

INCLUSIVE PARTICLE PHOTOPRODUCTION AT LARGE TRANSVERSE MOMENTUM

by

• MARK BURCHELL

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ABSTRACT

A search for final state strangeness and charm in γN interactions at high γ beam energies ($80 \rightarrow 120$ GeV) is described. A final state particle with large transverse momentum ($p_t \geq 0.8$ GeV/c) is required in all events; thus probing the target nucleon at the quark/gluon level.

Comparison of data taken with γ and π^- beams at near equal energies and with the same spectrometer setup, permits a search for sources of strangeness in photoproduction not present in hadroproduction. Evidence is presented for the presence of additional strange production in photo-, relative to hadro-production at large transverse momentum and high Feynman x .

Finally a search for photoproduction of the charmed F meson is described. No signal is found, and a cross-section*branching ratio limit for $\gamma N \rightarrow FX$ with $F \rightarrow \eta\pi$ is calculated which is incompatible with previous work on F photoproduction.

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Chapter I

INTRODUCTION

This thesis presents an analysis of data obtained by the NA14 photo-production experiment at CERN. Although a fixed target experiment, NA14 has almost 4π acceptance in the centre of mass for both charged and neutral particles, and in this thesis I make use of this. The data taking triggers used in this work require an interaction in the experiment's target, combined with observation of a particle in the spectrometer with a large transverse momentum (p_t). By use of these triggers the intention is to study photon hard scattering via observation of the properties of the final state particles. The unique features of NA14 compared to other photo-production experiments are the high energy, and high intensity, of the incident photon beam. A further feature of the experiment, is the ability to take data in the spectrometer with a π^- beam of equally high energy. A major contribution to the high energy photoproduction cross - section is expected to come from the hadron like character of the photon. This is assumed to be described by the vector meson dominance model, (VDM), and a direct comparison of photon and π^- beam data can be used to see where this assumption fails.

In this chapter I discuss the physics of photo-production at large transverse momentum (p_t), and explain how the NA14

experiment investigated the behaviour of the photon's direct coupling to quarks. I also discuss charm photo-production in some detail, as an introduction to an attempt to observe the F meson (Chapter 6).

1.1 PHOTON - NUCLEON INTERACTIONS AT LARGE pt .

It has often been suggested, see for example [1], that inclusive particle photo-production at large pt . would be a useful test of Quantum Chromodynamics (QCD). The rationale behind such suggestions lies in the ability of the photon to couple directly to a quark / anti-quark pair in a pointlike fashion. Viewing its interaction in such a way permits the photon to be used as a probe of the parton structure of the nucleus.

Of course the photon need not interact in this fashion. It is already well known that much of the time the photon interacts hadronically, that is the interaction proceeds via a manifestation of the photon's structure function.

The processes involved in photon - nucleon interactions can thus be grouped into 2 classes : a) Those involving direct coupling to a charged object, the most basic examples of this group are shown in figure 1; and b) via manifestation of the photon's structure function, see figure 2 (the shaded areas in figure 2 represent all hard point-like processes).

Looking first at figure 1, process a) is simply QED Compton. Here the photon scatters off one of the quarks in the nucleon. This is a deep inelastic process due to the need to resolve the

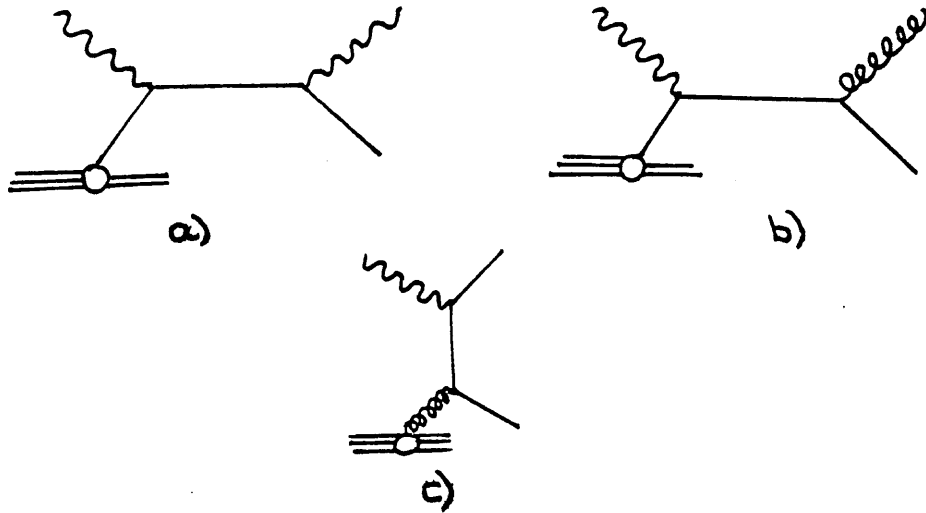


Figure 1: Photon point-like interactions

quark, and results in an isolated prompt photon at large transverse momentum in the final state. The second process in figure 1 is a QCD analogue of the previous one, in that the prompt photon in the final state is replaced by a gluon. It is called QCD Compton for this reason. The final of the three processes is also a QCD variant of a well known process. Here the more familiar diagram would be that of Bethe-Heitler pair production, but one of the photons has been replaced by a gluon. As will be discussed later, it has been found that this process of gamma-gluon fusion provides a good description of charm photo-production.

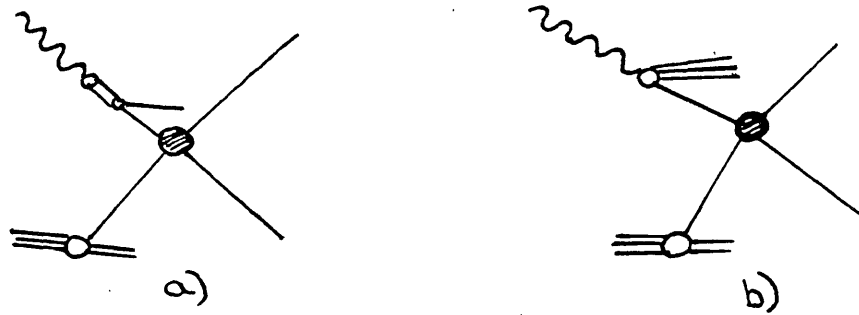


Figure 2: Photon non point-like interactions

A welcome feature of these 3 diagrams is that they are directly calculable with very little input, viz. the quark and gluon distribution functions of the target nucleons. Thus it is possible, for example, to try experimentally to observe a prompt photon signal, and after subtracting from it apparent or genuine prompt single photons from all other sources, compare the magnitude of the signal with that predicted by the QED Compton process. This is the achievement of NA14, where [2] a prompt photon signal has been measured and found to be comparable in strength with the calculated value of the QED Compton process.

Figure 2 shows the hadronic processes. At low $pt.$, figure 2 a) has been found to be dominant. As shown in this diagram, the structure function of the photon causes the photon to produce a quark / anti-quark pair, which build up into a vector (to conserve quantum numbers) meson by soft gluon exchange. This behaviour whereby at low q^2 (where q is the 4 momentum transfer) high energy photon interactions are dominated by poles at the vector meson masses, is called Vector Meson Dominance (VDM). Such behaviour has been widely investigated, and is described in many reviews, of which [3] is typical. The second type of hadron-like interactions, figure 2 b), is called the 'anomalous' term. Here the photon's structure function produces a quark / anti-quark pair as before, but now there is no soft gluon exchange. Perturbative QCD calculations lead to a contribution to the cross-section which grows with $\ln(Q^2)$ [4]. For this reason it is referred to as an 'anomalous' structure function.

Of course the processes in figures 1 and 2 are the most basic possible. With little imagination it is easy to produce diagrams for higher order processes, or indeed to combine the features of several of the diagrams into one process (see figure 3 for examples). Such diagrams can also produce prompt photons in addition to those from the QED Compton signal. The effect of such diagrams has been calculated [5], and either shown to be negligible, or their contribution to prompt photon production found as a fraction of QED Compton.

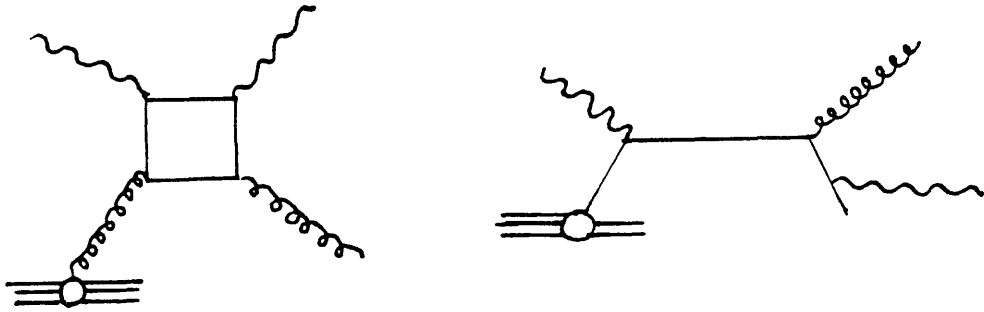


Figure 3: Some Other Sources of Prompt Photons

As well as looking at single photon production in NA14, π^0 photoproduction has also been investigated [6]. At low p_t and for $p_l < 40$ GeV/C, the VDM diagram is found to describe the data. For $p_t \geq 2.0$ GeV/C and $p_l > 40$ GeV, the observed cross-section requires the presence of the anomalous and pointlike processes shown in figures 1 and 2. The magnitude of the cross-section for each diagram has been calculated [7] and found to fit the NA14 data well with few assumptions. Thus providing further evidence for pointlike photon interactions. This study also helps the prompt photon work by permitting

accurate simulation of the level of contamination of the prompt photon signal by photons from π^0 decay. Since it is shown that VDM does not describe π^0 photoproduction, this contamination cannot be obtained from π^0 production in π^- beam.

Since NA14 has a large angular acceptance for charged tracks, it is possible to study hadronic photoproduction by looking at charged, as well as neutral, pions. This analysis [8] proceeds as for the π^0 , taking the observed cross-section and comparing to the calculated cross-section for the processes of figures 1 & 2; the VDM component of the cross-section again also being observed directly by taking data with a π^- beam. A particular problem of this work however is identifying the pionic content of the observed charged particles. This is performed using a Cerenkov counter (whose operation is described in Chapter 3); and the basic work of identifying particle types at large $pt.$ is described in Chapter 4.

Apart from vector mesons, one of the most copiously produced neutral mesons is the η . η photo-production however is not a well known process experimentally. Several experiments have observed it [9] [10], but not in the kinematic region seen in NA14. The most detailed results are those of Breakstone et. al. [10]. Their results are reproduced in figure 4, where η production is compared to that of the π^0 . A major variation of η production with Feynman x is evident, but all their data was taken at low pt (≤ 1 GeV/c). In NA14 the data is at a higher $pt.$, thus permitting an extension of the knowledge of η

photoproduction. After the π^0 , the η decaying to 2γ s is the most copious meson source of photons, which are then a background to the prompt photons described above. A knowledge of η photoproduction was thus essential for the prompt photon analysis.

Chapter 5 describes in detail a study of η production in NA14. Because the NA14 experiment can also take data with a π^- beam, the photo-produced η / π^0 ratio can be directly compared to that in pion - induced interactions, with similar systematic errors. Unlike the π^- , the photon can appear in an interaction as a $s\bar{s}$ quark pair, and this appearance of strangeness may be reflected in increased strangeness in the final state. Thus η production in γ beam may be enhanced relative to that in π^- beam, in the same way as, for example, charm photoproduction exceeds charm hadroproduction.

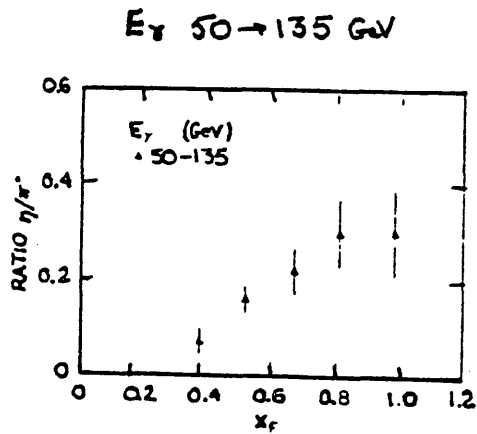


Figure 4: η / π^0 Ratio In γ Beam At Low pt.

1.2 CHARM PHOTO-PRODUCTION

1.2.1 A Review of the Experimental Results

The initial quark model contained only 3 quarks; up, down, and strange (u d s for short). However, early on, Bjorken and Glashow [11] proposed a 4th quark for reasons of symmetry between leptons and quarks in the weak interaction. The extra quark, charm, was later put into an isospin doublet with the strange quark by Glashow, Iliopoulos and Maiani; this, the so-called GIM mechanism, provided an explanation for the absence of flavour changing neutral currents. The first strong experimental evidence for charm was the discovery of the J/ψ in 1974 [12], which was interpreted as a $c\bar{c}$ bound state.

Mesons with open charm, that is with $c = \pm 1$, consist of a c quark bound to a u , d , or s anti-quark. The results are the D^0 , D^+ , and F^+ mesons (and corresponding anti-particles). These are the pseudo - scalar ($J = 0^-$) mesons, there are also the $J = 1^-$ vector mesons, the D^* and F^* .

The prediction of the existence of these mesons in the quark model [13], prompted many experimental searches. The D^0 and D^+ were soon well established experimentally, see for example the 1981 review by Trilling [14], with masses and lifetimes as shown in table 1 (the entries in this table are taken from the current Particle Data Group Tables [15]). The D^* was also soon established with a $D^* - D$ mass difference of $145 \text{ MeV}/c^2$, permitting both $D^* \rightarrow D\pi^0$ and $D^* \rightarrow D\gamma$.

TABLE 1		
Properties of the D Mesons		
	Mass (MeV/c^2)	Lifetime (secs)
D^0	1865	4.4×10^{-13}
D^+	1869	9.2×10^{-13}

The F proved more difficult to pin down. The decay of the F could proceed via an annihilation diagram, figure 5 a), but this is forbidden due to helicity mis-match (although this can be overcome by gluon emission prior to annihilation). The other possibility is a spectator type diagram, figure 5 b). The

presence of strange quarks in the resulting fragmentation process strongly suggests decays such as $F \rightarrow \eta + n\pi$ or $F \rightarrow K\bar{K} + n\pi$.

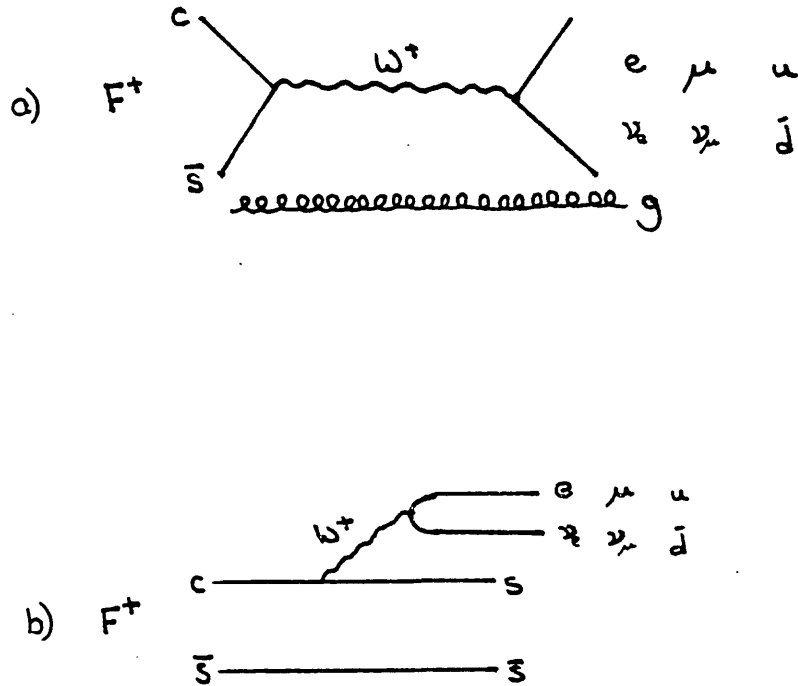


Figure 5: F decay diagrams

Initial F searches concentrated on $F \rightarrow \eta X$. The DASP collaboration were the first to present data on this topic [16]. They measured an excess in η production in e^+e^- collisions. This excess was interpreted as $e^+e^- \rightarrow F^* \bar{F} \rightarrow F \bar{F} \gamma$, with an F^* mass of 2030 MeV/ C^2 , and 2140 MeV/ C^2 for the F.

The large cross-section ($1 \mu\text{bn}$) for charm photo-production indicated by photo-production of the ψ , prompted a search for the

F in photoproduction. The CERN WA4 experiment [17] was carried out in the OMEGA spectrometer with photon energies in the range $20 \rightarrow 70$ GeV. The Collaboration reported F signals in the $\eta\pi$, $\eta3\pi$, and $\eta5\pi$ channels. The F mass they obtained was $2020 \text{ MeV}/c^2$. A subsequent experiment, WA57, was performed in the up-graded OMEGA spectrometer, and also reported [18] $F \rightarrow \eta\pi$, $\eta\pi^0\pi$ and $\eta3\pi$. Their F mass was $2017 \text{ MeV}/c^2$. The quoted error on the masses was typically $13 \text{ MeV}/c^2$ in the $\eta\pi$ channel. To obtain a cross-section in WA4, associated $F\bar{F}$ production was assumed with a simple diffractive model for production of the pair. The result, for $F\bar{F}$ production, was $\sigma.\text{Br}(F \rightarrow \eta\pi) = 27 \pm 7 \text{ nb}$. In the WA57 experiment the acceptance was calculated using γ -gluon fusion as the $c\bar{c}$ production model, resulting in (again assuming $F\bar{F}$ associated production), for $F \rightarrow \eta\pi$, $\sigma.\text{Br} = 38 \pm 14 \text{ nb}$, seeming to confirm the WA4 result.

There were also several emulsion experiments, e.g. [19], which reported F decays, but none has produced enough decays to cluster in a single region on an invariant mass plot. Due to the nature of emulsion work, the decays seen have been in the charged hadronic channels.

However, doubt has since been cast on these original results. Both Mark II and the Crystal Ball [20] fail to confirm the DASP result. Further, several experiments [21] have since observed F signals in $e^+e^- \rightarrow K\bar{K}\pi$ and $\phi\pi$ with a mass of $1970 \pm 8 \text{ MeV}/c^2$. The currently accepted view is that the F mass is indeed in this area and this raises questions as regards the photo-production

results. In Chapter 6 an attempt to observe $F \rightarrow \eta\pi$ is reported, and limits are calculated for the cross-section $\times$ branching ratio.

1.2.2 NA14 and Photo-Production of Charm Particles

As already stated, the process of gamma-gluon fusion is held to be the main mechanism for charm photo-production. There are however other possibilities which have to be considered. The photon can interact hadronically, such as in figure 6, where $q\bar{q}$ annihilation or gluon-gluon fusion occur. There is also the possibility of the appearance of charm intrinsic to the nucleon. This can come from the QED Compton process of figure 1 a), where the outgoing quark is charm. Or there can be diffractive dissociation of the photon, which in a QCD context is shown in figure 7.

The cross-section for charm quark production in all these diagrams is estimated by Fontannaz et. al. in [22]. They find that gamma-gluon fusion is the main source of charm photo-production for photon energies of 20 $\rightarrow$ 120 GeV. Total charm cross-sections from various experiments are used to illustrate their results as in figure 8. The figure shows the calculated cross-section for different parameters in the γg fusion model, and compares to observed values.

γg fusion of course, only predicts $c\bar{c}$ production, and although total charm cross-sections are calculable, for selected charm meson channels the calculations are more difficult, requiring a



Figure 6: Hadron-like charm photo-production

model for what fraction of c quarks dress into the desired meson. The EMC experiment at CERN (using a μ beam), has studied virtual photo-production of the ψ and open charm [23], and described both in terms of a γg fusion model. For the open charm case, a first order calculation sufficed to well describe the data. However for the ψ , 2nd order effects (as calculated by Duke & Owens [24]) were required to give reasonable fits to all the observed ψ properties. EMC also found that the γg fusion model of Berger & Jones [25], (which allows for soft gluon emission, permitting the $c\bar{c}$ pair to form a colour singlet, which

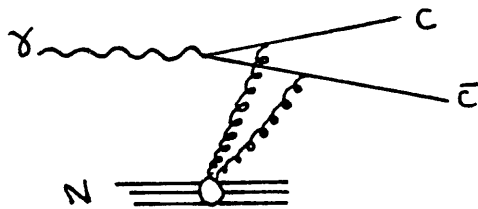


Figure 7: Diffractive dissociation

then can be described in terms of a specific ψ wave function), is not a good description of the data. Although this model avoids the need for an arbitrary normalization of the predicted to observed cross-section, the model only predicts cross-sections in reasonable agreement with data, if the mass of the c quark $\approx 1.2 \text{ GeV}/c^2$, which contradicts basic assumptions of the model which require a mass of $\approx 0.5 \cdot \text{mass}(\psi) \approx 1.6 \text{ GeV}/c^2$. Recent work on ψ photoproduction in NA14 [26], confirms this problem with the cross-section, but produces better agreement between the shape of the kinematic variable distributions of ψ s produced by the colour singlet model and real data.

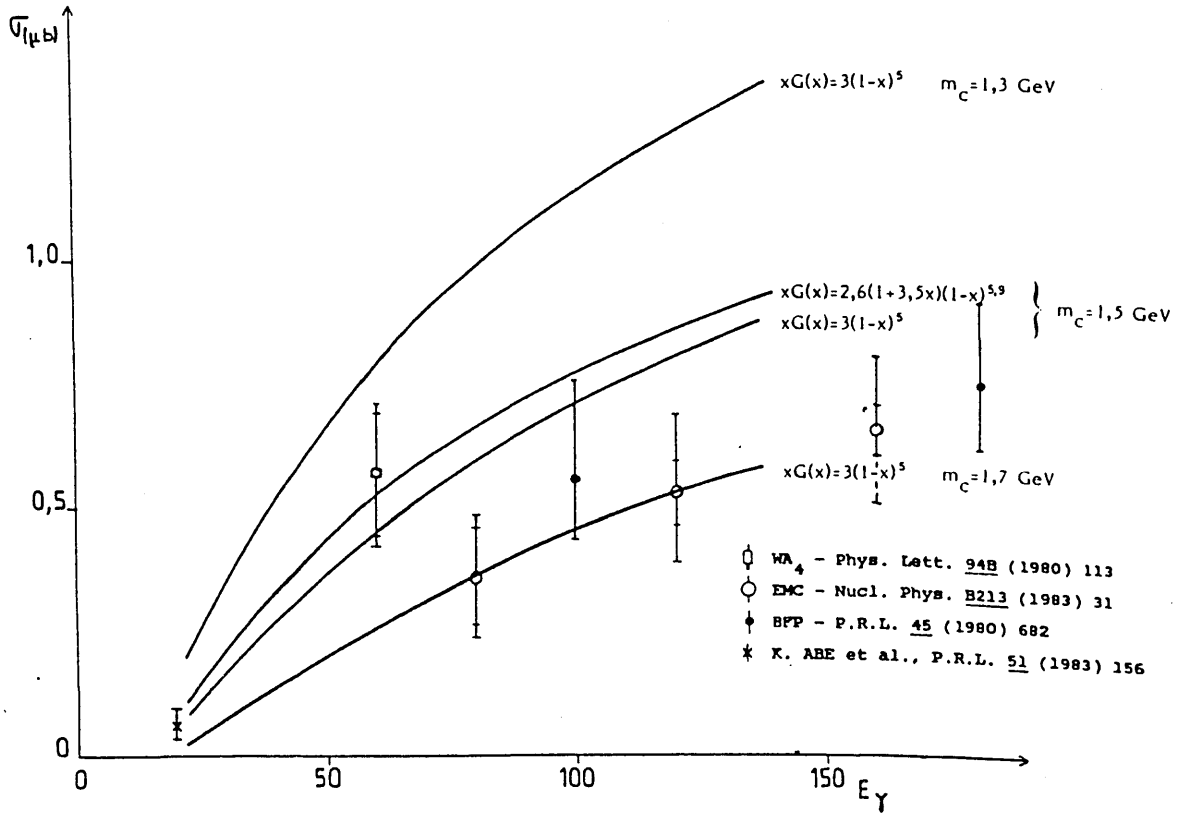


Figure 8: Charm Photoproduction Cross-sections

The total cross-section for $\gamma N \rightarrow c\bar{c}$ via γg fusion is

$$\sigma = \int_{x_s}^1 dx G(x) \sigma(xs) \quad : \quad x_s = 4m_c^2 / s \quad \text{Eqn 1}$$

with m_c = mass of the charm quark, x = fraction of nucleon momentum carried by the gluon, $G(x)$ = gluon distribution function in the nucleon, and $\sigma(xs)$ = cross-section for $\gamma g \rightarrow c\bar{c}$.

Taking $\hat{s}$ as the cm energy² for the γg system, we have [27]

$$\sigma_{\gamma g}(\hat{s}) = \frac{\pi\alpha\alpha_s}{3} e_c^2 \left((3-\beta^4) \log \left[\frac{1+\beta}{1-\beta} \right] - 2\beta(2-\beta^2) \right) \quad \text{Eqn 2}$$

where $\beta = \sqrt{1 - 4m_c^2/\hat{s}}$, $e_c =$ charge on c quark.

It can be seen that σ depends on $G(x)$, a_s and m_c . $G(x)$ is not a well known function. Certain conditions can be imposed upon it, such as that the sum of gluon momentum = 0.5 * the nucleon momentum. Also counting rules [28] suggest the form $xG(x) \sim (1-x)^5$, although fits to inelastic lepton scattering data suggest a power of 10 rather than 5. Clearly there is leeway in choosing the exact form of $G(x)$. a_s and m_c are also not well known, and indeed are related to the Q^2 of the interaction. In the literature a_s varies over $0.25 \rightarrow 0.5$, and m_c over $1.2 \rightarrow 1.6$ GeV/C². The Q^2 of the process is not well-defined, and typical choices are $Q^2 = m_c^2$, $4m_c^2$ or $4(m_c^2 + p_c^2)$.

The EMC Collaboration showed that the choice of values for these quantities is not an exact process because different combinations of values can yield the same predictions. To fix these values for use of the γg model in NA14, the approach of Fontannaz et. al. [22] is followed, where the predicted $\sigma(s)$ is required to fit the observed open charm cross-sections of figure 8. This leads to $a_s = 0.25$, $m_c = 1.5$ GeV/C², $Q^2 = 4(p_c^2 + m_c^2)$ and $xG(x) \sim (1-x)^5$.

Once produced, the charmed quark must combine with other quarks to form outgoing particles. Figure 10 shows several possible schemes for dressing the outgoing quarks (assuming γg fusion as the production model). For open charm production the presence of 2 outgoing charm particles is striking. An interesting feature of the EMC results is that they favour scheme

b) (in figure 10) over c). A particular feature of F meson production, is that the presence of a strange quark in the F requires a strange content in the accompanying particles in the event.

The short lifetime of the F (currently thought to be $1.9 \pm 1.3 \times 10^{-13}$ secs, see [15]) causes the rapid decay of the particle and it is the decay products that are observed in experiments. The possible processes for F decay are, as already noted, the annihilation and spectator diagrams of figure 5 and can result in hadronic, semi-leptonic or purely leptonic decays.

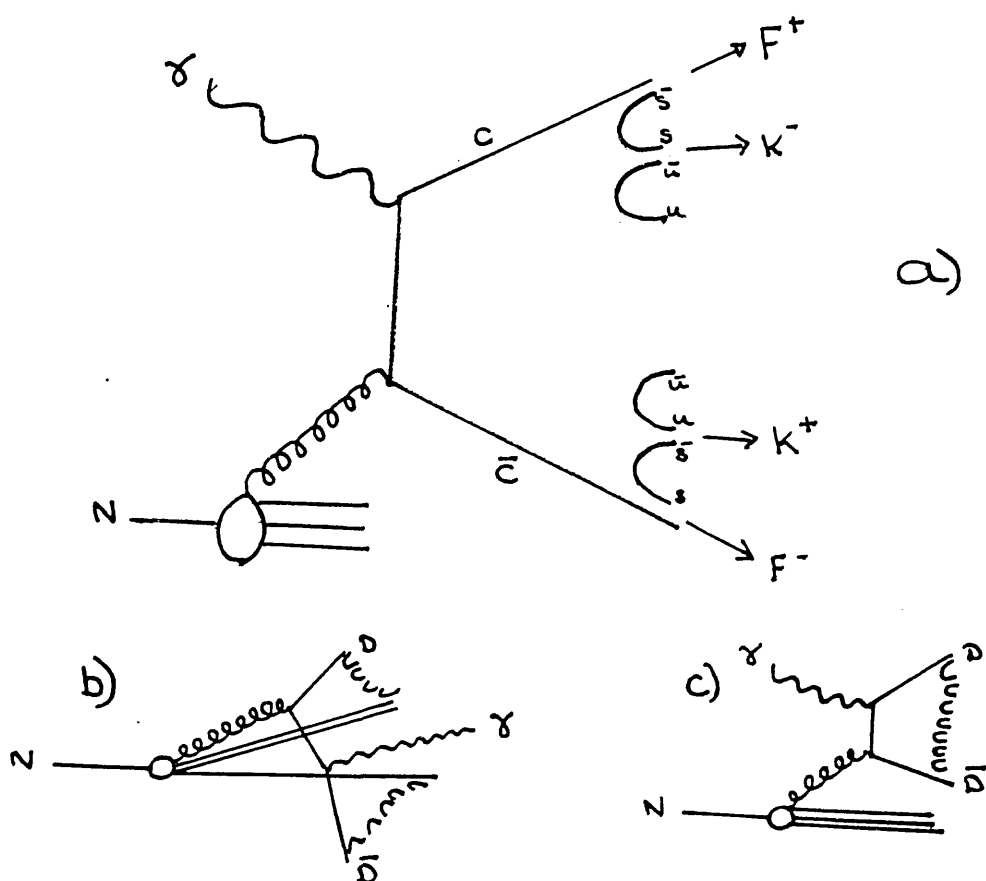


Figure 10: F dressing

NA14 is well suited to a search for hadronic charm decays, the charged and neutral particle detection allowing invariant mass reconstruction of the decay products. Although not considered in this thesis, NA14 has been updated with a high resolution vertex reconstruction device in order to see the decays directly. This device consists of planes of silicon divided into narrow strips. Each strip is operated as a fully depleted reverse biased diode, and passage of a charged particle through a strip produces a pulse in the associated electronics. 31 planes, with a strip width of 2mm., act as an active target. 10 more planes, with a strip width of 50 μ m, are positioned after the target for precision charged track reconstruction work. Using the silicon devices, it is hoped to be able to observe short-lived particles directly, and thus measure their lifetimes as well as remove the inevitable combinatorial background from invariant mass reconstruction.

Chapter II

THE NA14 SPECTROMETER

2.1 INTRODUCTION

In this chapter I describe the main features of the NA14 beams, spectrometer, and data-taking triggers. More detailed accounts exist for some parts of the apparatus, and references are given where appropriate. Emphasis is placed upon those features which are of direct interest to this thesis.

2.2 BEAMS

2.2.1 The Photon Beam

The NA14 experiment is directed towards a study of high energy photo-production. The design of the beam [29] represents an attempt to yield a high flux of photons at high energy, with minimal charged particle contamination. The chosen method uses protons which interact in a target. Amongst the interaction products are π^0 s which decay into γ s. These γ s are converted into electrons which in turn radiate to give a bremsstrahlung photon beam whose energy can be tagged. This is often referred to as the classical 2 step method.

The proton beam is provided by the CERN Super Proton Synchrotron (SPS) with an energy of, dependent on operating cycle, 400 or 450 GeV. The duration of the beam pulses is

typically some 2 seconds, with some $2 \cdot 10^{12}$ protons per pulse, and 10 seconds between pulses. These pulses of protons are directed onto a 0.5m long beryllium target, see figure 11. Given the interaction length in beryllium, the proton energy, and the length of the beryllium, some 70% of the protons are expected to interact. The 2 gamma decay of pizeros produced in these interactions provides the primary photon beam, and it is the requirement that these photons should emerge from the target that limits the target length. Indeed it is its ratio of radiation to nuclear interaction length that prompts the choice of beryllium for the target.

Magnets placed after the target sweep charged tracks out of the neutral particle beam into a dump, with the neutrals going on to hit a 4mm thick lead converter, positioned 14m after the beryllium. The electrons produced by photon conversions in the lead, are momentum selected by a chicane of 5 bending magnets. The other particles, remaining gammas, and the neutral and charged particles arising from interactions in the lead of the neutral hadron contamination of the primary photon beam, are dumped into a 4m thick iron wall. The beam of electrons is directed onto a 0.5mm thick lead radiator, resulting in approximately 10% of the electrons emitting a single high energy photon. There are then more magnets to deflect the electrons out of the 'photon' beam, and it is this bremsstrahlung photon beam which is the NA14 photon beam.

It should be pointed out that an intermediate beam of electrons rather than positrons, was used in order to reduce muon contamination of the final beam.

A schematic layout of this beam is shown in figure 11, and the numerical details at each step of the process are given in table 2.

Figure 11: NAL4 Beam Layout

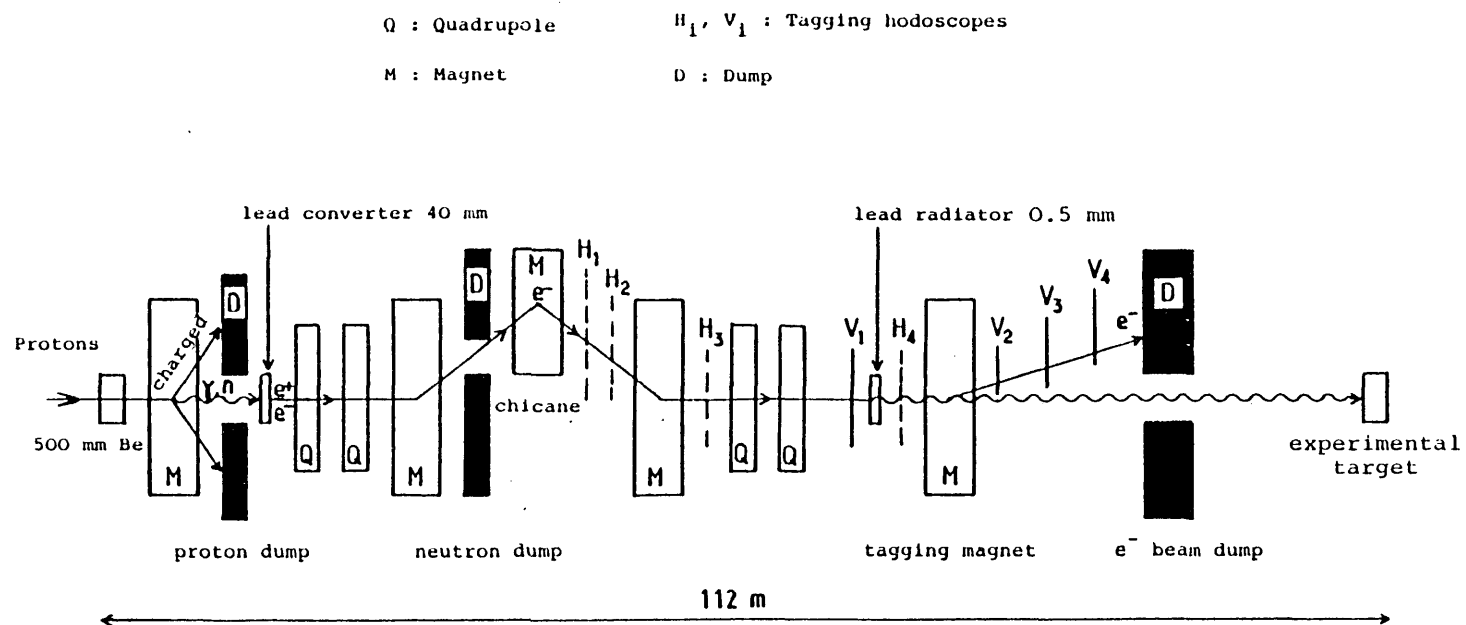


TABLE 2

Parameters Of Gamma Beam Production

Protons	Intensity/burst	2×10^{12}
	Energy range	400 - 450 GeV
Electron beam	Intensity/burst	10^8
	Energy range	120 - 250 GeV
	Mean energy	140 GeV
Bremsstrahlung photon beam (energy > 65 GeV)	Intensity/burst	5×10^6
	Mean energy	80 GeV
Beam size	Horizontal	$\pm 34\text{mm}$
	Vertical	$\pm 22\text{mm}$
Hadron contamination		$< 10^{-4}$

2.2.2 π^- Beam

Although primarily a photoproduction experiment, NA14 can also run using a π^- beam. Two methods have been used to produce the π^- beam, the first in 1983, and the second in 1984.

1983 π^- beam.

Describing these methods chronologically, we begin with the original π^- beam (which provided all the π^- beam data analysed in this thesis). Here, the π^- beam is formed from π^- produced in proton interactions in the primary beryllium target (see figure 11). The magnets positioned after the beryllium target are switched off, and both the lead convertor, and the lead radiator, are removed. The gap in the proton dump, shown in figure 11,

through which the particle flux from the primary target has to pass, is narrowed relative to its width for photoproduction, and the chicane of 5 magnets following it is used to select charged particles within a narrow momentum range. It is the beam of particles emerging from the chicane which forms the NA14 π^- beam. The resulting beam contains $\sim 3 \cdot 10^6$ particles/burst. From a consideration of proton-nucleon inclusive cross-sections at 400 GeV, this beam is mainly π^- with a small contamination of K^- and anti-protons. By altering the magnetic field strengths, it is possible to produce π^- beams with differing mean energies. NA14 has taken data with nominal beam energies of 70, 90, and 120 GeV.

In order to keep the π^- flux at a level which does not saturate the wire chambers in the spectrometer, the flux of protons hitting the primary target has to be reduced from that provided by the SPS. This is achieved by inserting 'plugs' of a low atomic mass material in the proton beam line upstream of the beryllium target. Approximately 99% of the protons interact in the 'plugs', reducing the flux to an acceptable level.

A π^- , rather than a π^+ , beam is used to prevent contamination of the final beam by non-interacting protons from the SPS.

1984 π^- beam

In 1984, a different method was used to produce the π^- beam. The new method involved producing π^- by the decay of a neutral particle. The neutral particles (K_S^0) were produced by protons from the SPS striking the beryllium target. The magnets in

figure 11 after the target, sweep away all charged particles emerging from the beryllium, and the decay in flight of the relatively long-lived K_L^0 produces a beam of π^- and π^+ . These head as a beam toward the usual 5 magnet chicane and proton dump. The chicane selects out a beam of π^- of a given momentum.

The advantage of this system over that of 1983 is that it permits the full SPS proton intensity to be used without saturating the NA14 spectrometer. This means that the muon background present in the photon beam (arising from interactions in the proton dumps) is faithfully reproduced.

2.3 TAGGING

2.3.1 Photon Tagging

The photons are tagged by measuring the energy of the radiating electron, both before and after emission of the bremsstrahlung photon. Scintillator hodoscopes, equipped with fast photomultipliers (to deal with the high electron flux), are positioned as in figure 11, in order to measure the electrons path before, and after, radiating. By splitting the signals from the scintillators and sending part to TDCs, a time for each hit is also recorded. The change in electron energy is then found off-line by calculating the momentum necessary for such a path in the magnet fields in the region. This change in energy is equal to the energy of the radiated photon. The tagging efficiency is such that in 52% of triggers there is 1 well-timed, unambiguous solution from the tagging. A spectrum of such tagging solutions is shown in figure 12.

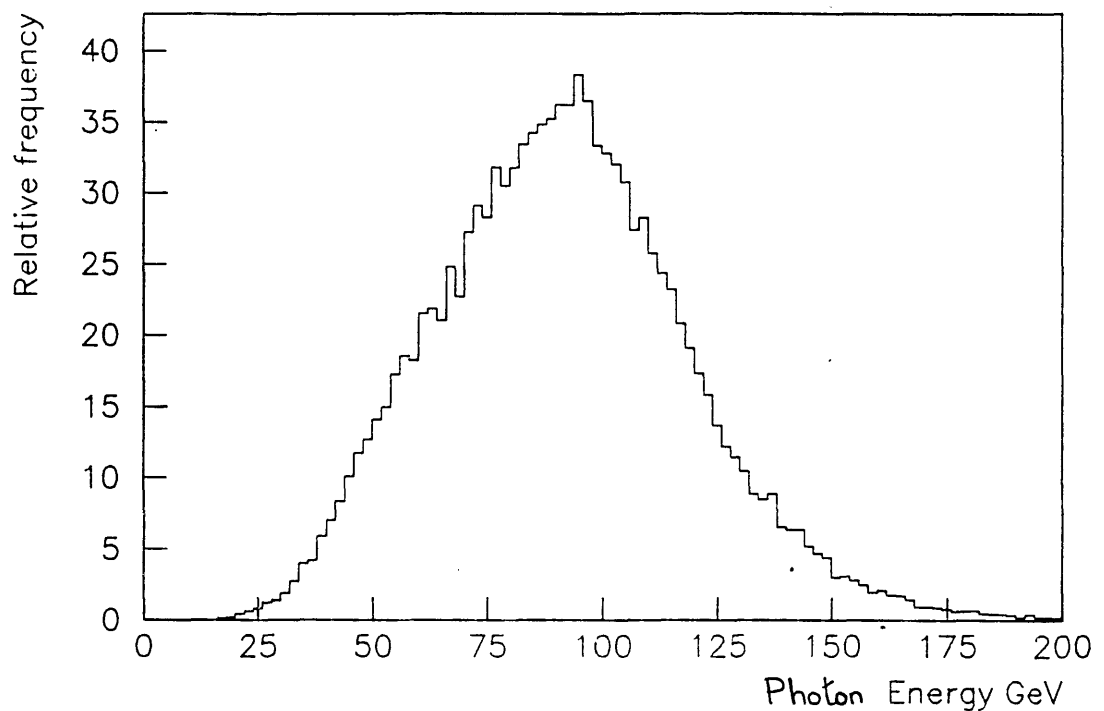


Figure 12: Raw in-time tagging solutions for gamma beam

The main sources of error in the tagging solutions are :

1. Multiple bremsstrahlung in the radiator
2. The angular resolution of the scintillators
3. Ambiguities in the electron path reconstruction when there are multiple hits in the hodoscopes

The effect of the first of these points is to reduce the real beam energy from that given by the tagging solution. The magnitude of this effect has been calculated, and a beam energy spectrum corrected for this is shown in figure 13. The last of these problems is partially solved by incorporating the timings from the TDCs when forming electron trajectories with the scintillator hits.

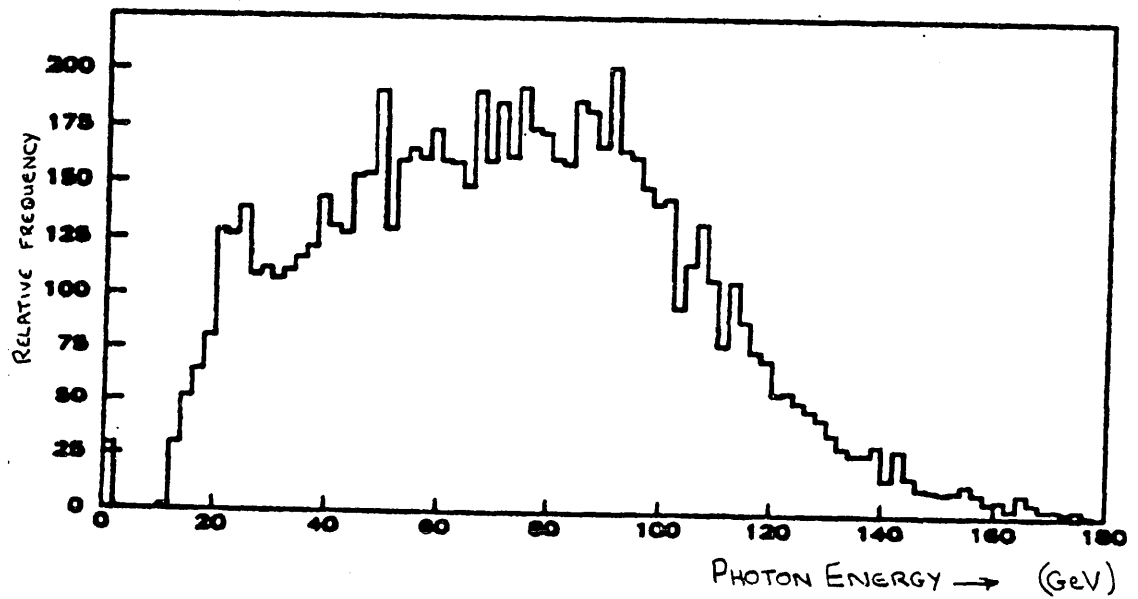


Figure 13: Corrected photon energy spectrum

2.3.2 π^- Tagging

The energy of the π^- is easier to find than that of the photon. Here the requirement is to find a path from the scintillators and fit a momentum (knowing the magnetic field strength). The task is made easier by knowing that the configuration of the beam layout restricts the energy of the π^- to a very narrow range. For the so-called '90 GeV' field configuration, tagging solutions are as shown in figure 14. All the π^- beam data analysed in this thesis were taken with this field configuration.

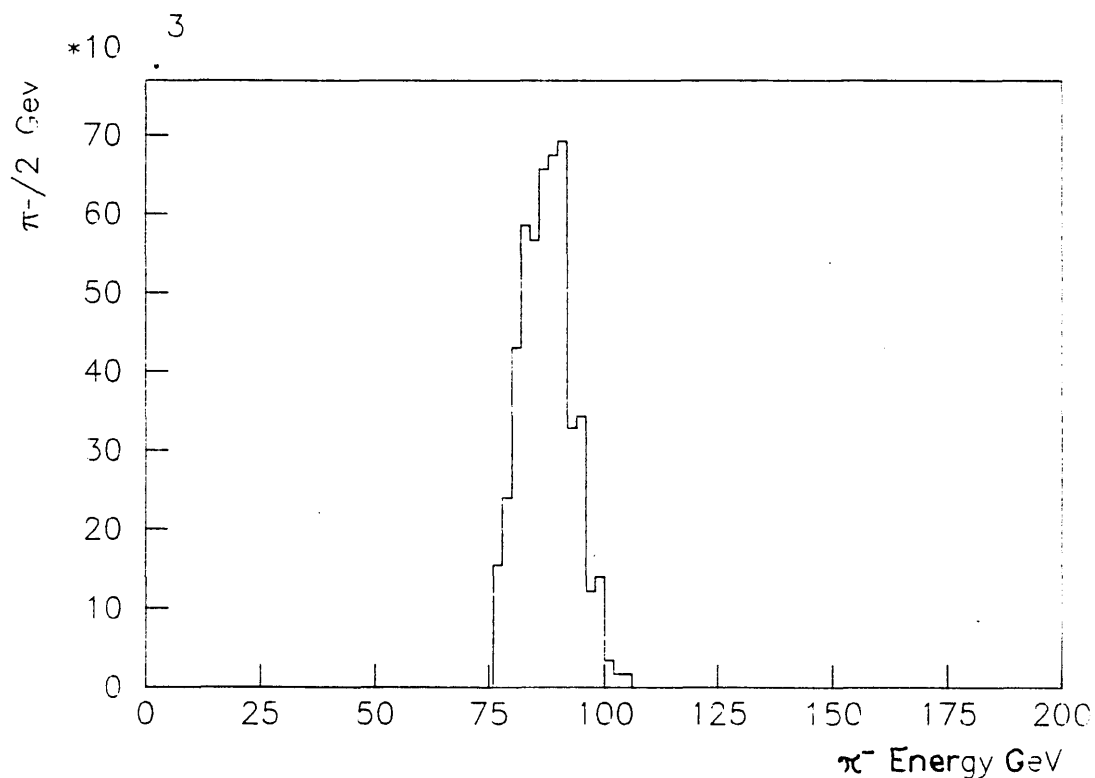


Figure 14: π^- tagging solutions

2.4 THE SPECTROMETER

2.4.1 Introduction

The aim behind the design of the NA14 spectrometer was to assemble a detector which would satisfy the following requirements :

1. To observe and measure the momentum/energy of both charged and neutral particles over a large range of energies.
2. To have near 4π acceptance for both charged and neutral particles in the interaction centre of mass.

The layout of the resulting spectrometer is shown in figure 15. The target is a 13.5cm long cylinder of Li^6 . It is situated in the AEG magnet ($\int B dl = 0.8 \text{Tm.}$), the field of which sweeps away the background low momentum e^+e^- pairs (energy $< 100 \text{ MeV}$). The AEG magnet also serves to deflect low momentum charged tracks coming from the interaction; this permits a fit to their momentum (see section 2.7.1) thus increasing the acceptance at low p_l . A second magnet, Goliath, ($\int B dl = 3.2 \text{Tm.}$) deflects charged tracks of a higher momentum. Both magnets have their fields in the vertical direction, so as to cause deflection in the horizontal plane. Thus the soft e^+e^- background, which is of low p_l and p_t , is confined to the median horizontal plane.

2.4.2 Multi-wire Proportional Chambers (MWPC)

The trajectories of the charged tracks are observed predominantly in three stacks of MWPCs. These stacks are outside the magnetic fields in order to avoid the problems of; the spiralling of soft

electrons in the chambers, and of track reconstruction in high magnetic fields. There are typically a total of 80 planes of wires in these stacks, although the exact numbers and positioning varied with time.

The arrangement of the 3 stacks is shown in figure 15. Pre - Goliath is Stack 1, which in August 1983, a typical period, consisted of 46 planes of wires and had a ± 400 mrad. acceptance to the target. Most of the chambers in this stack have a desensitized median horizontal region to avoid problems with the e^+e^- pairs opening in the plane. Three of these chambers (6 planes) are equipped with 'fast' electronics.

Post-Goliath are Stacks 2 & 3, which, in August 1983, contained 24 and 9 planes respectively. These chambers are physically larger than those in Stack 1, and none have desensitized regions.

The chambers are used to provide space points for the charged track finding software (see section 2.7.1). Some of the planes are also used in various of the data-taking triggers.

Figure 15: NA14 Spectrometer

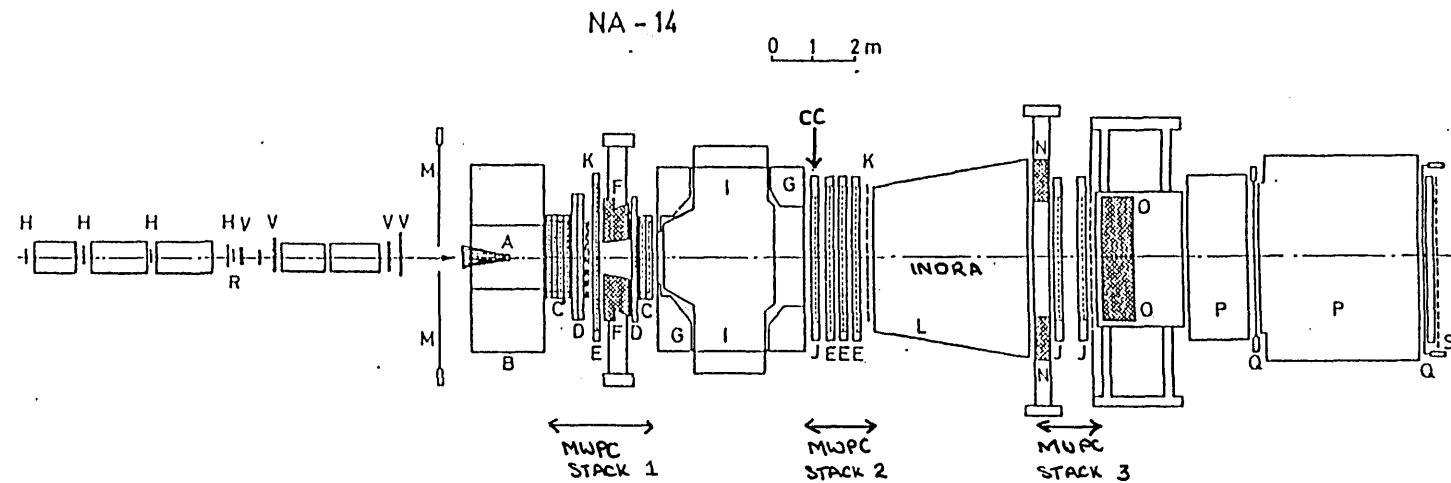


Figure caption:

II,V	tagging hodoscopes	F	"crown" lead glass calorimeter		
M	muon veto	G	Goliath Magnet		
A	active target	I,L	Čerenkov Counters	O	Olga-Penelope Calorimeter
B	AEG vertex magnet	K	trigger hodoscopes	P	iron filter
C,D,E,J	MWPC's	N	Imperial College Calorimeter	Q,S	μ hodoscopes

2.4.3 Scintillator Hodoscopes

There are several scintillator hodoscope arrays shown in figure 15. These serve several purposes. Most of them are used in the pre-trigger and act as :

1. A charged veto on the beam particle (the hodoscopes upstream of the target and the AEG),
 2. a muon veto (again pre-target),
 3. a filter for hadronic events rather than em triggers.
- These are G1, G2H and G2V and are positioned slightly up- and down-stream of the Goliath magnet.

There are also scintillator arrays used as charged vetos for the electromagnetic calorimeters.

Finally, at the downstream end of NA14 is a muon filter. This is a 5.4m length of iron which absorbs high energy charged hadrons, but not the electromagnetically interacting muons. These muons are identified as they traverse the iron by 4 planes of scintillators. These are placed after 0.7m of iron, after a further 2.2m and finally downstream of the iron.

With the exception of the muon filter planes, all the scintillators have a dead median horizontal plane region to avoid the e^+e^- pair population from beam gamma interactions.

2.4.4 The Cerenkov (INDRA)

NA14 has one Cerenkov operational (INDRA), and a second under construction. INDRA is positioned as shown in figure 15, and has been operational since the start of the experiment. The second Cerenkov is to be installed in the Goliath magnet in mid-1985. It therefore does not feature in this work and no further details are given. INDRA is a 48 cell threshold device, where each cell consists of a mirror, photomultiplier with light collecting cone, and ADC channel. The radiator is dry air, at room temperature and pressure. More complete details of INDRA design and operation are given in Chapter 3.

2.4.5 The Electromagnetic (E.M.) Calorimeters

There are 3 e.m. calorimeters in NA14; Crown, Ilsa, and Olga (see figure 15). They have an acceptance to the target of ± 300 mrad. The forward region, ± 85 mrad., is covered by Olga; the intermediate region, 85 - 150 mrad., is covered by Ilsa; and the backward region, 150 - 300 mrad., by the Crown. This coverage, as seen from the target, is shown (for 1 quadrant) in figure 16 (note that there is up/down, left/right symmetry in the coverage). The centre of mass coverage (assuming a beam energy of 100 GeV) is shown in the Peyrou plot of figure 17. The positioning of the e.m. calorimeters, with the Crown near the target, and Ilsa and Olga as a pair some 13 - 15m away, was determined by the need to position the Goliath magnet, the MWPCs, and the Cerenkov for good charged track coverage.

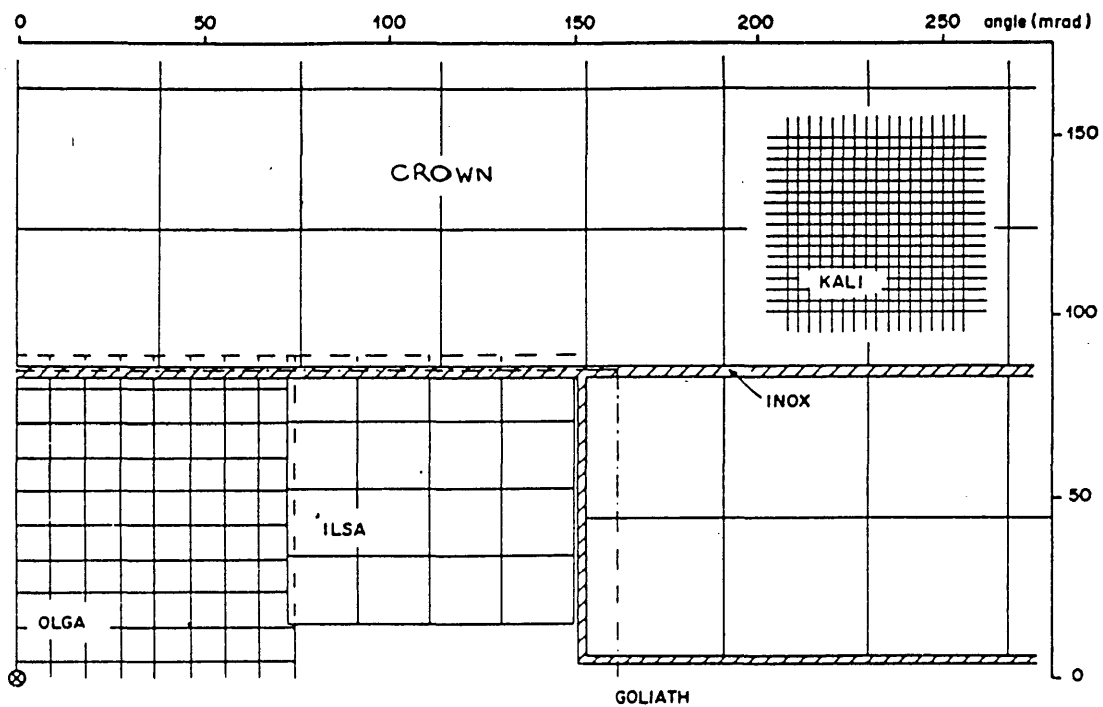


Figure 16: Coverage of the em calorimeters

2.4.5.1 The CROWN

This is a lead glass e.m. calorimeter. It has 3 components:

1. A passive converter. This is a sheet of lead, 4.5 radiation lengths thick.
2. A position detector (Kali), which consists of 2 orthogonally crossed arrays of scintillator fingers (each 8mm wide).

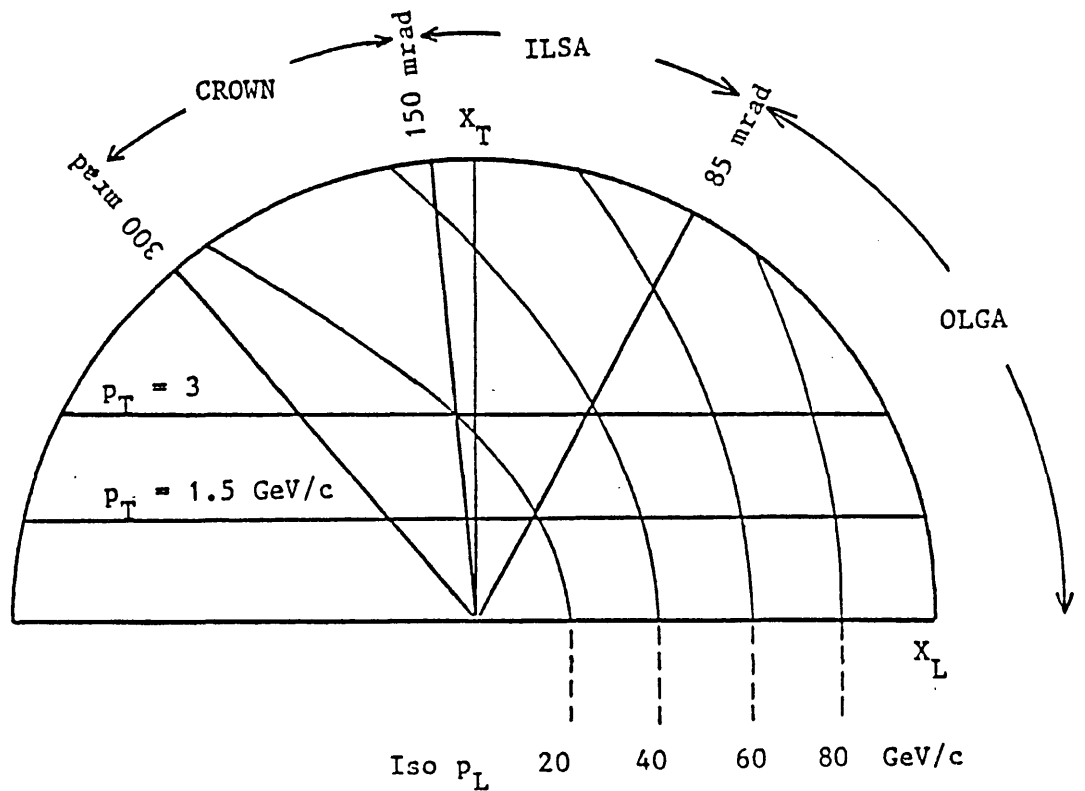


Figure 17: Peyrou plot of em calorimeter coverage

3. An arrangement of 192 lead glass blocks; with faces $9.3 \times 9.3 \text{ cm}^2$, and a depth of 25cm (14.8 radiation lengths).

The granularity of this detector is required by its proximity to the target, and the expected energy of the π^0 s heading for it. The 9.3 cm dimension of each lead glass block corresponds to the typical separation of 2 gammas from the decay of a 7 GeV π^0 .

A more detailed description of the Crown is given in [30].

2.4.5.2 ILSA

This calorimeter (see [31]), unlike Crown and Olga, is a lead - scintillator sandwich. It is arranged as 4 separate, yet identical, quadrants arranged symmetrically around the beam axis.

Each quadrant, has its own scintillator hodoscope charged veto. This is in front of a 1 rad. length passive lead convertor. A fine grained position detector, Ariadne, is situated after the first layer of the lead - scintillator sandwich. Ariadne consists of vertical and horizontal arrays of scintillator, each strip of which is 1.5cm wide. The sandwich itself is arranged in 4 layers ,A,B,C,D, with 4 modules in each layer. The layers are alternately vertical and horizontal, and each module in a layer presents a face to the beam of $100 \times 25 \text{ cm}^2$. The modules are made of layers of 5mm thick plexipop scintillator, between 3mm thick lead sheets. Layers A and B are 3.5 rad. lengths thick, while C and D are 5.5 rad. lengths. Each quadrant also contains 2 extra layers of scintillator counters, S and T, which are used in making the trigger.

2.4.5.3 OLGA

Olga (the Omega Lead Glass Array) like Crown, is a lead glass e.m. calorimeter. It was originally used in the CERN WA4 experiment [32]. A complete description of its use in NA14 is given in [33].

Like Crown, Olga has 3 principal components (see figure 18)

1. An active converter (unlike Crown where the converter is passive). This is a lead glass wall built from 38 slabs, each $145 \times 14.35 \text{ cm}^2$, and 10cm (3 rad. lengths) thick.
2. A position detector, Penelope, which consists of 2 orthogonally crossed arrays of scintillator fingers. Each finger is 152cm long, 1.53cm wide, and 1cm thick.
3. A wall of 344 lead glass blocks. Each block presents to the beam a face of $14.35 \times 14.35 \text{ cm}^2$, and has a depth of 47cm (18.5 rad. lengths). The wall is 19 blocks high by 17 blocks wide, with a central hole for the beam.

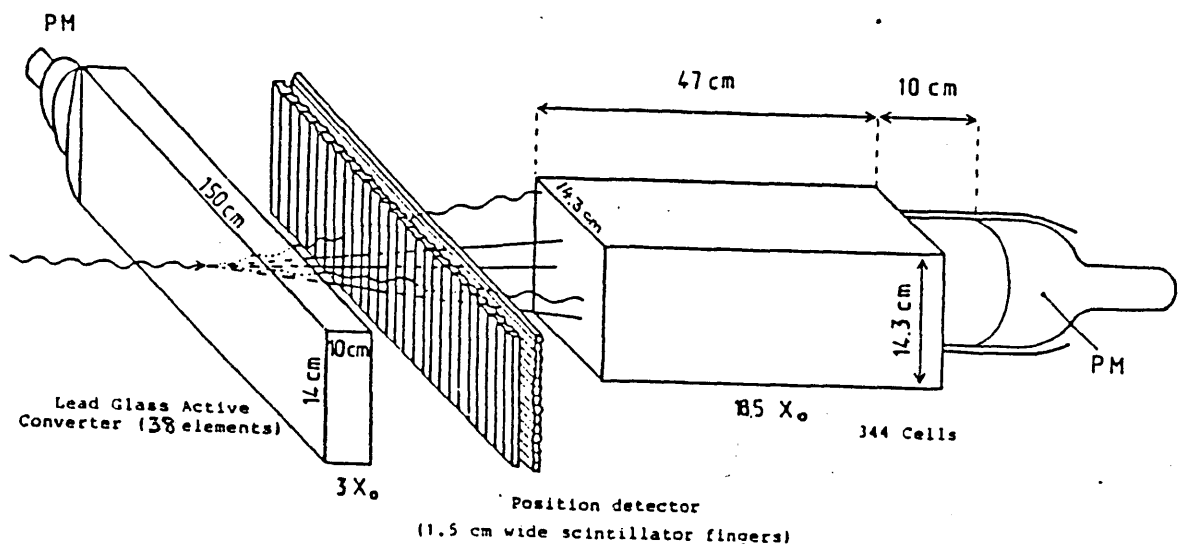


Figure 18: Apparatus of the Olga calorimeter

One important feature of Olga when studying π^0 decaying to 2 γ s, is that the two γ showers often merge in the lead glass wall (the implications of this are discussed again in Chapter 5). The reason for this is geometric, Olga is $\approx 15\text{m}$ from the target and the *typical* 2 γ separation from the decay of a π^0 of energy E , is :

$$d(E) = 405 / E \quad \text{cm.} \quad (E \text{ in GeV}) \quad \text{Eqn. 3}$$

Thus the *typical* separation for a 40 GeV π^0 is 10cm. Given that a single shower can extend into ≤ 4 blocks, and that a single block is 14.35cm across, it is not surprising that many π^0 are seen in clusters of 2 merged showers. More details of the operation of Olga, and of analysis of the arising data, are given in Chapter 5.

2.5 THE PRE-TRIGGER

With the exception of apparatus calibration triggers, all data-taking triggers are made in coincidence with a pre-trigger. The pre-trigger is an attempt to indicate that a high energy bremsstrahlung photon has been produced (as described earlier), and that within a fixed time window relative to this, an interaction has occurred in the target. It also provides the timing in an 'event' for the readout of the electronics by the data - acquisition system.

The pre-trigger demands a coincidence of :

- a) The emergence from the final radiator shown in figure 11, of an electron with momentum $< 80 \text{ GeV}/c$. This energy cut is equivalent to requiring the radiated photon to have an energy greater than 60 GeV . The detection of the electron provides a timing signal good to 1 nsec. , and it is this which provides the overall timing of the event.
- b) A charged veto is positioned just before the target, with a threshold of around 2 minimum ionizing particles. This helps protect against showering of high energy electrons in the last collimator of figure 11.
- c) A scintillator active target is positioned just after the lithium target in figure 15. At least 1 hit is required in this as evidence of an interaction having occurred in the lithium.
- d) Three planes of scintillator hodoscopes are used in conjunction with the muon veto in order to select 'hadronic' events, (i.e. an interaction where the gamma interacts inelastically producing charged hadrons). This requirement is either that there are ≥ 1 hit(s) in all 3 scintillator planes without any hit in the corresponding upper/lower half of the muon veto, or that there are ≥ 2 hits in the first scintillator plane, again with no muon veto.

Data has been taken with just the pre-trigger acting as the data - acquisition trigger, and analysis of the spectrometer information indicates that about 10% of such events are hadronic.

2.6 DATA-TAKING TRIGGERS

Data acquisition in NA14 occurs when any of a set of various conditions in the spectrometer or calorimeters, are satisfied in coincidence with a pre-trigger. There are around 80 events triggered per SPS burst, and they are written to tape by a DEC PDP 11/45 computer.

The main triggers are described in the following subsections.

2.6.1 Trigger : Interaction Trigger

This represents an attempt to trigger on the hadronic component of the pre-trigger. It requires the normal pre-trigger and at least one track through each of the upper and lower half of Goliath. The tracks are defined as for the pre-trigger using hits in 3 planes of scintillator hodoscopes. This trigger is also, for obvious reasons, called the ' Double Arm Pre-trigger ' (DARM). By considering the physics of the interactions and studying the contents of the spectrometer in DARM events, it is possible to infer the relation between the number of DARM triggers relative to incident beam photons, and the total cross-section. Thus whilst using any other trigger, it is possible, by simultaneously counting the number of DARM, to obtain the sensitivity of the data-set in terms of number of events per nanobarn of cross-section.

2.6.2 Trigger : Photon with large Transverse Momentum

There are three such triggers, one for each e.m. calorimeter. They are all constructed with the same idea; namely that for each region (block) in a calorimeter, a minimum energy threshold is set. These thresholds are chosen so that given the position of each region relative to the target, they correspond to a minimum pt. for a photon hitting that area. Whenever a pretrigger is received, all calorimeter blocks / modules are checked, using rough energy calibration constants, to see if any exceeds the required pt. value. Each calorimeter has its own additional requirements in order to avoid hadronic contamination of the triggers. Olga requires that there should be a minimum energy of 200 MeV in the converter, while Ilsa uses its S and T counters as a rough check on longitudinal shower development.

With the three calorimeters set to trigger on 900 MeV/c pt., the triggers are split between the calorimeters as shown in table 3. At times data has also been taken at pt. thresholds of 1200 and 1400 MeV/c, but all data in this thesis is with the 900 MeV/c value.

TABLE 3

Percentage of photon high pt triggers by calorimeter

Calorimeter	%
Olga	40
Ilsa	30
Crown	30

2.6.3 Trigger : Charged High Transverse Momentum

This title is slightly ambiguous, as, in the previous section, electrons can trigger the e.m. calorimeters. However due to the bending of such electrons in the magnet fields they are not necessarily at large pt. Here the intention is to trigger on any charged track with a large transverse momentum. This is achieved by correlating hits in one large wire chamber (CC in figure 15) situated just after Goliath, with hits in the Olga vetos. A matrix of hit correlations is used to define tracks and finds their momentum by assuming they come from the target and have been deflected in the field of Goliath. If a charged track with $pt > 1.5 \text{ GeV/C}$ is indicated, the trigger is satisfied. To reduce the level of fake triggers, once a trigger track is found, confirmation is sought by interrogating the appropriate elements of the G1 scintillator hodoscope (between the target & Goliath) and in the D₀ chamber (between CC and the Olga vetoes). Only if the trigger is confirmed is the event written to tape.

2.6.4 Trigger : $\mu^+\mu^-$

This trigger searches for $\mu^+\mu^-$ pairs in an event. The aim is to provide data containing the ψ decaying to a dimuon pair. It also finds Beithe-Heitler dimuon pairs. The method is to use the 4 planes of scintillator hodoscopes which form the muon filter. This is situated downstream of NA14, see figure 15. The strips of scintillator are angled to point towards the target to select muons from interactions in the target. There is also a desensitized median horizontal region to force the muons to be at high pt.

The number of each trigger per burst is shown in table 4. Although there are ~80 triggers per burst, the time taken to read out the spectrometer reduces the usable number of triggers to around 40.

TABLE 4	
Number Of Each Trigger Per Burst	
Trigger	Number
e.m.	56
Dimuon	23
Charged high pt.	1

2.7 SOFTWARE TOOLS

The NA14 data - taking is performed on a PDP 11/45, with two PDP 11/60s providing on line monitoring of apparatus, and also helping to form the triggers. The raw data tapes, once written, are then copied to high density tapes and made available for general off - line analysis.

2.7.1 TRIDENT and TYPHON

Charged track reconstruction is performed by the program TRIDENT [34], which is a multi-purpose track finding program originally written for the CERN OMEGA spectrometer, but which has since been modified for NA14. There is another faster track finding program called TYPHON written solely for NA14's use. TYPHON is less accurate in its momentum assignment but is much faster than TRIDENT, and is therefore used for fast filtering of data.

Both programs find track paths by taking hits in MWPCs and associating them to form space points which can be joined up to form roads through the spectrometer. Extrapolating through the magnetic fields permits a momentum assignment for each track

For high momentum tracks, which pass through Goliath, track segments on both sides of the magnetic field are seen and extrapolation through the field to produce a momentum is reasonably straight forward. Such tracks are known as 'flag 4' tracks. For low momentum tracks which the AEG deflects such that they cannot pass through Goliath, a vertex has to be formed to indicate where in the field of the AEG the track came from.

These tracks are called 'flag 2'. A third category of tracks are those seen only after Goliath, but which are still assumed to originate from the event vertex. These tracks are called 'flag 3', and, assuming that the lack of hits pre - Goliath is genuine, such tracks are presumably photon conversions.

The difference between the two programs is that TRIDENT contains a full map of each magnetic field, and uses relaxation methods to swim the track through them. TYPHON on the other hand approximates the fields with a thin lens type formula, applied at the middle of each magnet. TRIDENT is thus the more accurate of the two approaches.

2.7.2 NEPTUN

The remaining processing of raw data takes place in a program called NEPTUN. This contains sections as follows :

- a) TAGANL. This processes the data from the beam tagging hodoscopes described in section 2.3
- b) CRANAL. This set of routines decodes the data from the CROWN calorimeter and tries to group it into showers in the device. Energy and momentum 4 vectors are reconstructed for all hits and charged vetos are interrogated to see if the shower is from a photon or an electron. An output bank saving all relevant information for each shower is created for each event through CRANAL.
- c) ILSANL. This is similar to CRANAL but operates on the ILSA calorimeter.

- d) SNARK. Again similar to CRANAL, but a greater degree of sophistication is required. This is because whereas in the other calorimeters the γ showers are nearly always separate, in Olga (as already mentioned), for the decay of high energy π^0 s, the opening angle of the 2 gammas in the lab is such that the 2 resulting showers in Olga are almost invariably merged. SNARK has to be capable of recognizing such events and then correctly sharing the total energy between the 2 gammas.
- e) INDANL. This requires that charged track reconstruction has already taken place, and then associates the tracks with data from the Cerenkov to aid particle type identification. This is dealt with in more detail in Chapter 3.
- f) MUANL. This again requires that charged track reconstruction has occurred, and uses the muon veto hodoscopes to determine if a track was a muon.

After processing through one / several of the above sections, the original event is written to the output tape with the addition of an extra bank containing the result of each section.

Chapter III

THE CERENKOV INDRA

The interpretation of the NA14 data is obviously aided by particle identification. For charged particles there are three possibilities available:

- a) Electrons can be identified by projecting TRIDENT reconstructed tracks to the e.m. calorimeters, and searching for an associated shower. Due to the late showering of hadrons in the calorimeters, hadrons rarely produce ^{e.m.-like showers.} Furthermore, the ratio momentum (TRIDENT) / energy (calorimeter) should be ≈ 1.0 for electrons.
- b) Muons can be found by use of the muon filter positioned at the rear of NA14. The muons, unlike hadrons and electrons, pass through the iron and can thus be identified.
- c) Finally one can search for Cerenkov light emitted by charged particles traversing the Cerenkov counter Indra.

It is this last method that I consider in this chapter. I first describe the Cerenkov counter, and then I give details of its operation.

3.1 LAYOUT

The INDRA Cerenkov is positioned as in figure 15, It is essentially a box at the rear of which is a plane containing 48 mirrors (see figure 19) and 8 light emitting diodes (LEDs). There is a detachable extension at the front of INDRA (called the 'nose'), which is fitted to increase the length of the radiator. INDRA is both light and air tight to a high degree. However INDRA is not a pressure vessel, nor is it heated, so the radiator is a gas at room temperature and pressure. Throughout 1982, '83 and '84 the radiator was dry air, and the resulting Cerenkov light momentum thresholds are as given in table 5.

TABLE 5

Cerenkov Light Threshold Momenta

refractive index (air) = 1.000297

Particle	Momentum (GeV/c)
Electron	0.021
Muon	4.34
Pion	5.73
Kaon	20.27
Proton	38.52

The mirrors in INDRA are orientated so as to reflect all collected light towards separate photo-multiplier tubes (PM's). In order to maximize the efficiency of light collection at the PM's, each is fitted with a Winston cone [35] light funnel. The

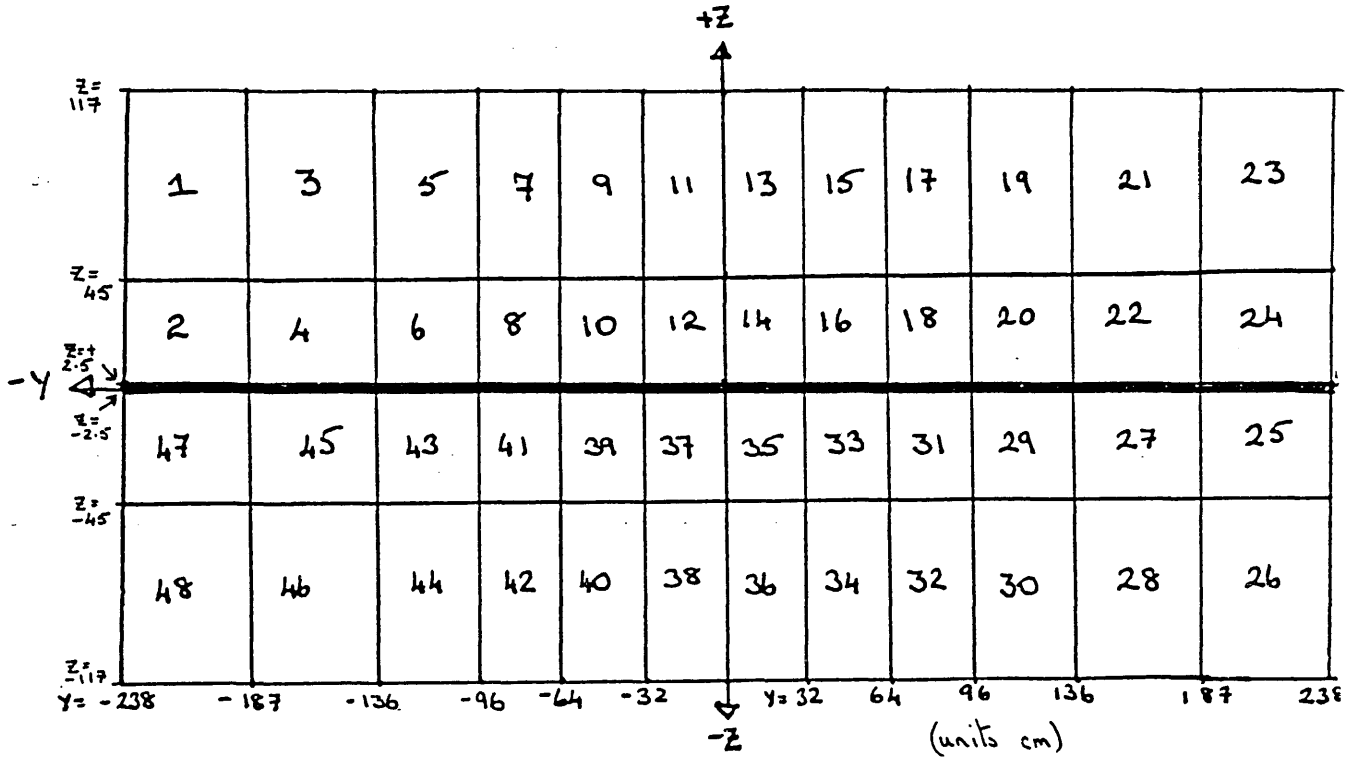


Figure 19: Layout Of Indra Mirrors

output from each PM is fed to a separate 1024 channel ADC, and all 48 ADCs are read by the data acquisition for each experimental trigger.

The size of the mirrors is dictated by a desire to concentrate light from a single particle into a single mirror. Cerenkov light is generated in a cone around the particle trajectory as in figure 20. The opening angle θ , is given by

$$\cos\theta = 1 / (\beta n)$$

Eqn 4

where n = refractive index, and $\beta = v/c$. The diameter of the base of the light cone (assuming a straight line track of length L) is thus $2L\tan\theta$. Given a typical track length in INDRA of 350cm., for a fully relativistic track ($\beta = 1$) a diameter of ~ 17 cm is expected (with air as the radiator). A mirror width of at least this value is required to contain all light from a track passing through the centre of the mirror, but obviously, in order to make this true for a hit anywhere in the greater part of the mirror's area, much larger dimensions are required. There is however a constraint on mirror size in that only 1 track per mirror per event is desired. In a typical event there are some 2 or 3 hits in INDRA, and the mirror size should thus be less than the typical track separation. The track density is expected to be largest nearest the beam, so finer segmentation is required here.

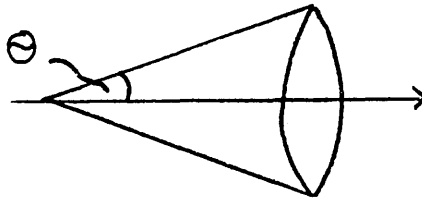


Figure 20: Cerenkov light cone

As the non-interacting component of the beam passes through INDRA, care is taken to prevent light generated by the beam

illuminating the mirrors. In the case of γ beam the light sources are the e^+e^- pairs produced at low pt by the beam. With π^- beam, the beam itself can generate light in INDRA. To shield INDRA from such effects, 2 horizontal, non-reflecting, opaque shields are fitted across INDRA just above and below the beam (at $z = \pm 2.5$ cm). To further isolate regions of INDRA from each other, an opaque, non-reflecting curtain is fitted in both the upper and lower sections. This curtain runs vertically along the beam axis and divides left from right.

3.2 CALIBRATION

To judge the performance of INDRA several measures can be defined. These are the calibration coefficients per mirror, and essentially they indicate if a light-giving track can be expected to produce an observable signal in an ADC. To detect light 'seen' by a mirror, the appropriate ADC must produce a signal above its pedestal. This pedestal is thus the first calibration constant per cell.

To have a high probability for responding to light from a particle, the amount of light at the PM must be sufficient to liberate a large number of photo-electrons (p.e.) from the photo-cathode. A measure of this is the mean number of p.e. from a $\beta \sim 1$ track with an average path length in the Cerenkov. (This is the 2nd calibration coefficient). Poisson statistics yields the probability of getting zero p.e. (i.e. no signal) from a distribution with a given mean, see table 6. Clearly to

have an efficient Cerenkov a large (> 5 say) mean number of p.e. is required.

TABLE 6							
Probability Of No Signal For Given Mean Number Of p.e.							
	Mean						
	0	1	2	3	4	5	6
Prob.	1.0	0.368	0.135	0.050	0.018	0.007	0.003

The third calibration value is the 'ADC gain' per p.e. (defined as the number of ADC counts per p.e.). This is needed to indicate if the expected signal from a given number of p.e., will be visible above the pedestal.

Details concerning each of these quantities are given in the following sections.

3.2.1 Pedestals

In the absence of an input signal, if interrogated an ADC returns a non-zero value for its contents; this is the pedestal. Typical pedestal distributions are shown in figure 21 for the 5 data taking periods in 1982 and '83. There is a clear difference after Aug. 1983, in that the twin peak structure disappears and the pedestal becomes narrower. This twin peak structure was held to be the effect of a ripple on the signal lines. Although the steady state signal is capacitively decoupled from the ADC the

ripple feeds through as a signal. Since a sinusoidal ripple spends more time in the high and low states rather than in between, the effect is to produce a 2 peak pedestal. After August 1983 the earthing on all cables in the electronics was improved, and the effect eliminated, the new pedestal shape being as in figure 2ld) & e). Note that the width (FWHM) of the pedestal is now 3 or 4 counts at most.

An investigation of pedestal stability over the duration of a data taking period, indicated that the pedestals are stable to ± 1 count. Between periods however, due to adjustments to the power supplies, replacing PMs etc, there can be large shifts. For this reason the pedestals are measured for each period separately. Pre-September 1983 a typical pedestal value was 130, afterwards it is more like 50. Pedestals are shown for some cells (June 1984) in table 7, and the typical spread in the values can be seen.

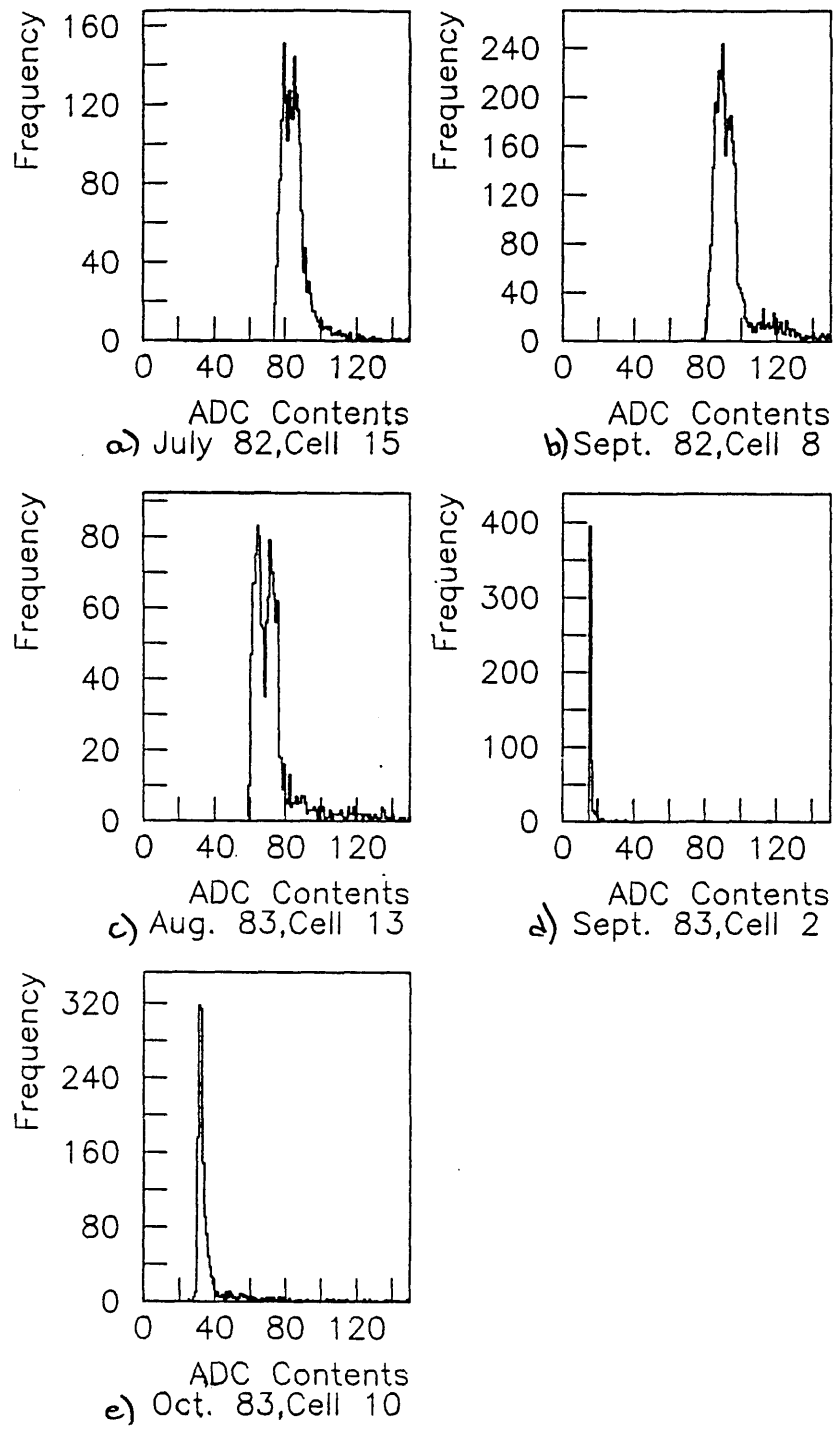


Figure 21: Cerenkov ADC Pedestals

TABLE 7
Typical Calibration Values (June 1984)

Cell	Peds.	ADC Gain per p.e.	Mean #p.e. ($\beta = 1$)
1	51	11	11.6
2	67	13	7.2
3	77	29	10.0
4	53	28	9.9
5	57	30	10.2
6	49	27	7.7
7	49	23	10.4
8	50	26	7.5
9	74	29	11.8
10	67	32	13.0
11	51	27	8.3
12	67	23	14.8
13	37	23	12.6
14	37	33	14.1
15	43	23	16.9
16	35	28	12.6

3.2.2 Gain per Photo-electron

There are 2 ways this value can be obtained. The first is by use of the LEDs mounted inside INDRA. These are connected to a power supply, and the current to the LEDs is strobed to produce short duration bursts of lights. The intensity of the light can be adjusted by attenuating the supply current of the LEDs. It can also be altered by entering INDRA and placing filters in front of the LEDs. Data taking can then be triggered on the strobe and tapes containing only INDRA data obtained.

It is possible to extract from these tapes pulse height distributions which exhibit single, double and multiple p.e.

signals. The separation of such peaks can be judged by eye, and gives the p.e. gain. The width of these peaks is due to the finite resolution of the PM.

A more sophisticated approach is to fit the data with a function ($f(x)$) representing the convolution of the Poisson distribution weighted at each value of n by the PM resolution (a gaussian).

$$f(x) = N \sum_{n=1}^{\infty} P_n(n) \frac{1}{c} G(\sigma_n) \quad \text{Eqn 5}$$

where c = number of ADC counts per p.e., σ_n = PM resolution for n p.e., and N = number of events.

Using the approximation (RCA Photomultiplier Handbook) $\sigma_n = \sigma_1/\sqrt{n}$, and writing the Poisson and gaussian explicitly gives,

$$f(x) = N \sum_{n=1}^{\infty} \frac{e^{-\bar{n}} \bar{n}^n}{n!} \frac{e^{-\left[\frac{((x-x_p)/c - n)^2}{2\sigma_1^2 n}\right]}}{\sqrt{2\pi} c \sigma_1 \sqrt{n}} \quad \text{Eqn 6}$$

By fitting this function to the data the gain per p.e. can be obtained. Such a fitting procedure was written for NA14 by R.Barate, and has been run on the data. The results vary from cell to cell and period to period, but the typical gain is 25 → 30 ADC counts per p.e. (see table 7 for examples).

3.2.3 Mean Number of Photo-electrons per $\beta = 1$ Track

Using data taken with normal NA14 triggers and then processed through TRIDENT, it is possible to find tracks passing through INDRA mirrors. For such hits, and for each mirror in turn, scatterplots of ADC contents v. momentum (p) can be filled.

Examples are shown in figure 22, where the further constraints that the hit must be > 8 cm from a mirror edge is imposed (so that all light must lie in the one mirror), and that all other hits are greater than 8 cm away from the mirror. Several interesting features are evident in these plots. They are:

- a) The data seem to be pions with the π light threshold clearly visible. In some plots the K threshold is also visible.
- b) The π data rises with p to a roughly constant ADC value (p > 10 GeV/C) This value is clearly distinct from the pedestal.
- c) The mean momentum is lowest in cells near the left/right edges.

By requiring $10 < p < 19$ GeV/C, and a signal $>$ pedestal (say 13 counts $>$ pedestal) it is possible to find the light from $\beta \sim 1$ tracks. The resulting ADC distributions for several cells are shown in figure 23. The shape of these distributions is well described by a gaussian. Taking the mean of these distributions and dividing by the gain per p.e., gives the mean number of p.e. per track. For Jun. 1984 typical such values are given in table 7.

If no LED data was obtained for a particular period, the mean number of p.e., and indeed the gain per p.e., can still be extracted. This is achieved by fitting a gaussian to the the data in figure 23. The width of the gaussian (σ) can be related to n, the mean number of the gaussian distribution, by

$$\langle n \rangle = \left(2.36 \frac{(\text{mean} - \text{ped.})}{\text{FWHM}} \right)^2 \quad \text{Eqn 7}$$

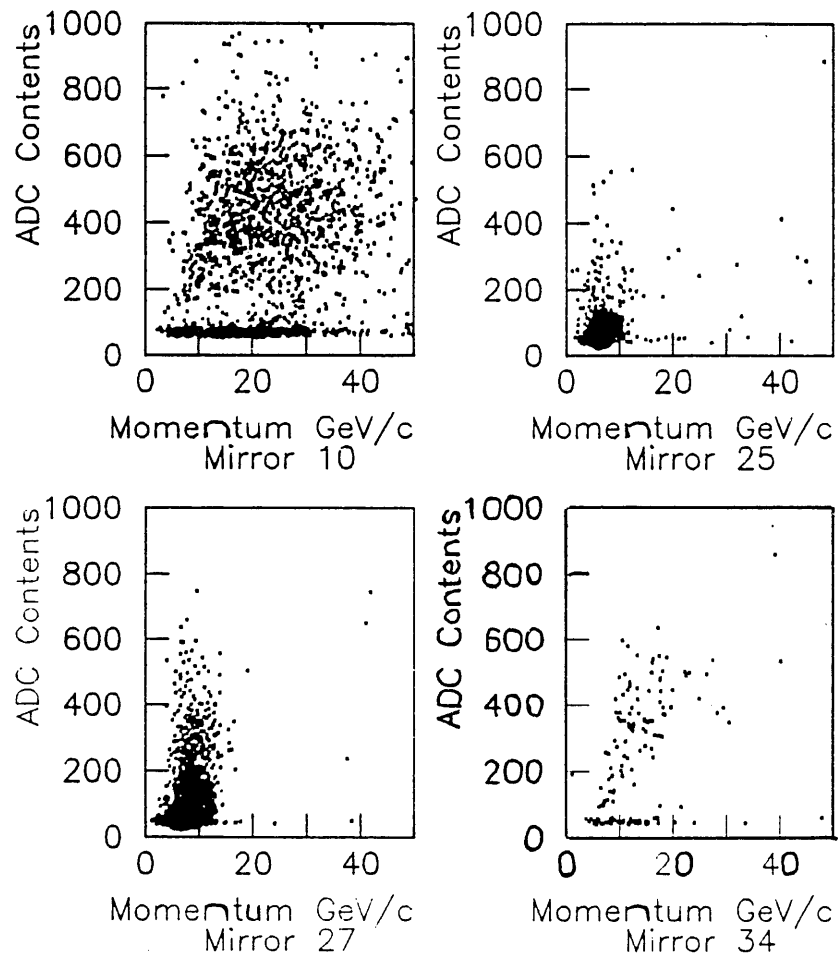


Figure 22: ADC v. Momentum

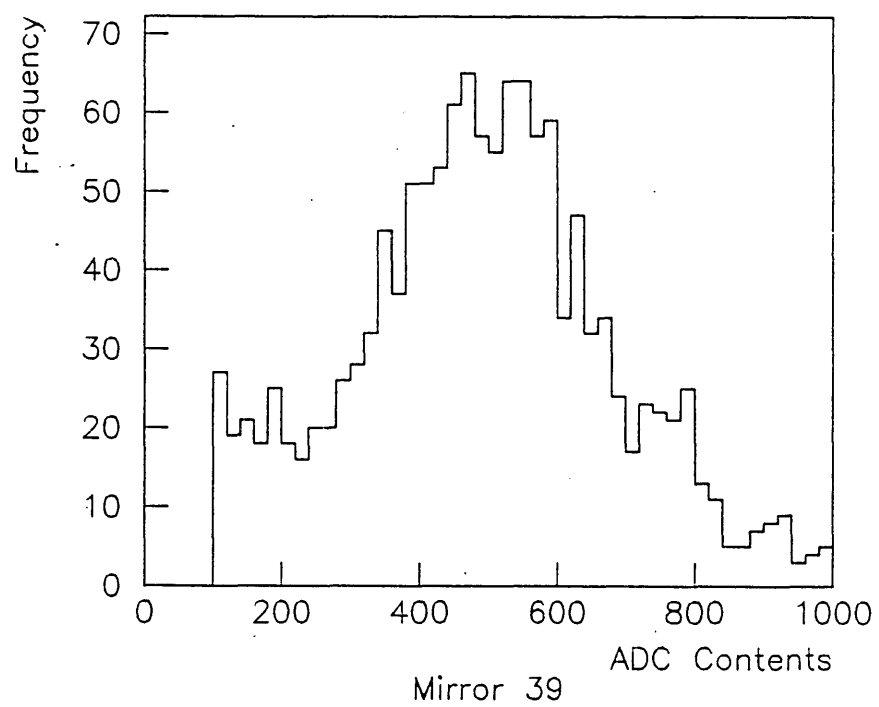
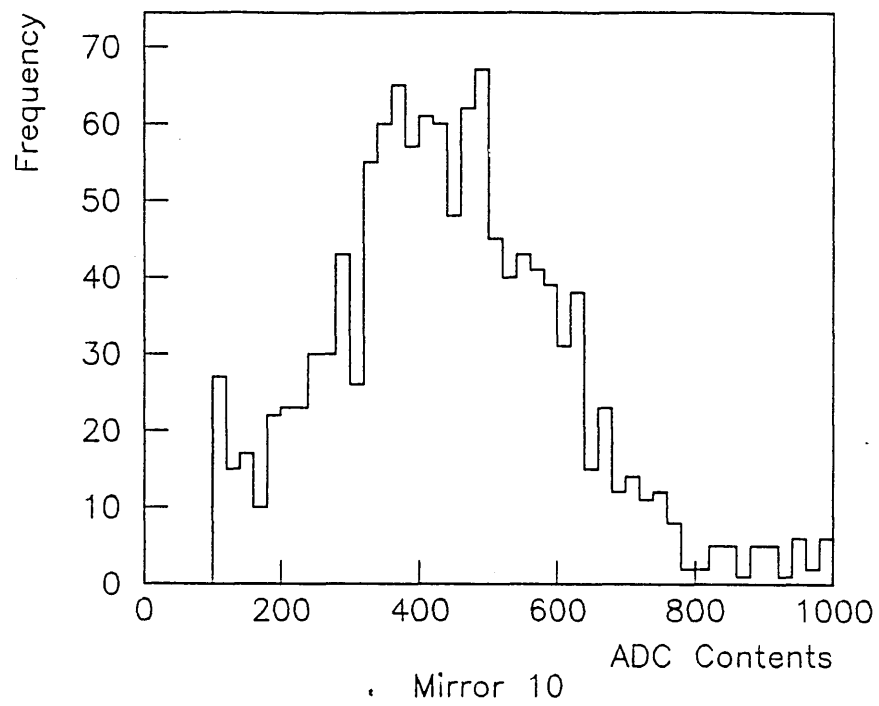


Figure 23: ADC Data For $\beta \sim 1$ Tracks

which is a simplification of eqn. 6 for large means. The result is the mean number of p.e., and this in turn yields the gain per p.e. . The method is checked by comparing results from the 2 methods inside a single period, and there is $\pm 20\%$ agreement between the 2 methods.

The second method however requires high momentum tracks in all cells, and this is difficult to achieve in the edge cells. Furthermore, to obtain a good gaussian distribution a large number of entries are required per cell, and this requires a large number of events (say 200k) to be processed through TRIDENT before INDRA calibration can be carried out.

3.3 SOFTWARE TOOLS

In order to use INDRA in data analysis, a set of routines is required to decode the ADCs, and carry out particle type determination. 2 methods of analysis have been tried; the first is a simple threshold analysis, the second is more complicated, and calculates the probability that a given particle type yields the observed light. As a first step, both methods obviously require reconstruction in space of charged tracks.

3.3.1 Threshold Analysis

This is the simplest method. Track impacts in the mirrors are found, and the appropriate ADCs are checked to see if they contain a signal. The definition of a light signal, was based upon a study of the pedestal shape combined with a knowledge of the gain per p.e., and is

$$\text{data} - \text{pedestal} > 13 \quad \Rightarrow \quad \text{light} \quad \text{Eqn 8}$$

This is equivalent to a cut at ~ 0.5 p.e. .

For each track hitting INDRA, several pieces of information are written into the track bank. These are ; the identity of the hit mirror, whether or not a signal is seen, the number of p.e. (if fully calibrated), and the number of ADC counts (pedestal subtracted). In the subsequent analysis of the event, the particle type can be found by comparing the light threshold momenta with the track's momentum, and considering whether or not light is seen. Clearly a 2nd Cerenkov (with different thresholds) would greatly assist in this.

3.3.2 Identification by Light Intensity

This method of particle type identification involves finding all the light coming from a track, and then calculating the probability of getting this amount from a given particle type of the same momentum. The particle types considered are electron, muon, pion, kaon and proton (e, μ, π, K, p).

Finding the total light yield from a particle is not simple. The ideal case is where even if $\beta \sim 1$ were true for all tracks in the event, all light from a given track goes into a single mirror without the possibility of light from any other track hitting that mirror. In this case all seen light in the mirror (if any) = all the light from the track. The complications arise when the qualifications in this criteria are not all met.

Accordingly a set of routines was prepared to assign light to tracks under non-perfect conditions.

The code is in 2 parts. The first part is a Monte Carlo (MC) simulation of the Cerenkov, which was adapted from a general purpose package prepared for a SLAC experiment and is described in [36]. The package requires the geometry of INDRA to be entered into the code. Then for each track the path and momentum must be known. A particular particle type is then assumed, and the angle θ of eqn. 4 found (if p is $>$ threshold). The path through INDRA is then divided into (10) equal steps and (10) rays are generated at equal intervals along each step. The rays have an opening angle θ , and are randomly distributed in the azimuth. The rays are traced to the mirror plane, reflected, and traced to the Winston cones and PMs. The % of generated rays hitting each PM is then found. This is done for each particle type above threshold.

The 2nd part of the code (prepared by myself) takes the reconstructed tracks and the observed light, and tries to divide the light amongst the tracks. The code was prepared assuming that all the calibration constants described above, are known for each cell. The main steps in the code are described below.

In an event, the charged track data set includes all those tracks passing through INDRA, and all ADC contents are converted into numbers of p.e. (which have been normalized so that the same track would give the same #p.e. in all cells). Once a track is associated with light, both the track and the light are

removed from the remaining processing of the event. This association is performed at levels of increasing complexity (see figure 24), and these are :

- a) Level 1. All tracks are assumed to be electrons and the resulting light cones projected to the mirror plane. A track's light cone may overlap any number of mirrors (or dead regions), and is level 1 if the cell the track passes through is dark (i.e. < 0.5 p.e. are seen). The result is that no light is associated with the track.
- b) Level 2. Assuming all tracks are electrons, all of a track's light cone must lie in just 1 cell, and no other light cone can overlap the cell. In this case, all light seen in the cell is associated with the track
- c) Level 3. Again all tracks are assumed to be electrons, and the light cones projected to the mirrors. This time the cone from a track can overlap > 1 mirror, but the hit itself must lie in a mirror not overlapped by any other track's light cone. For each hypothesis of particle type, the MC is used to predict what fraction of light goes into the hit mirror. The results are then used to scale the cell contents to get the total light yield from each particle type. If a particle type is below threshold, the scaling constant = 1.0 .
- d) Level 4. The level 4 hit is marked b) in the appropriate diagram in figure 24. As can be seen there are hits a) in neighbouring mirrors. The electron light cone(s) of hit(s)

- a) extend into the mirror containing b), but not vice-versa. The neighbouring hit(s) a), must have already been treated and a favoured hypothesis of particle type formed (this is described later). The amount of light hits a) contribute to the mirror containing b), is subtracted from the mirrors contents, and the remainder is attributed to b).
- e) Levels 5 & 6. These levels are similar in that they both lie in a mirror containing > 1 hit. In figure 24, hit a) is level 5 and b) is level 6. Hit c) is any previously treated hit. Level 5 is where the light cone for each hypothesis extends into a cell empty of light from any other hit (treated or untreated). The MC is used to predict the fraction of light expected in this cell and the observed light is scaled to give the total expected from that particle type. For level 6 the mirror overlapped contains part of the light cone from the favoured hypothesis for a treated track (or tracks), and the light content of this cell has been adjusted accordingly. The light from the level 6 track is then found as for level 5. If a track has a light cone which extends into > 1 mirror neighbouring the hit mirror, it is treated as level 5, rather than level 6, provided the requisite mirror contains $> 15\%$ of the predicted light.
- f) Level 7. Here the hit in the mirror plane does not lie in any mirror, but it is possible for the light cone to

extend into a mirror. The overlapped mirror may have to have its contents corrected for contributions from other tracks.

Per event, levels 1 $\rightarrow$ 3 are passed through once, and levels 4 $\rightarrow$ 7 are looped over until no more tracks were treated on the last pass. Of course, processing stops whenever all tracks have been treated.

Once a track has a light signal associated, it is possible to find the probability of the observed signal coming from a given particle type. This is calculated for each particle type and the resulting probabilities compared. If a track is below threshold for a given identity, and no light is seen, then the probability is 100%. If a track is above threshold, the expected light yield has to be predicted. For a track passing through a radiating medium of length L , the number of photons produced is $AL\sin^2\theta$ (θ as in eqn 4, A = a constant which includes such effects as light collection and photo-cathode efficiency). If photo-electrons are taken as the measure of light yield instead of photons, then the mean number of p.e for a $\beta = 1$ track can be used to find AL for each cell. Thus for a particle of momentum p and given type, the most likely expected number of p.e. can be found. Assuming that the observed number is distributed with Poisson statistics around the expected value, the probability of getting the observed light yield from a given particle type can be found.

For each track, once a table of probabilities has been found, a favoured hypothesis can be formed. The probabilities

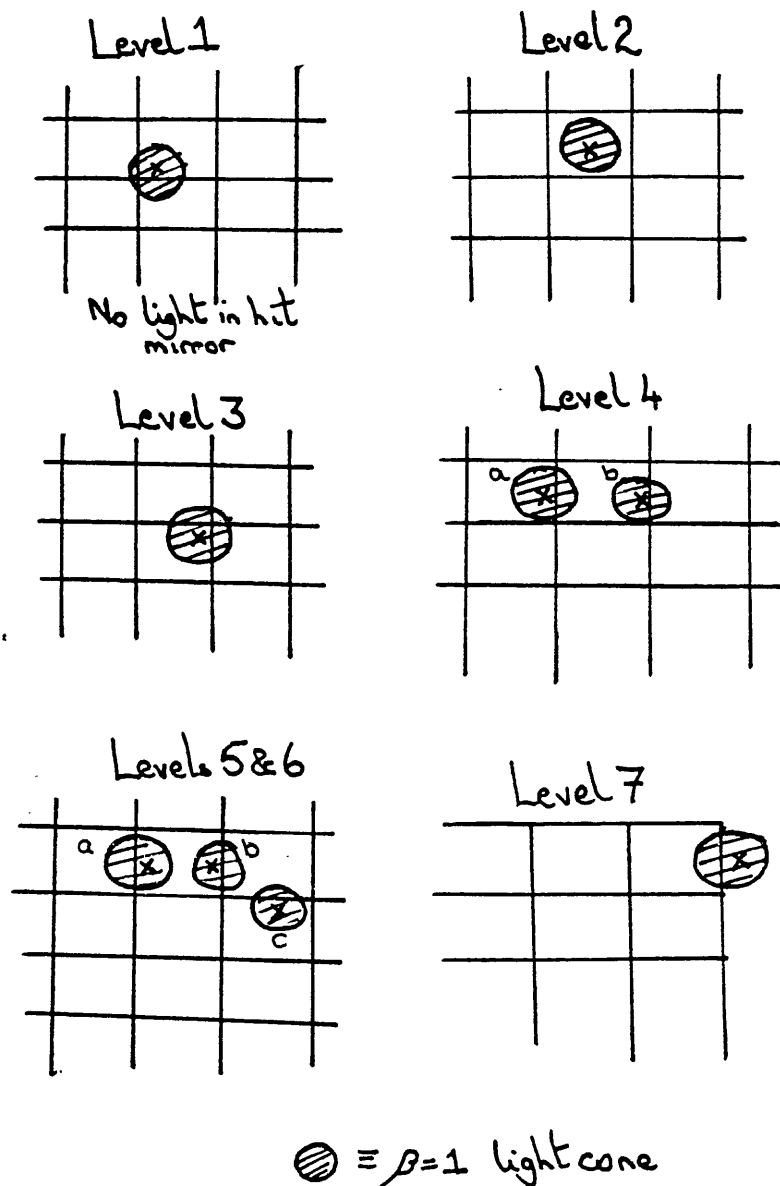


Figure 24: Levels Of Complexity In Finding All A Track's Light

themselves cannot be directly compared as the particle types are not equally probable. Thus when comparing probabilities, weights reflecting the relative expected yields are required. This can be improved if the e.m. calorimeters or the muon filter are used to flag electrons and muons.

3.4 PERFORMANCE OF INDRA WITH REAL DATA

Before undertaking a full analysis of real data, INDRA's performance was checked on individual and specially selected events. The latter events were selected so as to contain electrons identified by the e.m. calorimeters (Olga and Ilsa). A momentum cut of 2 GeV/c was placed upon the electrons, and the requirement that no other track in the event hit the same mirror or hit a neighbour within 8cm of the edges of the first mirror, was imposed upon the events. The surviving electrons were divided into 2 samples; a) all electrons, b) electrons hitting a mirror $> 8\text{cm}$ from its nearest edge (i.e. whole base of light cone lies in the mirror).

The fraction of hits per mirror in each sample giving light signals, was then found. Since the electrons are fully relativistic all are expected to give light, and the fractions are thus a measure of the Cerenkov's efficiency. For the 12 leftmost, and the 12 rightmost mirrors the fractions are; a) 0.971 ± 0.008 , b) 0.965 ± 0.008 . For the remaining 24 central mirrors the fractions are; a) 0.985 ± 0.003 , b) 0.986 ± 0.003 .

The lack of a significant difference between samples a) and b), indicates that the position of a hit in a mirror does not affect the efficiency of the response. The difference between the left/right edge mirrors and those in the centre, is not readily explicable but may reflect the different size and orientation of these mirrors.

Randomly selected events can be used to illustrate the performance of the software written for INDRA. A typical event is shown in figure 25, where the diagram shows the ADC contents - pedestal for each mirror, the mirror layout being as in figure 19.

In the threshold mode the particle identification is simply:

Track 1. e, μ, π or K

Track 2. K or p

Track 3. e, μ or π

Track 4. e, μ or π

Track 5. e, μ, π or K

In the probability analysis the interpretation would be:

Track 1. e, μ or π . The K hypothesis can be discarded.

Track 2. A K or a p would give the observed signal 100% of the time, but a π would also give the signal 40% of the time so can not be discounted.

Track 3. The e hypothesis is much less probable than that of μ or π , with π as the favoured choice.

Track 4. e, μ or π

Track 5. e , μ or π are the most plausible interpretations. The K hypothesis can be discarded.

If the calorimeters and muon filters are then used to explore the e and μ possibilities, the choice of particle types arising from the 2 analysis methods is as in table 8, clearly showing the advantages of the probability analysis.

TABLE 8		
Particle Type Choice From INDANL Analysis		
Track	Threshold	Probability
1	π, K	π
2	K, p	π, K, p
3	π	π
4	π	π
5	π, K	π

The final check to see if INDRA is functioning correctly, is to see in real data the various particle type light threshold momenta. Of course figure 22 shows some evidence of this, but much clearer evidence is obtained by plotting, as a function of momentum, the percentage of tracks giving no light (figure 26). Here the pion, kaon and proton thresholds can clearly be seen.

That INDRA is an efficient and reliable device for observing light signals from relativistic charged tracks is clearly established. However, there is a clear need for another Cerenkov with different light thresholds for unambiguous particle type determination.

4	1	0	0	0	0	-1	0	1	0	0	1
1	-1	1	0	242	185	0	241	0	0	0	0
2	-1	-1	-1	-1	0	6	469	43	119	39	0
1	1	0	0	0	2	2	0	1	1	-1	0

ADC CONTENTS

THRESHOLD ANALYSIS

TRACK 1 HIT MIRROR 33 LIGHT SEEN
 TRACK 2 HIT MIRROR 2 NO LIGHT
 TRACK 3 HIT MIRROR 29 LIGHT SEEN
 TRACK 4 HIT MIRROR 16 LIGHT SEEN
 TRACK 5 HIT MIRROR 12 LIGHT SEEN

PROBABILITY ANALYSIS

TRACK 1 Momentum = 23.5 GeV/c Level 2 #p.e. = 13.8
 predicted #p.e. $\begin{matrix} e \\ \mu \\ \pi \\ K \\ p \end{matrix}$ 13.7 13.2 12.9 3.6 0.0
 probability 0.1 0.10 0.10 0.17E-4 0.0

TRACK 2 Momentum = 5.8 GeV/c Level 1 #p.e. = 0.0
 predicted #p.e. $\begin{matrix} e \\ \mu \\ \pi \\ K \\ p \end{matrix}$ 12.6 5.9 0.9 0.0 0.0
 probability 0.33E-5 0.28E-2 0.40 1.0 1.0

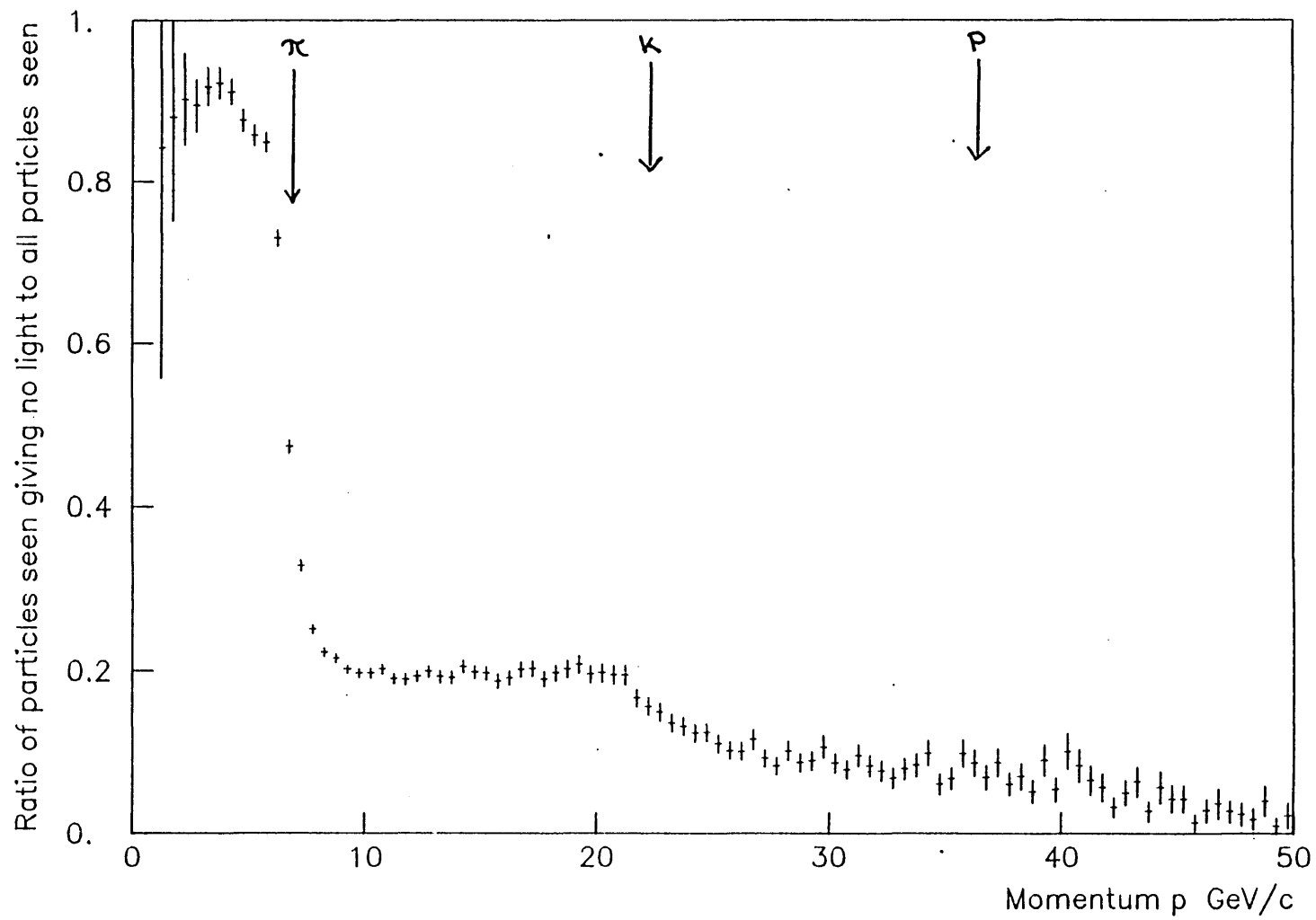
TRACK 3 Momentum = 10.4 GeV/c Level 3 #p.e. = 4.7
 predicted #p.e. $\begin{matrix} e \\ \mu \\ \pi \\ K \\ p \end{matrix}$ 8.7 7.3 5.4 0.0 0.0
 probability 0.07 0.12 0.17 0.0 0.0

TRACK 4 Momentum = 18.6 GeV/c Level 2 #p.e. = 8.6
 predicted #p.e. $\begin{matrix} e \\ \mu \\ \pi \\ K \\ p \end{matrix}$ 12.9 12.2 11.7 0.0 0.0
 probability 0.07 0.08 0.09 0.0 0.0

TRACK 5 Momentum = 25.5 GeV/c Level 3 #p.e. = 6.8
 predicted #p.e. $\begin{matrix} e \\ \mu \\ \pi \\ K \\ p \end{matrix}$ 9.8 9.2 7.8 3.9 0.0
 probability 0.1 0.11 0.14 0.05 0.0

Figure 25: An Event Seen In INDRA

Figure 26: % Of Tracks With No Light v. Momentum



Chapter IV

CHARGED PARTICLE PRODUCTION AT LARGE TRANSVERSE MOMENTUM

During early data taking in NA14, emphasis was placed upon the neutral particle triggers in order to study inclusive π^0 and γ production at large transverse momentum. However data were also taken with the charged high pt. trigger (described in Chapter 2 Section 6.3), with a view to studying inclusive charged pion production in both γ and π^- beams. As a preliminary to this work [8] a study was made, using the INDRA Cerenkov, of the identity of the charged particles giving the triggers.

4.1 THE DATA

During August 1983 ~1 million charged high pt. triggers were taken in γ beam, with a further 200k triggers using the 90 GeV π^- beam. Before the charged track reconstruction program (TRIDENT) was run on the events, a filter was run which checked that the trigger in an event did indeed come from a track with high pt, and not from a low pt. track and random coincidences. This filter checked the wire chambers in Stack 2, in order to reconstruct a track passing through the trigger hits. This requirement removed 2/3 of the events from the analysis. The remaining events were then passed through TRIDENT and a cut imposed requiring that the trigger track be a well reconstructed track originating from the target.

The result of all of these cuts was to leave 11.8k γ beam events for analysis, and 4.2k π^- beam events; each event containing a well-identified high pt. track (pt. ≥ 1.1 GeV/c).

As described at the beginning of Chapter 3, there are 3 main ways of identifying charged particle types in NA14. These are ; using the Cerenkov, associating charged tracks with hits in the em calorimeters (to flag electrons), and using the muon filter. Unfortunately the muon filter was not operational during charged high pt. data taking, so no muon identification was possible. For the electron filter, since the trigger involved the Olga charged vetoes, the Olga shower finding package (SNARK) was run on the events. The threshold version of INDANL (the INDRA software package) was also run on the events, yielding for each track in an event; the identity of the hit mirror (if any), and whether or not any light was seen in that mirror.

A DST was then prepared, which, per event, contained details of; all vertices, all charged tracks, all Olga showers, and the INDRA results. All subsequent analysis was performed upon the DST.

4.2 ANALYSIS

Before finding the various particle type samples, a set of cuts was imposed upon the charged tracks. These confirm that an event vertex was reconstructed in the target; that the fractional error in a tracks momentum is $< 15\%$, and that tracks are not used if the mirror intersected by the track in question is intersected by

another track. A check is then made to reject electrons by finding tracks with calorimeter showers such that energy (OLGA) / momentum (TRIDENT) ~ 1.0 . For $pt. > 1.2$ GeV/c, 0.20% of tracks in γ beam are so flagged, with 0.24% in π^- beam.

Particle type assignments are then made using the Cerenkov information. Referring to the light threshold momenta of table 5, I define particle types as follows:

$10 < p < 20$ GeV/c + light $\Rightarrow \pi$

$10 < p < 20$ GeV/c + no light $\Rightarrow K$ or proton

$25 < p < 35$ GeV/c + light $\Rightarrow \pi$ or K

$25 < p < 35$ GeV/c + no light $\Rightarrow$ proton

As stated in Chapter 3, INDRA has an efficiency of $< 100\%$ for responding to light from a highly relativistic track. For the region covering Olga this was found to be 98.6%. Looking at tracks with momentum > 40 GeV/c and which pass through INDRA without giving a light signal, gives an efficiency of $(97.5 \pm 0.6)\%$, in reasonably good agreement with the previously measured value. The value of 98.6% is used to adjust the samples of light & no-light data in a given momentum range, in order to allow for contamination of one sample by the other.

The resulting numbers of π , $K + p$, $\pi + K$ and p , are listed in table 9 for γ beam and in table 10 for π^- beam, as a function of $pt.$ and charge. The low numbers which appear in the low momentum values, reflect the fact that the high $pt.$ trigger has also required a high $pl.$ for the trigger tracks ($pl. \sim 15 \cdot pt.$).

TABLE 9

Charged Track Types Seen By INDRA (γ beam)

Pt. (GeV/c)	π	+ve charge		p
		(K + p)	(π + K)	
1.2 $\rightarrow$ 1.9	300	189	910	128
1.9 $\rightarrow$ 2.6	229	110	1015	123

Pt. (GeV/c)	π	-ve charge		p
		(K + p)	(π + K)	
1.2 $\rightarrow$ 1.9	216	71	949	65
1.9 $\rightarrow$ 2.6	172	29	962	50

TABLE 10

Charged Track Types Seen By INDRA (π^- beam)

Pt. (GeV/c)	π	+ve charge		p
		(K + p)	(π + K)	
1.2 $\rightarrow$ 1.9	164	107	180	53
1.9 $\rightarrow$ 2.6	59	45	246	83

Pt. (GeV/c)	π	-ve charge		p
		(K + p)	(π + K)	
1.2 $\rightarrow$ 1.9	149	50	331	29
1.9 $\rightarrow$ 2.6	47	8	414	38

Due to the use of only one cerenkov, the pions at low momentum, and the protons at large momentum are the only well

identified particle samples. However if one makes the assumption that the proton contribution to the total charged track sample is constant over the momentum range $10 \rightarrow 20$ GeV/c, as it is over the range $25 \rightarrow 35$ GeV/c, then the $(p + K)$ sample can be subdivided into the p and K contributions. Using the resulting π , K and p samples, the particle/anti-particle ratios can be found, as can the K/π and p/π ratios. These are shown for both beams in figures 27, 28 and 29. Also shown in each figure is the ratio of ratios between the 2 beams. No acceptances were used in finding these ratios, as by taking limited p and p_t ranges, unless the cross-section for one process relative to another varies rapidly over the kinematic region, then the acceptances are the same and thus cancel.

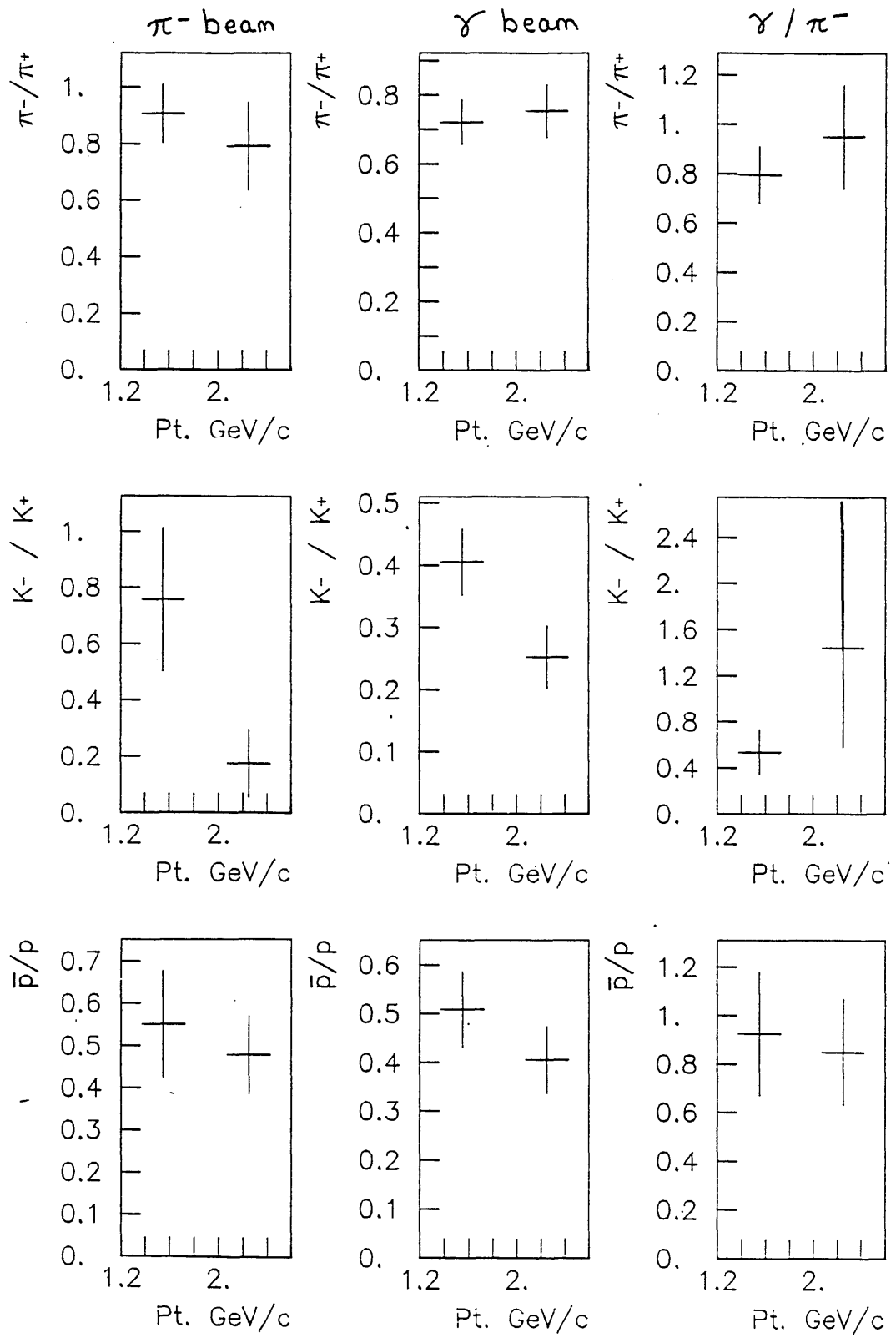


Figure 27: Anti-particle / Particle Ratios

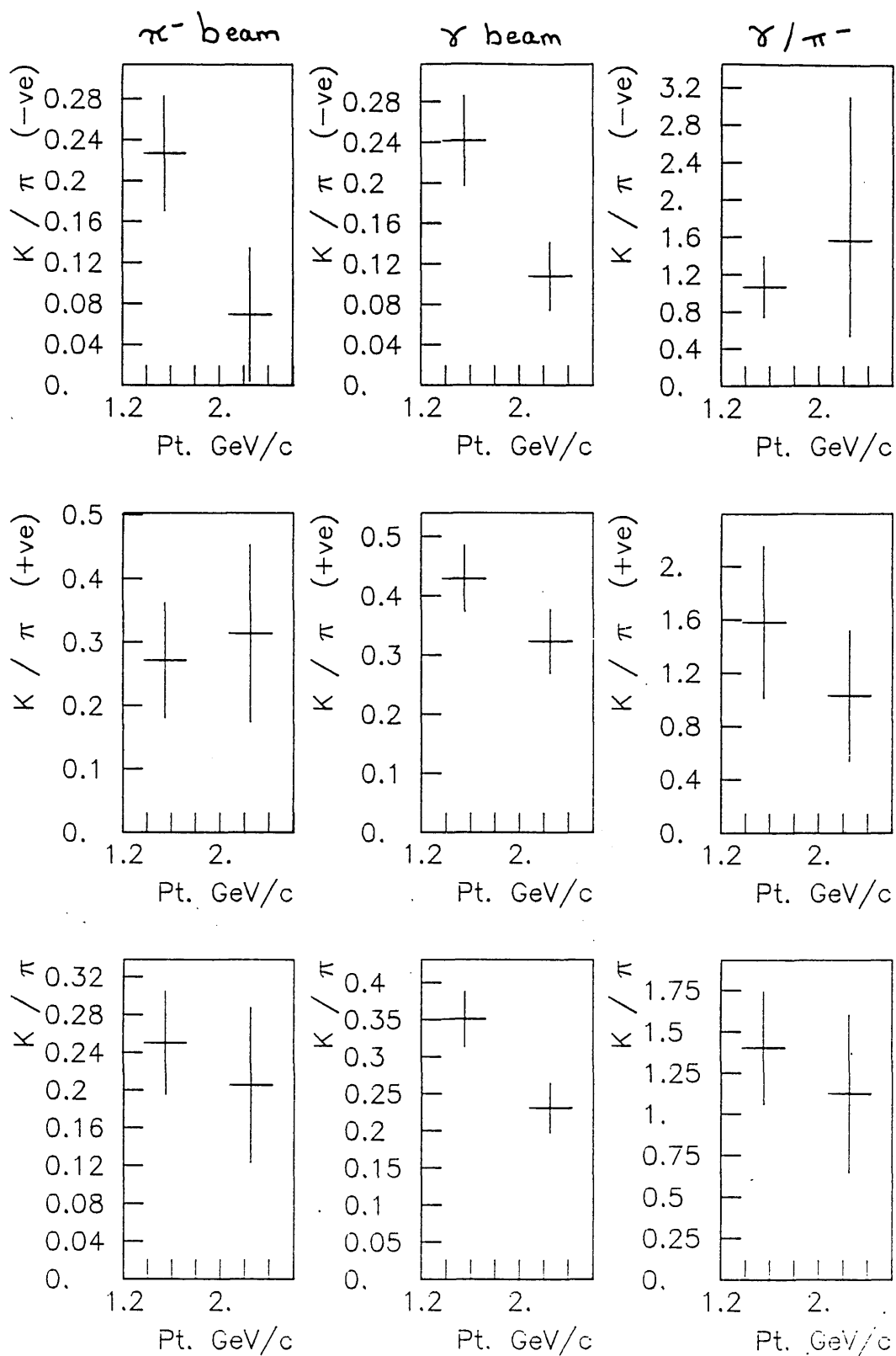


Figure 28: K/π Ratios

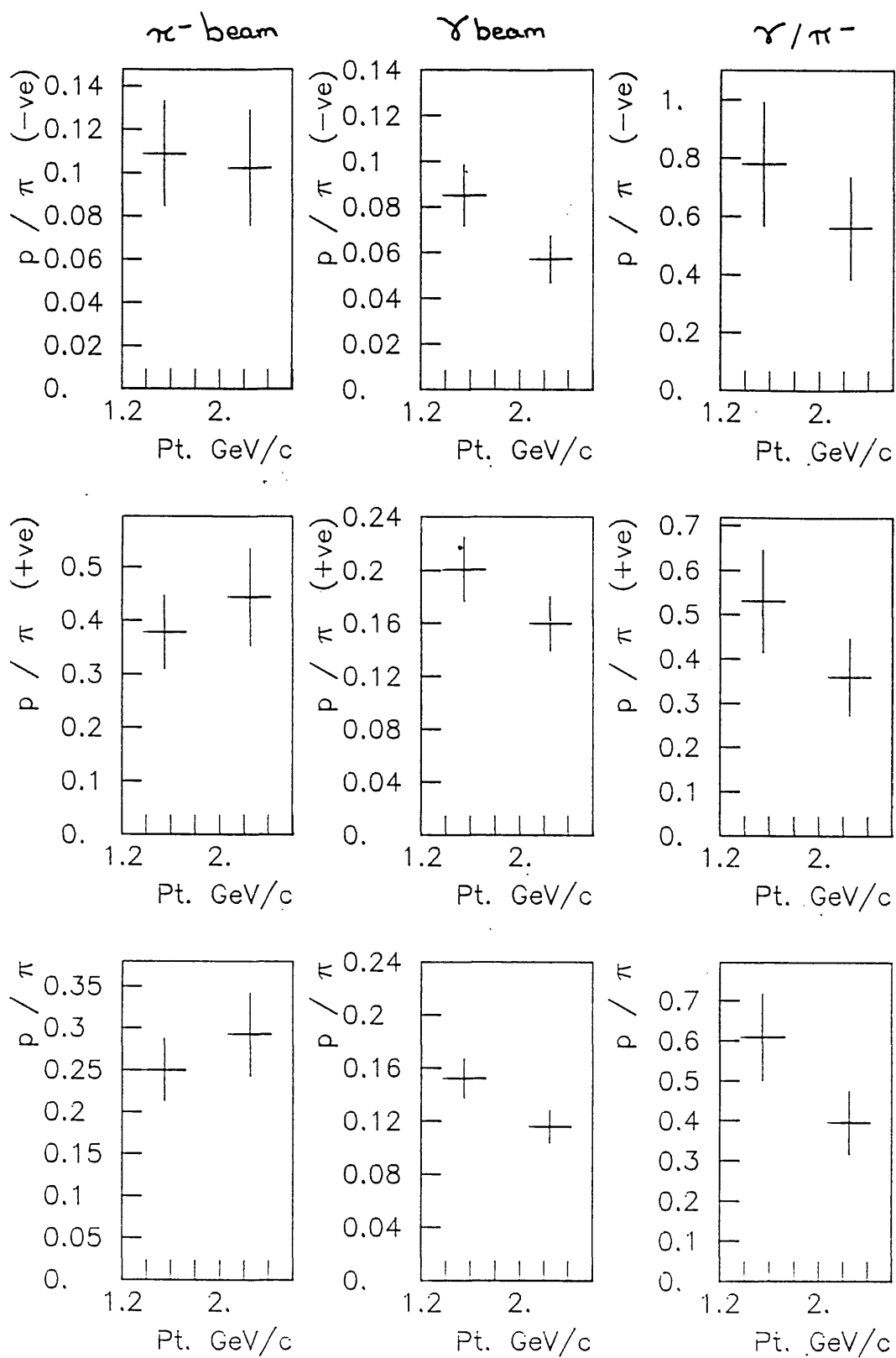


Figure 29: p/π Ratios

4.3 OBSERVATIONS ON THE RESULTS

A study of various charged particle production ratios in π^- beam has been carried out by Frisch et al [37] at beam energies of 200 and 300 GeV. A similar study in γ beam, at a beam energy of 18 GeV is reported by Boyarski et al in [38]. These results, albeit at different beam energies and over different momentum ranges can be referred to when studying the above results.

- a) π^- / π^+ . There is a striking result here in that in both beams this is < 1 . This agrees with Boyarski's γ beam result, but contradicts the result of Frisch, where the ratio is $\sim 1.12 \pm 0.04$. In π^- beam interactions it would not be surprising to see more π^- than π^+ , but this is clearly not the case here. The beam to beam ratio seems to be just below 1, which would be consistent with relatively more π^- production in π^- beam than in γ .
- b) K^- / K^+ . The results here seem to indicate a similar fall with increasing p_t in both beams. However there is relatively more K^- production in π^- beam than there is in γ , presumably reflecting the common valence u anti-quark on the K^- and π^- . That there are more positive than negative K's may well reflect the well known charge asymmetry involved with associated lambda production.
- c) $\bar{p} / p$. This is roughly equal in both beams at $0.4 \rightarrow 0.5$, in agreement with previous work.
- d) K / π . The valence quarks of the π^- can appear in neither of the K^+ or the π^+ . They both contain a u quark

however, so their relative production may well reflect the probabilities of obtaining s and d quark pairs from the vacuum. Similar behaviour need not be expected in both beams as the γ could couple to a $s\bar{s}$ quark pair introducing extra strangeness. The results do indeed show a slightly larger value of this ratio in the γ beam. For the negatively charged kaons and pions, the situation changes as in π^- beam π^- production can obviously be expected to be preferred. The K^- also has a valence quark in common with the π^- so its production may also be enhanced in π^- beam. The results are however similar in both beams, showing a sharp fall with increasing p_t .

- e) p / π . This ratio is clearly lower in γ beam than π^- . The π^- beam result agrees well with Frisch, but the γ values are twice those of Boyarski.

4.4 CONCLUSIONS

The use of only one Cerenkov counter, and the effect of the trigger in selecting high momentum tracks unfortunately adversely affects this analysis, limiting it in both momentum range and accuracy. However, in the momentum range $10 \rightarrow 20$ GeV/c, the identification of the pion content of the charged particles coming from beam-target interactions is clearly demonstrated.

The interpretation of the anti-particle/particle ratios, and the ratios of different particle types, in terms of a naive model

of π^- valence quarks with a more democratic quark content of the photon, is fairly successful. The one apparant failure being the π^-/π^+ ratio in π^- beam. This result is also not as seen in the Frisch experiment (although that was at higher beam energy and over a wider range of pion momentum). There is no apparent experimental feature to bias the data towards a certain charge sign, so the result is not explained.

Chapter V

MEASUREMENT OF η/π^0 RATIO

5.1 INTRODUCTION

Using gammas reconstructed in the calorimeters, it is possible to search for mesons produced by beam-target interactions, which decay to gammas. Chief amongst these are the π^0 (99% branching ratio to 2 γ s), and the η (39% branching ratio to 2 γ s [15]). These mesons are seen by forming $\gamma\gamma$ invariant mass plots and looking for bumps/signals. It is possible to extract strong π^0 and η signals from our data, and this Chapter describes analysis based upon π^0 and η reconstructed from γ s found in the Olga calorimeter. The aim of the work is to derive a measure of the ratio of π^0 and η production. The use of NA14s facility for providing both γ and π^- beams, permits a comparison of the production ratio in photo- and hadro- production.

The data used in this work were obtained with the high pt. neutral trigger (see Chapter 2 Section 6.2) in Olga. When analysed the data are presented as a function of pt. A second method is to present the data as seen in various Feynman x_t regions. This is possible due to the facility for tagging the beam energy as described in section 2.7.3 .

In order to correct for non-uniform acceptance I have prepared a Monte Carlo simulation of particle production and observation.

An analysis of this permits me to infer from observed to produced quantities in the real data.

5.2 RAW DATA AND ITS PROCESSING

As already stated, events observed in both γ and π^- beams are used in this work. The events were taken during running in 1983. All events used triggered the Olga calorimeter, which was set with a nominal 900 MeV/c trigger pt. The γ beam energy was as given in figure 13, and the π^- beam energy was 90 GeV (see Chapter 2 Section 2.2).

The gamma beam data set contains 356,000 events (out of a total of 1.2 million such Olga triggers recorded in 1982/1983).

In π^- beam 256,000 events were recorded, all of which were used in this analysis.

All these events were copied from the central library of NA14 data tapes maintained at CERN, and then transported to Imperial College. All the computing for this work was performed on a IBM 4341 at Imperial College.

5.2.1 Neutral Particle Identification

The Olga particle reconstruction program, SNARK, is described in Chapter 2 Section 7.2. All 606,000 raw events were processed through it. The output for each event contained the original event + a kinematic bank. Each identified hit in Olga is flagged as a gamma/electron or hadron, by its shower profile. The requirement is that a minimum energy (500 MeV) in a shower

should be deposited in the Sampler. Hadrons in general fail to meet this requirement. The gamma/electron showers are found by matching hits in both projections of Penelope, with energy in the Sampler and the lead glass wall. The electrons and gammas are then distinguished by examination of the output from the veto counters upstream of the Sampler.

For the reasons described in Chapter 2 Section 2.4.5.3, the 2 γ s from π^0 decay are often so close together at Olga that their showers merge in the lead glass blocks. However, some π^0 s and all η s yield pairs of γ s whose showers in Olga are completely separate. Thus the SNARK kinematics bank contains both single gammas and gammas in pairs (merged into 1 cluster); for the latter the entry is as for a single neutral particle, whose energy equals the total energy of the cluster. A sub-gamma bank is then created, which for each merged pair contains the computed energy and momentum components for each of the (assumed) 2 gammas. These sub-energies etc. are calculated using the position information from Penelope (which is of a much greater resolution than the lead glass wall) and an energy sharing algorithm based upon a shower model as described in [33].

Using the information in these kinematic banks, $\gamma\gamma$ invariant mass combinations can be found using all single gammas in each event, and also between the subgammas in a cluster. The average number of single or merged showers per event is ~ 5 . (This value is similar in each beam). Figure 30 shows the $\gamma\gamma$ invariant mass distribution for all single gammas in events, and

figure 31 shows the same for all merged clusters. Clear π^0 signals can be seen in these plots, and it is possible to discern an η signal in the plot for pairs of single γ s.

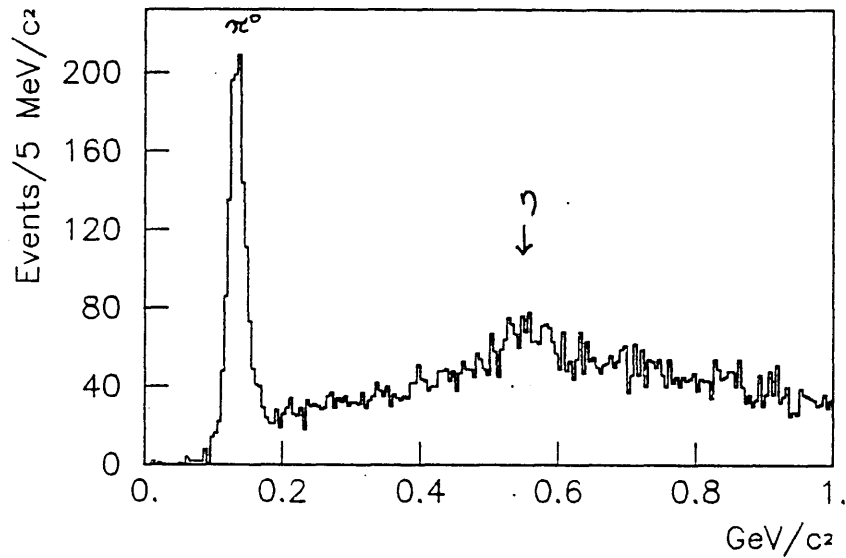


Figure 30: $\gamma\gamma$ Invariant Mass Using All Single γ s

Here I introduce a piece of terminology; π^0 reconstructed from 2 single γ s, are called $\pi^0(s)$, and those seen as merged clusters are called $\pi^0(m)$.

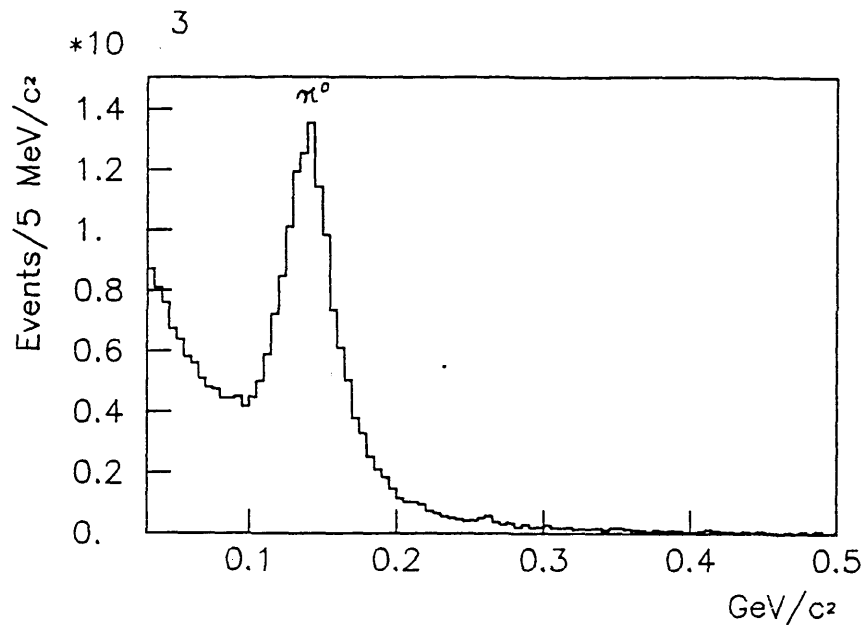


Figure 31: $\gamma\gamma$ Invariant Mass For Merged Clusters

5.2.2 Beam Energy

In order to look at the data in terms of Feynman's x_L variable, (the fraction of available centre of mass longitudinal momentum carried by the particle, $x_L = p_L / (2\sqrt{s})$ where $s = \text{cm energy}^2$), it is necessary to know the energy of the beam particle as well as the longitudinal momentum component of the observed particle. The beam particle energies were obtained by running the analysis program TAGANL (described in Chapter 2). Because the tagging required an average of 4 seconds computing time per event, not all events were tagged. The decision as to which events to tag was made as follows :

- a) Gamma beam. It was decided early on in the analysis to require a minimum neutral pt. per event of 1.2 GeV/c. Therefore all reconstructed events with a neutral pt. of > 1.1 GeV/c were filtered off for tagging. There were 65,000 such events. It is these events which give the tagging characteristics quoted in Chapter 2.
- b) π^- beam. The energy spectrum shown in figure 14 was obtained from some of the 256,000 events. It is clear that the beam energy is well defined as 87 ± 5 GeV. Another early decision of the analysis was that the x_1 bins into which the data would be placed would have a width of 0.2. Clearly using $E(\pi^-) = 87$ GeV would not greatly affect the x_1 distribution given such (relatively) coarse binning. The x_1 distributions of the $\pi^0(s)$, $\pi^0(m)$ and η candidates seen in the mass plots for π^- beam are shown in figure 32.

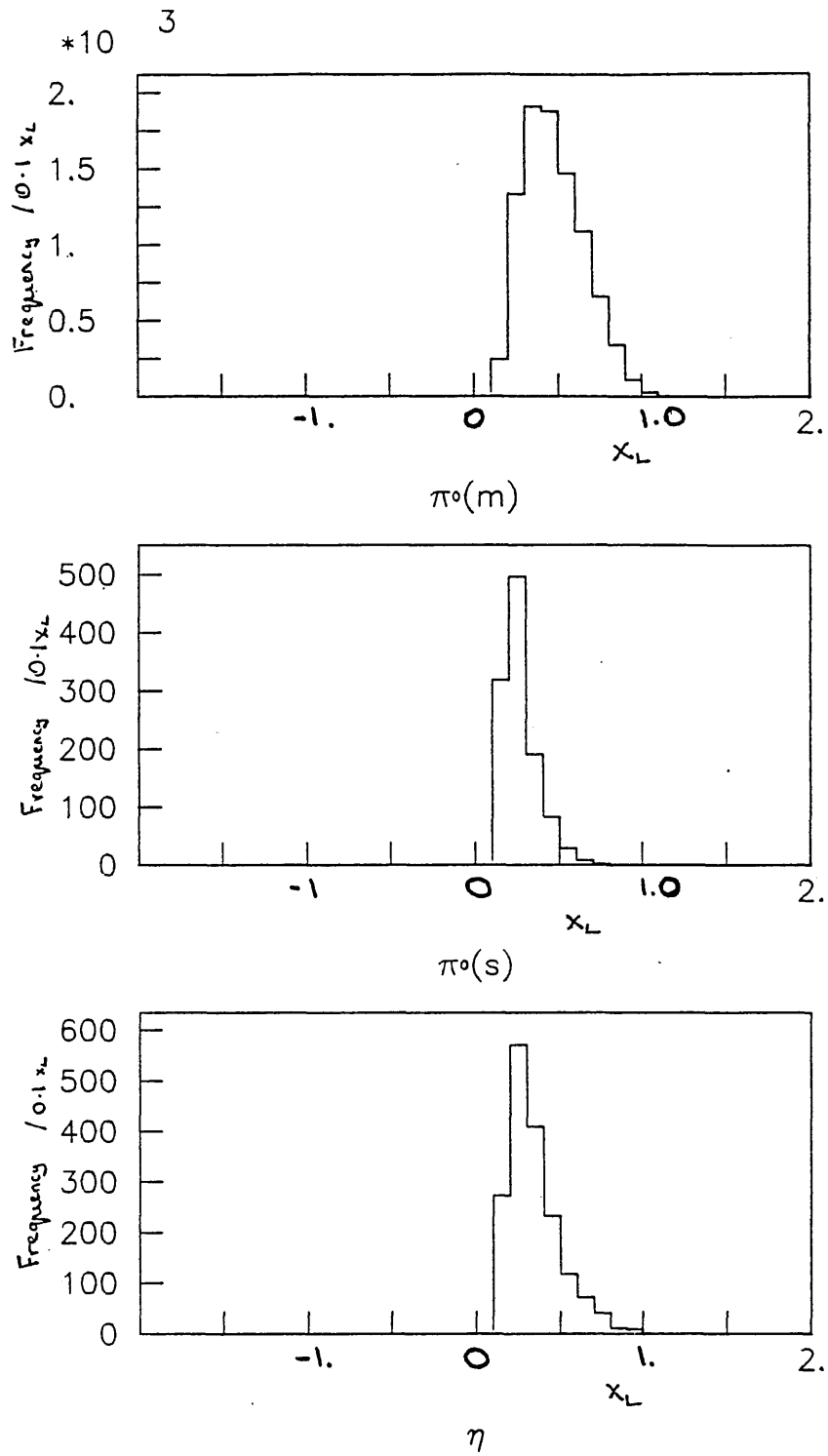


Figure 32: Feynman x_L Distributions In π^- Beam

5.2.3 Data Summary Tapes (DSTs)

After running SNARK and TAGANL on the relevant events, no further processing of the raw data was required. Therefore a DST format was prepared, which dropped the raw data per event, and kept the relevant parts of the kinematic and tagging banks.

All subsequent analysis was performed upon the DSTs.

5.3 ANALYSIS

Once the DSTs were prepared the analysis of the data was fairly straightforward. The aim was to count the numbers of π^0 and η seen in various kinematic regions with minimal cuts. These conditions would then be reproduced in a MC simulation.

5.3.1 Cuts on Data

Although the data taking trigger is ostensibly at 900 MeV/c pt., it is not a step function at this pt. Much work on data in Olga has already been carried out, and estimates of the trigger efficiency are given in [33] and [39]. Plotted v. pt., the trigger efficiencies for $\pi^0(\eta)$ and single γ s are shown in figure 33 as solid curves. These estimates of trigger efficiency were made for use with data of pt. > 1.5 GeV/c, and thus at lower pt are not as accurate. As described later I make a more accurate estimate of the π^0 trigger efficiency at low pt, and this is shown in figure 33 as a broken line. Because the trigger is formed from energy deposited in Olga's lead glass blocks the efficiency differs for merged clusters and single showers. A

further component of the trigger is the requirement of energy in the Sampler, and, due to the poor resolution of this device, both gammas from a merged cluster often pass through the same element in the Sampler, thus contributing to a different trigger efficiency for π^0 (m) and single γ 's of equal pt. .

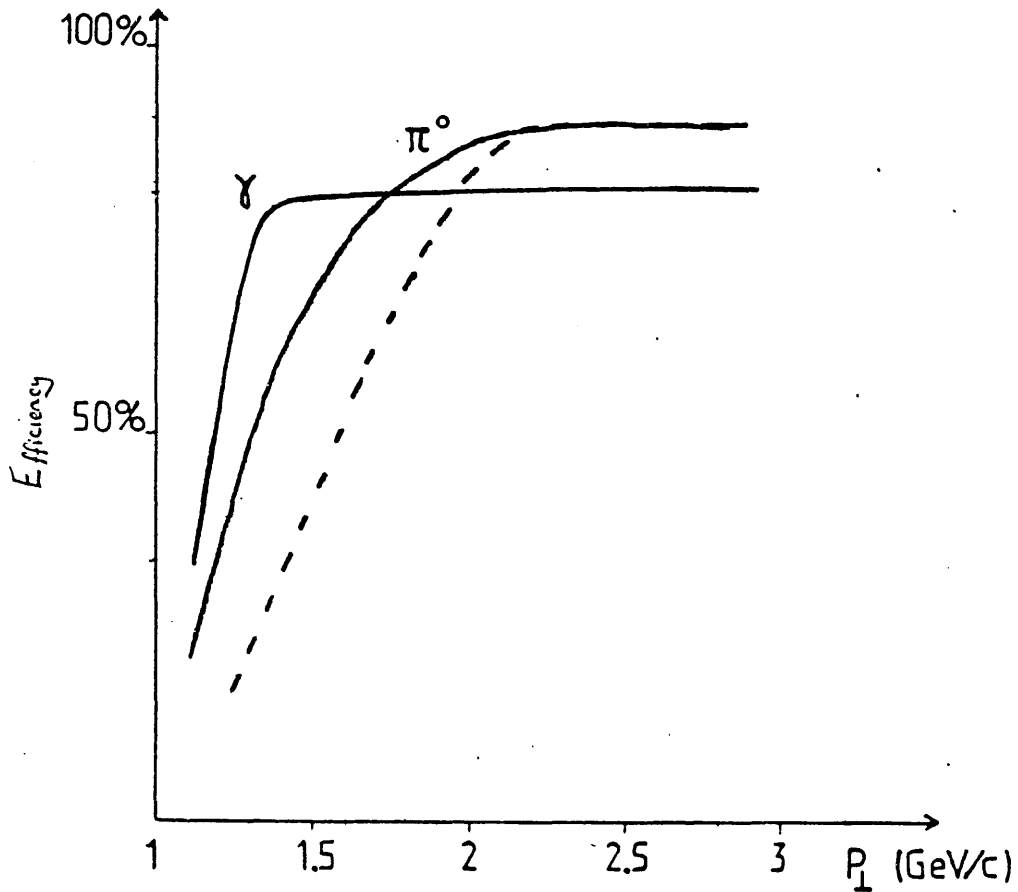


Figure 33: Estimate Of Trigger Efficiency

As can be seen from figure 33, the trigger efficiencies do not rise to a significant value (i.e. $\geq 50\%$) until pt. ≈ 1.2 GeV/c. Therefore this was chosen as a minimum pt. cut in the analysis; that is, in an event there had to be either a 1.2 GeV/c pt. single γ , or a 1.2 GeV/c merged cluster.

A further cut arises because of the finite dimensions of Olga. In order to avoid mis-measurement of shower energies due to showers extending outside Olga, a fiducial area cut was imposed. Single γ s had to strike Olga ≥ 14.35 cm. from an Olga edge. Merged clusters (due to their greater width) had to strike Olga ≥ 22.5 cm. from an edge. Further, due to copious production of soft e^+e^- pairs in the median horizontal plane, there is a dead region in z of ± 14.35 cm., imposed on the analysis.

A cut is also imposed on the minimum shower energy. This is due to the poor energy resolution for low energy γ s, and a cut is made at 1 GeV energy. A maximum γ energy of 120 GeV was also imposed. For the reconstructed π^0 and η , energy limits of 15 and 100 GeV were set. The lower limit is set for two reasons; to reduce backgrounds, and, for $\pi^0(m)$, due to limitations in resolving the 2 sub- γ s.

5.3.2 Counting the η and π^0

The numbers of π^0 and η were found by studying $\gamma\gamma$ invariant mass plots. The counting of the mesons in these plots was made difficult by the presence of a background under the signals. For $\pi^0(m)$ the π^0 mass peak is always clearly visible on a well defined background. These $\gamma\gamma$ mass distributions were 'fitted' with a 3rd order polynomial to approximate the background, + a gaussian for the π^0 . The 'fitting' was performed by the HFIT routine of HBOOK [40], the CERN histogramming package. Figures 34 and 35 show the fitted merged γ 's $\gamma\gamma$ mass distributions in γ and π^- beam respectively.

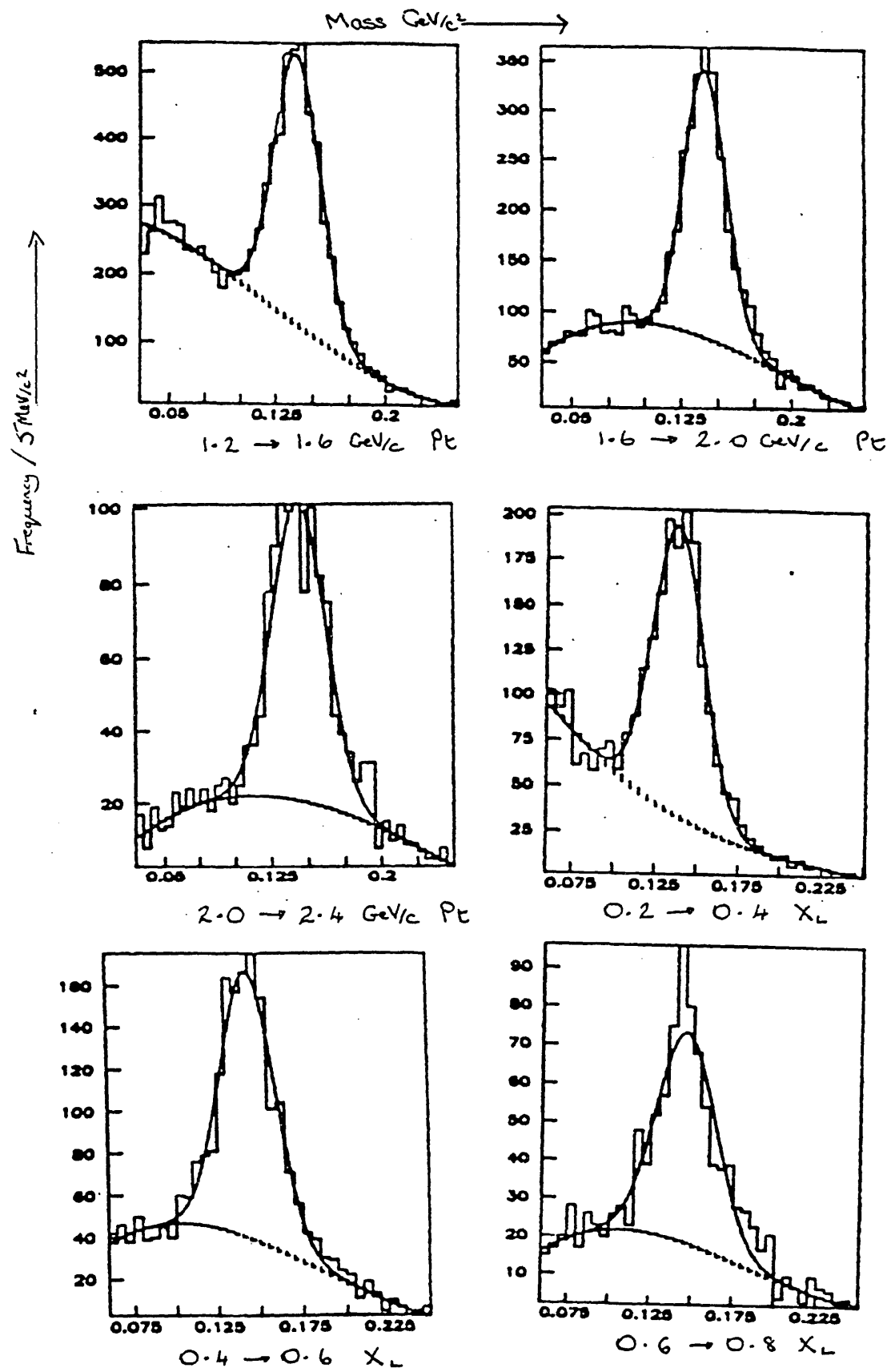


Figure 34: $\pi^0(m)$ In Gamma Beam

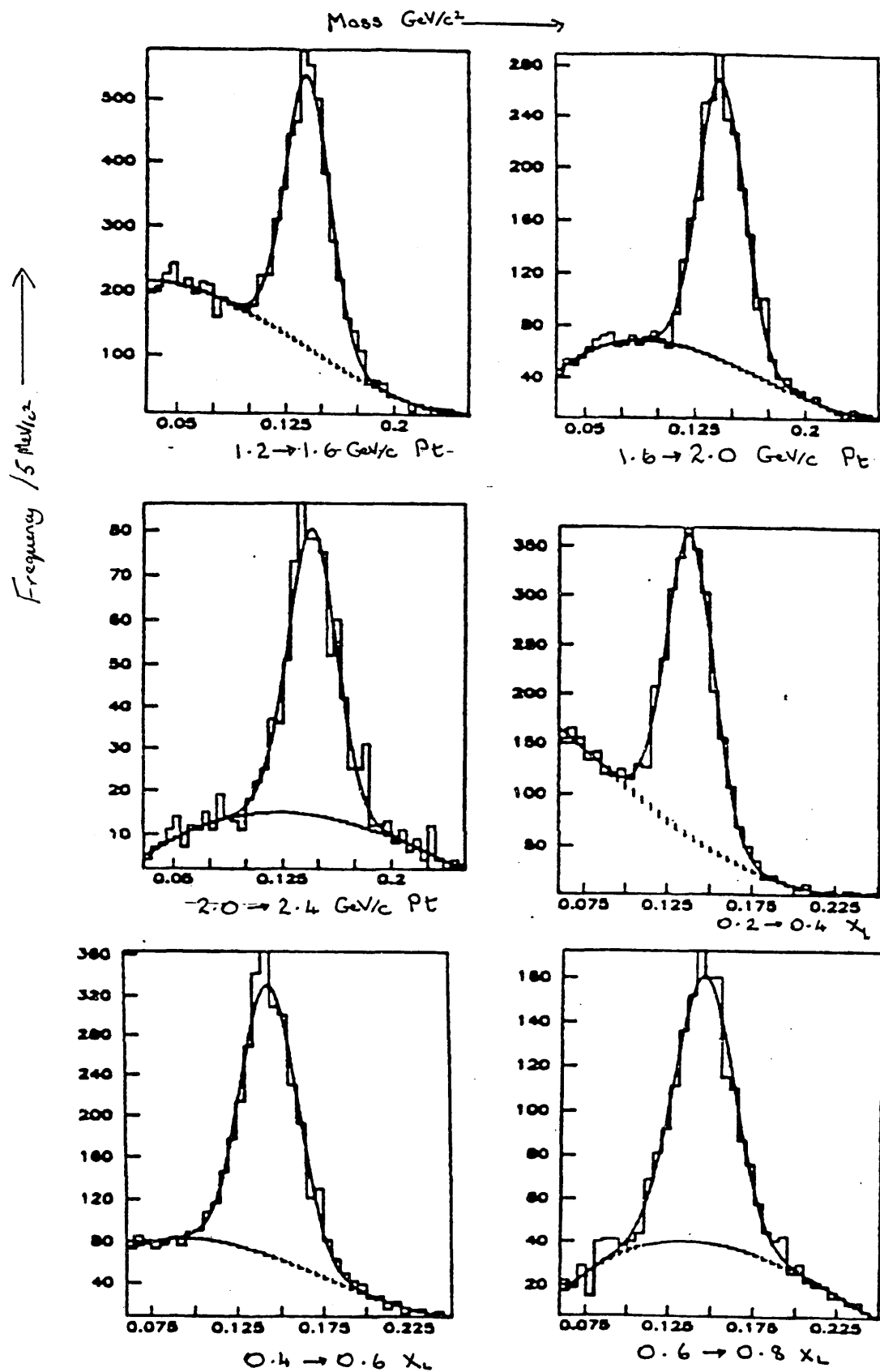


Figure 35: $\pi^0(m)$ In π^- Beam

For $\pi^0(s)$ this fitting procedure was repeated when both signal and background were well defined. However, as figures 36 and 37 show, at high pt. and x_t this is not always the case, and in such cases the counting is by hand.

As might be expected, the width of the $\pi^0(m)$ mass, (typically $\text{FWHM} = 38.5 \text{ MeV}/c^2$) is wider than that of the $\pi^0(s)$ ($\text{FWHM} = 28 \text{ MeV}/c^2$). This is due to the effect of the energy splitting algorithm in SNARK when applied to the merged showers. The different energies of these two categories of π^0 is also reflected in the differing widths, due to the energy dependence of the calorimeters energy resolution.

For the η the counting is more difficult. This is due to two effects;

- a) The poor signal/background ratio.
- b) The fact that the background peaks at approximately the η mass.

Once again a fitting procedure was used with a 3rd order polynomial for the background plus a gaussian for the mass peak. However this time the width of the gaussian was fixed. The σ value of the width was chosen to be $40 \text{ MeV}/c^2$.

This value was chosen for two reasons :

- a) MC Mass Resolution. The peak has its finite width not due to any structure intrinsic of the η , but rather due to the energy resolution of the Olga calorimeter and the deficiencies of the algorithms in the reconstruction program SNARK. This will be discussed in more detail in

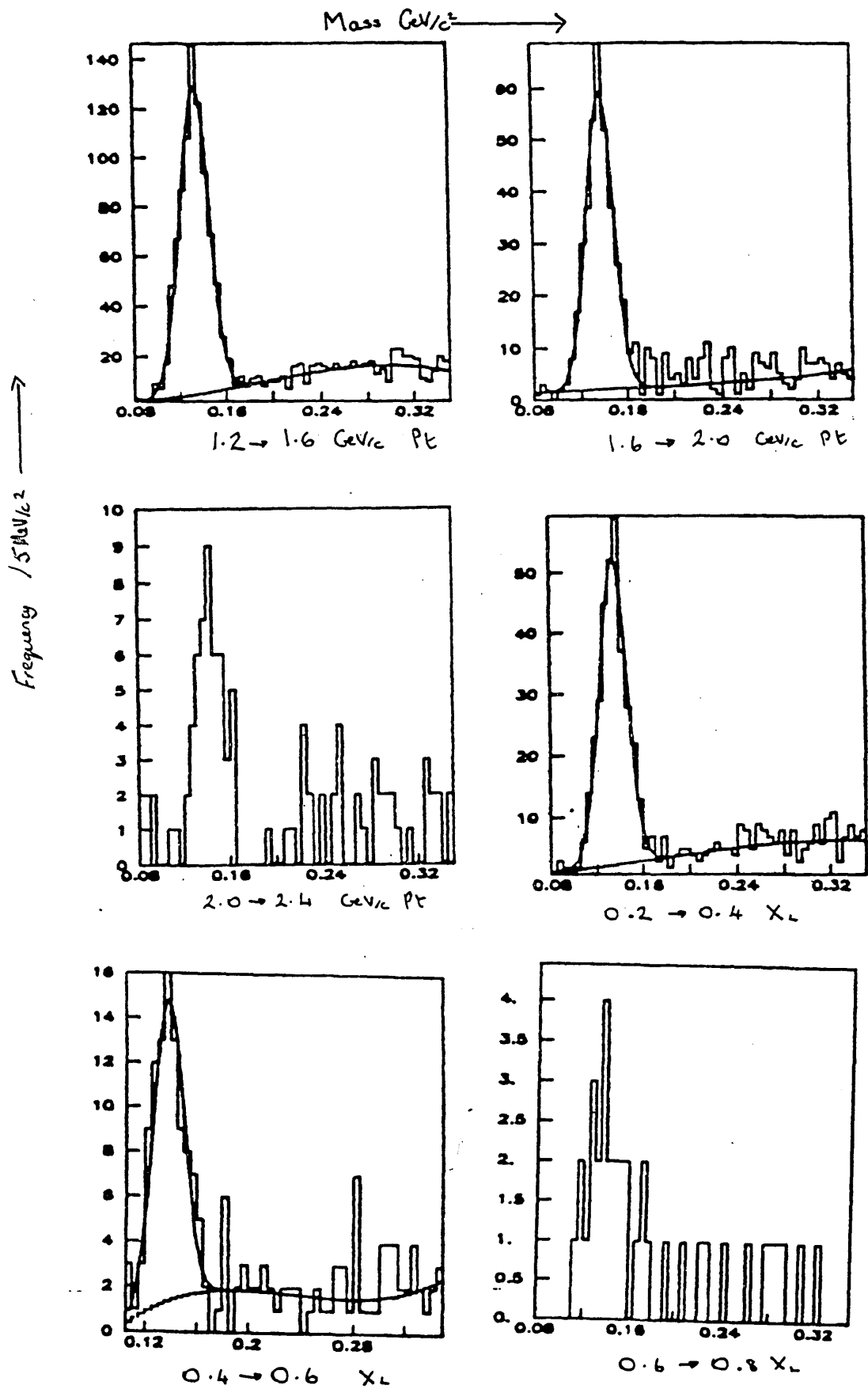


Figure 36: $\pi^0(s)$ In γ Beam

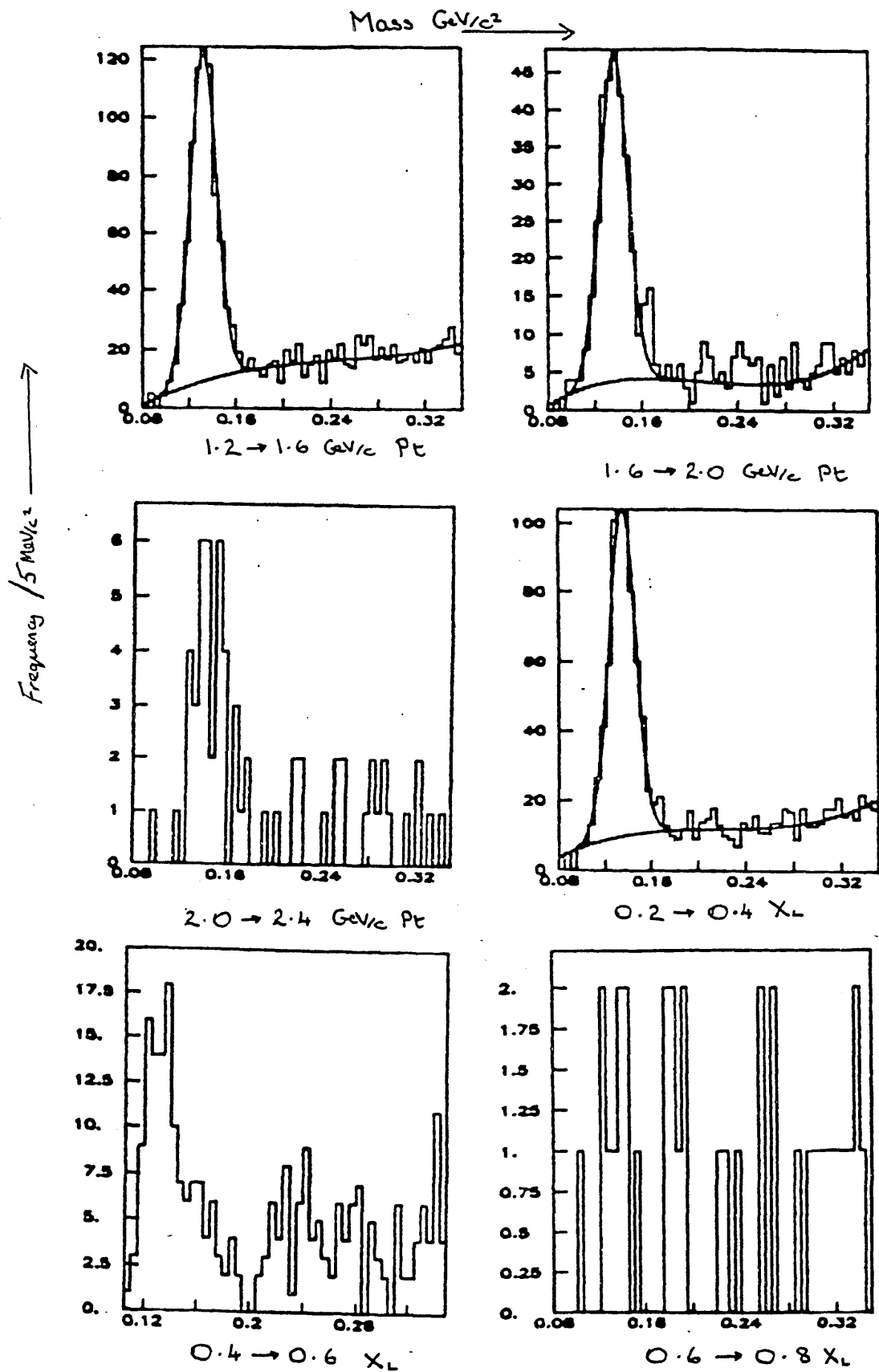


Figure 37: $\pi^0(s)$ In π^- Beam

this chapter in section 5.4, where the development of the MC simulation is discussed, but the following point can be made here. The simulation is constrained to reproduce the observed width of the $\pi^0(s)$, and since the η is also seen as 2 single γ s, the width of the η in the simulation can be taken as an indication of the width in the real data. This value = 40 MeV/c².

b) Fit to a well resolved η peak. In chapter 6 the extraction of an η signal from the data is described with a view to searching for decays in η + charged tracks. The η signal used is well resolved and fits to the mass peak yield $\sigma \approx 40$ MeV/c².

Figures 38 and 39 show the results of the fitting procedure applied to γ and π^- beams respectively. As a further check, the mass distributions are fitted by hand. The numbers of η s was then compared to those found by HFIT.

The results of counting the π^0 and η are listed in tables 11 and 12. The errors quoted are systematic, and are found by varying the shape of the background function used in the fitting procedure.

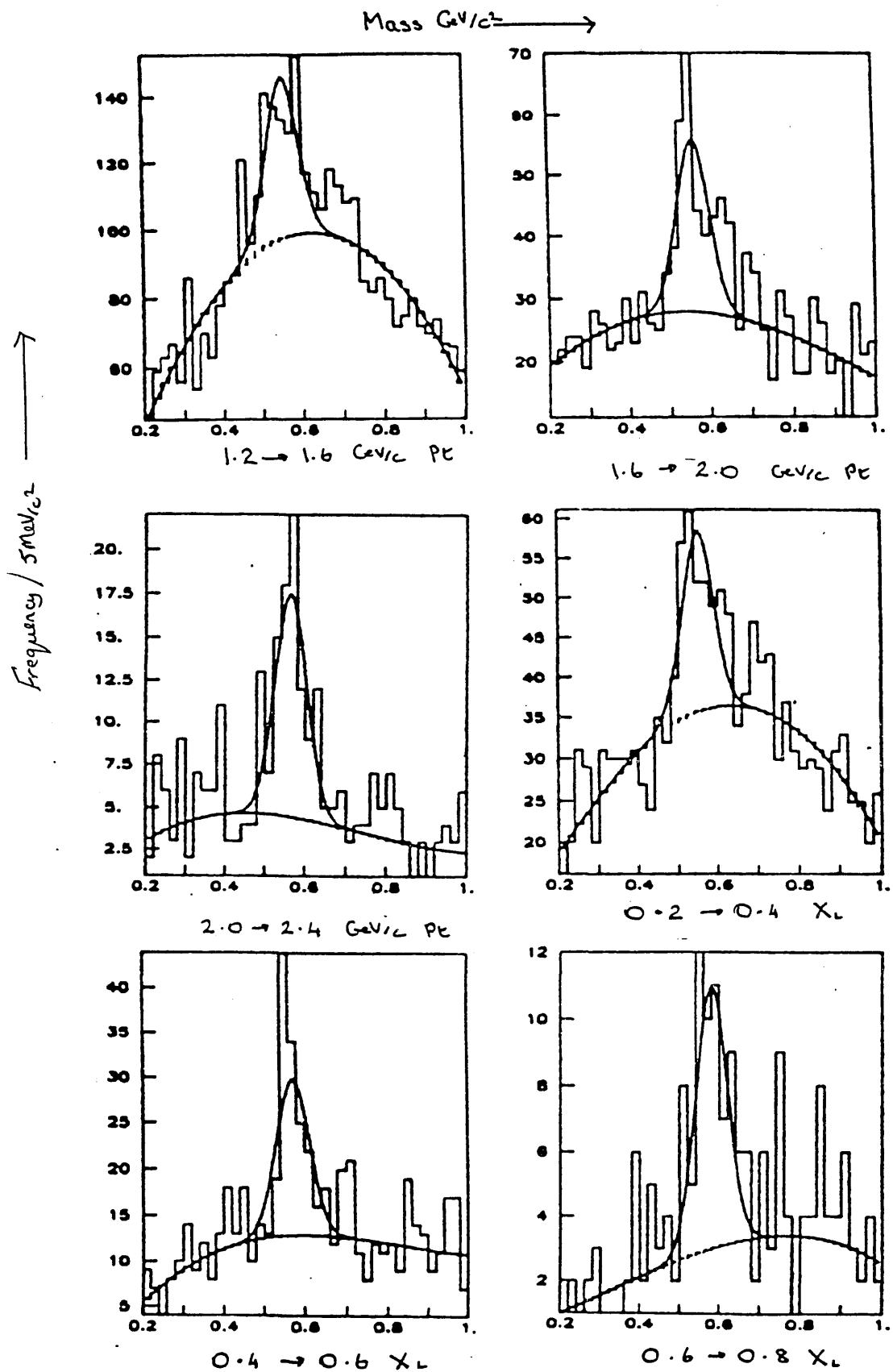


Figure 38: η In Gamma Beam

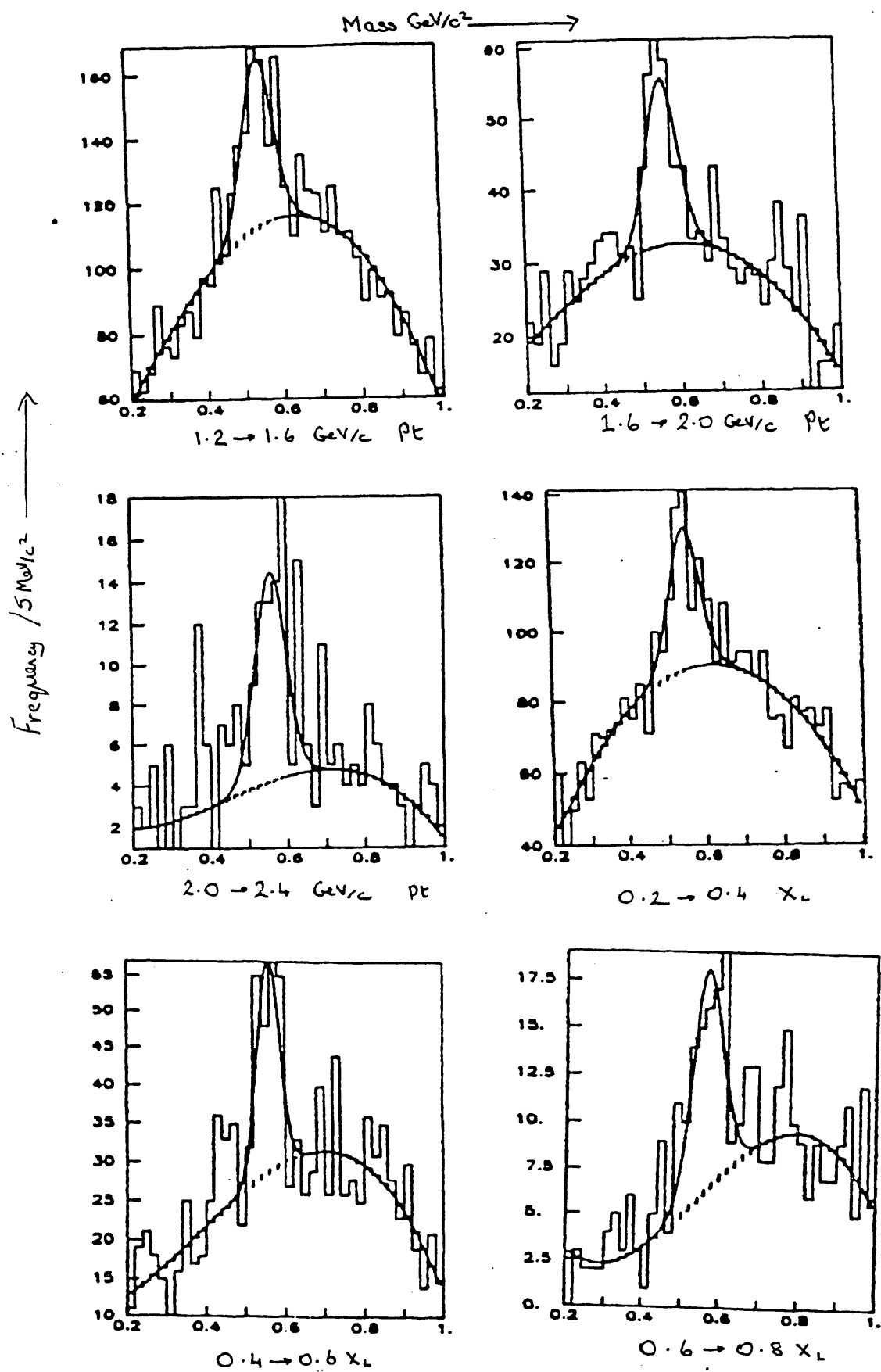


Figure 39: η In π^- Beam

TABLE 11

Observed Numbers Of Mesons In γ Beam

(Pt. in GeV/c)	$\pi^0(m)$	$\pi^0(s)$	η
1.2<Pt<1.6	3169 $\pm$ 63	800 $\pm$ 16	241 $\pm$ 10
1.6<Pt<2.0	1913 $\pm$ 38	337 $\pm$ 8	164 $\pm$ 2
2.0<Pt<2.4	748 $\pm$ 15	44 $\pm$ 3	72 $\pm$ 3
0.2< x_L <0.4	1240 $\pm$ 25	303 $\pm$ 8	113 $\pm$ 8
0.4< x_L <0.6	1027 $\pm$ 21	90 $\pm$ 6	85 $\pm$ 3
0.6< x_L <0.8	495 $\pm$ 10	23 $\pm$ 2	40 $\pm$ 3

TABLE 12

Observed Numbers Of Mesons In π^- beam

(Pt. in GeV/c)	$\pi^0(m)$	$\pi^0(s)$	η
1.2<Pt<1.6	3311 $\pm$ 66	654 $\pm$ 13	254 $\pm$ 9
1.6<Pt<2.0	1680 $\pm$ 33	263 $\pm$ 8	117 $\pm$ 2
2.0<Pt<2.4	563 $\pm$ 11	25 $\pm$ 5	54 $\pm$ 3
0.2< x_L <0.4	2133 $\pm$ 43	561 $\pm$ 11	206 $\pm$ 8
0.4< x_L <0.6	2138 $\pm$ 42	123 $\pm$ 8	115 $\pm$ 3
0.6< x_L <0.8	1083 $\pm$ 21	6 $\pm$ 1	58 $\pm$ 3

5.4 MC SIMULATION

The MC simulation of particle production and detection was prepared so that when subject to a similar analysis as real data, it would allow me to proceed from observed to produced quantities.

5.4.1 Beam Energy

a) π^- beam. For π^- beam the energy spectrum of figure 14, obtained by tagging real events, is used. As in real data, when Feynman x_L is required $E(\pi^-) = 87$ GeV is used.

b) Gamma beam. It is not so simple for γ beam however. Here as well as producing γ s with an energy similar to those in real events, an estimate of the tagged measure of the energy is also required.

The tagging system (described in Chapter 2) measures the beam electron energy before and after its passage through a radiator. The difference in energies is then given as the gamma energy. However, as already mentioned, single bremsstrahlung is not the only possibility as regards the radiation of energy; multiple bremsstrahlung is also possible. Therefore the observed (tagged) energy spectrum of figure 12 cannot be used as the beam energy spectrum in the MC.

The true energy spectrum can be calculated. The calculation relies upon the approximation that there is first radiation of a single hard photon, followed by further soft gammas. For a given electron energy, the probability of emitting a hard γ of energy K falls as $1 / K$. It can be shown [29] that the probability of emitting further soft γ s with total energy $k < \epsilon$ is given by :

$$P(k < \epsilon) = \left(\frac{\epsilon}{E - K} \right)^{\frac{4t}{3}} \quad \text{Eqn. 9}$$

where t = thickness of radiator in radiation lengths, and
 E = electron energy (incident)

Thus for a given incident electron energy, a table of probabilities can be drawn up for emitting a hard γ of energy K + soft gammas of energy k . These probabilities are simply $(1 / K) * \text{prob. for } k \text{ obtained from eqn. 9.}$

The incident electron energy and the electron energy after radiating are measured in real data by the tagging system described in Chapter 2. In the simulation these distributions are used to generate an incident electron energy and a total radiated energy. The total radiated energy is then divided into its hard and soft components by reference to the appropriate table of probabilities (described above).

Thus per event, both a corrected and a tagged γ energy are generated. The tagged γ energy spectrum being as in figure 12, and the corrected γ energy spectrum is as in figure 13.

5.4.2 Event Cross-section

In each event a meson, either a π^0 or η , is generated. These have flat pt. and pl. distributions, and their energy is required to be less than the beam energy. A cross-section is then generated for each event and is used as a weight for the event in the analysis of the simulation.

For π^0 the choice of cross-section is straightforward as it has previously been measured. In π^- beam at 200 GeV incident beam energy, Donaldson et al. [41] have parametrized their data on π^0 production with,

$$E \frac{d^3\sigma}{dp^3} = A \frac{[1 - \sqrt{(x_t^2 + (x_L - 0.14)^2)}]^{3.21}}{(p_t^2 + 0.96)^{5.03}} \quad \text{Eqn. 10}$$

where A = a normalization factor, 10.7 mb/GeV/c^2 .

This parametrization of the cross-section was obtained with a H_2 target. Assuming a linear dependence on nuclear mass the cross-section is found for the Li^6 target in NA14, and the result is found [31] to well describe π^0 production in the NA14 π^- beam.

π^0 photo-production has also been heavily investigated in NA14, and, as described in Chapter 1, it has been shown to be possible to divide the cross-section into two components:

- a) The first is a hadronic term. The parametrization in eqn. 10 is scaled by the ratio of the inelastic cross-sections in γ and π^- beam, giving a new normalization factor A , of $56 \mu\text{b} / \text{GeV/c}^2$.
- b) There is then a QCD like term. To lowest order this has been calculated by Fontannaz et. al. (see Chapter 1) and their equations have been encoded in FORTRAN to provide the appropriate contribution to total cross-section as a function of p_t . and p_l . at a given beam energy.

For the η the choice of cross-section is not immediately clear. Completely flat p_l . and p_t . were tried in the simulation, but yielded results obviously dis-similar to real data. The use of the same shape cross-section as for π^0 was then tried. In π^- beam work, the main p_t . slope parameter (5.03 in eqn. 10) was varied and the results compared to real data. If the slope parameter was kept within 30% of the original value the overall acceptance/efficiencies for the η in the simulation varied by $<5\%$. Further, using the Donaldson value of the coefficient in

the simulation produces pt. and pl. which are roughly similar in shape to those of real data. For example, in π^- beam, the mean η pt. in the simulation (after analysis) is 1.57 GeV/c, compared to 1.52 GeV/c in real data. Similarly the mean pl. in the simulation is 35.1 GeV/c and 33.7 GeV/c in real data.

Given the level of agreement between MC and real data, I feel it is sufficient to use the same shape cross-section for η as for π^0 .

5.4.3 Apparatus Layout and Beam-Target Interactions

The apparatus layout is taken as given in Chapter 2. It is assumed that π^0 and η are produced in the target with a flat distribution over the target length. The mesons then decay into 2 γ s which travel in straight lines through the spectrometer. The intersection of these lines with Olga is then found.

In the case of π^- beam a complication arises due to the positioning of the target in the AEG magnet. In both γ and π^- beams, the beam is assumed incident along the x axis with no transverse momentum. However the π^- have been deflected by the AEG'S field when they reach the target. Knowing the field strength and π^- momentum the deflection is simulated in the MC. The magnitude of the bending is such that a 90 GeV π^- traversing the AEG to the centre of the target, if it then continued undeflected would hit Olga (1510 cm. away) with a horizontal deflection of 3 cm.

For a γ travelling through the material of the spectrometer, there is of course the possibility of a conversion prior to reaching Olga. This effect is allowed for, both for conversions pre-Goliath (where the e^+e^- are opened by Goliath and thus can give 2 hits in Olga), and also post-Goliath where the pair shower correctly in Olga but the charged veto is fired.

5.4.4 Gammas in Olga

The observation and measurement of photons hitting Olga has to be reproduced correctly. There are several reasons why a photon in Olga will not be registered correctly.

The following effects have all been investigated [33] :

- a) Charged veto due to coincidence with a charged track in the event.
- b) Charged veto due to backscattering of the shower from the calorimeter into the veto counters.
- c) Probability of depositing sufficient energy in the Sampler. This identifies the shower as non-hadronic. For $\pi^0(m)$ this is included in the trigger efficiency, as it is for the trigger γ from a $\pi^0(s)$. However, for the non-trigger γ from a $\pi^0(s)$ there is a 10% probability of not depositing sufficient energy.
- d) Due to the method of producing the γ beam, the beam is accompanied by a flux of muons. This gives a 10% probability that a single γ or a merged cluster is associated with a charged veto from such a muon.

- e) Good shower shape. It is required in SNARK that a single γ gives a shower in ≤ 4 Olga blocks. 95% of single γ s satisfy this requirement. Over 99% of $\pi^0(m)$ satisfy the requirement that ≤ 8 blocks are in the cluster.
- f) The performance of Penelope is not perfect. For example, the matching between projections is not always correct. Further several strips of scintillator are 'dead' due to darkening or electronics problems, and this can give shower profiles not recognizable as γ s.
- g) For a merged cluster there is only a certain probability of correctly resolving the 2 sub- γ s. This effect depends amongst other things, upon the separation of the 2 γ s in each projection of Penelope.

There are two effects which prevent precise measurement of a shower's energy. The simplest of these is that in SNARK, once the γ energy is known, the momentum components are calculated assuming that the photon came from the centre of the target. This is repeated in the simulation.

A more complicated effect is that of 'energy smearing' due to the calorimeter's intrinsic energy resolution. For lead glass calorimeters the standard parametrization of this effect is of the form [42] :

$$\Delta E = A/E + BE \quad \text{Eqn. 11}$$

The parameters A and B in eqn. 11 were varied until the MC produced $\pi^0(s)$ of a width which agreed with real data. The resulting values are : $A = 0.145$, $B = 0.068$ (E in GeV).

5.4.5 Separation of MC π^0 into $\pi^0(s)$ and $\pi^0(m)$

The splitting of π^0 into the separate and merged γ categories is performed after π^0 generation. The splitting algorithm checks the 2 γ separation at Penelope, 'd', and compares it to an energy dependent variable. This indicates what the fraction of π^0 at this d and energy are $\pi^0(s)$ and $\pi^0(m)$, and categorizes accordingly. The variable in the algorithm was obtained by looking at real data, and then scaling the observed numbers by the MC calculated efficiencies for observation. The scaled numbers were then used to find the variable as a function of d and π^0 energy.

5.4.6 Trigger Efficiencies

As already mentioned, The single γ and $\pi^0(m)$ trigger efficiencies have already been estimated [33] [39]. These are shown as the solid curves in figure 33. The triggers are applied to all $\pi^0(m)$ and each γ from a $\pi^0(s)$ or η in the simulation.

5.5 COMPARISON BETWEEN MC AND REAL DATA

The analysis of the MC simulation involves applying the same cuts to the events as already described for real data. The output from the MC and the real data can then be compared as a means of looking for omissions/errors in the simulation. As the major signal is the π^0 , it is the π^0 s in MC and real data that are compared.

The results are as follows :

a) Pt. For $\pi^0(m)$ the real data and MC pt. distributions are as shown in figure 41 (the two data sets are normalized at 1.8 GeV/c pt.). There is a clear excess of π^0 in the MC at low pt. The large error on the MC points at low pt. comes principally from the poor estimate of the trigger efficiency in this region.

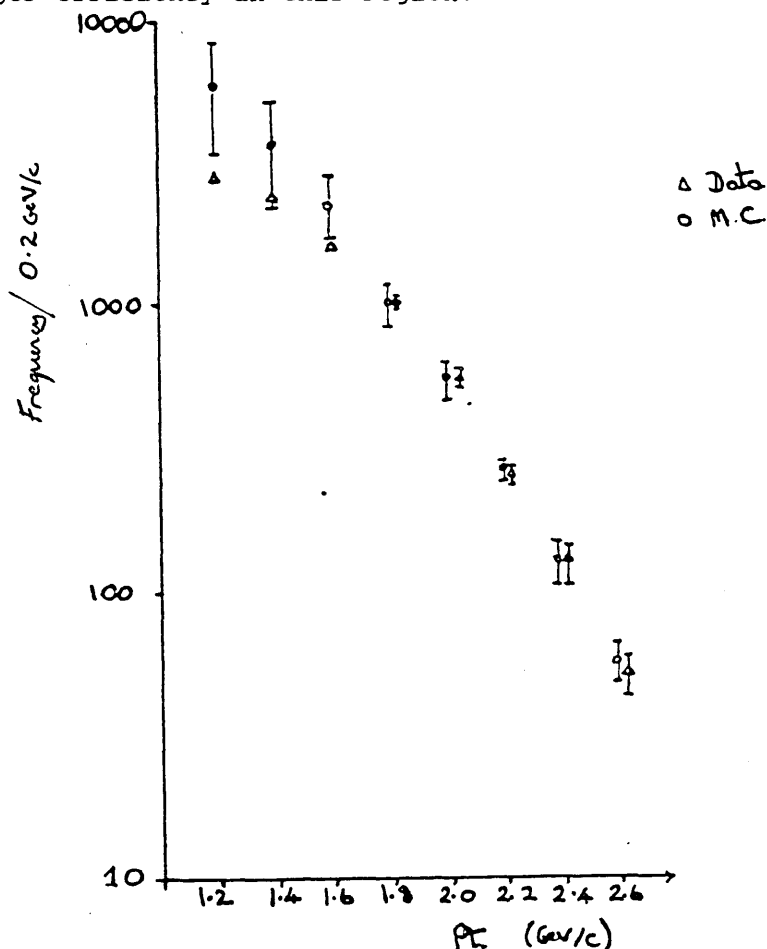


Figure 41: Comparison Of $\pi^0(m)$ Pt. Between MC & Data

For $\pi^0(s)$ figure 42 shows good agreement between the MC real data (again the 2 data sets are normalized at 1.8 GeV/c pt.).

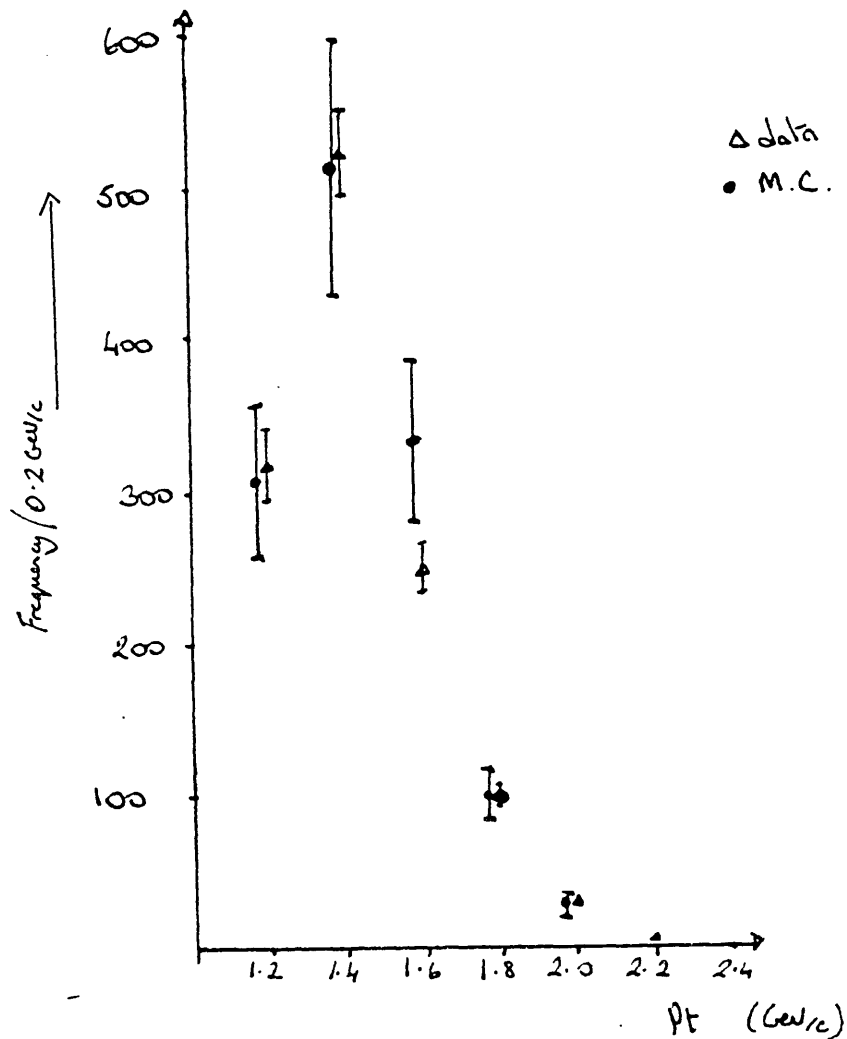


Figure 42: Comparison Of $\pi^0(s)$ Pt. Between MC & Data

- b) Pl. The pl. distribution of π^0 s can be plotted in various pt. regions. Figure 43 a) and b) shows MC and real data for $\pi^0(m)$ and $\pi^0(s)$ respectively. For $\pi^0(s)$ there is good agreement. In $\pi^0(m)$ there is moderately good agreement except at low pl. . Overall, in all pt. regions, the mean pl. in data and MC agrees to 1 or 2 GeV/c.
- c) $\cos\theta^*$ θ^* is the angle between a daughter γ 's line of flight in the parent meson centre of mass, and the line of flight of the meson in the lab. Figure 44 compares MC and real data for $\pi^0(s)$ and $\pi^0(m)$. There is good agreement for $\pi^0(s)$, but there is clearly something amiss for $\pi^0(m)$. The

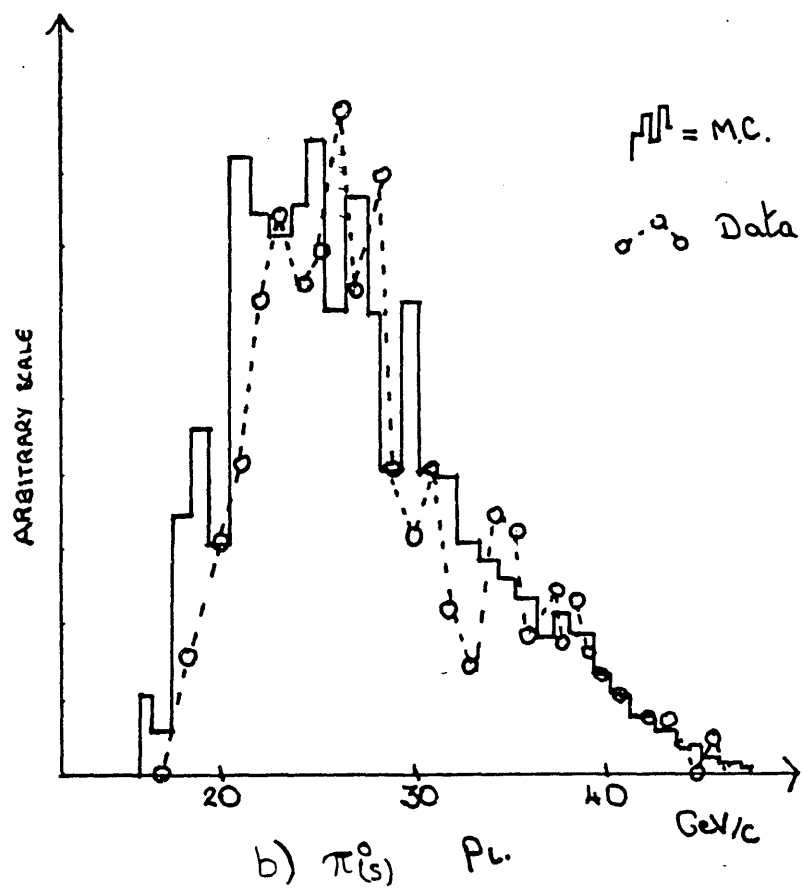
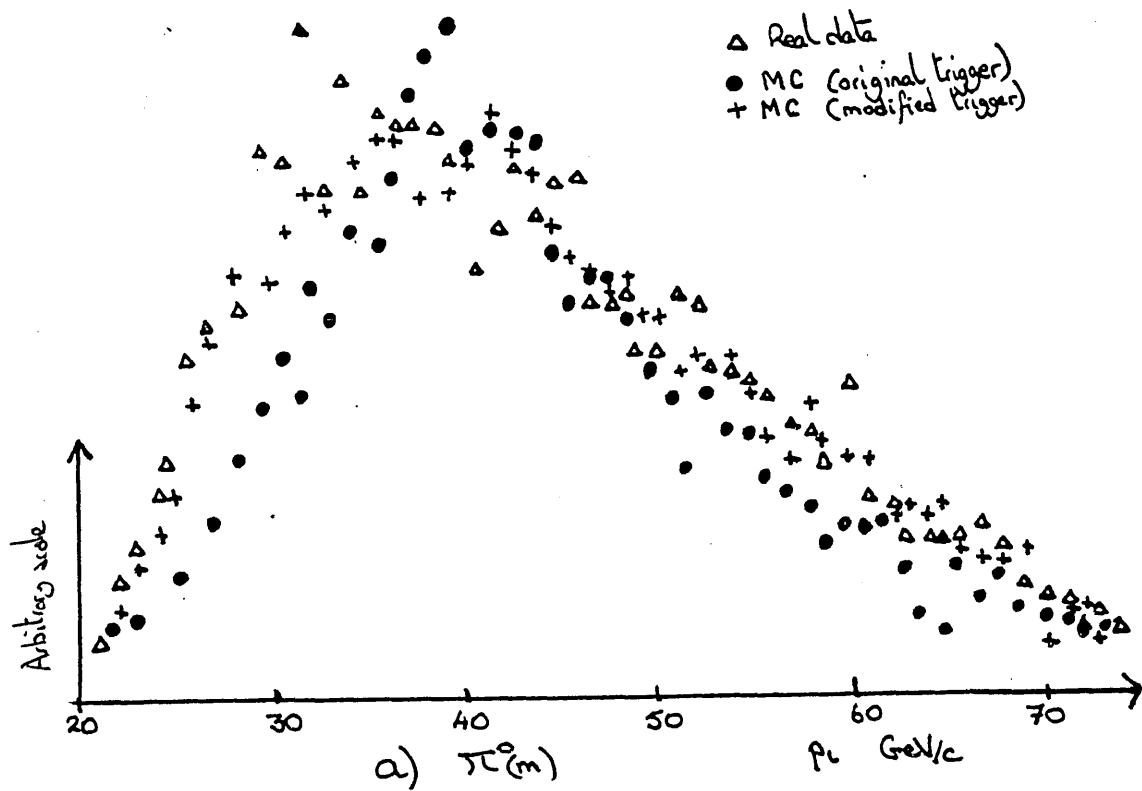


Figure 43: Comparison Of π^0 Pl. Between MC & Data

spike just above $\cos\theta^* = 0.0$ in real data is simply not reproduced in the MC. Close investigation reveals that the spike arises when both γ s in a merged cluster hit the same Olga lead glass block. In this case the energy sharing algorithm in SNARK begins by assuming equal γ energies. Equal, or nearly equal, γ energies in the lab implies θ^* of $\approx 90^\circ$, hence the spike. This effect of energy sharing is reproduced nowhere in the MC and there is thus a divergence between MC and data. However, the π^0 in the spike are still reconstructed as π^0 (albeit with poorer mass resolution) and are thus not cut from the data set.

- d) Ratio $\pi^0(s):\pi^0(m)$. The method (described earlier) of deriving the splitting algorithm used in the MC, is heavily dependent upon real data. To check its proper implementation table 13 shows the % of π^0 seen as $\pi^0(m)$ in MC and real data, in all pt. regions and in both beams. If anything, there is perhaps a tendency at times to overproduce $\pi^0(s)$ in the MC.

- e) Counting the number of double arm triggers recorded at the same time as the data was taken, gives an estimate of the sensitivity of the data set in terms of the number of events per nanobarn of cross-section (see Chapter 2 Section 2.6.1). The total number of events produced in real data can then be used to produce a measure of the observed cross-section. As the MC cross-sections are based upon shapes normalized to the (assumed) true

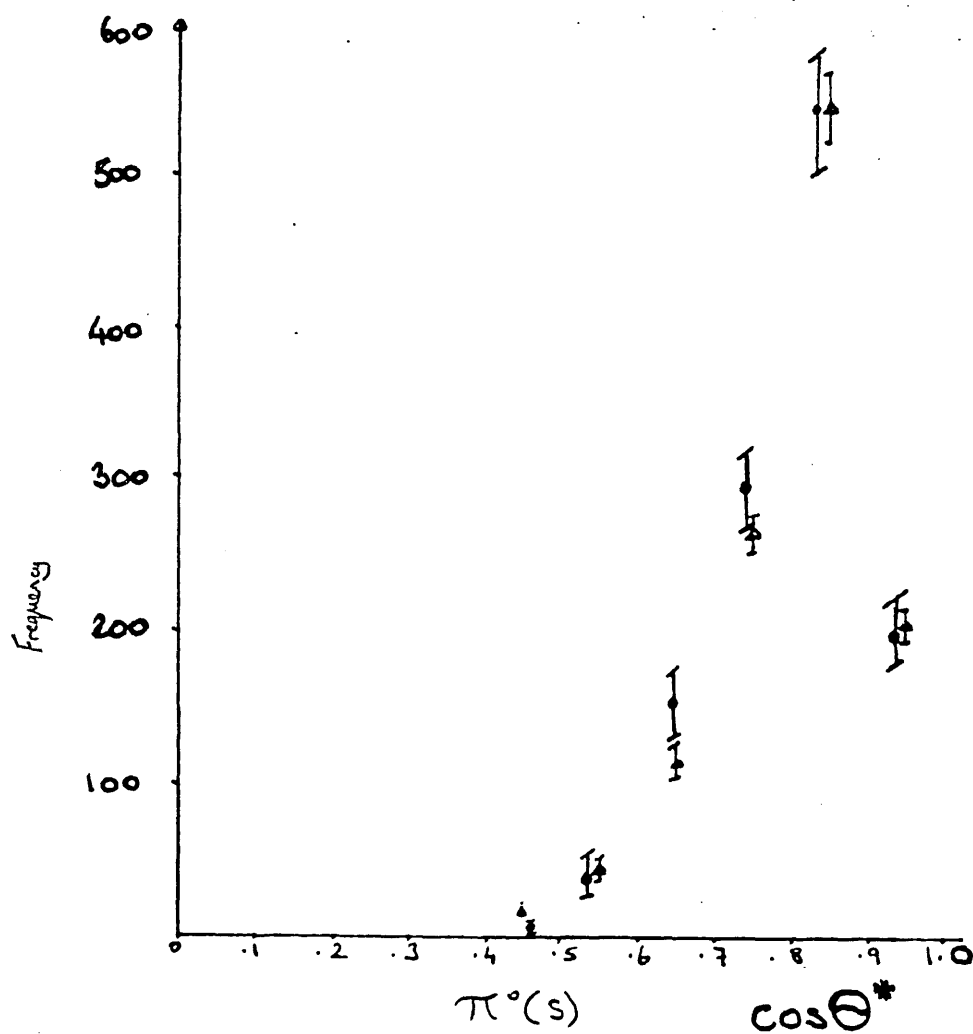
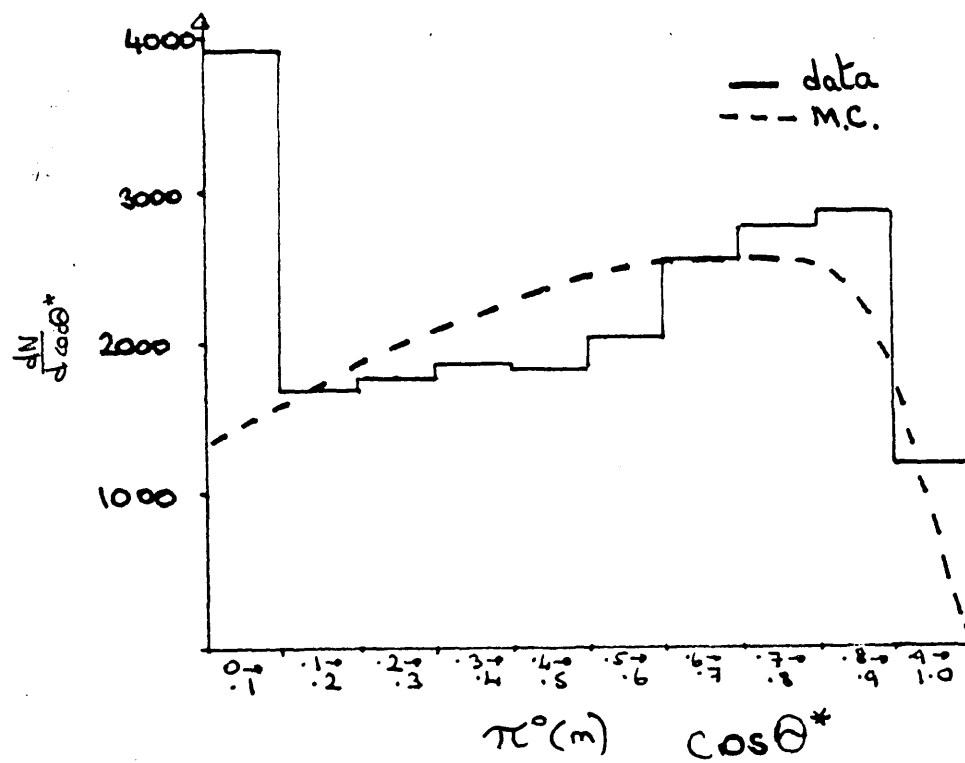


Figure 44: Comparison Of $\pi^0 \cos \theta^*$ In MC & Data

TABLE 13

Comparison Of % Of π^0 As $\pi^0(m)$ In MC And Data

(Pt. in GeV/c)	π^- Beam % $\pi^0(m)$		γ Beam % $\pi^0(m)$	
	MC	Data	MC	Data
1.2<Pt<1.6	84	80 $\pm$ 1	85	75 $\pm$ 1
1.6<Pt<2.0	81	85 $\pm$ 1	82	82 $\pm$ 1
2.0<Pt<2.4	93	96 $\pm$ 1	94	95 $\pm$ 1
0.2< x_L <0.4	77	74 $\pm$ 2	78	76 $\pm$ 2
0.4< x_L <0.6	91	94 $\pm$ 0.5	92	91 $\pm$ 1
0.6< x_L <0.8	94	99 $\pm$ 1	95	95 $\pm$ 0.5

cross-section, the number of events generated in the MC and real data can be directly compared. I have done this for $\pi^0(m)$ where the numbers produced in the MC are compared to the numbers produced in real data (the observed quantities have been scaled by the acceptance and reconstruction efficiencies). The results are shown in figure 45 versus both pt. and Feynman x_L . At high pt. there is good agreement, but at lower pt. the MC overproduces. This effect has already been noted under an earlier point. In x_L the excess at low pt. feeds into all bins giving the poor agreement shown.

The main feature of the above results is that the MC overproduces $\pi^0(m)$ at low pt. . This is the region where the trigger efficiency is most poorly estimated. I have therefore adjusted the $\pi^0(m)$ trigger efficiency so as to reproduce the real data in the MC. The new efficiency is shown as the broken line

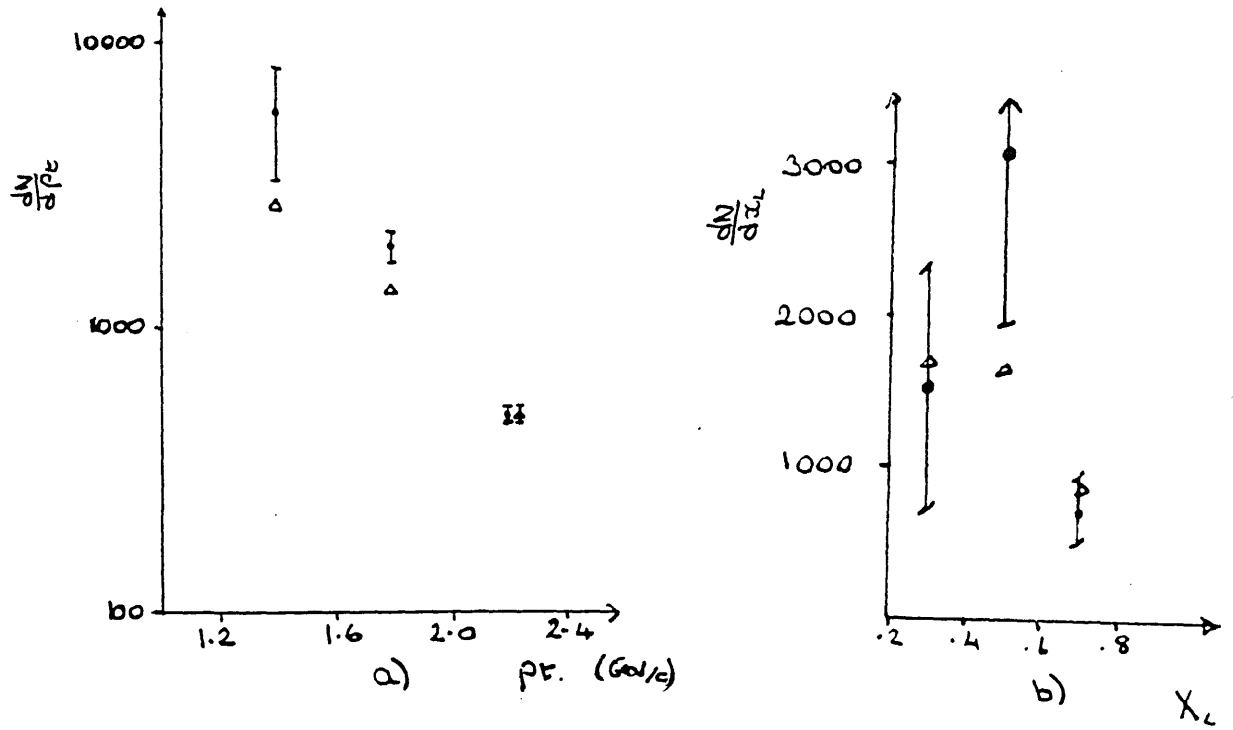


Figure 45: Comparison Of $\pi^0(m)$ Numbers In MC & Data

in figure 33 . Given that at high $pt.$ in figure 41 the agreement between MC and data is $\pm 12\%$, the new trigger efficiency at low $pt.$ can only be good to this accuracy. The effect on $\pi^0(m)$ pl. is shown in figure 43 a), and indeed represents an improvement as regards agreement between MC and real data.

All MC results used in the remainder of this work feature this correction.

5.6 RESULTS

To get from the observed numbers of mesons given in tables 11 and 12, to the produced quantities, the following was used :

For $\pi^0(m)$ the appropriate relation was ;

$$\text{Produced} = \text{Observed} / (G T C P \mu) \quad \text{Eqn. 12}$$

where G = geometric acceptance, T = trigger efficiency, C = energy dependent calorimeter effects, P = non energy dependent effects, μ = probability of muon veto (γ beam only).

For $\pi^0(s)$ I have;

$$\text{Produced} = \text{Observed} / (G T C C_1 C_2 P^2 \mu^2 FD^2) \quad \text{Eqn. 13}$$

with G, T, C as above, C_1 and C_2 calorimeter effects applied to the separate gammas, P and μ as before but squared to allow for the 2 separate gammas, and FD^2 referring to getting good shower shape for both gammas (i.e. a legal topology of hit blocks)

For the η eqn. 13 is used but with an extra term for the 2 γ branching ratio (0.39 from [15]).

The MC dependent values in these equations were calculated separately for each kinematic region. The results of scaling the numbers of mesons are given in tables 14 and 15 for γ and π^- beam respectively.

The values in ^{tables} 14 and 15 can be combined to yield the η / π^0 production ratios in each beam. These values are shown in figures 46 and 47. Of the 2 errors on each value in these figures, one is statistical (shown by solid vertical lines),

TABLE 14

Produced Numbers Of Mesons In γ beam

(Pt. in GeV/c)	$\pi^0(m)$	$\pi^0(s)$	η
1.2<Pt<1.6	130250	51364	53595
1.6<Pt<2.0	22594	5015	10041
2.0<Pt<2.4	4510	465	2605
0.2< x_L <0.4	33904	12149	14510
0.4< x_L <0.6	19610	5795	12716
0.6< x_L <0.8	12410	3450	8834

TABLE 15

Produced Numbers Of Mesons In π^- beam

(Pt. in GeV/c)	$\pi^0(m)$	$\pi^0(s)$	η
1.2<Pt<1.6	108501	35687	47754
1.6<Pt<2.0	17928	2860	5730
2.0<Pt<2.4	3283	284	1613
0.2< x_L <0.4	76109	11569	22196
0.4< x_L <0.6	21593	1530	8859
0.6< x_L <0.8	13580	179	4783

found by taking the square root of each produced quantity and propagating through the equations. The second error on each value is the systematic error arising from the combination of all terms in eqns. 12 and 13.

It should be pointed out that the numbers in the x_L distribution are not the same as the total in the pt. distribution, due to the different cuts used. In pt. there are

several hundred $\pi^0(m)$ with $pt. > 2.4$ GeV/c which are included in the $x_{\perp}$ data. Equally, the $x_{\perp}$ cuts of > 0.2 and < 0.8 remove (differing) amounts of $\pi^0(s)$, $\pi^0(m)$ and η from the x data set which are included in the $pt.$ data set. Further, the 52% tagging efficiency in γ beam greatly cuts the data in x as compared to $pt.$. All of these effects have been investigated and none materially alters the results in either beam.

Finally figure 48 shows the ratio of η / π^0 ratios observed in the γ and π^- beams.

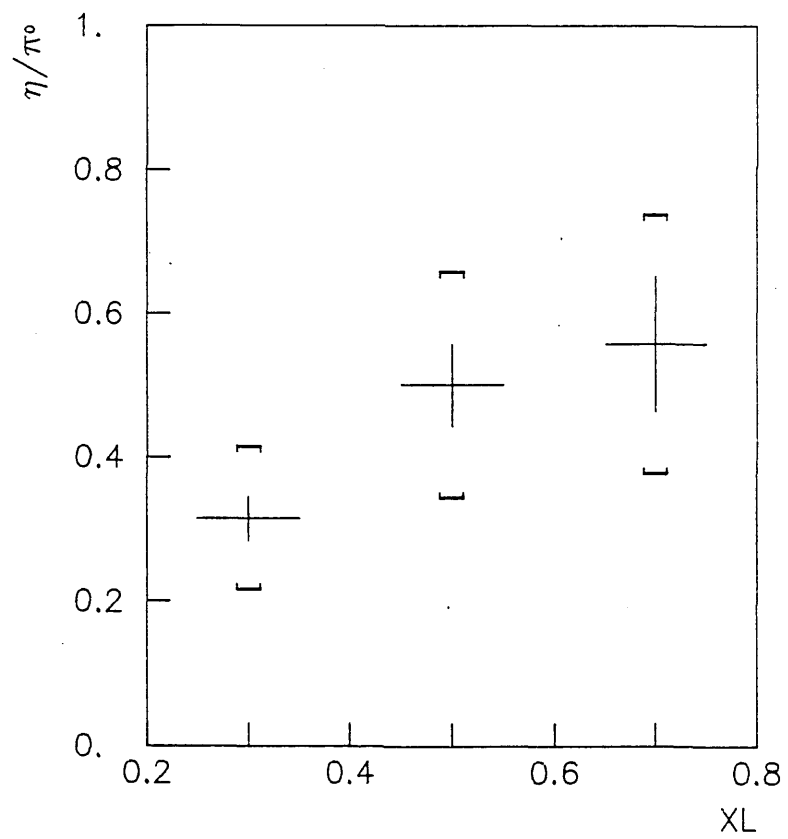
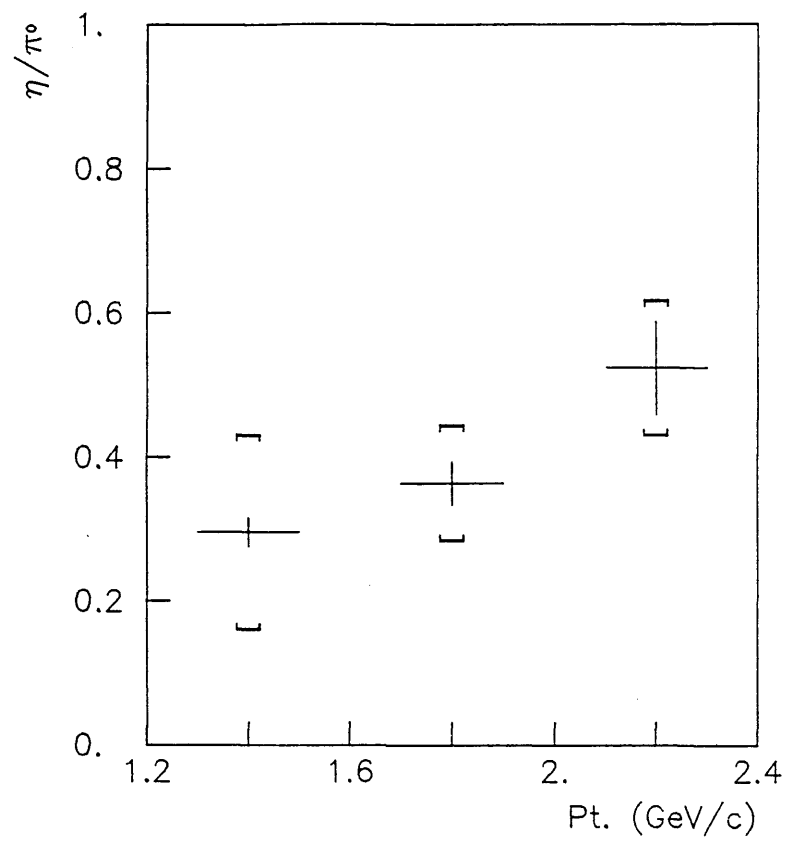


Figure 46: η / π^0 Production In γ Beam

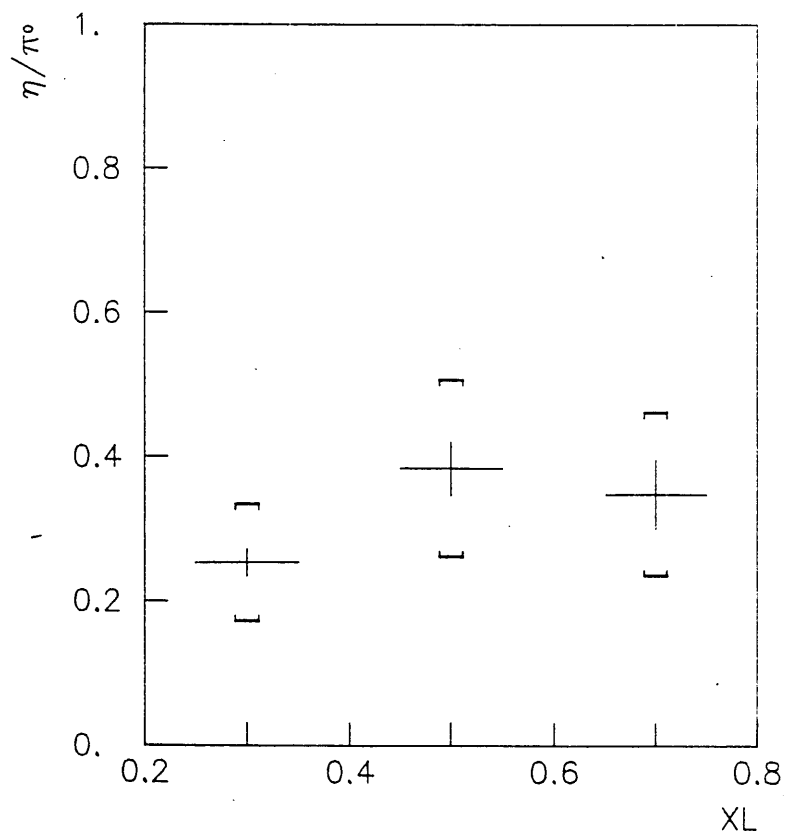
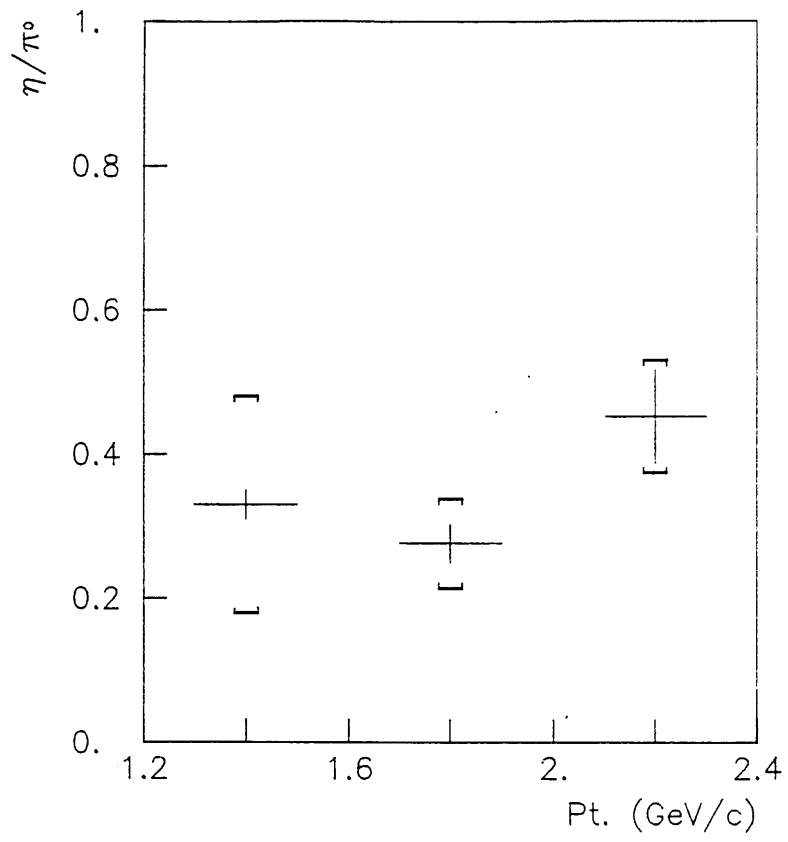


Figure 47: η / π^0 Production In π^- Beam

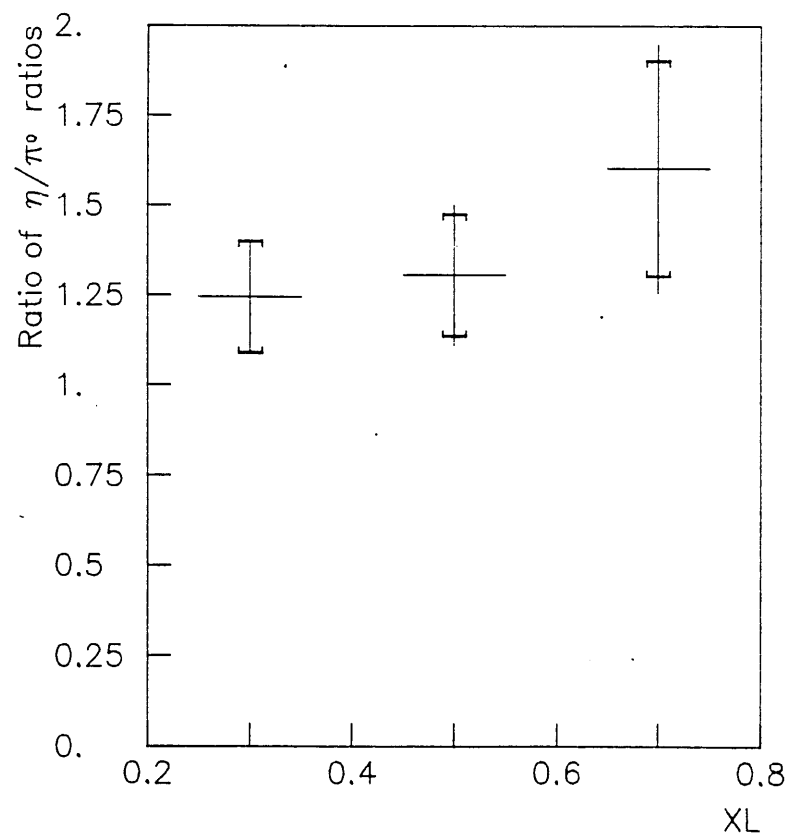
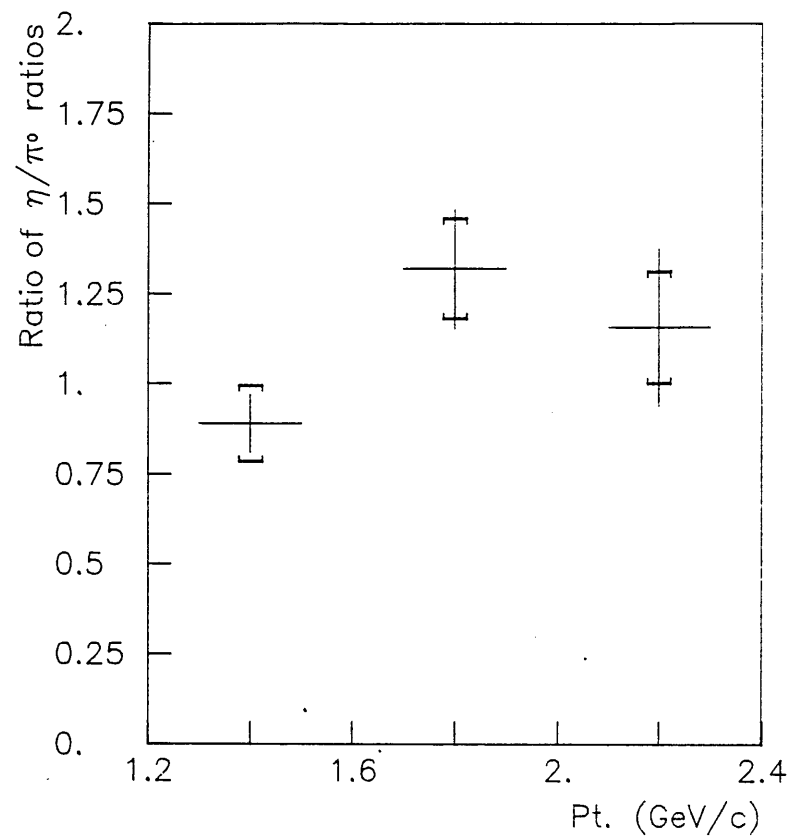


Figure 48: Ratio Of η / π^0 Production Ratios In The 2 Beams (γ/π^-)

5.7 OBSERVATIONS BASED UPON THE RESULTS

Inside each beam v. pt., the η / π^0 ratio is between 0.3 and 0.5 . There is a hint that this value is rising with pt. but this is not clear in π^- beam. Plotted v. x_L the ratio is level at high x_L (≥ 0.4) but shows a clear fall in the lowest x_L bin in both beams.

A previous experiment, [9], has studied η / π^0 v. x_L in γ beam at low pt. (pt. < 1.1 GeV/c). Their results (fig. 4) are generally lower than here and show a sharper fall at low x_L , a fall which starts at $x_L \approx 0.7$. They ascribe this fall to the well known accumulation of low momentum π^0 from heavy meson decay. Due to the high pt. in my work only my lowest x_L bin could be affected by such a phenomenon.

Another experiment, [43], has investigated η / π^0 v. x_L in π^- beam at high pt. (pt. > 2.0 GeV/c). Their results are consistent with those here, except they show no fall at low x_L . Their pt. cut is even higher than mine, so they will be even less sensitive to heavy meson decay.

Overall the ratio of ratios is just above 1.0, and seems to rise at high pt. and x_L . This is not inconsistent with the idea of additional strangeness in photoproduction coming from the photon itself.

Chapter VI

SEARCH FOR F DECAY

6.1 INTRODUCTION

As described in Chapter 1, building from both theory (the quark model) and experiment (DASP, WA4 etc.) it seems reasonable to look in the channel ηX for F decay. In this chapter using a strong η signal, I search for evidence for F photoproduction by looking at decay channels involving an η .

6.2 DATA

Triggers in Olga on photons with $p_t > 900$ MeV/c form the basic data set. The η is seen in Olga as 2 well separated γ 's, and a software filter was prepared which required the presence in an event of a γ - γ invariant mass near the mass of the η . All gamma beam triggers in the 5 NA14 data taking periods in 1982 and 1983 were examined with the filter. Also seen in the 2γ mass combinations is the π^0 . As evident in the previous chapter, there is very little background under such a π^0 peak, so all γ 's forming a π^0 candidate were flagged and not used in the η filter. This had a minimal effect on the number of η 's seen, but greatly reduced the combinatorial background under the η signal. For the early periods, July & Sept. '82, a mass in the range $0.50 \rightarrow 0.62$ GeV/c² was required for the η candidates, in 1983 this was relaxed to $0.4 \rightarrow 0.7$ GeV/c².

Table 16 shows the numbers of η 's and events per period satisfying the filter. It also includes the associated luminosity in evts / nb per period. The luminosity was found by counting double arm triggers (as described previously) in the Aug. and Sept. '83 periods whilst the initial filtering was performed. This gave luminosities for the two periods which reflected the relative η yield to within the statistical error on the quantities. This method of associating the η yield with luminosity was then used to find the luminosities for the other periods.

TABLE 16			
Amount Of Data Per Period For F Search			
Period	# Of Events	# Of η	Luminosity (evts/nb)
July '82	1964	855	443
Sept '82	5544	1266	656
Aug '83	12478	1322	700
Sept '83	12658	1679	874
Oct '83	8695	702	365

The filtered data was then processed at Imperial College through the SNARK, TRIDENT and INDANL software packages. A DST tape was then prepared with the resulting gamma, charged track and Cerenkov information.

6.3 IDENTIFICATION OF η AND CHARGED PION CANDIDATES

6.3.1 The η

The η is found by selecting $\gamma\gamma$ mass combinations in a given mass range. To be used in such combinations, the γ 's must satisfy several conditions. They must hit Olga ≥ 1 block away from the up/down, left/right edges of the Calorimeter (to avoid shower leakage from the Calorimeter) and greater than 1 block's width (14.35 cm) from the horizontal median plane to avoid contamination from the e^+e^- pairs copiously produced in NA14. Due to the limit in energy resolution at low energy, all γ 's must have energy > 1 GeV.

When SNARK finds P_x, P_y, P_z for a γ , it assumes that the event vertex is in the centre of the target. As a result of the TRIDENT processing, a more accurate estimate of the vertex position is available, based upon the reconstructed charged track trajectories. Thus all γ momentum components are re-calculated using the TRIDENT position. Of course TRIDENT may not find a vertex, in which case the event is rejected from the analysis. TRIDENT may also find a false vertex, and to guard against this cuts are imposed upon the TRIDENT vertex to require it to be in the region of the target.

As the trigger in Olga requires a large transverse momentum shower, it follows that the η seen will also be at high p_t . Looking at the p_t of the leading γ seen in an event (e.g. figure 49) shows the effect of the trigger and also reveals the presence of a low p_t tail. This arises where the trigger hit

was not reconstructed in SNARK as a good γ : the trigger shower might have been an electron for example. In order to require a high pt. η , the leading γ is required to have pt. > 800 MeV/c, and it must feature in all $\gamma\gamma$ combinations.

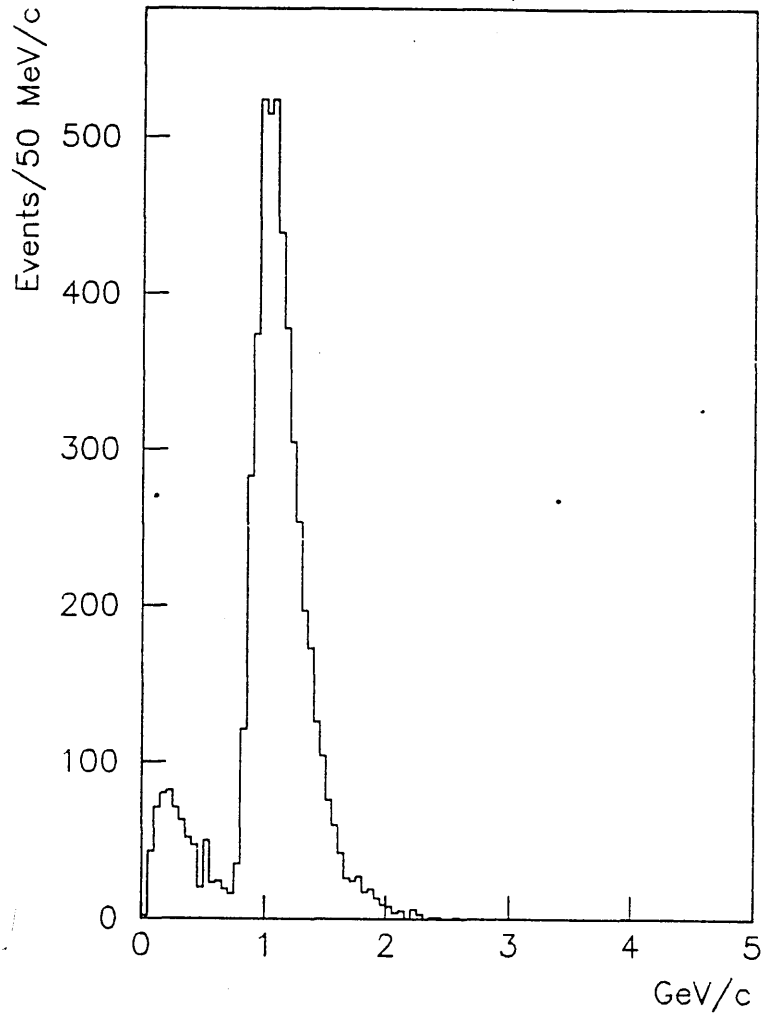


Figure 49: Leading γ Pt. (Sept. 1982)

The resulting $\gamma\gamma$ mass plots per period, are shown in figure 50. In order to select η 's from the plots a mass cut is imposed.

This is chosen to maximize the signal / background so it does not select all the η seen. For the 1982 data a mass in the range $0.5 \rightarrow 0.62 \text{ GeV}/c^2$ (95.7% of visible η) is required, and for the 1983 data the cut was $0.5 \rightarrow 0.6 \text{ GeV}/c^2$ (92.4% of η). The difference between the 2 cuts reflects a slightly different η width, arising from a better performance of Olga in 1983.

Once an η candidate is found, the two γ (E,p) 4-vectors are taken and kinematically constrained to give the η mass. The resulting η 4-vector is then used in all subsequent analysis.

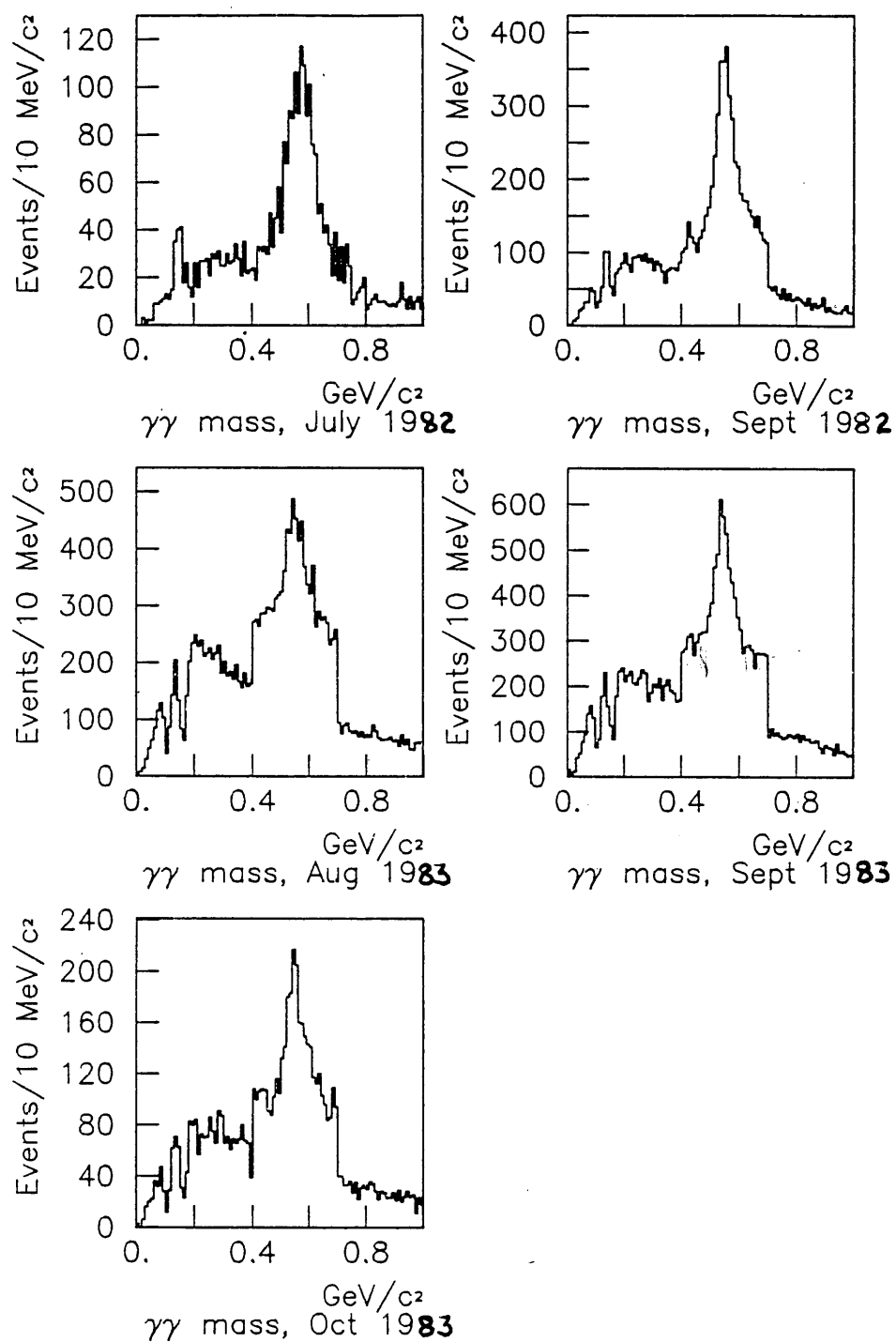


Figure 50: $\gamma\gamma$ Mass Plots Per Period

6.3.2 The Charged Tracks

The charged tracks, measured in the spectrometer, are reconstructed using the program TRIDENT. The tracks must either be flag 2 (seen before the Goliath magnet only) or flag 4 (seen both before and after Goliath). The following cuts are then applied to the tracks :

For flag 2's, the momentum (p) is required to be in the range $1 \rightarrow 20$ GeV/c, and $\Delta P/P$ must be < 0.80 . For flag 4's these cuts are $2 < P < 80$ GeV/c and $\Delta P/P < 0.60$. Each track must also have an opening angle to the beam of > 3 mrad. They must have $P_z > 200$ MeV/c, and $pt. > 150$ MeV/c. These cuts fulfill two requirements, they cut tracks accompanying the beam particle (which are parallel to the beam axis), and they reduce contamination from the e^+e^- pairs which are produced with low $pt.$ and are opened by the magnetic fields in the horizontal plane.

Two cuts are also possible based upon particle type. The first of these finds tracks identified as electrons. These are flag 4 tracks associated with a hit in Olga, and which have energy (Olga) / momentum (TRIDENT) of ~ 1.0 . These tracks are flagged as electrons and rejected from the analysis whenever a pion is required. For flag 4 tracks it is also possible to use the Cerenkov information. This cut is used only to flag definite non-pions. Such tracks have $p > 8.0$ GeV/c (i.e. they are well above the pion Cerenkov light threshold in INDRA), have a hit in INDRA but are associated with no light. Given the $> 98\%$ efficiency of INDRA for responding to light, such tracks are clearly not pions.

6.4 $\eta' \rightarrow \eta\pi\pi$

Before proceeding to look for a rare decay, it seems reasonable to check the data for any well known particles. Given a data set of η s and charged pions, the particle with the lowest combinatorial background should be the η' . This has a mass of 958 MeV/c² and a branching ratio to $\eta\pi^+\pi^-$ of 65.3%.

Accordingly $\eta\pi\pi$ mass plots were filled under various conditions. For the 1982 data, figure 51 shows a typical result where all η were used in the plot with the conditions on the pions as shown in the caption. No η' signal is visible. With the 1983 data (where the MWPC efficiency, and hence charged track reconstruction efficiency, is higher), a similar plot is shown in figure 52. This time there is an accumulation evident at the η' mass. The significance of the signal however, lies more in the absence of background than in the strength of the signal itself.

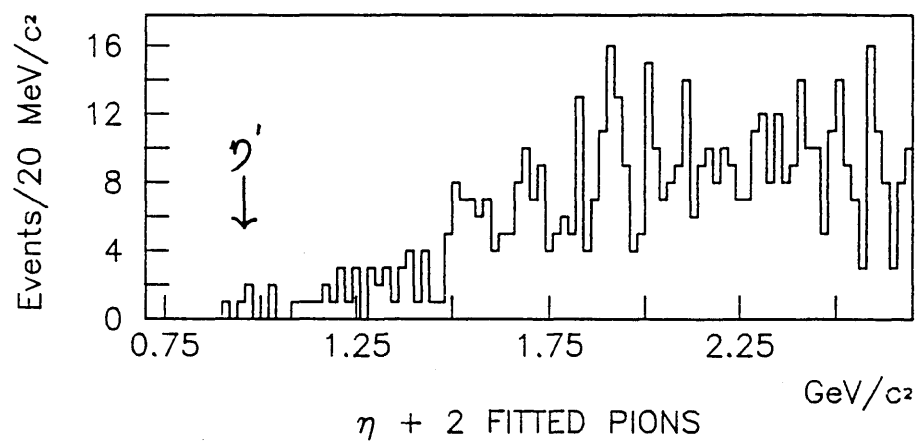


Figure 51: $\eta\pi\pi$ Invariant Masses With 1982 Data

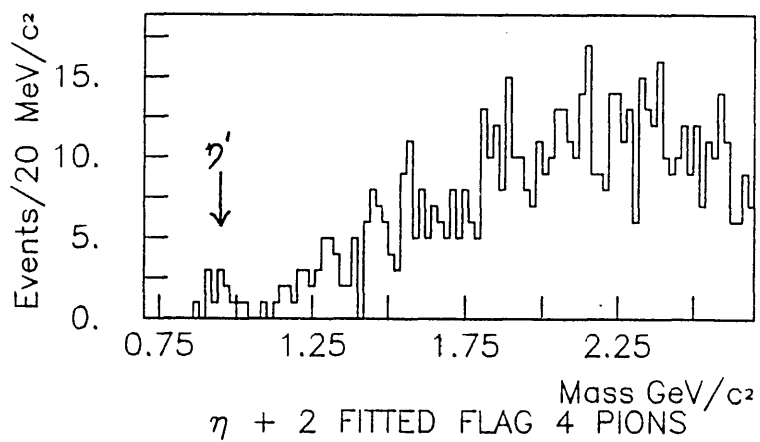


Figure 52: $\eta\pi\pi$ Invariant Masses With 1983 Data

6.5 SEARCH FOR F DECAY

6.5.1 F $\rightarrow \eta\pi$

For $F \rightarrow \eta X$ decays, the most obvious channel to check is $F \rightarrow \eta\pi$. Using the η and charged tracks (pion) data described above, a search was made for evidence of the F in $\eta\pi$ invariant mass plots. All the η candidates were used in each plot but the π candidates were split into categories as follows ; a) all tracks, b) all tracks fitted (attached) to the vertex, c) all flag 2's fitted to the vertex, d) all flag 4's fitted to the vertex. Mass plots for these 4 categories are shown for the 1982 data in figure 53, for the 1983 data in figure 54, and for all data combined in figure 55. The weight given to tracks fitted to a vertex in these selections reflects the results of later MC work where the track arising from the pion in F decay is almost invariably seen attached to the vertex. On none of these plots is a signal evident to the eye in the mass range $1.9 \rightarrow 2.1 \text{ GeV}/c^2$.

As an aid to studying these mass plots, 'background' plots were produced. These are made by substituting a non- $\eta \gamma\gamma$ mass combination for the η . These combinations are found with the single γ 's used in the normal analysis, but the mass cut is changed to $0.4 \rightarrow 0.7 \text{ GeV}/c^2$ with the condition that the mass does not satisfy the normal η mass requirement. These 'background' candidates are then constrained to have the η mass and treated just like the real η 's. The resulting background $\eta\pi$ mass plots are shown for the 1982 data in figure 56, for 1983 data in figure 57, and all data combined in figure 58. To the eye these plots

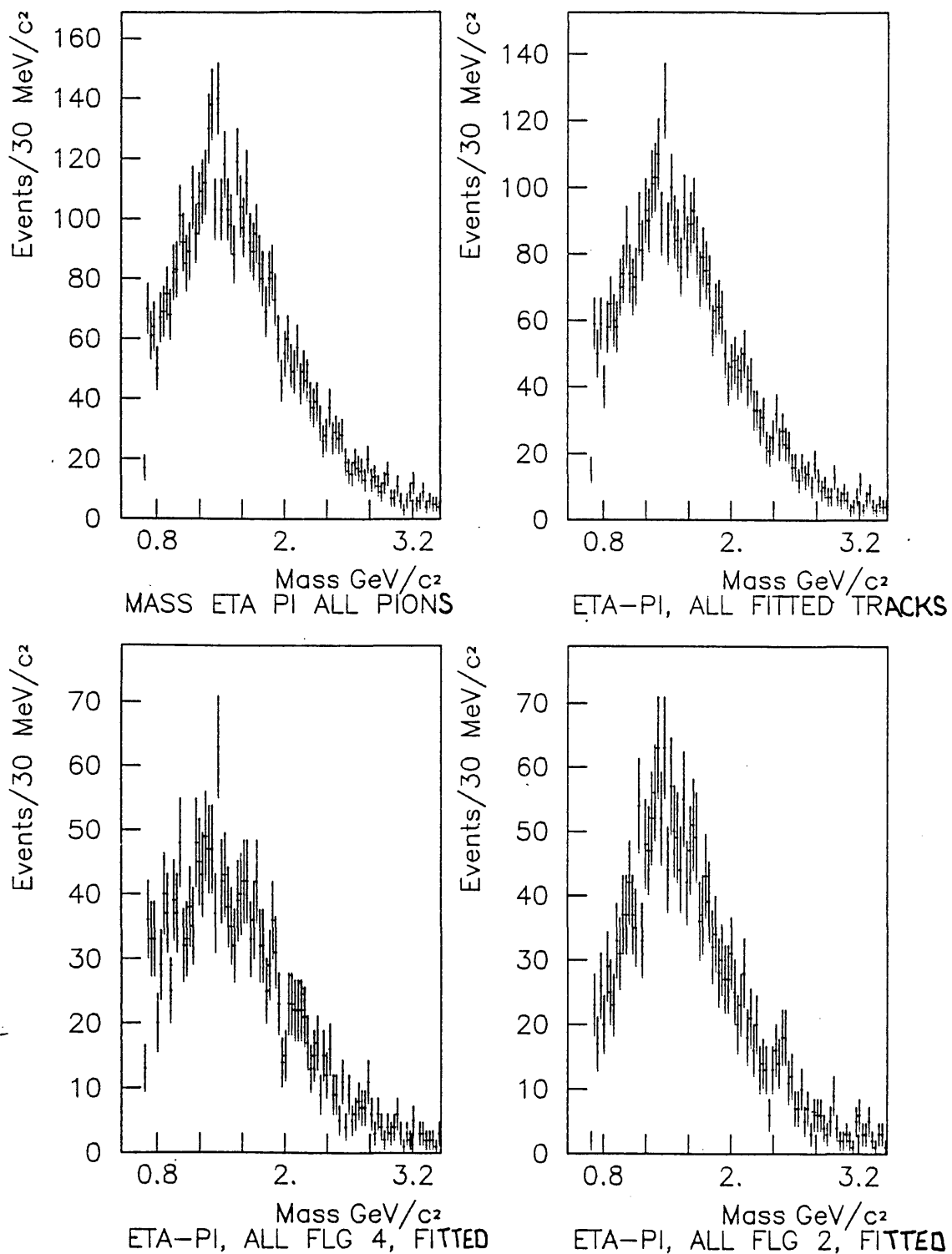


Figure 53: $\eta\pi$ Invariant Mass With 1982 Data

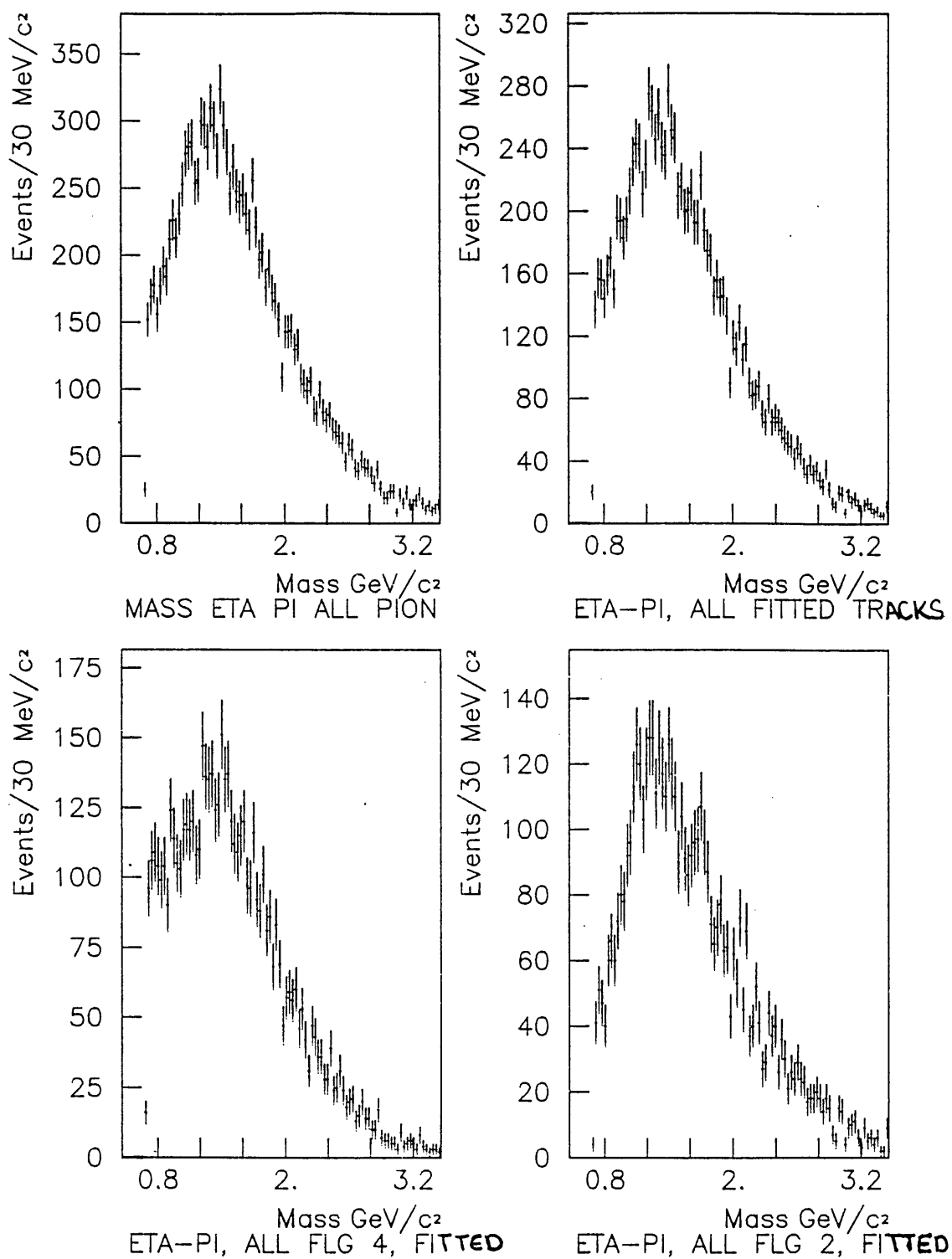


Figure 54: $\eta\pi$ Invariant Mass With 1983 Data

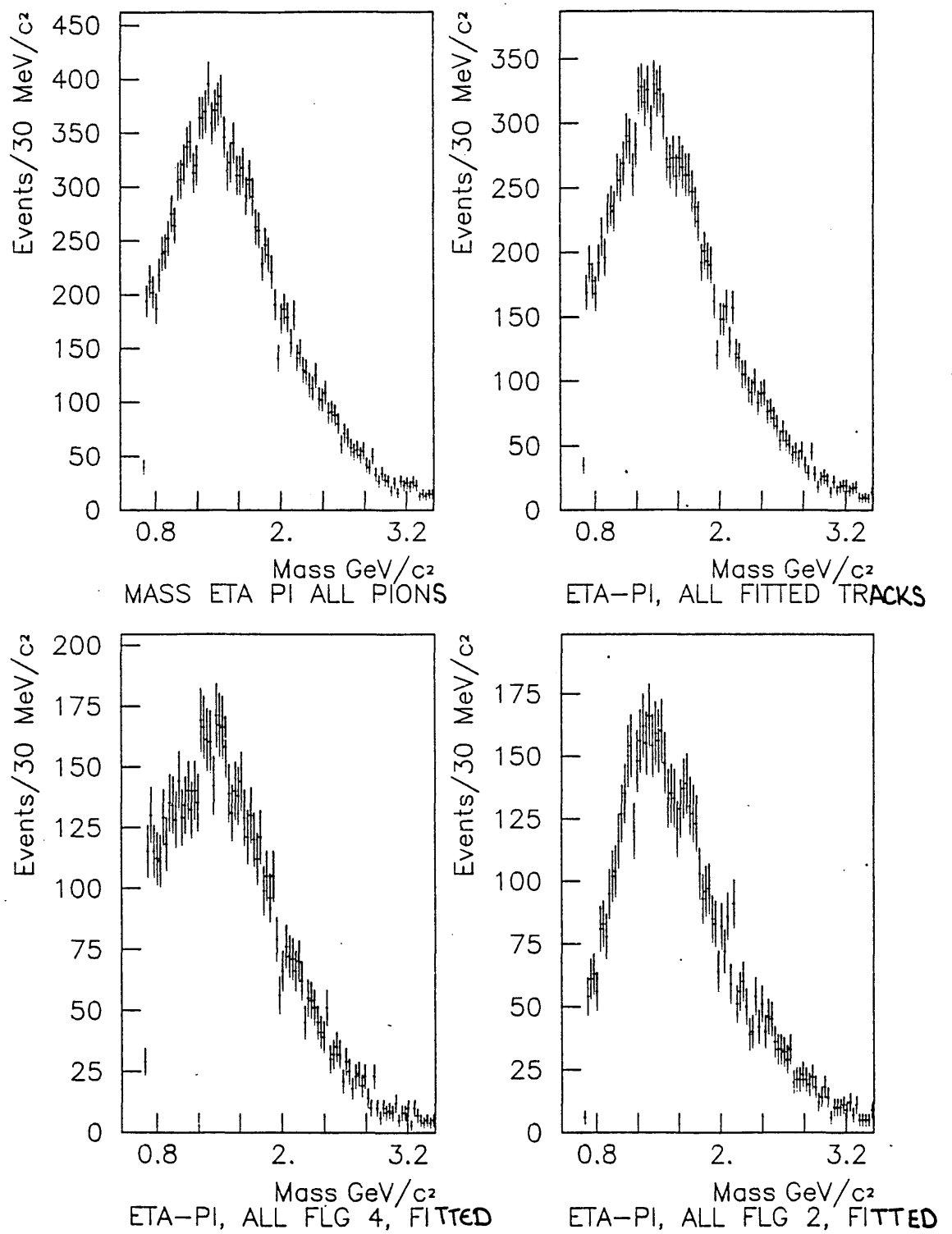


Figure 55: $\eta\pi$ Invariant Mass In All Periods

well reproduce all features of the genuine data. This is confirmed by scaling the number of entries on a background plot by the number in the appropriate genuine data plot, and then superimposing the two. In no case does a clear discrepancy appear.

One feature that appears in several of the mass plots, is a spike just above the $\eta\pi$ mass threshold. This appears on background plots as well as the real ones, for flag 2's and for flag 4 tracks, and upon investigation proved to arise from events where the TRIDENT vertex used is a poor estimate of the true vertex. In events where several flag 4 tracks are attached to the vertex, this spike is not visible.

As a further check for any signal, several curve fitting procedures were tried. In all cases a background curve and a gaussian for the F are added and fitted to the data. The background in the genuine plots can be found in three different ways : a) by fitting a curve to the background mass plot and then scaling the resulting function by the relative number of entries in the background and genuine plots. In this work a 3rd order polynomial was found to be the simplest function which consistently gave good fits to the background. b) The same as a) except now the relative normalization of the background function to the real data is a variable in the fit. c) Here a 3rd order polynomial is fitted directly to the genuine mass plot.

In all cases the fits were performed over the mass range $1.5 \rightarrow 2.5 \text{ GeV}/c^2$, and were repeated where the mean mass of the gaussian

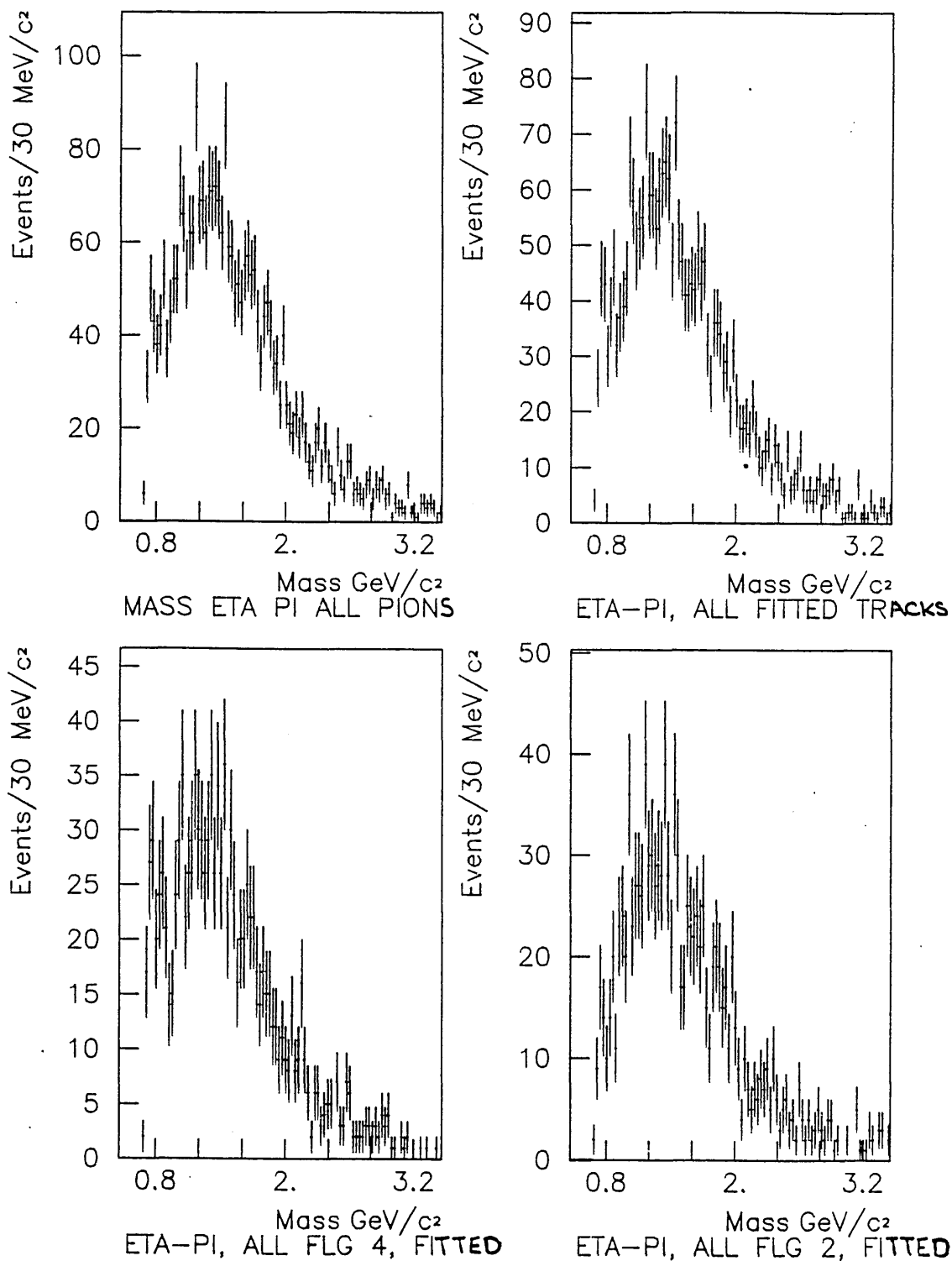


Figure 56: Background $\eta\pi$ Invariant Mass In 1982 Data

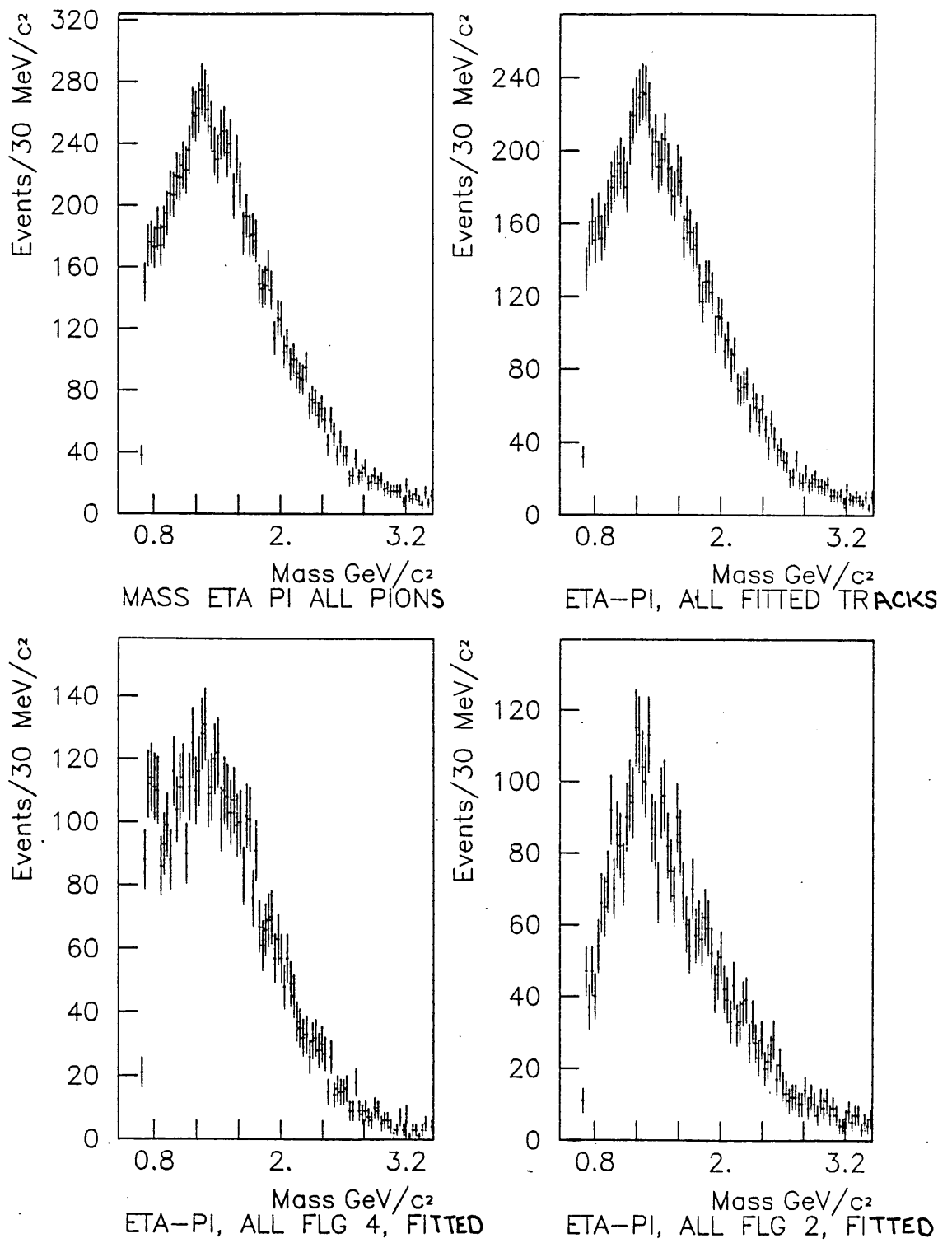


Figure 57: Background $\eta\pi$ Invariant Mass In 1983 Data

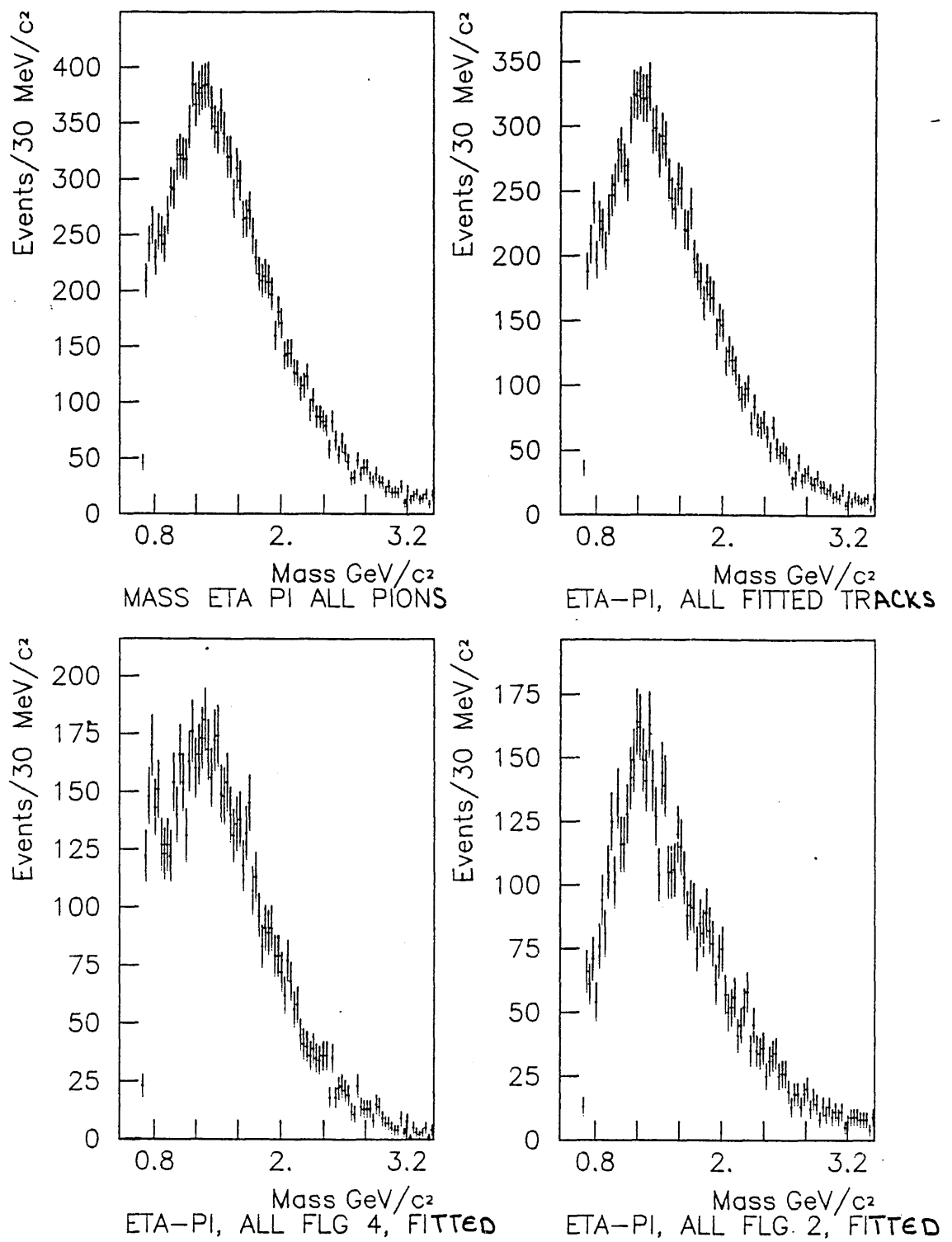


Figure 58: Background $\eta\pi$ Invariant Mass In All Periods

(which was fixed in the fit) was stepped over the range $1.71 \rightarrow 2.25 \text{ GeV}/c^2$ in $30 \text{ MeV}/c^2$ increments. The width of the gaussian was also fixed in the fits, and was chosen as a result of the MC work described later. All 3 types of fits produced similar results, with fits type c) being slightly better quality.

For no value of F mass in any fit on any plot was a gaussian of significant magnitude required by the fit. Here significant is set to be : number of entries in gaussian $> 3 \times \sqrt{\text{number of entries in background curve under the gaussian}}$.

It is still possible however, to cut the data in fashions which might favour $F \rightarrow \eta\pi$ over background $\eta\pi$ events. There are two ways of doing this, both of which involve making greater use of the Cerenkov information. The first of these methods is simply to tighten up the criteria for identifying pions. The previous cut only removed definite non-pions. By requiring a hit in INDRA associated with light, and $6.5 < P < 19.5 \text{ GeV}/c$, a much tighter requirement is imposed. Nevertheless, if the original mass plots are reproduced using these 'pions' as the charged track, there is still no signal apparent.

To understand the next criteria it is useful to review the process of F production and decay. Every F should be accompanied by another charmed particle in order to conserve charm. This could be an F or a D meson. Either way its decay could well proceed via a channel containing a final state charged kaon (e.g. $D^0 \rightarrow \text{charged kaon anything}$, 52% of the time [15]). Another source of final state strangeness arises from the way an

outgoing c quark dresses into an F. If figure 10 is a good representation of this, then F's can well be expected to be accompanied by a final state kaon. The result of all of this is that the presence of a charged kaon may well 'tag' F events. Kaon candidates can be found in INDRA where there is a hit with no light, and $6.5 < P < 19.5$ GeV/c. Such tracks are either kaons, protons or fake tracks.

The original mass plots were reproduced for events in which either one or two kaons accompanied the $\eta\pi$. In no case was any F signal or interesting accumulation in the region of the F mass apparent.

6.5.2 $F \rightarrow \eta\pi^0\pi$

Using the non η γ s in an event (both the single γ s and the merged cluster γ s described in the previous chapter) it is possible to search for a π^0 accompanying an η . Figure 59 shows such $\gamma\gamma$ combinations, a) is for single γ s and b) is for merged clusters, and clear π^0 signals are visible. Using a mass cut of $0.10 \rightarrow 0.168$ GeV/c², π^0 candidates are found and then kinematically constrained to yield the correct π^0 mass.

There are 401 events containing $\eta\pi^0$. These combinations are then taken and added to charged tracks to form $\eta\pi^0\pi$ invariant mass combinations. The usual 4 basic plots are formed and are shown in figure 60. On none of these plots is a signal evident. Using the already described tighter Cerenkov criteria for identifying pions produced no signal, nor did only using events where a kaon was seen in INDRA.

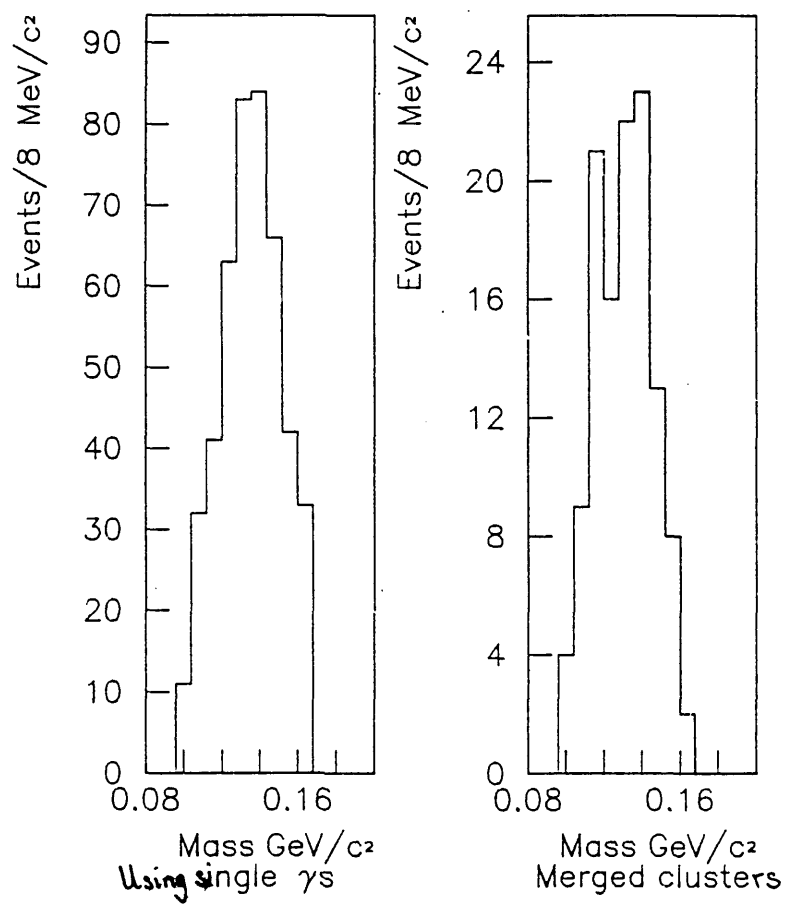


Figure 59: $\gamma\gamma$ Invariant Mass For γ s Accompanying η s

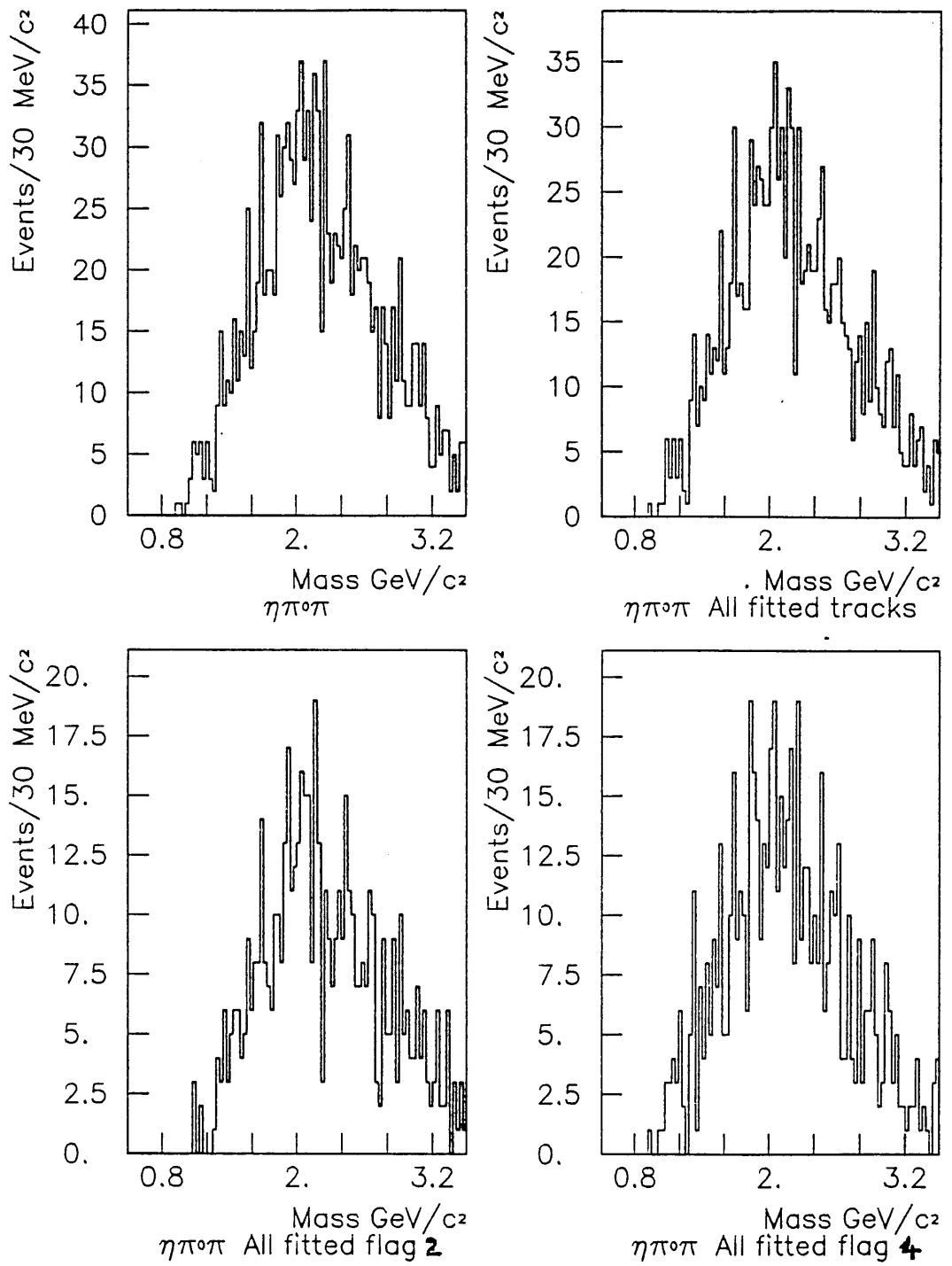


Figure 60: $\eta\pi^0\pi$ Invariant Mass Plots

6.5.3 $F \rightarrow \eta + n\pi$ ($n = 3, 5$)

There is no good reason why the F should not decay to $\eta 3\pi$ or $\eta 5\pi$. Indeed WA4 & WA57 report signals in these channels. Accordingly, the basic η and charged track data sets were used to form $\eta + 3\pi$ and $\eta + 5\pi$ mass plots. Typical results are shown in figure 61.

No combination of conditions on the charged tracks (i.e. all tracks, all tracks fitted to the vertex, all flag 4's etc) produced a mass plot with a significant or interesting accumulation of data in the region of the F mass.

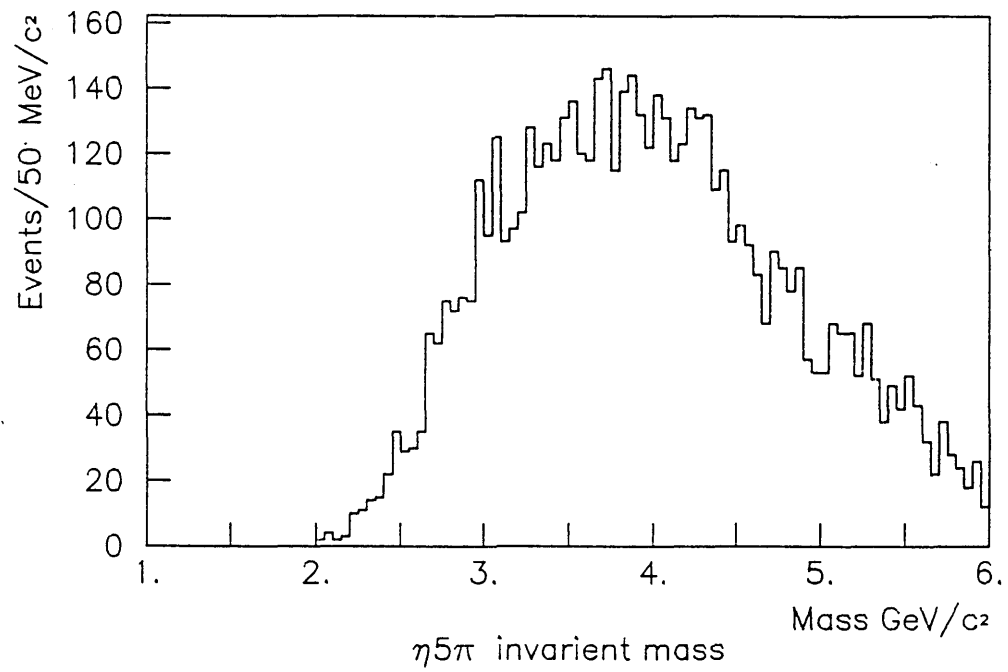
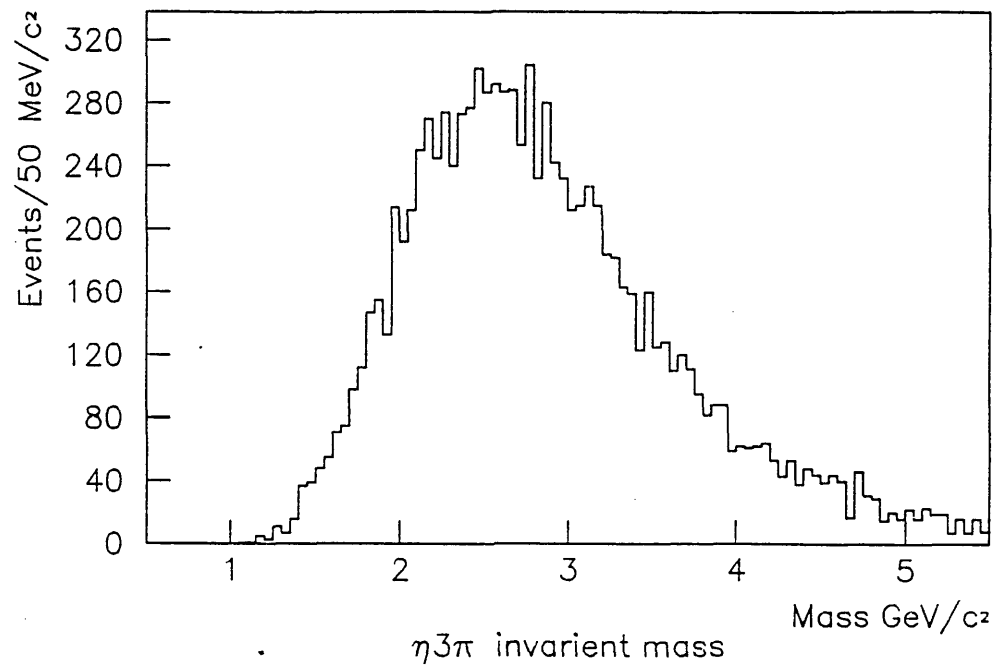


Figure 61: $\eta 3\pi, \eta 5\pi$ Invariant Masses With 1982 Data

6.5.4 $K\bar{K}\pi$

As already stated, associated charm photoproduction is expected. The second charm particle can also be an F meson, and need not decay to ηX . Other experiments have reported $F \rightarrow K\bar{K}\pi$ or $\phi\pi$. Since this data set is essentially η containing, I have searched for associated $F\bar{F}$ production, where one F decays to ηX and the other to $K\bar{K}\pi$. I therefore took the η candidate events as my basic data set.

To identify kaons, the standard criteria of a hit in INDRA with no associated light and $6.5 < P < 19.5$ GeV/c was applied. As a first step (to look for a ϕ) $K\bar{K}$ mass plots were formed where one kaon was flagged by INDRA and the other was any other track simply assumed to be a kaon, see figure 62a). $K\bar{K}$ mass plots were also formed when both tracks were flagged as K's in INDRA, figure 62b). As can be seen, no ϕ signal is evident.

I then formed $K\bar{K}\pi$ mass plots for the 2 $K\bar{K}$ categories. The π was any other charged track with various conditions for filling different plots. Figure 63 show typical results (a) is for one K flagged in INDRA, and b) has both K's flagged). No signal is visible in the mass region $1.9 \rightarrow 2.1$ GeV/c² on any of the plots.

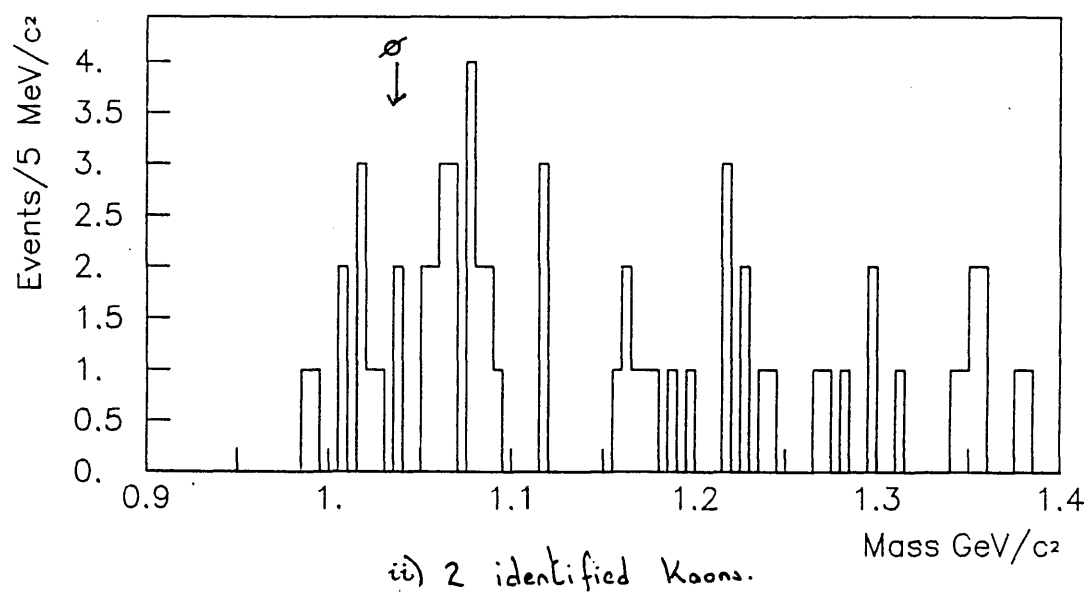
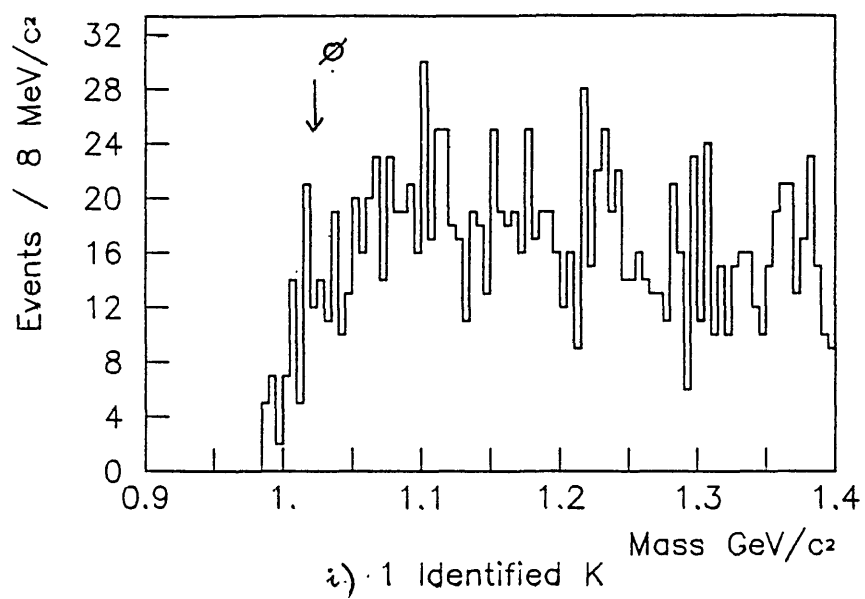
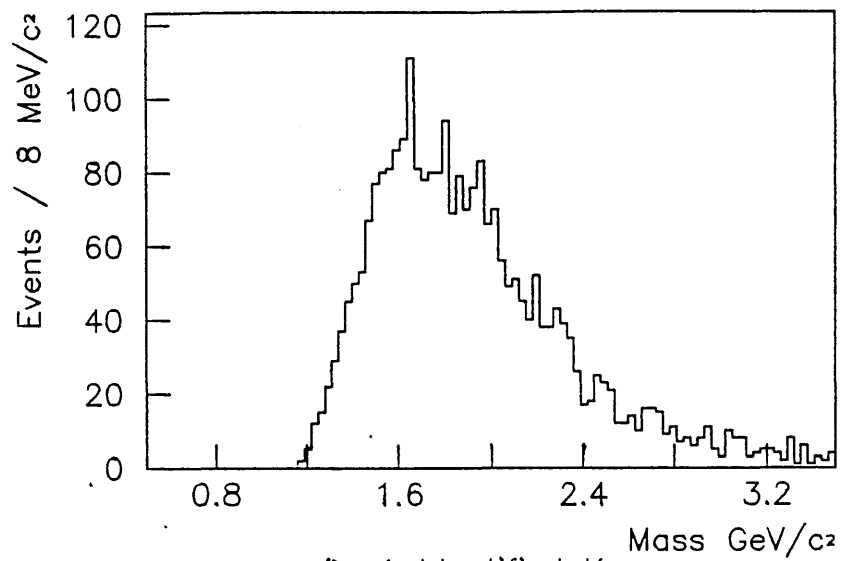
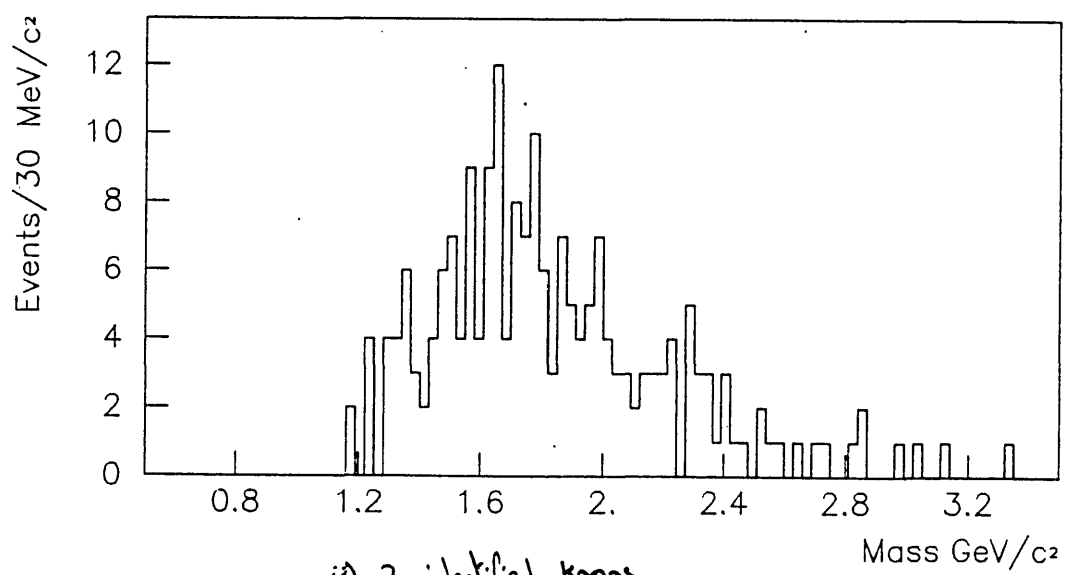


Figure 62: $K\bar{K}$ Invariant Mass Plots



i) 1 Identified K



ii) 2 identified K mesons

Figure 62: $K\bar{K}\pi$ Invariant Mass Plots

6.6 CROSS-SECTION LIMIT FOR $F \rightarrow \eta\pi$

Given the non-observation of $F \rightarrow \eta\pi$, I have calculated a cross-section limit using the sensitivity of the data. To do this I need a limit on the maximum number of F 's which could be expected to be present but not produce a signal in the data due to statistical fluctuations, and to combine this number with the known luminosity and an event reconstruction efficiency found from a MC simulation.

6.6.1 The MC Simulation

In this simulation I require a production mechanism, a model of the detection of particles in NA14, and a knowledge of the performance of the software (TRIDENT & SNARK).

For the production, a parametrization of the $\gamma\gamma$ fusion model was used. The various coefficients used were those suggested as agreeing best with existing experimental results (see Chapter 1). The resulting charm quarks were then hadronized in a LUND MC. [44], with the requirement of at least 1 F per event. All F 's had to decay 100% $\rightarrow \eta\pi$, and the η had to decay 100% to $\gamma\gamma$.

As the analysis of real data requires an η seen as 2 γ s in Olga, with one γ having a large transverse momentum, once an event was generated it was checked to see if the 2 γ s met these conditions. The particular cuts imposed were that both γ s had to be heading for an area slightly larger than Olga presents to the target, and at least one γ had to have $pt. > 1.1 \text{ GeV}/c$. The magnitude of this latter cut reflects a software cut to be

applied in the analysis of the real data (this is due to the known Olga trigger efficiency for single γ s not reaching a significant value, 50%, until $pt = 1.2 \text{ GeV}/c$).

Out of 15k events generated, 959 events (containing 1185 F's) survive these cuts. These events were then run through a simulation of the MWPC's in NA14. This was performed inside the framework of the CERN GEANT software package [45]. This was set up to contain the position of all wires inside the MWPCs in NA14, along with an estimate of the efficiency of the response of each wire. The result of running GEANT is a simulation of the expected digitizations arising from the passage of the charged tracks through the MWPCs. Since the positions of the chambers, and their efficiencies, varied between 1982 and 1983, GEANT was set up differently for each year and thus run twice on the 957 events. Each set of output from GEANT was run through TRIDENT (the standard NA14 track reconstruction program) just like real data.

Studying the TRIDENT and GEANT output banks simultaneously, permits an unambiguous identification of the TRIDENT track, if any, arising from the pion in the F decay. These TRIDENT tracks are cut in the fashion of real data described earlier, and the numbers surviving are used in measuring the overall acceptance * reconstruction efficiency.

For the η , the method outlined in the previous chapter is broadly adhered to. The fiducial cuts applied to the real data are applied. Each γ then has its energy smeared by the energy

resolution formula already derived. The γ momentum components are then found using the vertex reconstructed in the event by TRIDENT, which is cut as for real data. A leading γ pt of > 1.2 GeV/c is now required. The probability of getting a trigger is then applied to each γ using the efficiency shown in figure 33 as a function of pt. . If no trigger is indicated, the event is rejected. All energy independent reconstruction efficiencies, and the $\eta \rightarrow 2 \gamma$ branching ratio are applied later.

To complete the analysis of the η data, the minimum energy cut of 1 GeV is applied to each γ . The γ (E,p) 4-vectors are then kinematically constrained to yield the η mass just as for the real data.

The numbers of events surviving this treatment was noted and used to find the efficiencies for reconstructing $F \rightarrow \eta\pi$ for different categories of charged tracks fitted to the vertex. These quantities are given in table 17, where the total numbers of F seen and produced are used with the assumption of one F per event. The efficiencies are low due mainly to the high pt. γ trigger. It is also possible to use these results to predict the width (σ) of the F gaussian in real data; this is $\sigma = 92$ MeV/c² for flag 2 pions, and $\sigma = 69$ MeV/c² for flag 4's.

TABLE 17

 $F \rightarrow \eta\pi$ MC Reconstruction Efficiencies

	Flag 2	Flag 4
1982	3.34×10^{-4}	2.82×10^{-3}
1983	2.20×10^{-3}	6.83×10^{-3}

6.6.2 Estimate of Limit on Number of F's Expected

The real data was re-analyzed in the same fashion as originally, but with a new software cut on the leading γ pt. ; this now had to be greater than 1.2 GeV/c. The 4 basic mass plots were reproduced for 1982 and 1983 data separately, and are shown in figures 64, and 65. Once again there is no obvious F signal visible to the eye, so a curve fitting procedure was implemented.

As before, for the F's a gaussian of fixed mass and width (set from MC) was used, and added to a 3rd order polynomial (simulating the background). This was then fitted to the data over the mass range 1.5 $\rightarrow$ 2.4 GeV/c², and repeated for masses of the F incremented in 30 MeV/c² steps over the range 1.7 $\rightarrow$ 2.25 GeV/c² (this fitting procedure was the most accurate of the 3 mentioned earlier). For no F mass on any plot was a gaussian of a statistically significant magnitude required.

For each fit the maximum number of F's which could have been expected given the sensitivity of the data, but which, due to statistical fluctuations in the signal and the expected

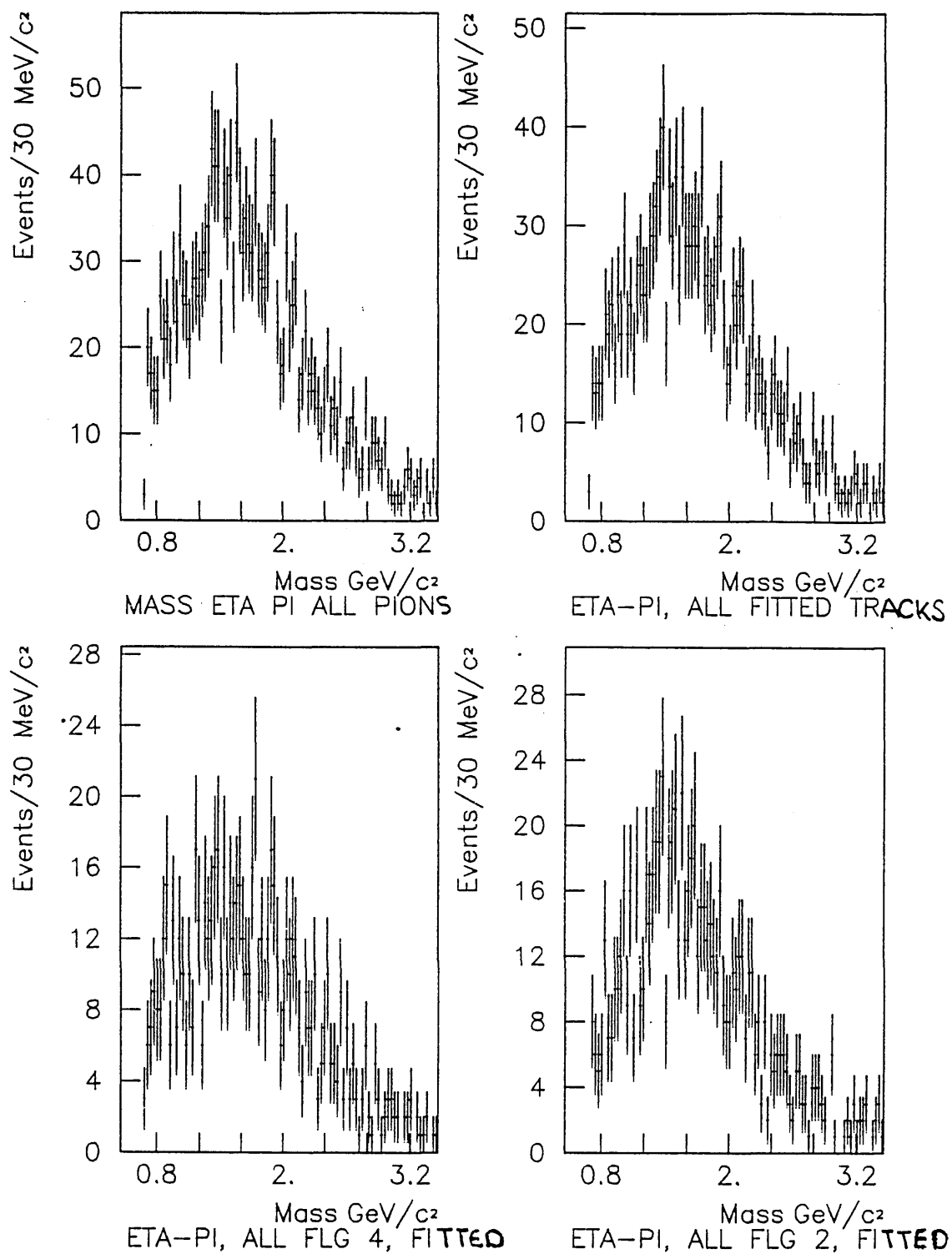


Figure 64: $\eta\pi$ Invariant Mass With γ Pt. > 1.2 GeV/c (1982)

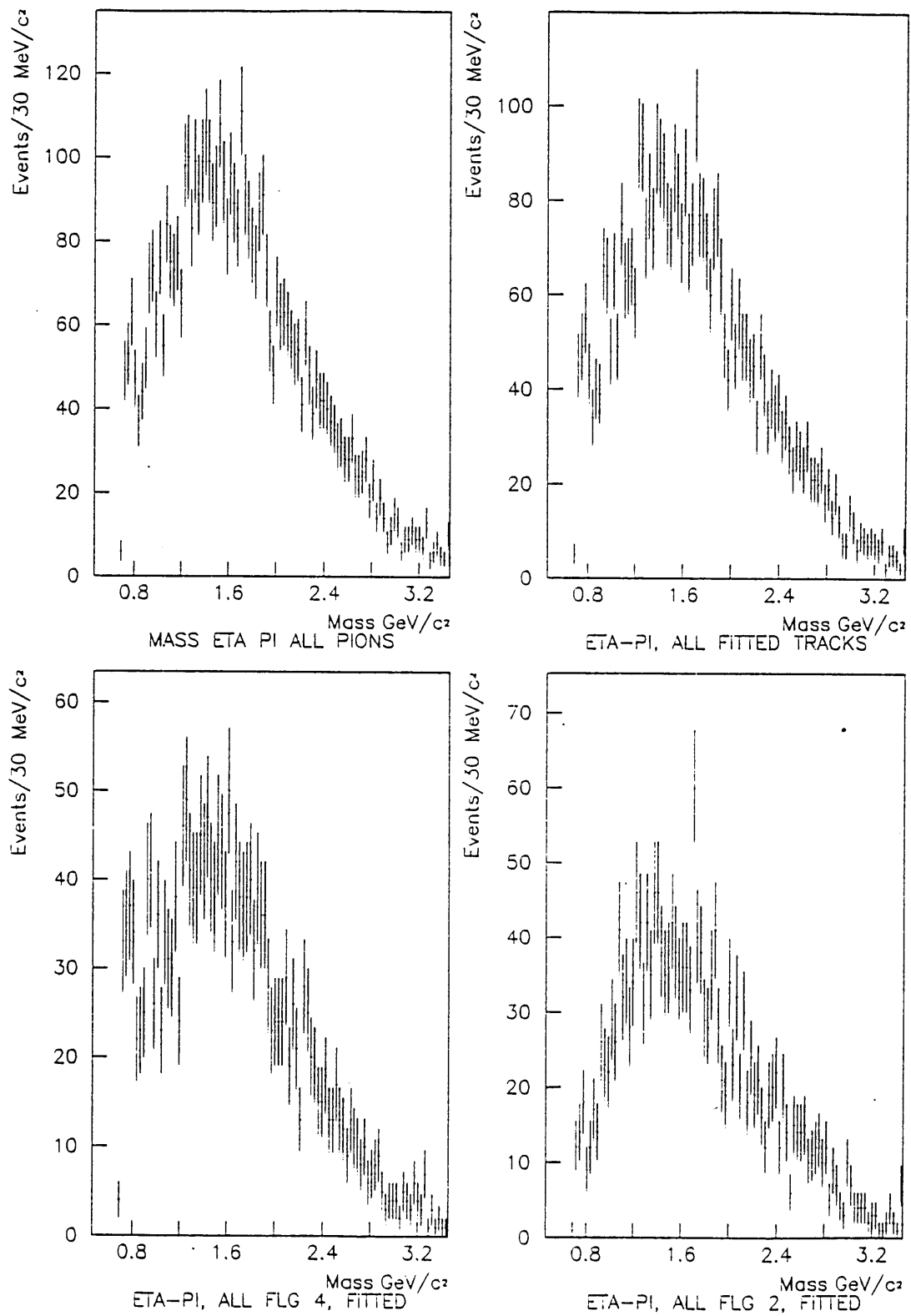


Figure 65: $\eta\pi$ Invariant Mass With γ Pt. $> 1.2 \text{ GeV}/c$ (1983)

background, could produce the observed data with 5% probability (i.e. 95% confidence level), was calculated in the following fashion :

In the region of the F mass the data obeys

$$\text{Expected} = (\text{Signal} + \text{Background}) \quad \text{Eqn 14}$$

However there can be statistical fluctuations in both of the quantities on the right hand side of this equation. For a downward fluctuation such that the observed value has a 5% possibility of coming from a given expected number we have (from gaussian statistics)

$$\text{Observed} = \text{Expected} - 1.65\sigma(\text{Expected}) \quad \text{Eqn 15}$$

Given a small signal, I then apply the approximation that $\sigma(\text{Expected}) = \sigma(\text{Observed})$ and, since Poisson, $\sigma(\text{Observed}) = \sqrt{[\text{Observed}]}$. This allows me to write

$$\text{Signal} = \text{Observed} + 1.65\sqrt{[\text{Observed}]} - \text{Background} \quad \text{Eqn 16}$$

The number in the background is found by integrating the fitted 3rd order polynomial over the range of the gaussian. The 'observed' is simply the total number of entries in the mass plot over the same range.

The resulting number of F's (in 1982 and 1983) v. F mass is shown in table 18. The troughs in the numbers v. mass reflect where the data dips below the fitted background curve in several successive bins in the mass plots.

TABLE 18

Estimate Of Maximum Number Of F's Consistent With Data

F Mass (GeV/c ²)	# Of F's			
	1982		1983	
	Flag 2	Flag 4	Flag 2	Flag 4
1.735	39	23	94	58
1.765	30	29	83	58
1.795	27	36	71	73
1.825	19	38	65	72
1.855	23	33	54	66
1.885	3	27	41	57
1.915	3	30	8	42
1.945	7	28	4	24
1.975	15	33	5	20
2.005	20	35	20	7
2.035	30	29	33	6
2.065	38	21	38	2
2.095	42	20	34	3
2.125	38	21	34	13
2.155	43	17	42	22
2.185	39	21	50	30
2.215	35	15	49	38
2.245	29	9	49	35

6.6.3 Results

The results of this work can be put together to yield an estimate of cross-section $\times$ branching ratio ($\sigma \cdot Br$) for the photoproduction of $F \rightarrow \eta\pi$, using the relation

$$\sigma \cdot Br = \#F / (\text{Luminosity} * \text{Efficiency}) \quad \text{Eqn 17}$$

where the luminosity for each period is given in table 16.

As a function of possible F mass, the resulting $\sigma \cdot Br$ from the 1982 and 1983 data, with the pion seen as a flag 2 or a flag

4 track, are plotted in figure 66. Also on these plots is the original WA4 result. The WA4 result however was calculated for $F\bar{F}$ associated production, and as the results here assume 1 F per event, has been scaled by a factor of 2 from the value given in [17].

There is a clear incompatibility between the WA4 result and that obtained here with flag 4 pions in the 1983 data set. The WA4 experiment was not identical to NA14 in several respects. The differences are mainly a different beam energy (20 to 70 GeV), and a lower leading γ pt. cut (0.8 GeV/c compared to 1.2 GeV/c). Also the Collaboration calculated the acceptance for the F using a diffractive model, unlike the γg fusion model used here. If charm photoproduction is poorly modelled the differences between the two experiments may account for the incompatibility of the results.

● = WA4 result

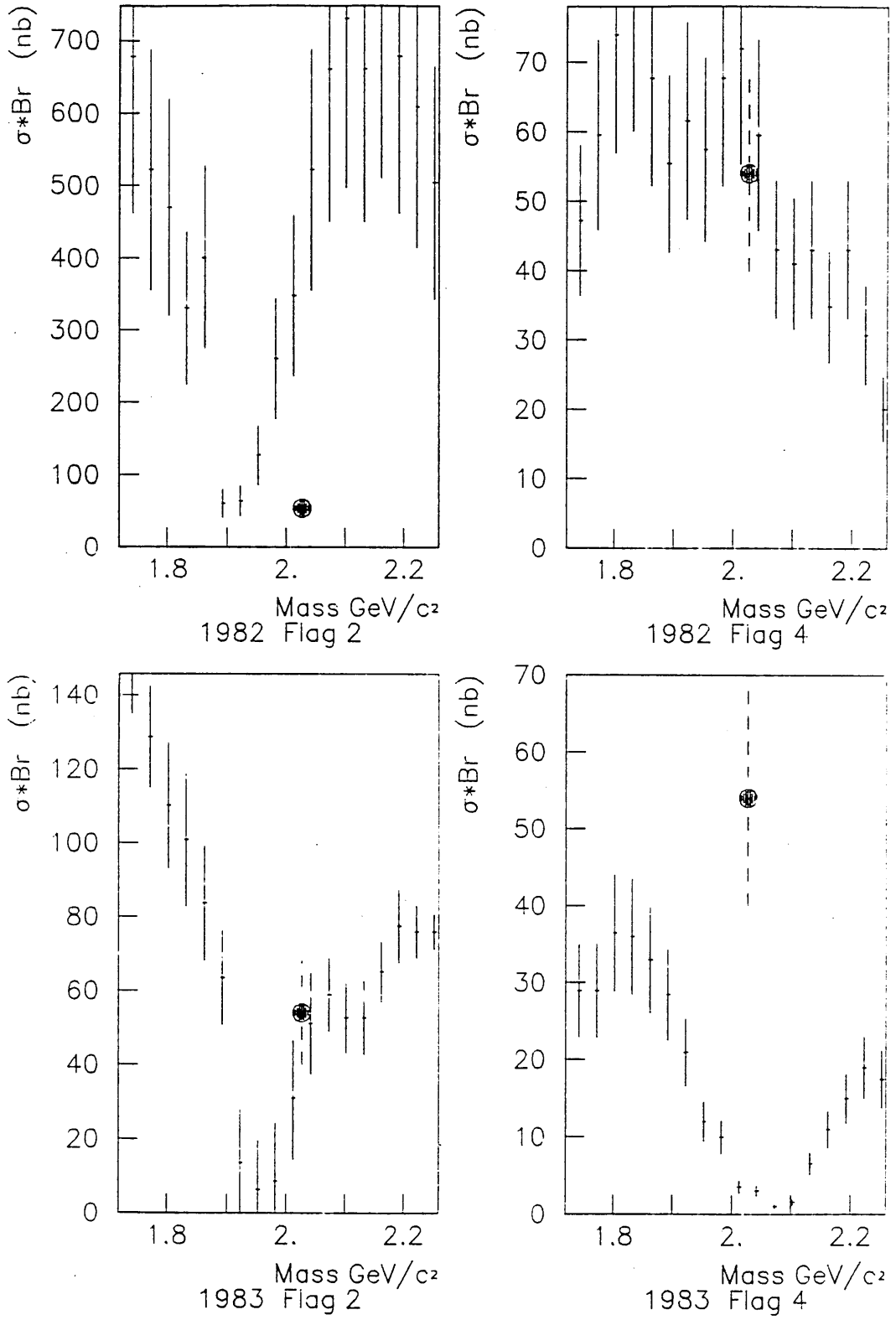


Figure 66: Upper Limit $\sigma \cdot Br$ for Photoproduction of $F \rightarrow \eta\pi$

Chapter VII

CONCLUSIONS

In this thesis, having considered the processes involved in the photon interacting in a point like fashion with a quark/anti-quark pair, I have searched for evidence of heavy flavour (strangeness and charm) photoproduction. Using the facility in NA14 of taking π^- beam data in the same spectrometer, I have contrasted the γ beam results featuring strangeness with those obtained in hadroproduction.

In Chapter 4, the work presented concerning the charged tracks in events, is at a basic level. That there was only one Cerenkov counter operational greatly restricted the charged track type recognition. At different momenta the pions and protons are identified, but the kaon contribution to the charged track multiplicities has to be inferred. The anti-particle/particle ratios and ratios of various particle types in Chapter 4, are not in the main incompatible with the expectations of a naive quark model. In such a model the valence quarks of the incident π^- are expected to be favoured in the particles produced in beam-target interactions, while the photon is presumed to have a more democratic quark composition. The one result not apparently predicted by such a model is that for π^-/π^+ in π^- beam. This is < 1 although the model would clearly favour π^- production. There

is no obvious feature of the apparatus or analysis which would bias charged track observation and cause the expected ratio to appear as that observed. Work to investigate all these ratios at low transverse momentum (pt.) is underway and the π^-/π^+ will be investigated further.

As stated in Chapter 1, a knowledge of η photoproduction was necessary for the analysis of the prompt photon signal in NA14 [2] , in that the γ s coming from η decay appear as isolated γ s and hence are a background to the prompt photon signal. The amount of η photoproduction (relative to the π^0) measured in Chapter 5, was then used in MC simulations to find the $\eta \rightarrow \gamma\gamma$ ^{contamination} of the prompt photon sample.

The results in Chapter 5 concerning the η , can be viewed in terms of the η 's strange quark content. At high pt., and in particular at large $x_\perp$, there seems to be an excess of η production in γ , relative to π^- , beam. If this increase in strangeness were associated with the photon interacting as a $q\bar{q}$ pair, then the appearance of this phenomena at high $x_\perp$ is readily understood; a (strange) quark from the $q\bar{q}$ pair has gone into the η . Such behaviour would not be possible in π^- beam, thus qualitatively yielding the observed trend in the ratio of η/π^0 ratios in the 2 beams.

Further work to investigate this would require an 'exclusive' study of the η events. The charged particle content of the events would be particularly interesting, as the idea of the $\gamma \rightarrow s\bar{s}$ with one s quark going into an η , leaves the other s quark

unaccounted for. It would not be too naive to expect the presence of say a charged kaon accompanying the η in such a model. Such a study of the η events is now under way.

The search for evidence of charm photoproduction described in Chapter 6, was not successful. No evidence for $\gamma N \rightarrow FX$, with $F \rightarrow \eta X$, was found. As already described, earlier photoproduction experiments at CERN published F signals in the ηX channel, but subsequent experiments have cast doubt on this. The comparison between the σ_{br} limit calculated here for $F \rightarrow \eta\pi$, and the observed σ_{br} of WA4 (confirmed by WA57) indicates that the 2 results are not compatible. The cross-section calculations are of course model dependent, using MC events to find acceptances and simulate the effect of cuts on the data. As noted, WA4 did not use $\gamma\gamma$ fusion as their charm production mechanism as I did. In Chapter 1, I explain why $\gamma\gamma$ fusion is held to be the major contributor to the charm photoproduction cross-section, and I thus feel it to be the appropriate model to use. Indeed WA57 also used $\gamma\gamma$ fusion when calculating their measure of σ_{br} for $F \rightarrow \eta\pi$ photoproduction.

I thus state that assuming $\gamma\gamma$ fusion (as described) as the expected production mechanism, I fail to find the $F \rightarrow \eta\pi$ signal expected using the published σ_{br} of WA4 and WA57.

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