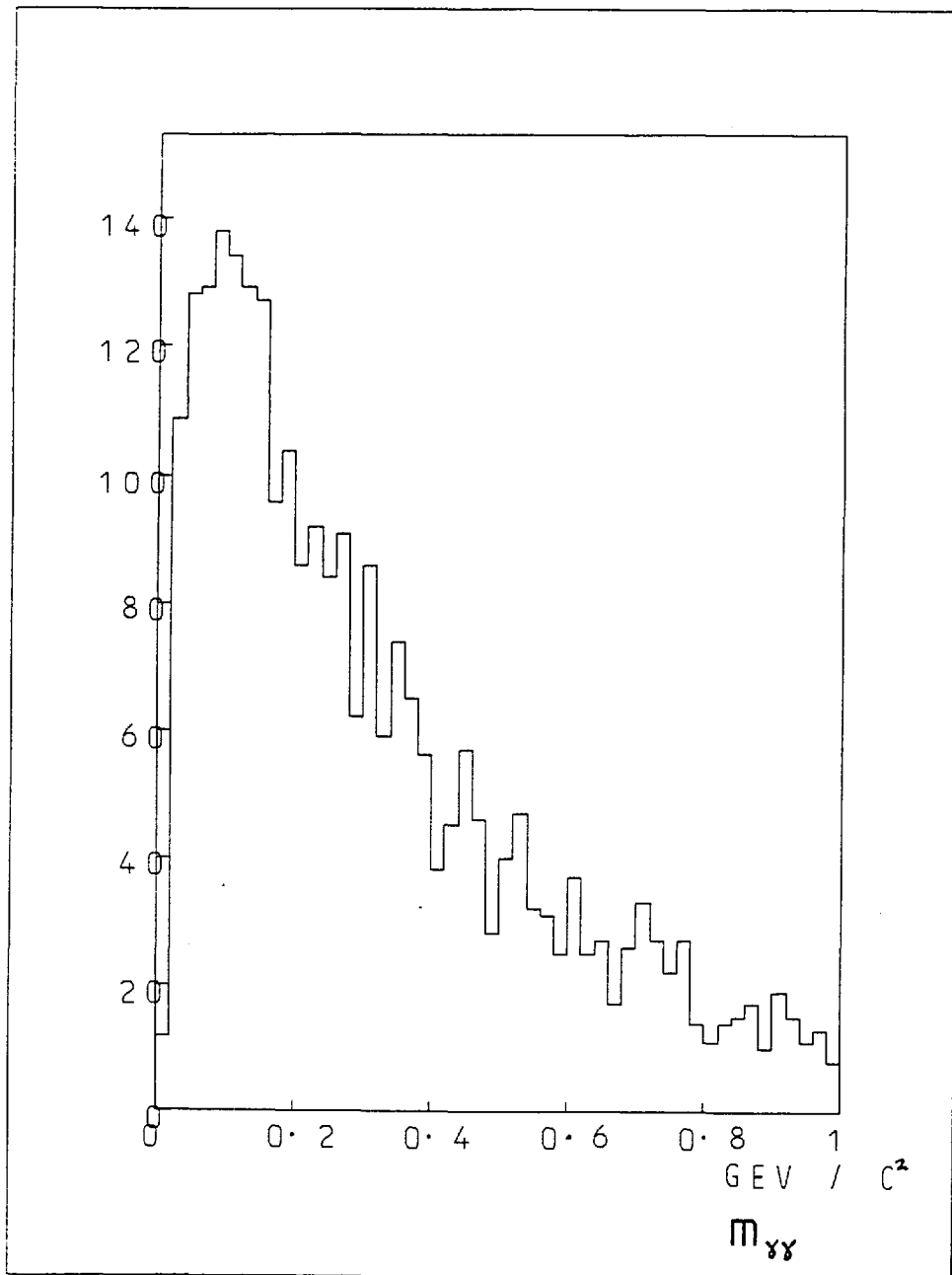


Fig 6.8: $\gamma\text{-}\gamma$ MassPlot (2μ Trigger)

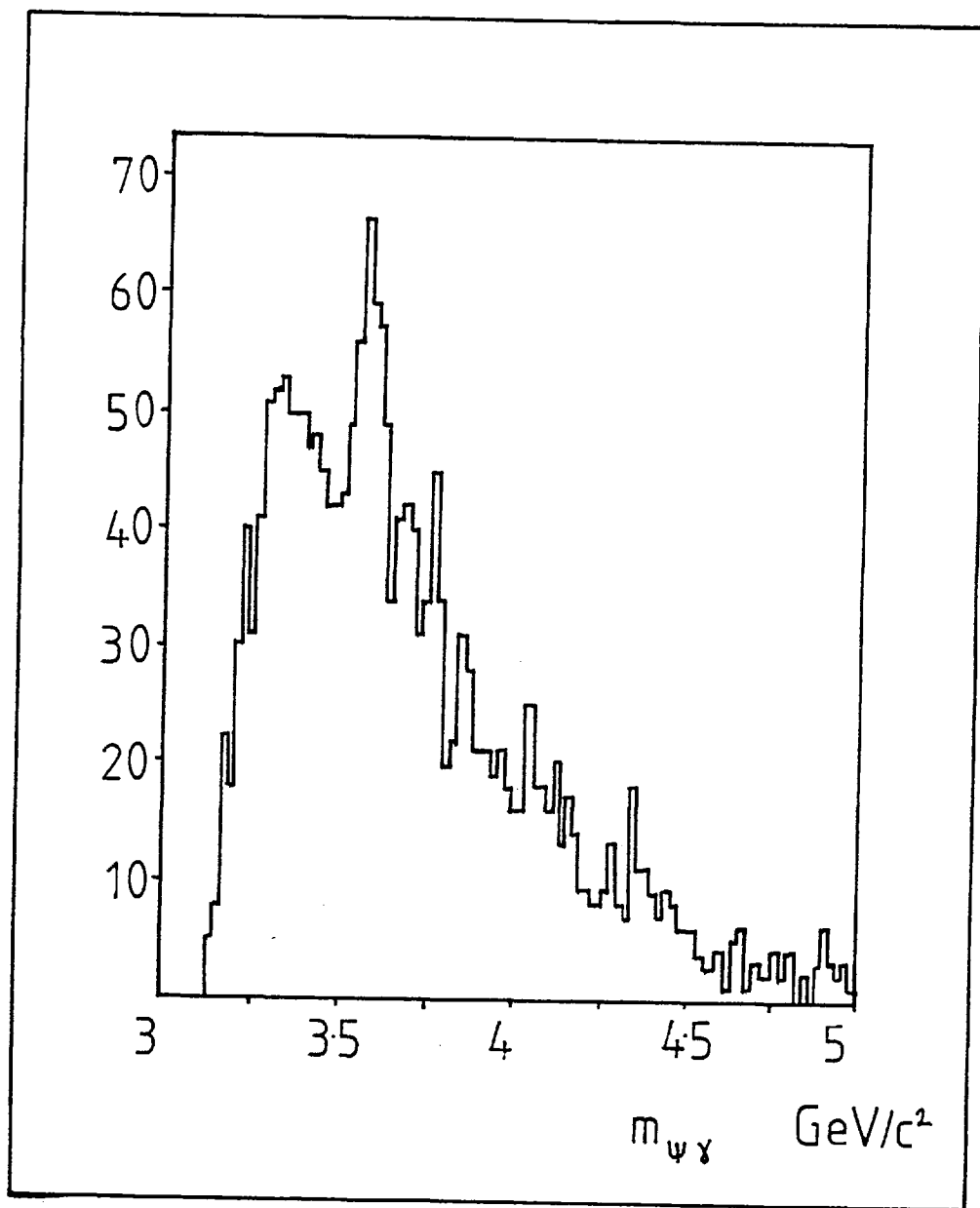


Fig 6.9 : $m_{\psi\gamma}$ Spectrum π^0 Removed

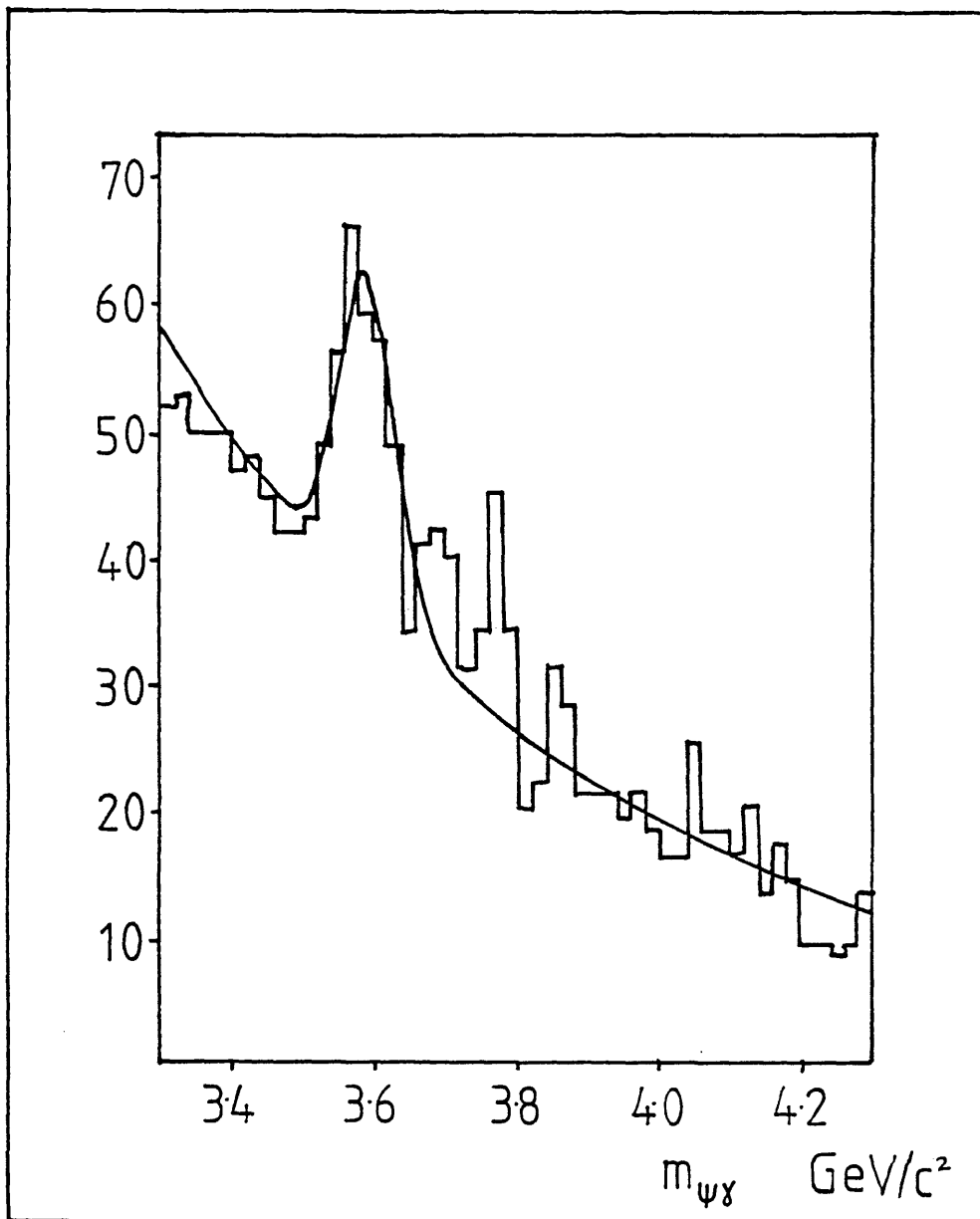


Fig 6.10: Fitted $m_{\psi\gamma}$ Spectrum

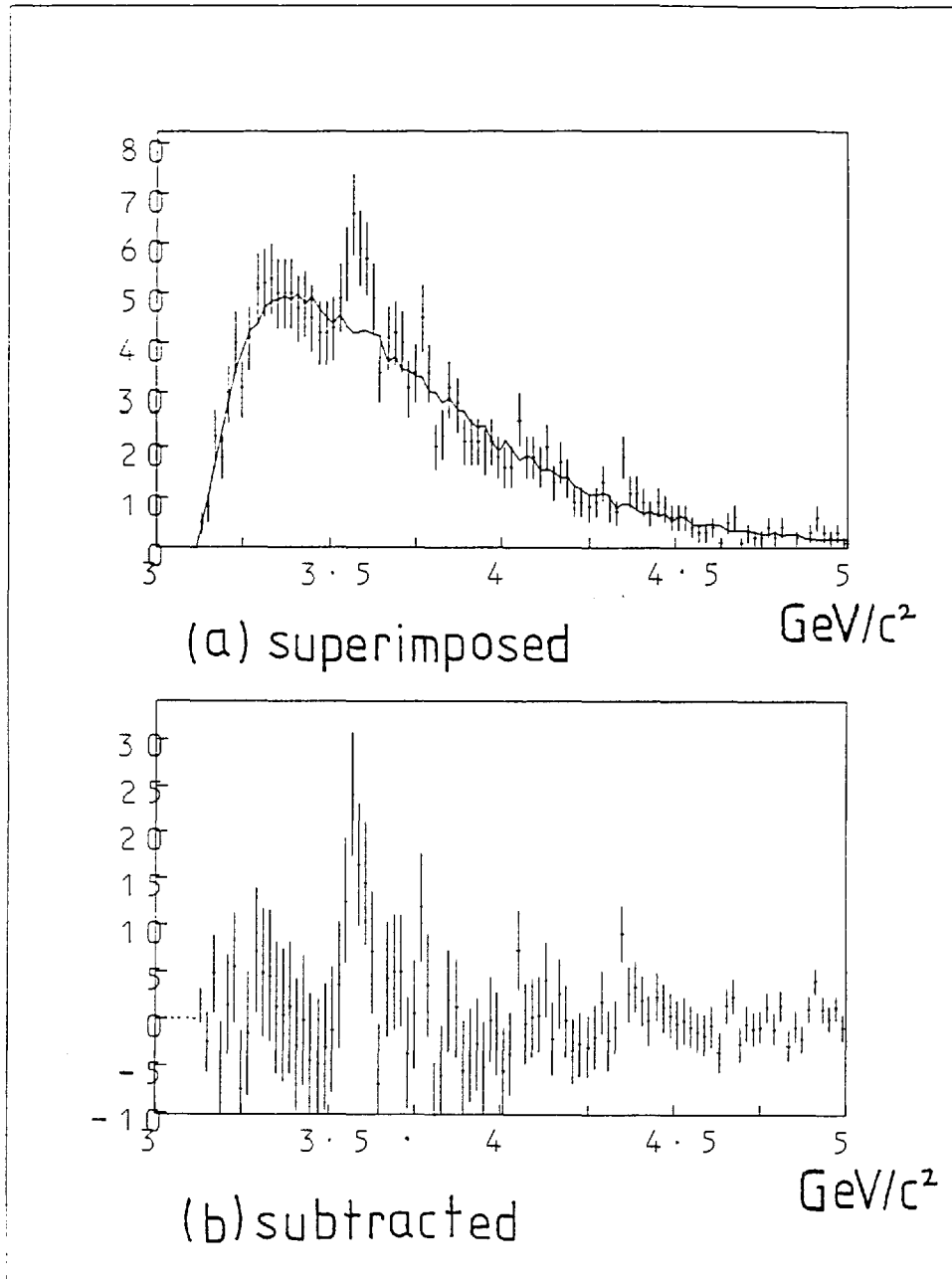


Fig 6.11: $m_{\psi(8)}$ with Generated Background

effective
acceptance
%

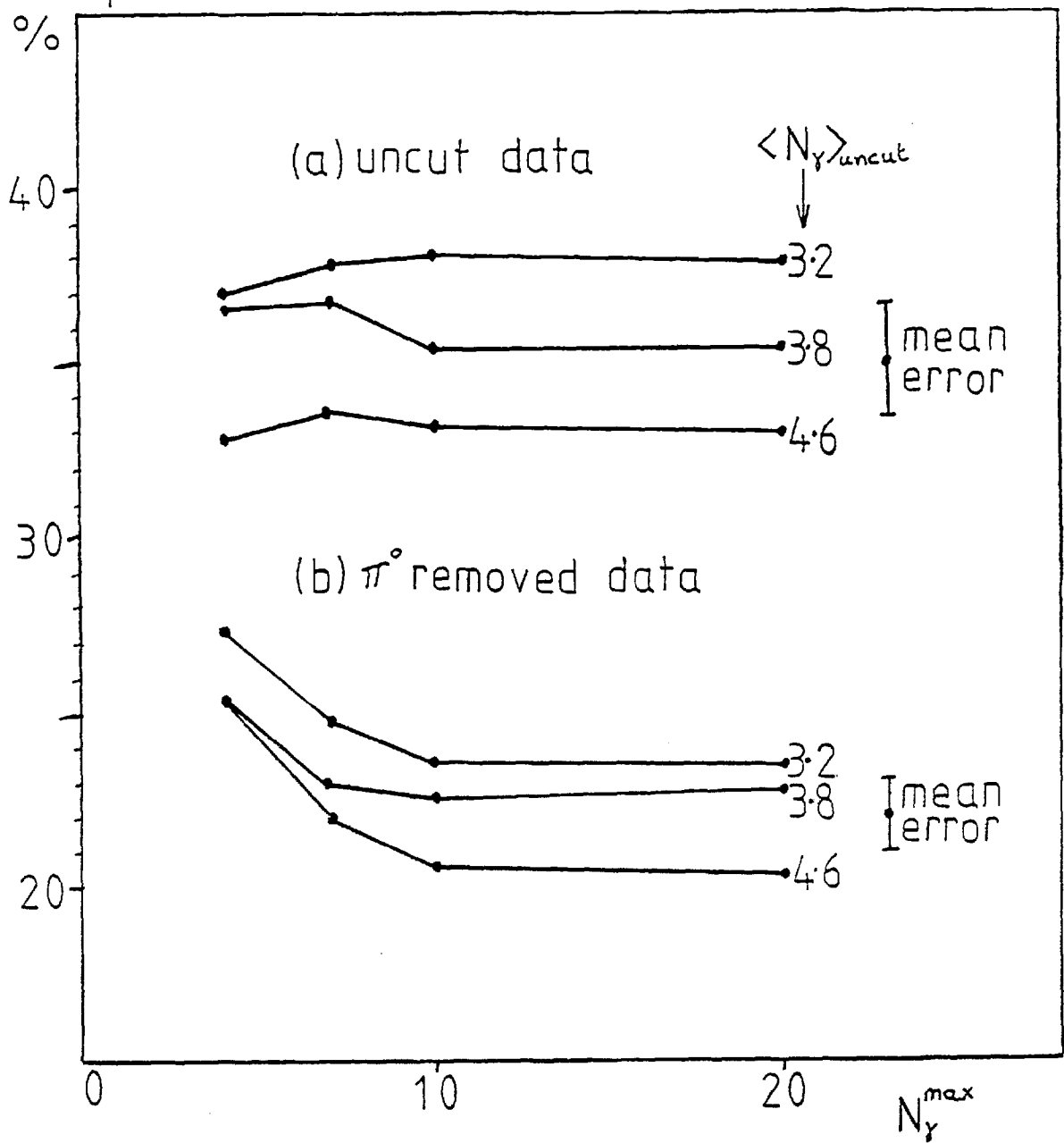


Fig 6.12 Sensitivity of Acceptance

$m_{\chi\chi}$ cut-off (MeV/c ²)	200	250	300
Number χ 's (observed)	84 ± 25	78 ± 16	66 ± 14
Effective Acceptance	27.9%	23.6%	19.5%
Number χ 's (corrected)	301 ± 90	331 ± 68	338 ± 72

Fig 6.13 : Effect of $m_{\chi\chi}$ Cut-off

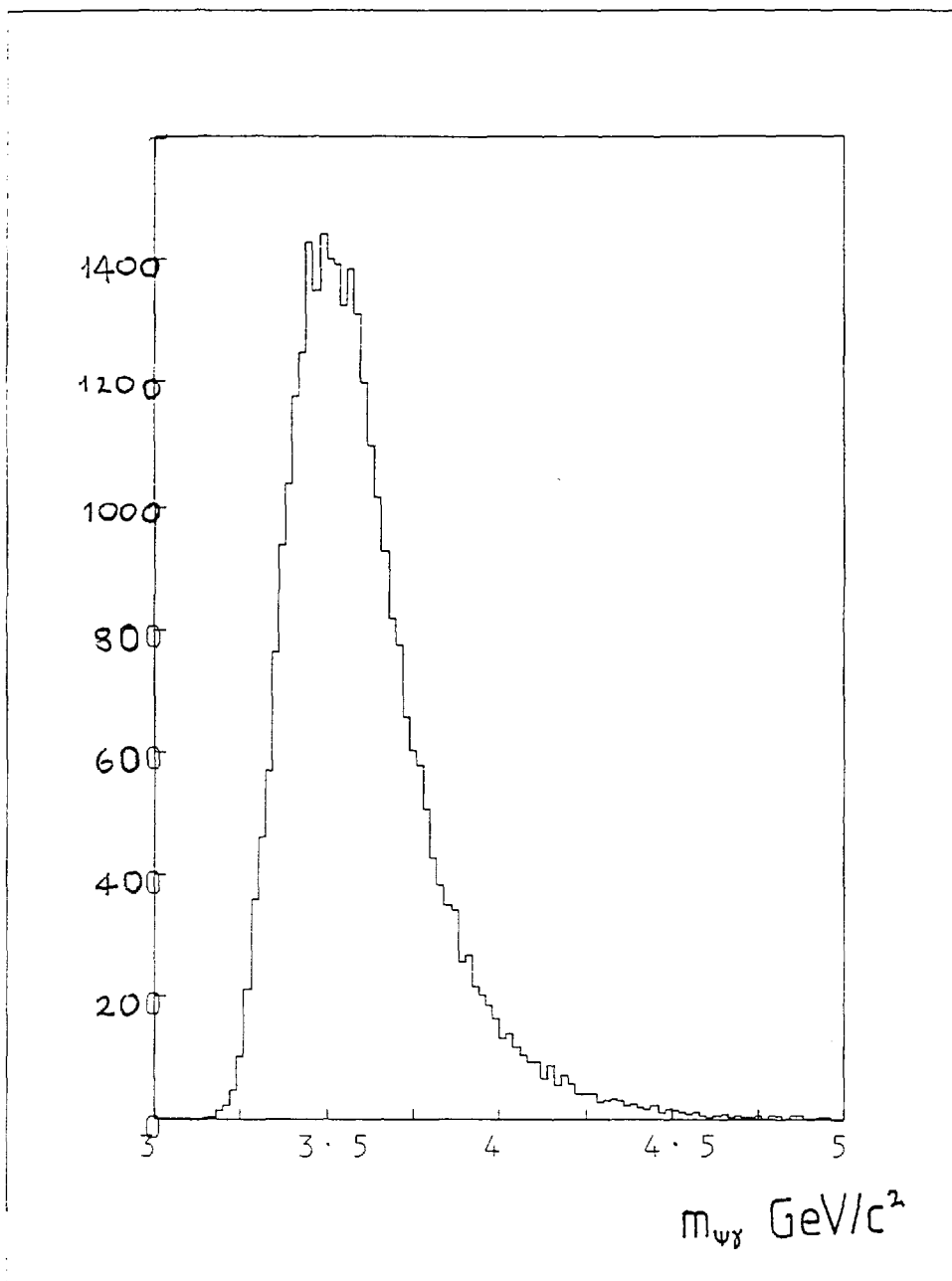


Fig 6.14: Monte Carlo Mass Spectrum of
Uncorrelated ψ 's and γ 's

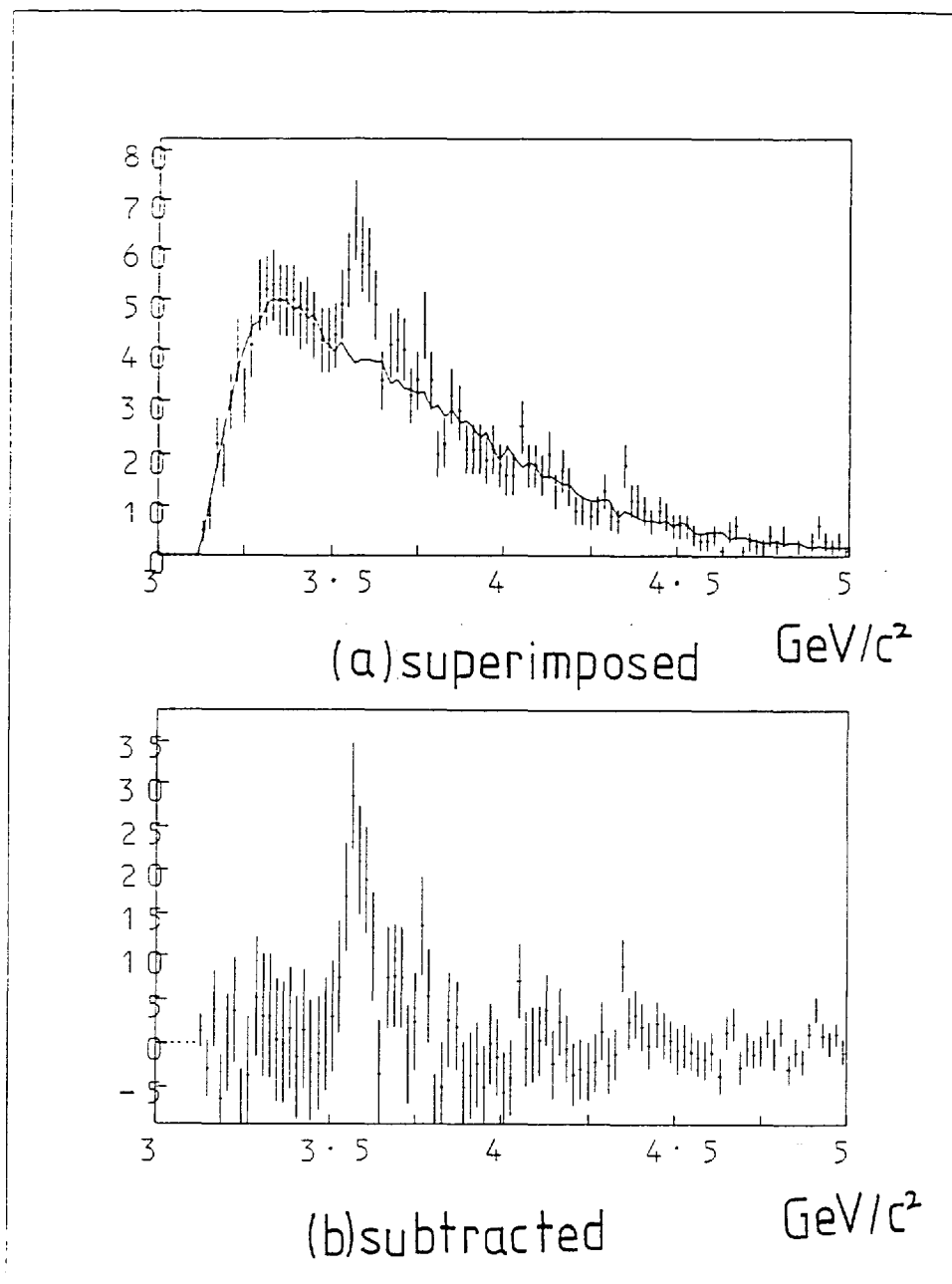


Fig 6.15: $m_{\psi\chi}$ with Corrected Background

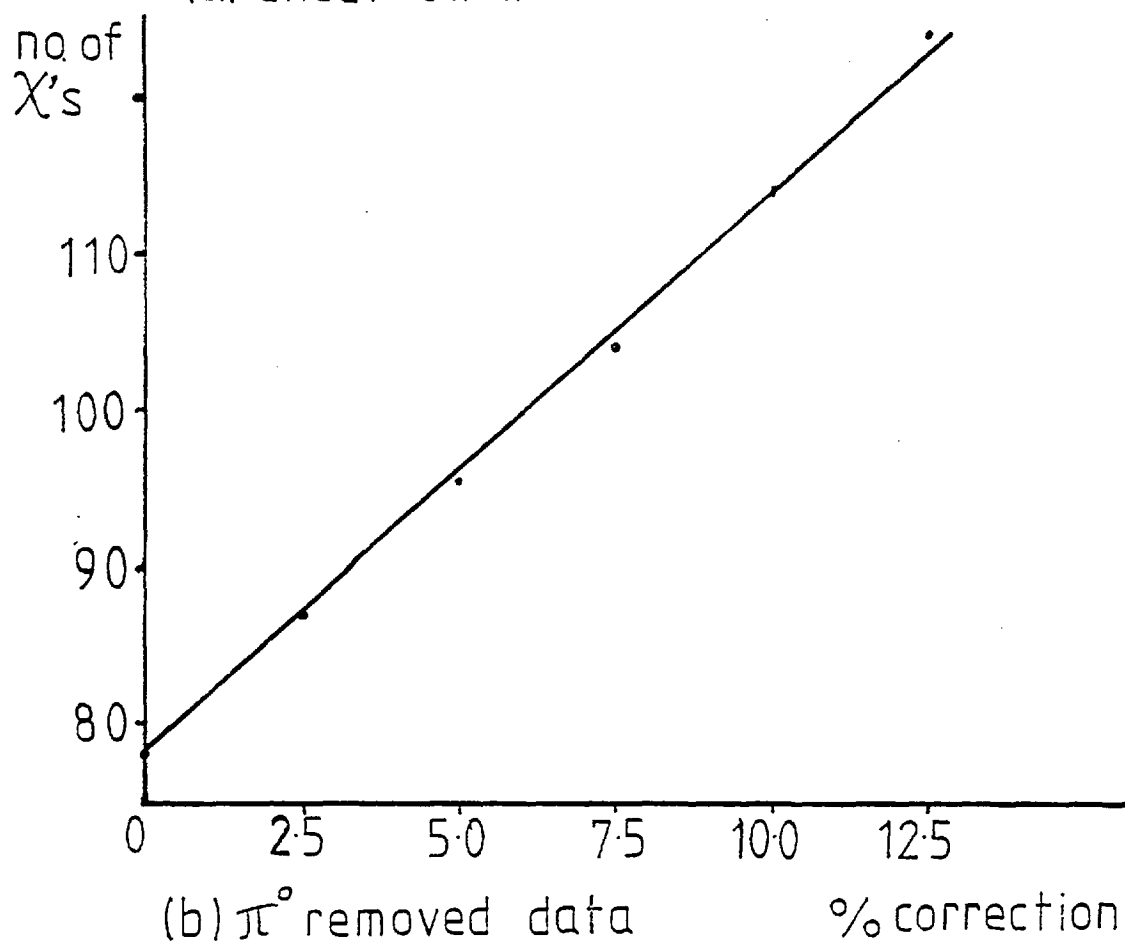
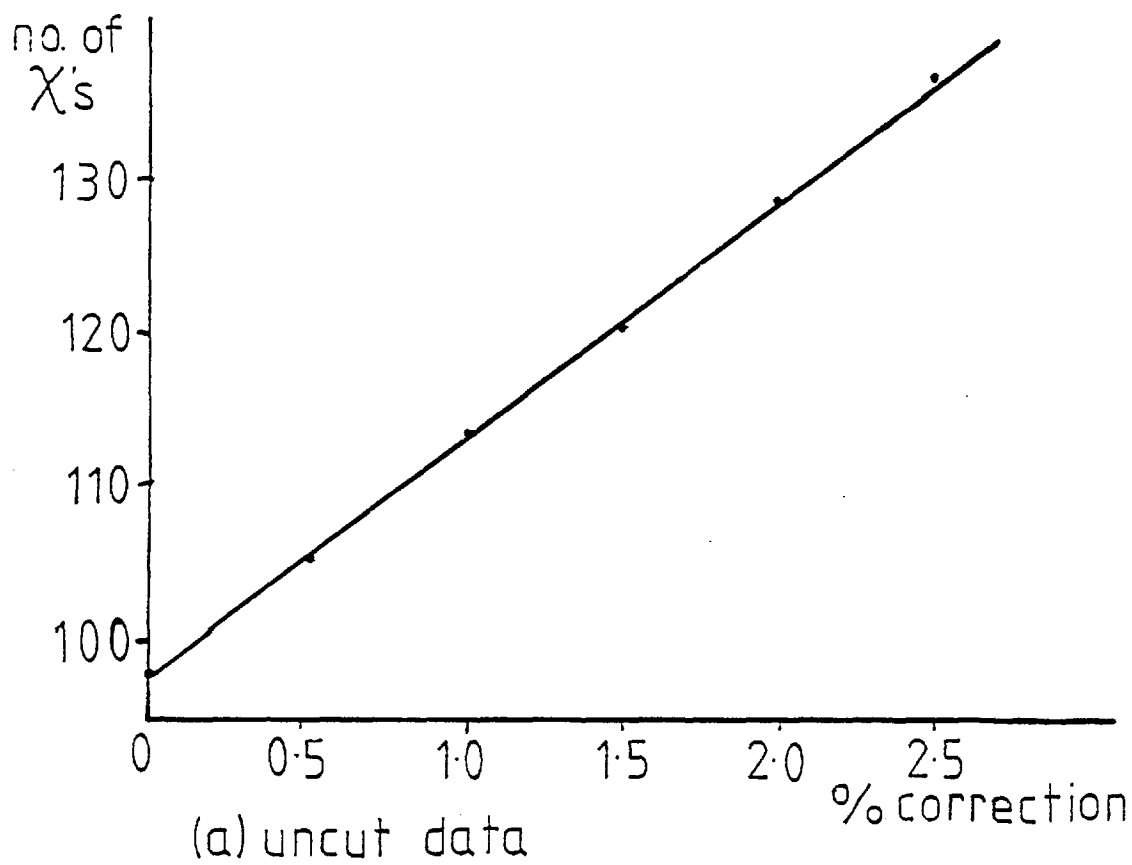


Fig 6.16: Effect of Correction

Appendix A

Monte Carlo of Bremsstrahlung Radiation

The bremsstrahlung process is the emission of photons by charged particles as a result of deflection of their trajectory by a nuclear electric field. For an electron of energy E_0 traversing dx mg per cm^2 of material, the probability of emitting a photon of energy in the range k at dk is given by (Ref 27)

$$\phi(E, k) dx dk = 4 \alpha \frac{N}{A} Z^2 r_e^2 \frac{dk}{k} F(E_0, v) \quad (1)$$

$F(E_0, v)$ is a slowly varying function of E_0 and v , and its form depends on whether or not screening of the nuclear electric field by the outer electrons is taken into account. For high energy electrons in the GeV range, screening can be considered complete, and F is given by

$$F(E_0, v) = \left[1 + (1-v)^2 - \frac{2}{3} (1-v) \right] \log_e \frac{183}{Z^{1/3}} + \frac{1}{9} (1-v) \quad (2)$$

An idea of the range of F can be found by evaluating it numerically at the limits :

$$\text{when } v=0, \quad F = \frac{4}{3} \log_e \frac{183}{Z^{1/3}} + \frac{1}{9} = 6.4$$

$$\text{when } v=1, \quad F = \log_e \frac{183}{Z^{1/3}} = 4.7$$

If the latter figure is chosen for simplicity little

inaccuracy will result. Thus, if X_0 is defined by

$$\frac{1}{X_0} = 4\alpha \frac{N}{A} Z^2 r_e^2 \log_e \frac{183}{Z^{1/3}} \quad (3)$$

equation (1) is simplified to

$$\phi(E, k) dx dk = \frac{dx}{X_0} \cdot \frac{dk}{k} \quad (4)$$

The presence of the factor $r_e^2 = \frac{e^2}{m^2 c^4}$ in the radiation length makes the process less important for μ 's by a factor of $m_\mu^2/m_e^2 = 4.10^4$. Integration of equation (4) gives the mean energy $\langle E \rangle$ of an electron

$$\langle E \rangle = E_0 \exp^{-\frac{x}{X_0}}$$

Thus, the radiation length can be defined as the distance (in any material) after which an "average" electron's energy is reduced by a factor of $1/e$. Despite the simplicity of the formulae, allowing for bremsstrahlung in calculations is not trivial. To simply reduce the energy of all electrons by some fraction is incorrect, as this would cause, in an extreme example, all electrons just above threshold to no longer trigger the apparatus, which is not the true case - most of the electrons would be virtually unaffected by 10% of a radiation length present. Choosing the energy loss at the calorimeter under an exponential distribution would be more accurate at calculating the acceptance, but would not allow for kinks in the tracks due to recoil against the photon. This could lead to the

electron entering a different module, and may even lead to failure of the pattern recognition program to follow the track. Most important of all, it would not allow for energy loss of the electron before having its momentum analysed in the spectrometer, which will lead to an incorrectly simulated reconstructed mass. A more satisfactory method is to follow the tracks from the vertex, randomly selecting the energy and angle of emission of the photon, and the appropriate distance to be travelled before its radiation.

One of the first problems to solve is the infra-red divergency which arises from the $1/k$ term in equation (4). i.e. that the probability of emitting very soft photons tends to infinity as their energy tends to zero. This can be avoided and yet still represent fairly well the relevant physics by ignoring photons whose energy is below some "cut-off" value, E_c . 1 MeV was chosen as being the minimum energy of interest, the results being only logarithmically dependent on the value chosen.

The probability of emitting a photon of energy k in the range $E_c < k < E_0$ is given by

$$\frac{dx}{X_0} \int_{E_c}^{E_0} \frac{dk}{k} = \frac{dx}{X_0} \text{Loge} \frac{E_0}{E_c}$$

Thus, starting with an initial photon population of N_0 electrons in the range $E_0 \pm E_c$, the number of them left in this range, N , after a distance x is

$$\int_{N_0}^N \frac{dN}{N} = - \int_0^x \frac{dx}{X_0} \log_e \frac{E_0}{E_c}$$

$$\Rightarrow N = N_0 \exp^{-\frac{x}{X_B}}$$

where $X_B = X_0 / \log_e (E_0/E_c)$

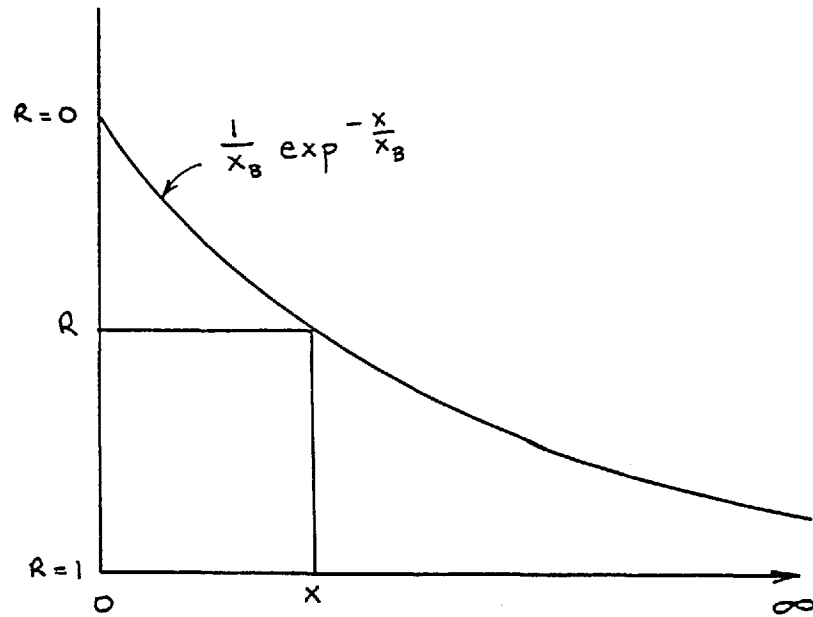
Thus, the probability distribution $P(x)$ of the distance to be travelled before radiating a photon is an exponential distribution whose scale, X_B , can be considered as a "bremsstrahlung length" :

$$P(x) = \frac{1}{X_B} \exp^{-\frac{x}{X_B}}$$

the $1/X_B$ factor being necessary to normalise to unit probability. Thus, if a random number is chosen in the range $0 < R < 1$ it can be mapped by the probability function as shown onto the range $0 < x < \infty$. A distance x can thus be chosen under the distribution and expressed as a function of R .

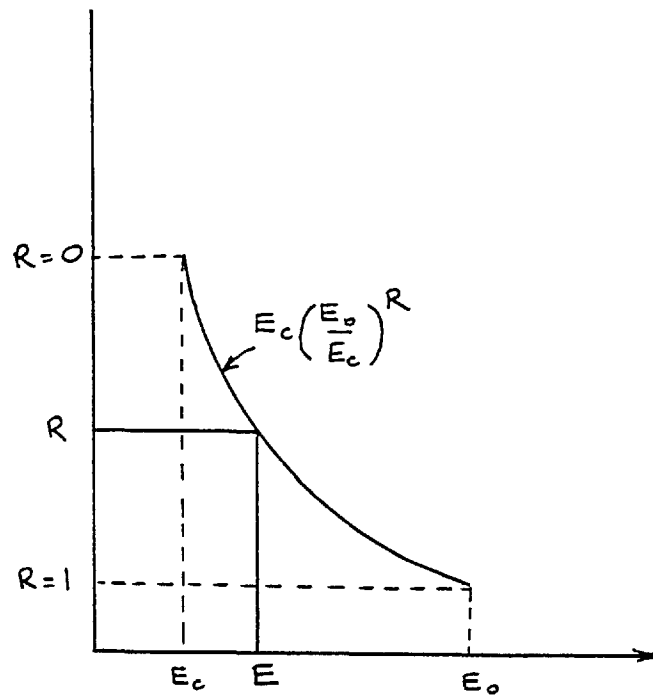
$$R = \int_0^x \frac{1}{X_B} \exp^{-\frac{x}{X_B}} dx$$

$$\Rightarrow x = X_B \log_e \frac{1}{1-R}$$



Having chosen a position where bremsstrahlung occurs, the photon energy, k , must be selected under a distribution $1/k$ within the range $E_c < k < E_0$. Once again, after normalising to unit probability a random number in the range $0 < R < 1$ can be used to select the photon energy, as shown

$$\begin{aligned}
 R &= \frac{1}{\log_e \frac{E_0}{E_c}} \int_{E_c}^E \frac{dk}{k} \\
 &= \frac{1}{\log_e \frac{E_0}{E_c}} \log_e \frac{E}{E_c} \\
 \Rightarrow E &= E_c \left(\frac{E_0}{E_c} \right)^R
 \end{aligned}$$



The final variable to calculate is the angle of emission. This is chosen (Ref 27) under a Gaussian of r.m.s.

$$\langle \theta^2 \rangle^{1/2} = \frac{m_e}{E} \log \frac{E}{m_e}$$

This angle is largest for small momenta, and for a 5 GeV/c electron is of order 1 mrad.

Appendix B

Effect of Experimental Resolution

Using the Lorentz Invariant mass-energy relation for a π^0 which decays into 2 photons of energy E_1, E_2 , and momentum p_1, p_2 (with $E_1=p_1, E_2=p_2$) it can be shown that

$$m_{\pi^0}^2 = 2 E_1 E_2 (1 - \cos \theta)$$

where θ is the opening angle between γ_1 and γ_2 . For small angles, $\cos \theta \sim 1 - \theta^2/2$, so the above is simplified to

$$m_{\pi^0} = \sqrt{E_1 E_2} \theta \quad (1)$$

Differentiating (1) to find the experimental mass resolution for the case of $E_1 = E_2 = E$

$$\frac{\partial m}{\partial E} = \theta \quad ; \quad \frac{\partial m}{\partial \theta} = E$$

Thus, the mass resolution is given by adding the errors in quadrature

$$\begin{aligned} \left(\frac{\delta m}{m} \right)^2 &= \left(\frac{1}{m} \frac{\partial m}{\partial E} \delta E \right)^2 + \left(\frac{1}{m} \frac{\partial m}{\partial \theta} \delta \theta \right)^2 \\ &= \left(\frac{\delta E}{E} \right)^2 + \left(\frac{\delta \theta}{\theta} \right)^2 \end{aligned}$$

For 5 GeV γ 's the energy resolution is $\delta E/E = 0.5/E = 22\%$ FWHM. D0 is 8m downstream of the central target and has a position resolution of about 3.5cm FWHM, giving an angular error of $\delta \theta = 4.4 \text{ mrad}$, and so the

angular resolution is $d\theta/\theta = 16\%$ FWHM. Thus, the mass resolution is

$$\frac{\delta m}{m} = \sqrt{(0.22)^2 + (0.16)^2} = 27\% \text{ FWHM}$$

$$\Rightarrow \delta m = 0.27 \times 135 = 36 \text{ MeV}/c^2 \text{ FWHM}$$

In reality the width is larger than this because in general $E_1 \neq E_2$. Monte Carlo studies find a more accurate width of about $40 \text{ MeV}/c^2$ FWHM. NB, this is for $10 \text{ GeV } \pi^0$'s which decay into two $5 \text{ GeV } \gamma$'s. The least energetic detectable π^0 is one which decays into two $1 \text{ GeV } \gamma$'s, and has a mass resolution of

$$\frac{\delta m}{m} = \sqrt{\left(\frac{0.5}{11}\right)^2 + \left(\frac{4.4}{135}\right)^2} = 50\% \text{ FWHM}$$

$$\Rightarrow \delta m = 0.50 \times 135 = 67 \text{ MeV}/c^2 \text{ FWHM}$$

Similar arguments can be applied to estimate the χ width. Using the small angle approximation as above, the mass formula is

$$m_\chi^2 = m_\psi^2 + E_\psi E_\gamma \theta^2 \quad (2)$$

Differentiating this (neglecting the resolution of E_ψ)

$$2 m_\chi \frac{\partial m_\chi}{\partial \theta} = 2 E_\psi E_\gamma \theta \quad ; \quad 2 m_\chi \frac{\partial m_\chi}{\partial E_\gamma} = E_\psi \theta^2$$

These can be used in conjunction with (2) to give the mass resolution

$$\left(\frac{\delta m_\chi}{m_\chi}\right)^2 = \left(\frac{1}{m_\chi} \frac{\partial m_\chi}{\partial E_\gamma} \delta E_\gamma\right)^2 + \left(\frac{1}{m_\chi} \frac{\partial m_\chi}{\partial \theta} \delta \theta\right)^2$$

$$= \frac{m_\chi^2 - m_\psi^2}{m_\chi^2} \left[\left(\frac{\delta E}{2E}\right)^2 + \left(\frac{\delta \theta}{\theta}\right)^2 \right]$$

Analysis of the 2μ data shows that $\langle E_\psi \rangle = 40$ GeV, and Monte Carlo studies find $\langle E_{\gamma_\chi} \rangle = 7.2$ GeV. Using (2) above, the mean ψ - γ opening angle is found to be $\langle \theta \rangle = 105$ mrad. Thus, the $\chi(3550)$ width is expected to be $\delta m = 87$ MeV/ c^2 FWHM. This value is obtained allowing neither for the continuous energy spectra of the ψ 's and γ 's, nor for the photon energy sharing algorithm used in the analysis. A Monte Carlo program taking these into account found the width to be ~ 100 MeV/ c^2 .

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