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Study of Double Charm events in the NA14/2 Photoproduction Experiment

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[†]Ph. D. dissertation

Abstract

A study of the correlations among fully reconstructed charmed particles pairs has been performed. First one presents the method followed to extract the data sample where both charmed particles have been detected. One uses, as the starting point of the selection process, a sample of D mesons decaying in the following channels: $D^0 \rightarrow k\pi$, $D^+ \rightarrow k\pi\pi$ and $D^0 \rightarrow k\pi\pi\pi$. Considering the $(1.835 - 1.875)$ GeV/c^2 mass region one disposes of $1,134 \pm 35$ D mesons on a background of 671 ± 27 .

Two subsamples were extracted, one containing 71 double charm candidates with 22 ± 5 fully reconstructed $D\bar{D}$ pairs, and a cleaner single charm sample containing 796 ± 30 D mesons on a background of 274 ± 18 .

The p_T , p_T^2 , p_L and Y (rapidity) distributions for the single D meson are studied (Inclusive analysis). The theoretical expectations are obtained using the computation at order $O(\alpha_s\alpha_{em})$ of perturbative QCD (γg fusion) together with the LUND fragmentation model. The effect on the theoretical predictions of two fragmentation functions and of two mean values of the intrinsic p_T^2 of the target nucleon ($\langle p_T^2 \rangle_N$) are studied. A good agreement between the data and the Monte Carlo predictions is achieved.

The inclusive analysis yields $\chi^2/dof \sim 1.1$ and $\chi^2/dof \sim 0.6$ for the single charm and double charm samples respectively using a soft fragmentation function, $zD(z) \propto (1-z)$, and intrinsic p_T of $\langle p_T^2 \rangle = 0.1 \text{ (GeV}/c)^2$.

The correlations analysis is based on the p_T , p_T^2 , p_L , Y and M (mass) distributions for the $D\bar{D}$ system and the angle between the transverse component of the momentum, φ , and the rapidity gap, ΔY between the two D mesons (D and $\bar{D}$). The comparison to the theoretical expectations yield some discrepancies on the mean values of the distributions and larger values of χ^2/dof (1.1-2.1) than those found in the inclusive analysis. But, given the statistical significance of the double charm sample one concludes that the theoretical predictions are compatible with the measured values in the data.

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To Paz, Alicia and Patricia

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Chapter 1

Introduction.

The topics that will be fully developed in the thesis are briefly described here. Also an outline of the structure of the document is presented.

1.1 Overview

The cleanness of the charm photoproduction process makes it ideal to study the production dynamics and to test the validity of the QCD predictions. It is also a good place to test the different hadronisation models.

In particular, very little data has been available for the study of events where both charm particles have been fully reconstructed. These kind of events will give extra information, and the hadronisation models can be fine tuned to reproduce the correlation between the two charmed particles.

Here two analysis have been carried out. First, the inclusive study of charmed particle has been fully developed. The main aim was to verify that the QCD predictions at the lower order together with the standard LUND fragmentation model are able to reproduce the measured quantities of the real data. The second part consisted in the study of the correlations of a fully reconstructed double charm sample.

1.2 Chapter outline

The thesis has been divided in eight chapters, the first one being this introduction. A brief description of the remaining chapters follows:

- Chapter 2

In this chapter the theoretical background needed to understand the charm photoproduction is developed. Also, the usual techniques of Monte Carlo simulation and their applications to the present work are given.

- Chapter 3

The experimental setup, emphasizing the detectors more closely related to the analysis, form the main body of this chapter.

- Chapter 4

Here a brief description of the data acquisition process is presented. There are also some details about the monitoring of the apparatus.

- Chapter 5

The set of programs used to obtain the final samples are described. The different "filters" used to obtain many of the data samples, and some of the standard programs available to the NA14/2 collaboration are summarized.

- Chapter 6

The samples used in the analysis are presented in the form of mass plots. The different characteristics of the samples are summarized. The statistical information is also given.

- Chapter 7

Here the analysis process is fully described. And the final results are presented.

- Chapter 8

The conclusions drawn from the analysis are summarized.

Chapter 2

Theoretical background

2.1 The Standard Model

This is the name given to the set of theories which best describe the experimental results up to date. Included in the standard model are the Weinberg-Salam electroweak theory and Quantum Chromo Dynamics (QCD) [1,2].

The electroweak part of the model has been extensively compared with the experimental results and the agreements has been found to be impressive. QCD, on the other hand has been found to be more difficult to manage.

The main reason for this is the coupling constant. One of the most common ways of calculating the effect of an interaction is using series expansion of the "collision matrix" (perturbative computation). One can stop the computation at a given term (order) of the expansion if the terms of higher order contribute only a fraction of that of the lower order terms. This is the case of the Weinberg-Salam electroweak theory since the coupling constants (g and g') are smaller than one.

In QCD, the perturbative approach is not always valid since the effective coupling constant, α_s , changes depending on the momentum transfer, Q^2 , of the reaction under investigation. Therefore, the QCD predictions can only be computed in the limit where $\alpha_s < 1$. This is usually called "Perturbative QCD".

2.2 Photoproduction

2.2.1 Interaction of the photon with matter

Considering the interaction of the photon with the target, two type of interactions may take place:

Diffractive

The photon is “transformed” into a final state consisting in a coupled $q\bar{q}$ pair, which carries most of the initial photon energy. This results in forward production of particles with a relative low multiplicity in the final state. the relative importance of the diffractive process has been estimated [14]($E_\gamma \sim 100 \text{ GeV}$) to be only a few percent of the total charm photoproduction cross section.

Non-Diffractive

In this process the photon “collides” with the target-object (gluons, quarks) and new particles are produced. These interaction products will be produced essentially at rest in the CM frame.

Figure 2.1 shows an example of diffractive charm production. In figure 2.2 one finds a non-diffractive process yielding charmed final states.

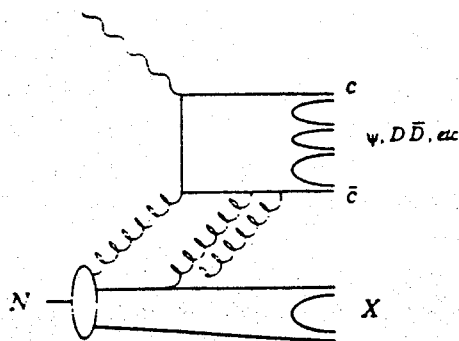


Figure 2.1: Diffractive charm production

One can further classify the interaction by taking into account the effect of the target nucleus:

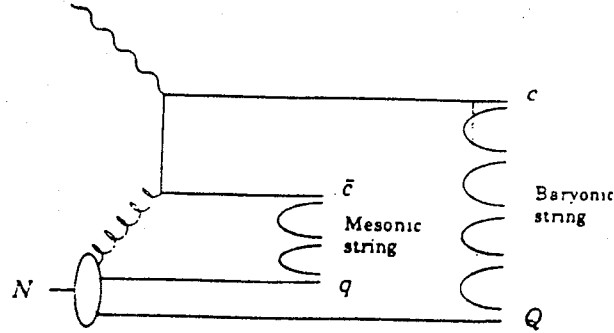


Figure 2.2: Non-diffractive charm production

Incoherent

The photon interacts directly with the nucleon and the nucleus is broken into pieces (nuclear break-up). This is observed by the existence of highly ionizing nuclear fragments emitted isotropically in the nuclear rest frame, called "black-tracks", (emitted at large transverse angles to the beam direction), and the existence of the so called "grey tracks" (protons coming from the nuclear disintegration). Both terms are taken from emulsion experiments.

Coherent

In this case the nucleus interacts as a whole and recoils without disintegrating. Then, the interaction products can only be produced by the creation of a $q\bar{q}$ pair, i.e. there are diffractive events. The contribution of coherent events, when using a silicon target, can be calculated to be :

$$\sigma_{c\bar{c}}(\text{coherent}) \sim 0.3\sigma_{c\bar{c}}(\text{diffractive})$$

The effect of the nucleus in the measured cross-section is parametrized as :

$$\sigma(\gamma A \rightarrow c\bar{c}x) = A^\alpha \sigma(\gamma N \rightarrow c\bar{c}x)$$

Where A is the mass number of the nucleus and α measures the screening effect produced by the presence of other nucleons in the nucleus. For charm photoproduction one expects little screening. It has been measured [19] in J/ψ meson production :

$$\begin{aligned} \alpha_I &\sim 0.94 && \text{Incoherent} \\ \alpha_C &\sim 1.4 && \text{Coherent} \end{aligned}$$

where one would expect $\alpha_I \sim 1$ and $\alpha_C \sim 2$ if there were not screening.

Concerning the photon behavior when interacting with matter, one can divide in:

Pointlike

The photon interacts directly with the target. As an example the QED compton and QCD compton scattering are shown in figure 2.3.

Hadron-like

In this case one considers that the photons dissociates into quarks which then interact with the target. This behavior is schematically shown in fig 2.4

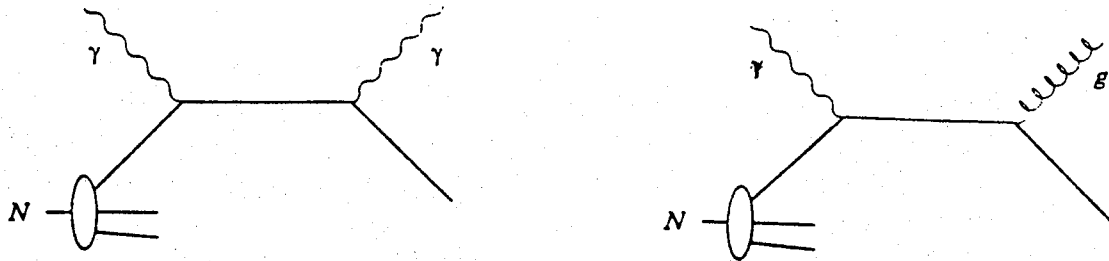


Figure 2.3: Pointlike interaction of the Photon

- a) QED compton
- b) QCD compton

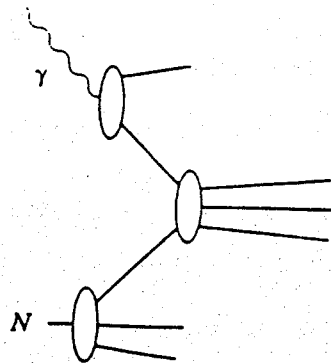


Figure 2.4: Hadronlike interaction of the Photon

2.2.2 Vector Meson Dominance

An early model proposed that the photon was “formed” by a superposition of vector mesons [3]. In this model the photon dissociates preferably into coupled states $q\bar{q}$ with a vector behaviour (thus Vector Meson Dominance, VMD) and the same quantum numbers of the photon. In fig 2.5 the vector meson behaviour of the γ is shown.

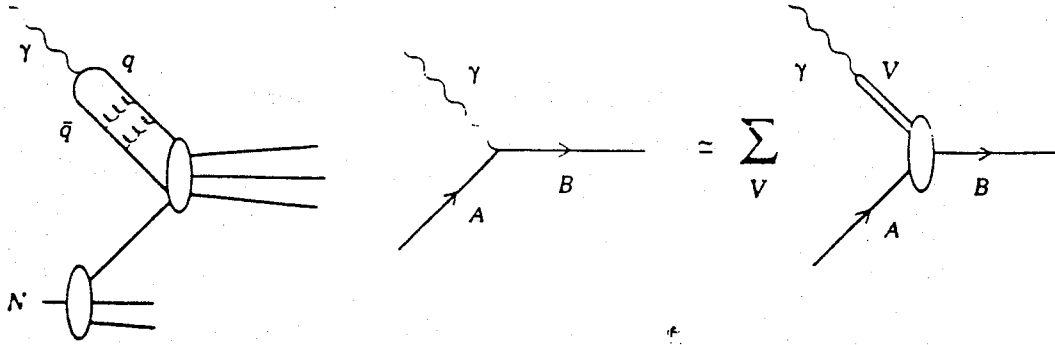


Figure 2.5: Vector Meson Dominance

The invariant amplitude (M) can be written as

$$\mathcal{M}(\gamma A \rightarrow B) = \sum_v \frac{1}{g_v} \frac{m_v^2}{m_v^2 - q^2 - i\Gamma_v m_v} \mathcal{M}(V A \rightarrow B) \quad (2.1)$$

Here g_v is the coupling of the vector meson, V , measured from its leptonic decay, m_v and Γ_v are its mass and width respectively, and $q^2 = (P_A - P_B)^2$ is the 4-momentum transfer of the process.

This model is in principle “contained” in QCD. Usually, the momentum transfer, Q^2 , of the reaction is small and perturbative QCD is not applicable.

2.2.3 Charm Photoproduction

The Q^2 of a reaction yielding a quark, q , of mass m_q and transverse momentum P_T is of the order of

$$Q^2 \sim m_q^2 + P_T^2$$

In the case of a charm quark, one has $m_c \sim 1.5 \text{ GeV}/c^2$ then $Q^2 > 2 \text{ GeV}^2/c^2$ which is larger than the hadronisation scale of QCD. Therefore, in charm-production processes, perturbative QCD should be valid (even for low P_T) and charm photoproduction experiments should be a good place to test the validity of QCD predictions.

2.3 QCD Charm Photoproduction

2.3.1 Lower Order

In perturbative QCD the lowest order contribution to charm photoproduction is the one described by the graphs shown in fig 2.6

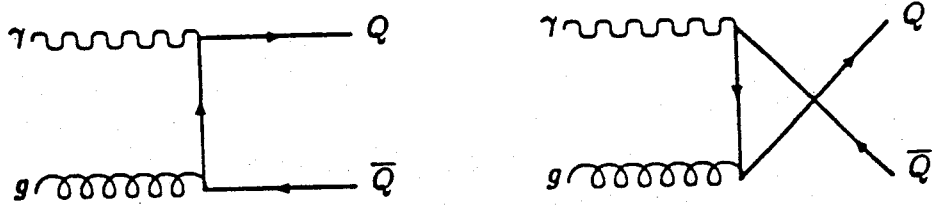


Figure 2.6: Lower order graphs for $\gamma N \rightarrow c\bar{c}X$

Since the photon interacts with a gluon from the target nucleon, this is known as Photon-Gluon Fusion (PGF or γg fusion).

If one uses the distribution function of the gluon in the nucleon $G(x)$. The cross section for the process $\gamma N \rightarrow c\bar{c}$ can be written as :

$$\sigma(\gamma N \rightarrow c\bar{c}, S) = \int_{x_{min}}^1 dx \sigma_{\gamma g}(\gamma g \rightarrow c\bar{c}, xS) G(x) \quad (2.2)$$

where x is the fraction of the nucleon momentum carried by the gluon, $\sigma_{\gamma g}(\gamma g \rightarrow c\bar{c})$ is the cross section obtained from the graphs represented in fig 2.6. x_{min} is the

lower value of the fraction of momentum ($x_{min} = 4m_c^2/s$) allowed by the kinematics of the process, and s is the Mandelstam s -variable of the process γN , given by : $s = (2E_\gamma + M_N)M_N$, E_γ being the photon energy in the frame where the nucleon is at rest.

At this order the cross section of the process $\gamma g \rightarrow c\bar{c}$ has been calculated [4] :

$$\sigma_{\gamma g} = \frac{\pi\alpha\alpha_s e_c^2}{\bar{s}} \left((3 - \beta^4) \log \left(\frac{1 + \beta}{1 - \beta} \right) - 2\beta(2 - \beta^2) \right) \quad (2.3)$$

where e_c is the charmed quark electric charge, α and α_s are the electromagnetic and strong coupling constants respectively. $\bar{s}$ is the Mandelstam s -variable of the γg system, $\bar{s} = xs$, and β is the charm quark velocity

$$\beta = \left(\frac{P_c}{E_c} \right)_{CM} = \sqrt{1 - \frac{4m_c^2}{\bar{s}}}$$

2.3.2 Next Order Calculations

The second order $O(\alpha_s^2\alpha_{em})$ have been calculated recently [5]. This is the first order where the hadronic components and the radiative corrections start to contribute to the photoproduction cross section.

The hadron-like contributions are the same as in hadro-production, but its importance on the γN cross section is controlled by the distribution functions of the quarks in the photon. In hadro-production, the distribution functions used are those of the quarks in the incoming hadron (the beam in a fixed target hadro-production experiment). The calculation of this contribution can be found in ref. [6]

The point-like component (where the photon couples directly to the partons in the target nucleon) are explicitly calculated in ref. [5]. The main conclusions found in that paper are the following :

- a) Using the standard [7] photon structure function, the hadronic component is found to contribute less than 5% to the total cross-section in the energy range $50 < E_\gamma < 400 \text{ GeV}$. So, for fixed target experiments it can be neglected.
- b) Including a gluon distribution of the type:

$$xG(x) = 3(1 - x)^5 \quad (2.4)$$

one can compute the evolution of the cross section with the energy. In this case the choice of the value for the mass of the charm quark is of great importance at the fixed target experiment energies. In figures 2.7, 2.8 and 2.9 this evolution is presented and compared with the experimental results. The corresponding values for NA14/2 have also been included. A complete description of the process followed to determine the quoted NA14/2 results can be found in references [8,9]

From these figures one can conclude that small ($m_c = 1.2 \text{ GeV}/c^2$) values of the quark charm are ruled out whilst a $m_c = 1.5 \text{ GeV}/c^2$ reproduces quite well the experimental results.

- c) Using the Peterson phenomenological fragmentation function

$$D(Z) = \frac{1}{Z} \left(1 - \frac{1}{Z} - \frac{\epsilon}{(1-Z)} \right)^{-2} \quad (2.5)$$

one can calculate the differential cross-section

$$\frac{d\sigma(\gamma N \rightarrow DX)}{dx_F} \quad \text{and} \quad \frac{d\sigma(\gamma N \rightarrow DX)}{dP_T^2} \quad (2.6)$$

In figures 2.10 and 2.11 these quantities are plotted and a comparison to the lower order calculation is made.

It can be observed that the effect of the $O(\alpha_s^2 \alpha_{em})$ is small. Actually the differences will be unobservable within our experimental errors.

2.3.3 Parameter Selection

From eq. 2.2 and 2.3 one can see that the cross-section depends on the following free (not fixed by the theory) parameters : the gluon structure function, the mass of the c-quark and the choice of Q^2 (there is also Λ , the QCD scale, but this is usually fixed to $\Lambda \sim 250 \text{ MeV}$). Once a Q^2 and the form of the gluon distribution function have been selected, the running coupling constant $\alpha_s(Q^2)$ can be determined and the gluon distribution function computed at the given Q^2 .

Mass of the c-quark :

The quarks are not found as free particles since they are said to be confined to the nucleon radius. In this case it is difficult to estimate the right value for their masses. The only experimental information available is the mass of the particles containing c-quarks, but the binding energy of the components are unknown so the mass is not a straightforward computation. Usually one selects

$$m_c = \frac{1}{2} M(J/\psi) \sim 1.5 \text{ GeV}/c^2$$

This value is compatible with the preferred value obtained by the counting rules [10] $m_c \sim 1.46 \pm 0.5 \text{ GeV}/c^2$. And, as has been shown in the previous section, is suitable for reproducing the experimental results.

In any case, the theoretical calculations depend strongly on the value of m_c and this will be the main source of uncertainties in the predictions.

Choice of Q^2 :

Since Q^2 is interpreted as the momentum transfer of the reaction, the logical choice (observing the lower order graphs of fig. 2.6) is to take it equal to the Mandelstam t -variable of the γg reaction. This would yield

$$Q^2 = \bar{t} = \frac{\bar{s}(1 - \beta \cos \theta)}{2} - m_c^2$$

where θ is the angle between the gluon and the charmed quark in the $\gamma - g$ CM frame. This will not be the same for the second graph of fig. 2.6 because the sign of the $\cos \theta$.

A more symmetric choice would be

$$Q^2 = \bar{s}_T = 4m_c^2$$

where $\bar{s}_T$ is the threshold value of the $\bar{s}$ value, $\bar{s}_T = x_{\min} \cdot s$. This choice is also the preferred one in ref. [5].

Gluon structure function:

In Deep Inelastic Scattering (D.I.S.) experiments [11] it has been determined that the non-charged partons (the gluons) carry about half of the momentum of the nucleon

$$\int_0^1 xG(x)dx \sim 0.5 \quad (2.7)$$

with this result and using general criteria as those found in ref. [12] (dimensional counting rules) we can write for a generic parton :

$$xG(x) \sim (1 - x)^{2n-1}$$

where n represents the minimum number of partons involved apart from the one under consideration. In the case of the gluon in the target nucleon $n=3$ (the three valence quarks). Therefore :

$$xG(x) \sim (1 - x)^5$$

The Q^2 evolution of the gluon structure function yields an increase of n for increasing Q^2 . For $Q^2 \sim 10 \text{ GeV}^2$ one finds $n \sim 7 - 10$. [11]. In ref. [13] one can find a very thorough study of the general parametrization of the parton distribution functions together with a fit of the parameters to existing data.

2.3.4 Intrinsic Charm

In the lower order calculation discussed above, the assumption that only the valence quarks are present in the target nucleon has been made. In this case the only mechanism yielding c-quark production is the gamma-gluon fusion.

On the other hand, if one considers the target proton to be a superposition of states $a \cdot |udd\rangle + b \cdot |u\bar{u}dd\bar{c}\bar{c}\rangle$ then there is a possibility at order $\alpha_s\alpha_{em}$ to produce c-quarks in the final state. This was mentioned in section 2.2 as QCD compton scattering.

The contribution of this process to the $\gamma N \rightarrow cX$ cross section is controlled by the charm-quark structure function in the target nucleon. Normalizing the charm structure function to 1% of the total, the contribution of the intrinsic charm is found [14] to be negligible. Thus, it will not be taken into account in our total cross-section calculation.

2.3.5 Charm Cross-Section

Using the lower order contribution one can compute the charm photoproduction cross-section to be of the order of 500 nb/nucleon (at the NA14/2 mean beam energy, $E\gamma \sim 100 \text{ GeV}$). If we compare with the 100 μb /nucleon of the total hadronic photoproduction cross section one gets :

$$\frac{\sigma_{c\bar{c}}}{\sigma_{TOT}} \sim 0.5 \times 10^{-2}$$

The same ratio for hadroproduction yields :

$$\frac{\sigma_{c\bar{c}}}{\sigma_{TOT}} \sim 0.5 - 1 \times 10^{-3}$$

Therefore the recognition of charm events, among all the produced hadronic events, will be more easily done in photoproduction than in hadroproduction experiments.

Furthermore, the lowest order diagrams for hadroproduction are of order α_s^2 while in photoproduction they are of $O(\alpha_s)$, since only one structure function is involved compared to two needed in hadroproduction. This will make it, in principle, simpler to study the production dynamics in photoproduction as compared to those of hadroproduction.

The hadron-like contribution ($O(\alpha_s^2)$), will have the same form as in hadroproduction, but the contribution to the $\gamma N \rightarrow c\bar{c}$ cross section will be "depressed" by the presence of the quark structure functions of the photon, as compared to the quark structure function of the beam particle in hadroproduction.

2.4 Hadronisation

The dynamics of the c -quark production seems to be well understood, the dominant contribution being that of photon-gluon fusion. But the observed final states consist of hadrons and not of free quarks. Thus, the mechanism of dressing the quarks must be introduced. To be a complete theory, QCD, must eventually describe the process of Hadronisation (the dressing of the free quarks). However, this process involves low Q^2 transfer and perturbative QCD is not applicable.

In order to compensate for the lack of knowledge on the hadronisation process, and to be able to compare the measured hadronic quantities with the predicted parton level ones, some models have been introduced [15,16,17,18]. All of these models are based on general aspects of QCD and describe hadronisation in a phenomenological way. This implies that a fine-tuning of the parameters of the models must be performed, using measured quantities on real data.

2.4.1 The Lund Model

Among the different models proposed to describe the hadronisation one of the most commonly used is the LUND Model [18]

Within the LUND Model, the quarks produced in the interaction and those present in the target nucleon, not having interacted, get grouped in color multiplet. Each color multiplet is bound by a color string. When the members of the color multiplet try to separate from each other the energy density of the strings grows until the string is broken and a pair $q\bar{q}$ or diquark-antidiquark ($Q\bar{Q}$) is created. The newly created q (Q) is bound to the antiquark or antidiquark of the color multiplet, and the $\bar{q}$ ($\bar{Q}$) with the remaining quark or diquark. The next time that one of these strings is broken a meson or baryon can be created. The process continues until the energy originally present is exhausted.

The fraction of the energy of the original color multiplet used for the creation of the final state mesons-baryons is controlled by the so called "fragmentation function". This fragmentation function must be determined experimentally.

In the production of baryons, and when the initial energy of the string is small, the fragmentation process tend to not reproduce the number of Λ_C observed. This is corrected by introducing an Energy cut-off below which a selected final state is produced without going through the hadronisation process. The value of the energy cut-off is chosen so that it reproduces the measured production ratios of different final states.

2.5 Charmed particle decays

The decay of charmed particles must proceed through the weak interaction. The electroweak interaction will predict the decay of a free quark system into a set of decay products. But once again one has to take into account that quarks are not free, and the strong interaction they undergo must be considered when computing the decay of hadrons. Here, perturbative QCD can not be applied, and a set of different models have been proposed.

In order to completely describe the decay of a particle one should be able to predict the lifetime (the width) and the relative size of the different decay channels.

A very detailed description of the different models proposed, can be found in references [20,21].

The relevant parameters (lifetime and branching fractions) to reproduce the decay properties of the different charmed particles are taken from the world average values [22]

2.6 Montecarlo simulation

In order to compare the theoretical predictions with the data obtained in the detector, the use of a Monte Carlo program is needed. In a general way, the physics is given as input parameters to the program which will produce final states following the imposed rules. These final states will be passed through a detector simulation program and the output can be used in much the same way as the real data coming from the data acquisition program.

If the same analysis programs chain is used for the MC and RD then the comparison can be made directly. The most common procedure is to use the MC to compute the effect introduced by the program chain and by the detector (Acceptance corrections), so that the "measured" quantities can be corrected, and the final result presented in a detector free way.

Here the physics input for the simulation are described. They are separated in the four relevant topics for the simulation, namely beam, production, hadronisation and decay.

BEAM

The real beam energy spectrum is used. This has been computed using the

measured beam spectrum corrected by the effect of multiple bremsstrahlung. The evolution of the cross-section with the photon energy, and the effect of trigger acceptance are convoluted with the real beam spectrum. This “effective” beam energy spectrum is used to generate the photon.

Production

- The lower order QCD calculation is used (γg fusion)
- A gluon structure function

$$xG(x) = 3(1 - x)^5$$

is used.

- No Q^2 evolution is introduced and a value

$$Q^2 = 4m_c^2$$

is selected.

- The mass of the charmed quark is taken as

$$m_c = 1.5 \text{ GeV}/c^2$$

Hadronisation

- Only non-diffractive events are generated. Actually, diffractive events have been generated for specific analyses [23].
- Two strings are formed. A mesonic string stretches between the charmed antiquark ($\bar{c}$) and a quark (q) from the target nucleon. A baryonic string stretches between the charmed quark (c) and the diquark (Q) of the nucleon (see fig. 2.2).
- The fraction of the momentum left by the gluon for the target fragments is taken from low P_T physics [24], for the quark one will have:

$$f(x) = \frac{1}{\sqrt{x}}(1 - x)^{\frac{3}{2}}$$

This function produces a $x^{-1/2}$ behavior for the quark and a $x^{-3/2}$ behavior for the diquark at low x . Since the energy carried by the charm q is the same as the one carried by the anticharm, the higher energy given to the diquark yields a higher energy on the baryonic string (see fig 2.12).

- An intrinsic P_T ($\langle P_T^2 \rangle_N = 0.1 \text{ GeV}/c$) is given to the target nucleon. This can somewhat modify the observed final particles P_T distribution.
- A fragmentation function

$$Z \cdot D(Z) = \frac{1}{\sqrt{1-Z}} e^{-0.7 \frac{m_T^2}{Z}}$$

$$m_T^2 = P_T^2 + m_c^2$$

is used to control the fraction of the energy of the original string carried by the final charmed particle. Notice that this function is peaked towards $Z \sim 1$ ("hard").

- The lund model is used to independently hadronise the Mesonic and the Baryonic string.
- An energy cut-off is imposed in the Baryonic string $M_a = 4 \text{ GeV}$. If the mass of the baryonic string is smaller than M_a then the $\Lambda_c \pi$ production is forced.

Decay

The word average values [22] for the lifetime and branching fractions are used as fixed parameters. A particular decay channel can be forced at generation time. The other decay parameters can be changed at will. This is mainly used to compare samples generated with different lifetimes for particular decay modes.

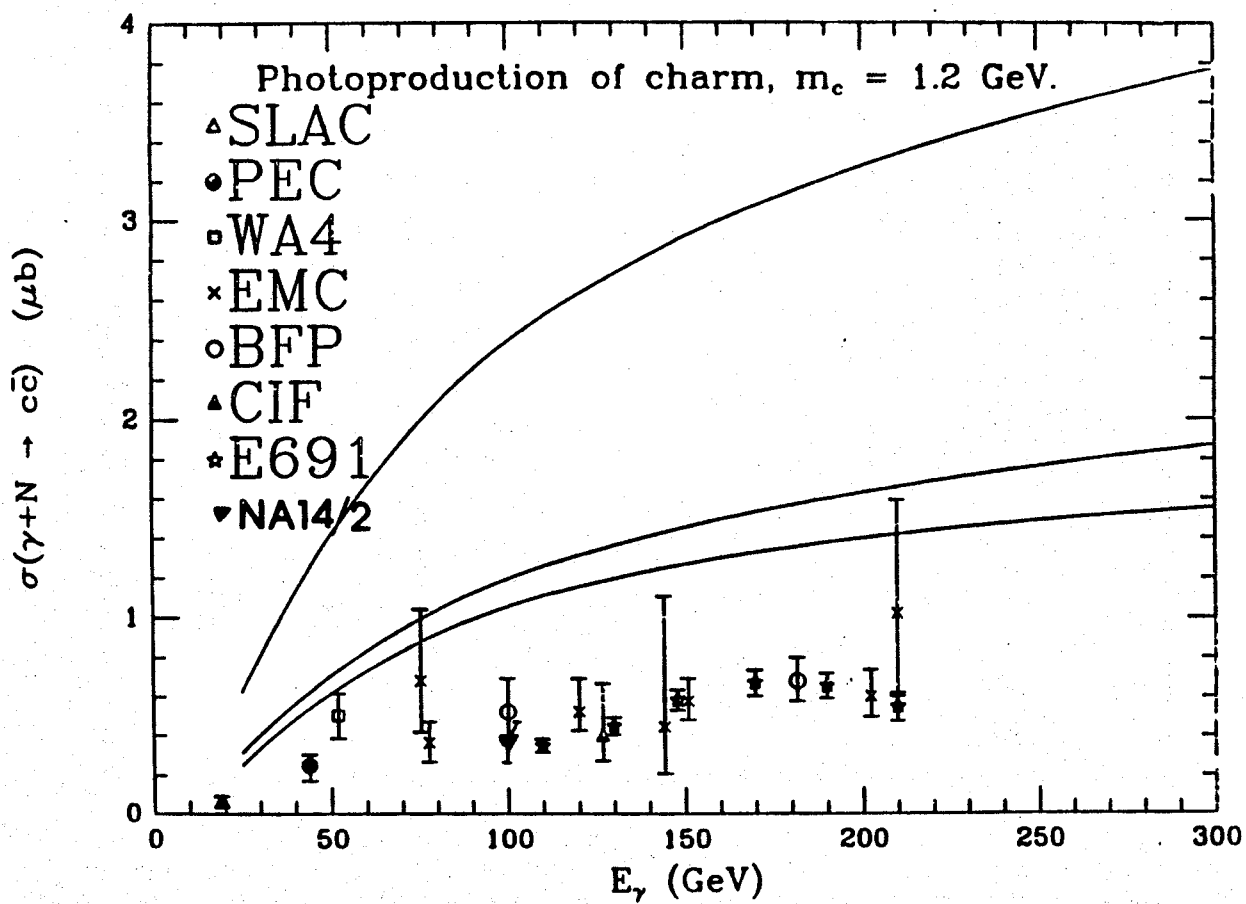


Figure 2.7: Charm photoproduction cross-section dependence with energy. $m_c = 1.2 \text{ GeV}/c^2$

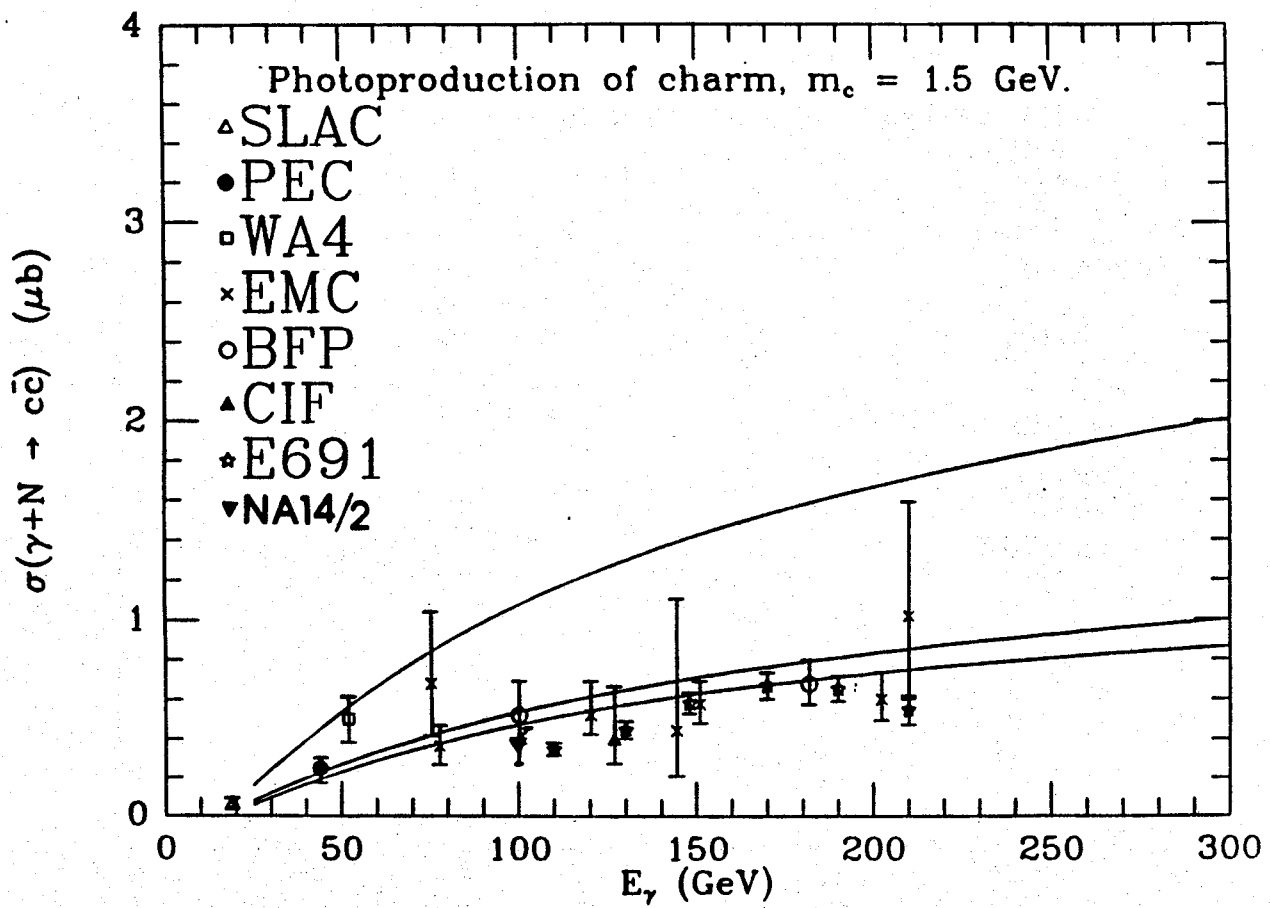


Figure 2.8: Charm photoproduction cross-section dependence with energy. $m_c = 1.5 \text{ GeV}/c^2$

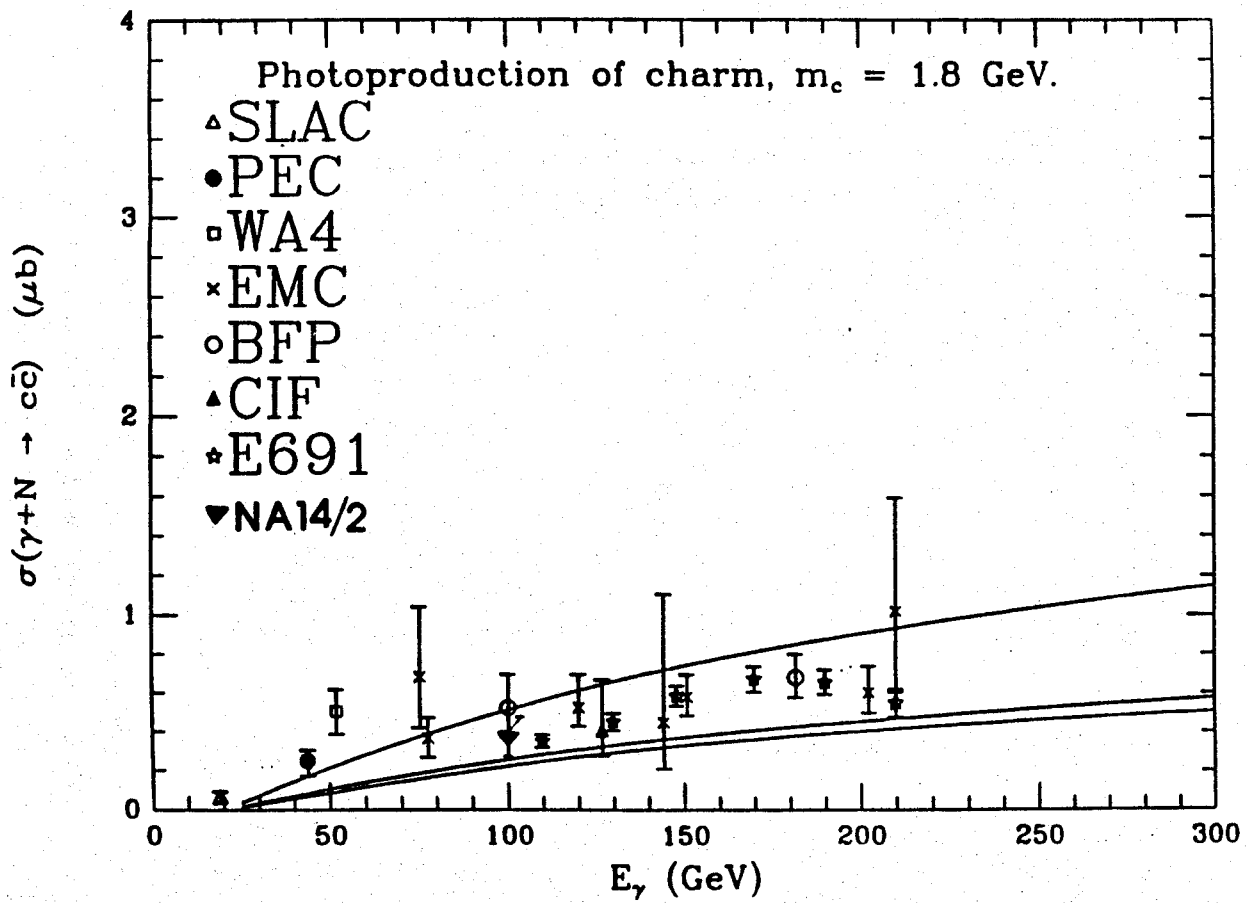
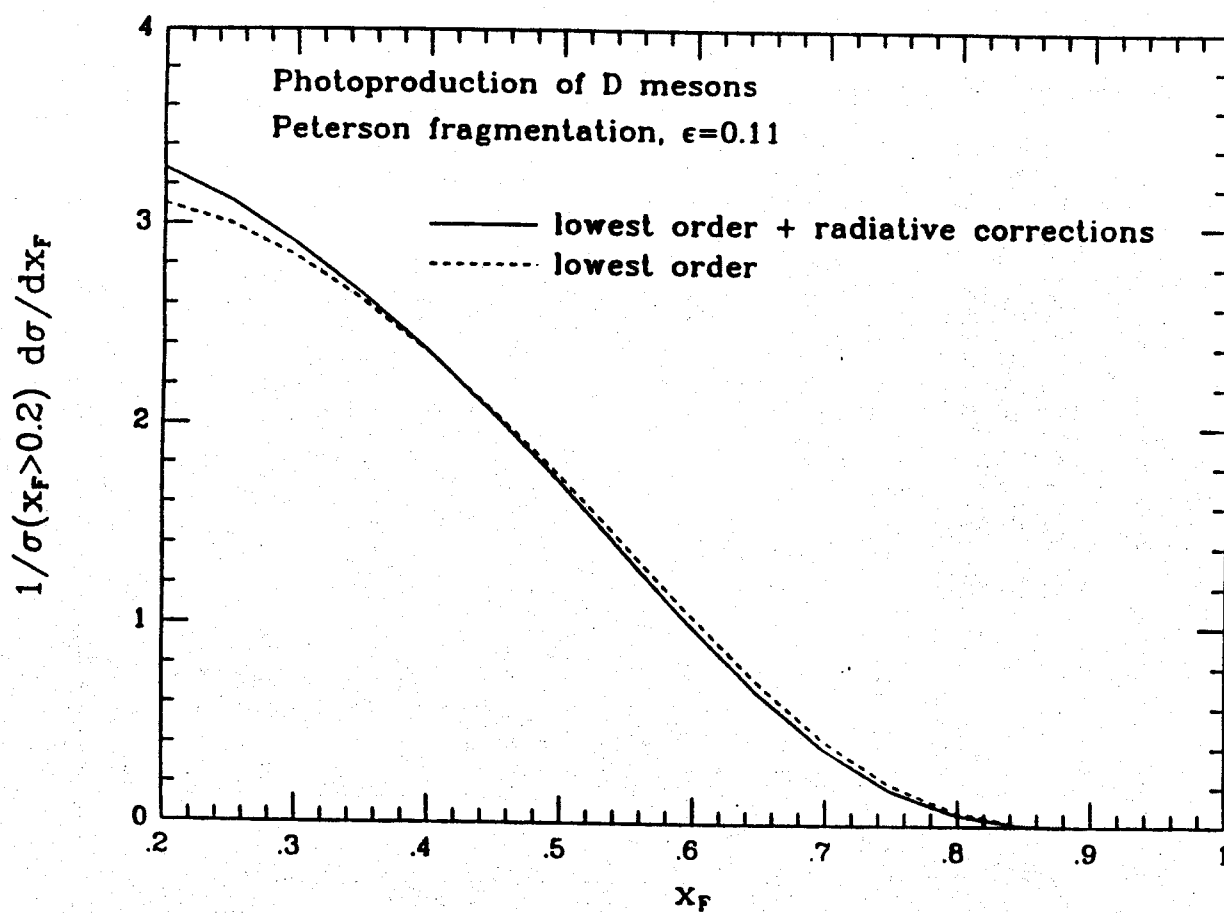
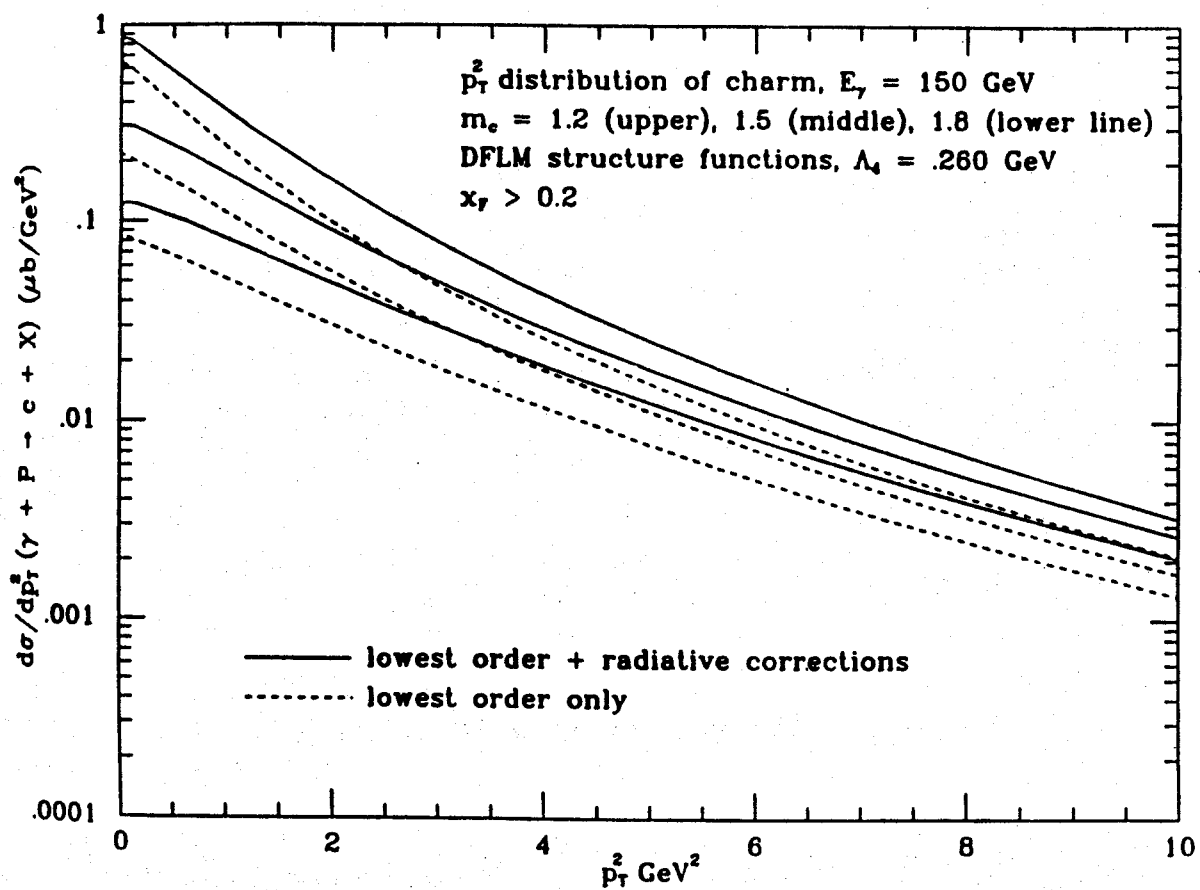


Figure 2.9: Charm photoproduction cross-section dependence with energy. $m_c = 1.8 \text{ GeV}/c^2$

Figure 2.10: Differential charm photoproduction cross-section. x_F

Figure 2.11: Differential charm photoproduction cross-section. P_T^2

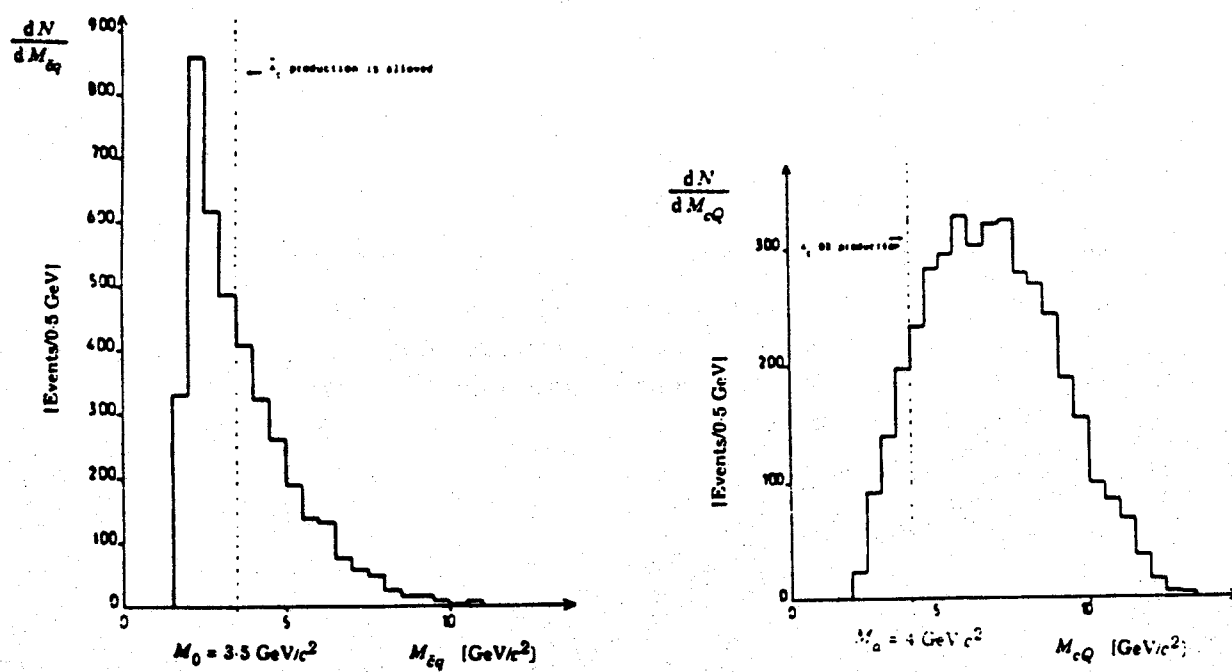


Figure 2.12: Mesonic and Baryonic string masses

Chapter 3

The NA14/2 Apparatus

3.1 The NA14 experiment

NA14 is a fixed target charm photoproduction experiment located in the North Area (NA, where the name comes from) at CERN. The high energy photon beam (100 GeV) is created indirectly using the proton beam (450 GeV) from the SPS (Super Proton Synchrotron). An aerial view of the CERN area, indicating the relative position of NA14 to the SPS, is shown in Fig. 3.1

A schematic layout of the NA14/2 Spectrometer is shown in fig. 3.2, its approximate dimensions are 26 m along the beam direction (X-Axis in the analysis) and 6 m in the transverse plane (Y or Z axis). This size leads to a large angular acceptance, 300 mrad in the Lab. frame for neutral and charged particles (5-130 degrees in the Gamma-Nucleon CM frame).

The photon beam collision takes place in the Active Target (Si). Following, and quite close to the target, the Micro-Strips system (Si strips) which permit a very accurate determination of the vertices in the event. Both the active target and the micro strip system are located within the first NA14 magnet (AEG, 1.2 Tm) with sweeps e^+e^- pairs out of the acceptance of the detector and permits a measurement of low momentum and wide angle tracks using the first set of MultiWire Proportional chambers (MPWC1). The energy of Wide-angle photons and electrons is measured in the first electromagnetic calorimeter (CROWN). The last magnet (GOLIATH, 3 Tm) permits accurate momentum measurement for high energy tracks in the second set of MWPCs, particle identification is made using the two Cherenkov counters ODYSSEUS and INDRA. Immediately after INDRA there is the second Electromagnetic Calorimeter (ILSA), the third set of MWPCs, and OLGA the last EM calorimeter. Following OLGA one finds an Iron wall

Figure 3.1: NA14 location. Aerial view.

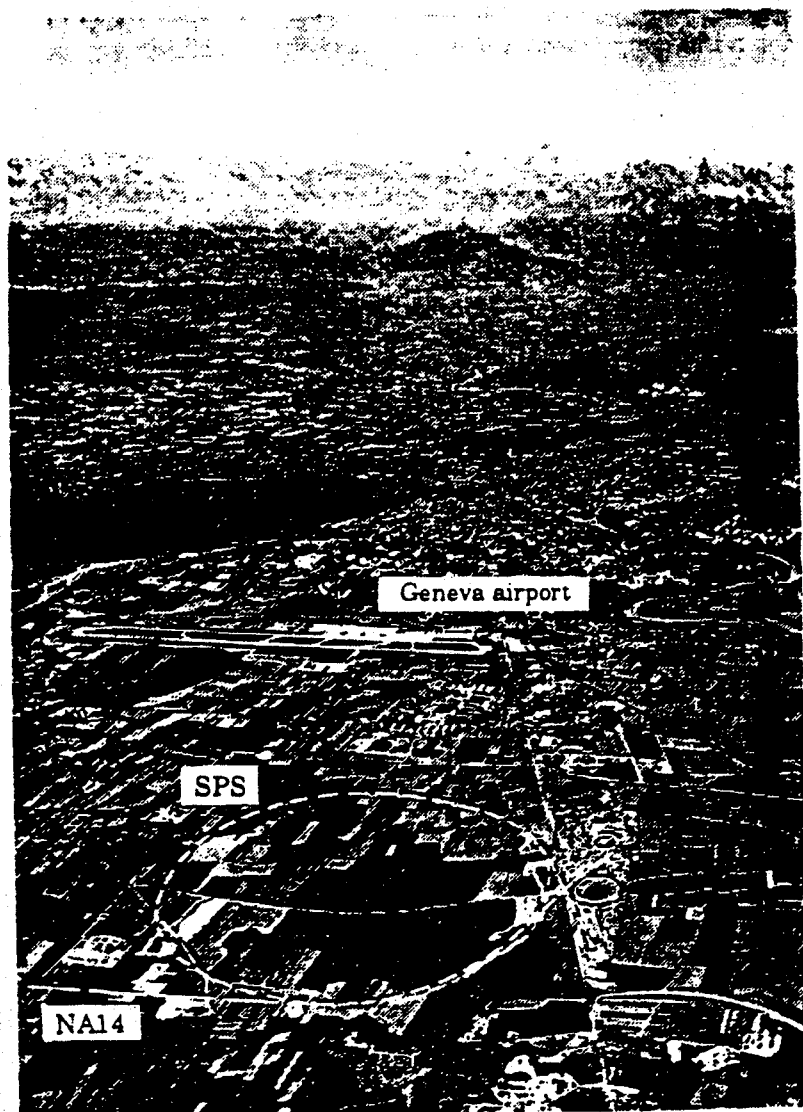
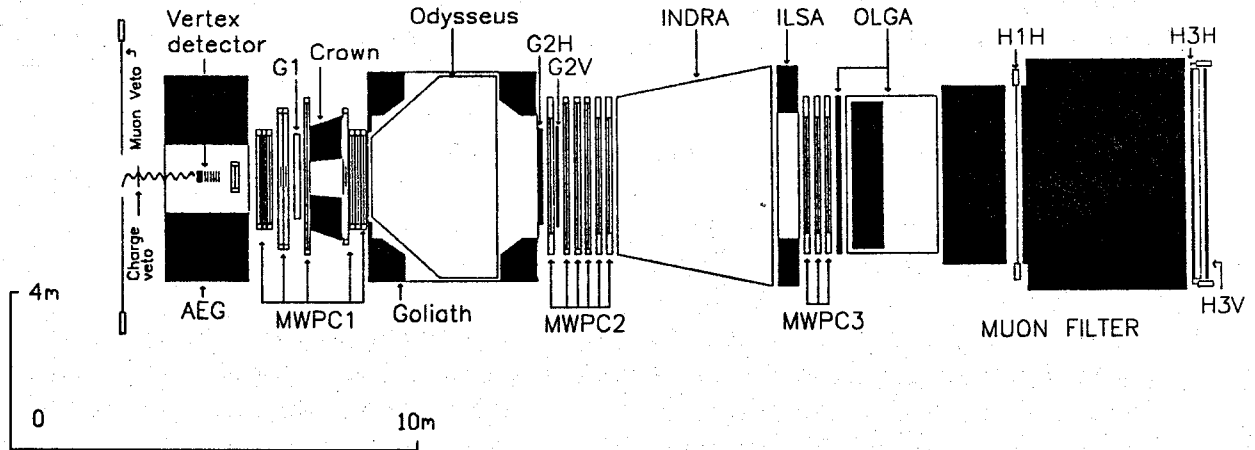


Figure 3.2: NA14 apparatus. Schematic layout.



followed by the H3 hodoscope which serve as a muon filter.

A more detailed description of each piece of the detector can be found in references [21,20,27,29]. In the following paragraphs a brief description of the detectors more directly related to the analysis described in this thesis is given.

3.2 The Photon beam.

3.2.1 The photon beam production

The Broadband Electron Gamma (BEG) beam used by the NA14 experiment is produced in a three step process ($p \rightarrow \gamma \rightarrow e \rightarrow \gamma$) using the 450 GeV proton beam delivered by the SPS at CERN (see Fig.3.4).

The protons are accelerated during a 12s period in the SPS until they reach the nominal energy, following this step they are directed towards the NA14 experimental area. This 2 seconds "spill" provides $2 \times 10^{12} p/\text{burst}$.

These protons are dumped onto a 100 mm thick beryllium block (T10. Production target) where about 20% of them interact. Among the interaction products there are a large quantity of π^0 which, by electromagnetic decay, will produce the first γ beam ($\pi^0 \rightarrow \gamma\gamma$, 99%).

The selected material for the production target (Be) and its size (100mm) are of great importance, since on one side we wish to have a large probability of nuclear interaction (short nuclear interaction length), in order to maximize the number of protons interacting, and on the other side we would like to minimize the $\gamma \rightarrow e^+e^-$ conversion (long radiation length), in order to avoid losses in the number of usable γ 's. Beryllium has a good radiation length to nuclear interaction length ratio, due mainly to its low atomic number ($L_R = 352mm, L_{int} = 406mm$). Another point entering in the selection of the target size is the production of muons (The μ halo), which is directly related to the length of the target and the main source of background to the experimental beam.

Besides gammas and muons we will have hadrons, produced in the p -Be interaction, and the protons which have not interacted. In order to eliminate most of the charged particles one finds, just after the production target, a couple of "sweeping" magnets (B1A,B1B) which drive the charged particles onto a 5 m iron block called proton dump (COLT10).

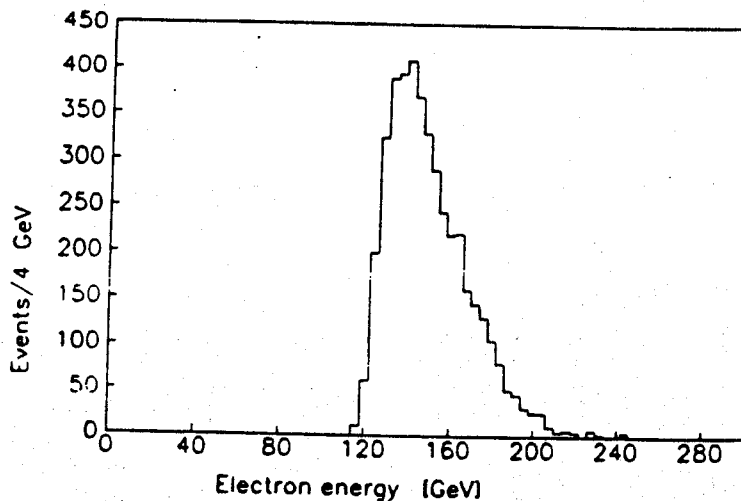
At this point the beam is made of approximately 5×10^{10} neutral hadrons and 3×10^9 gammas with energies larger than 50 GeV, and the unavoidable $10^6 \mu/m^2 \cdot s$ of the muon halo ($\langle E_\mu \rangle = 90\text{GeV}$).

This neutral beam pass through an aperture in the proton dump to interact immediately with the converter target and produce a electron-positron beam. For this target one would like to have a high efficiency in $\gamma \rightarrow e^+e^-$ conversion and a low probability of nuclear interactions to avoid the production of charged hadrons by the interaction of neutral hadrons in the converter. A 4 mm thick block of Lead was selected in this case ($L_{int} = 170mm, L_R = 5.6mm$) which leads to a 40% $\gamma \rightarrow e^+e^-$ conversion efficiency.

Using a set of five bending magnets (chicane: B2A,B3A,B3B,B2B,B4) the negative charged component (e^-, μ^-) is selected, the neutral and positive component being dumped on another iron wall. Selecting the negative part of the beam minimizes the muon contamination since almost twice as many μ^+ are produced as μ^- . An adjustable slot in the neutral dump permits a momentum range selection for the electrons, typically 120-240 GeV/C. At this point one has $10^8 e^-/\text{burst}$ with a mean energy of 140 GeV.

After the Chicane the electrons are focussed (Q1,Q2) into the radiator-target, a $500 \mu m$ thick lead block, where about 10% of them will radiate at least one photon

Figure 3.3: Electron beam energy.



by bremsstrahlung. These photons are the experimental beam. Here again one has a compromise in the selection of the target thickness, a thicker lead block will increase the number of radiated photons but the probability of producing more than one photon by multiple bremsstrahlung will also be increased thus reducing the tagging system accuracy, since the production of a single high-energy photon is assumed.

A final bending produced by the "tagging magnets" (B5,B6) will eliminate the electrons and other remaining charged particle dumping them onto the "electron dump".

After the whole process we end up with a photon beam of about $1.5 \times 10^7 \gamma/\text{burst}$ of energy larger than 50 GeV and a Hadron contamination of the order of $10^{-5} \text{Hadrons}/\gamma$.

3.2.2 Beam Characteristics.

In the previous section the experimental photon beam production steps were described, in each of the steps the beam composition was mentioned, in table 3.1 a summary of such composition is given.

The energy spectrum of the experimental beam is obtained using the tagging system (see next section). In fig. 3.5.1 the spectrum as it comes from the tagging

Figure 3.4: Beam production schematic layout.

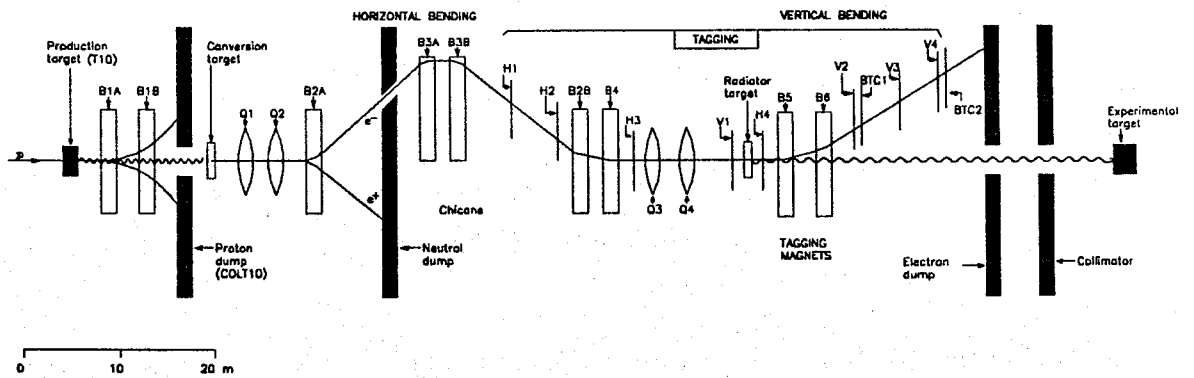


Table 3.1: Beam composition

INITIAL BEAM (p)	$2 \times 10^{12} p/\text{burst}$	$E_p = 450\text{GeV}$	
INTERMEDIATE BEAM (e)	$10^8 e/\text{burst}$	$E_e \in [120, 250] \text{ GeV}$	$\langle E_e \rangle = 140 \text{ GeV}$
EXPERIMENTAL BEAM			
γ	$10^7 \gamma/\text{burst}$	$E_\gamma \in [40, 180] \text{ GeV}$	$\langle E_\gamma \rangle = 100 \text{ GeV}$
CONTAMINATION			
Hadrons	$10^{-5} \text{ Hadrons}/\gamma$	$E_H > 50\text{GeV}$	
μ (Halo)	$10^6 \mu m^{-2} s^{-1}$		$\langle E_\mu \rangle \sim 90 \text{ GeV}$

program is shown while fig 3.5.2 shows the corrected spectrum when multiple bremsstrahlung is taken into account.

In order to determine the spatial dimensions of the beam, one will use the position distribution of the main vertex in the transverse plane for each event, this vertex has been reconstructed using charged tracks. In fig 3.6.1 the vertical coordinate (Z) is plotted, fig 3.6.2 shows the horizontal coordinate (Y), and finally in fig 3.6.3 one finds the position distribution in the YZ plane. The effect of including some ionization requirement in the central part of the active target into the trigger is clearly visible in fig 3.6.2. A sharp decrease is observed thus the horizontal dimension of the beam will be underestimated.

From these figures one concludes that the beam size is

$$Y \times Z = 13 \times 7 mm^2 (FWHM)$$

Concerning the angular dispersion of the beam one will have [20]

$$\sigma_Z = 0.55 mrad$$

$$\sigma_Y = 0.72 mrad$$

Besides the beam contamination mentioned previously, the most serious source of background to the experiment is the photon to pair ($\gamma \rightarrow e^+e^-$) conversion in the experimental target. In order to minimize the effect of this source of background in the detector, some measures have been taken. Firstly the experimental target is located in a vertical magnetic field (AEG). This will sweep low energy pairs ($E_{e^+e^-} < 250 MeV$) produced by low energy photons coming from synchrotron radiation, out of the acceptance of the detector. Also, at the trigger level a requirement of ionization deposited in the target to be larger than that of a single pair is made. The remaining pairs could be easily identified by their small opening angle in the non-bending plane (ZX plane).

The AEG magnet sweeps the pairs into a horizontal band. All the pieces of the detector not able to withstand the high rate of pair production, will have non-active slices just above and below the horizontal plane.

3.2.3 The Tagging System.

One of the advantages of a photon beam produced in a multiple step process is the possibility of determining a single photon energy by measuring the energy (mo-

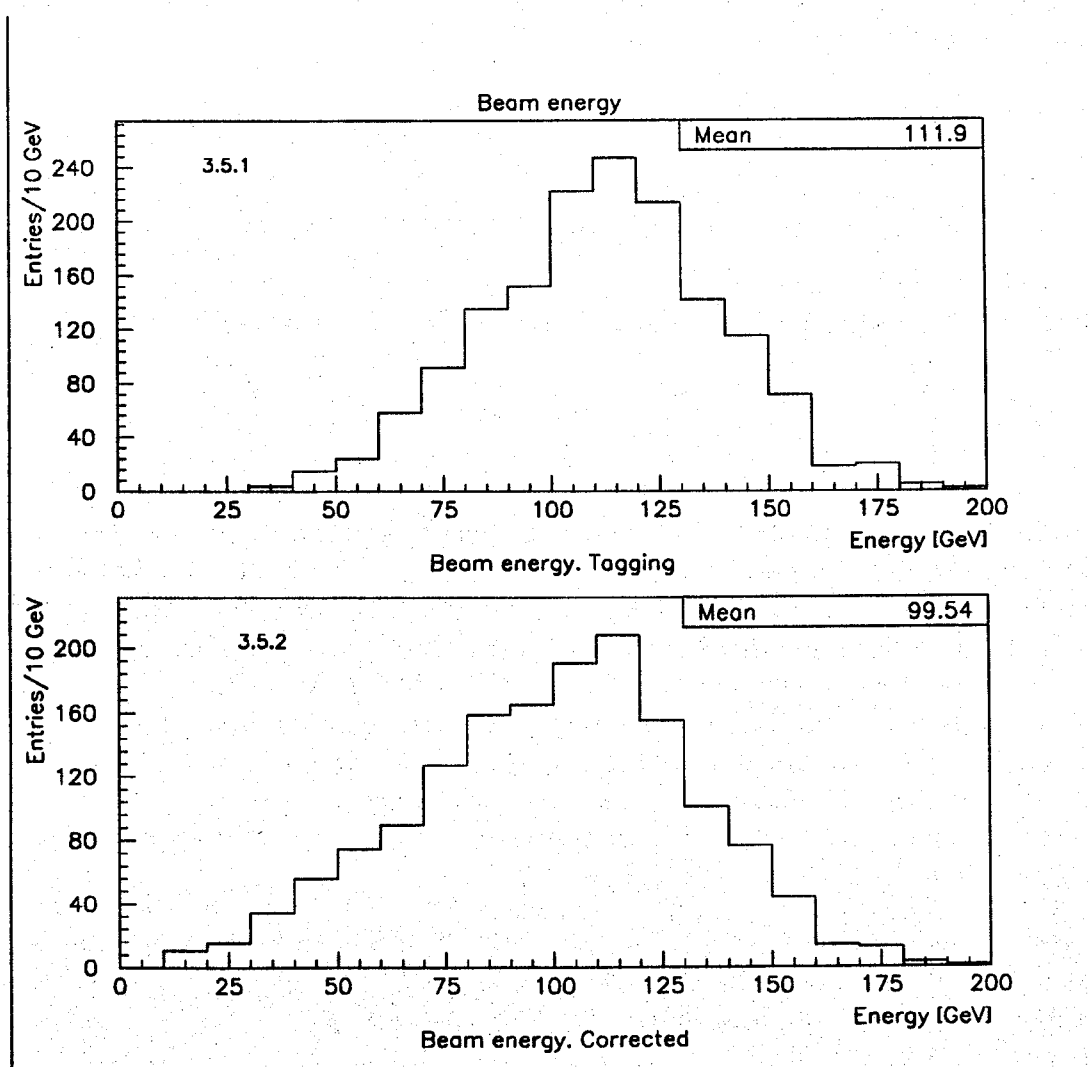
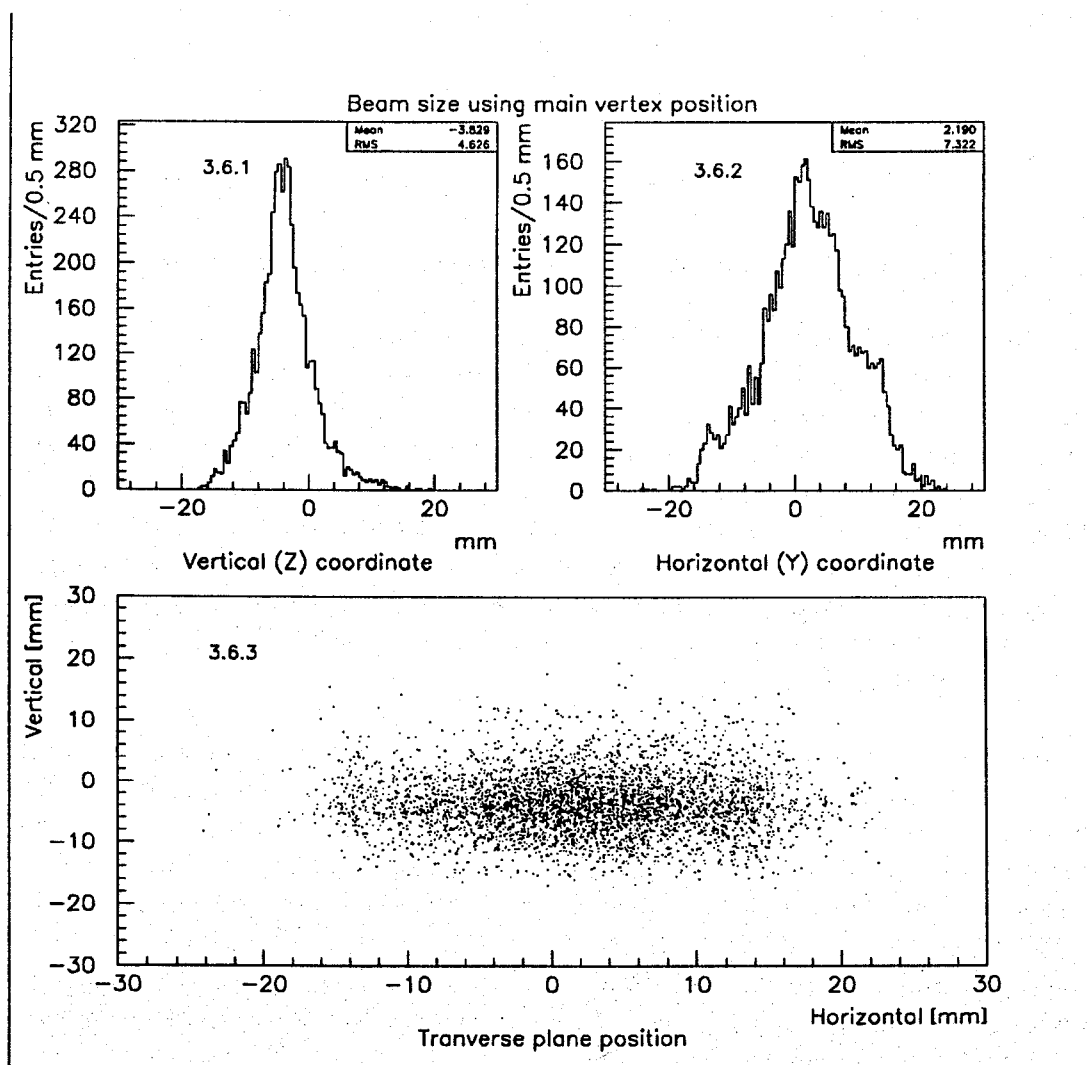
Figure 3.5: γ beam energy spectrum

Figure 3.6: Beam dimensions



1.000	0.088	0.012	0.011	0.008	0.007	0.006	0.005	0.000	0.000
0.000	0.912	0.124	0.053	0.029	0.025	0.025	0.022	0.014	0.009
0.000	0.000	0.864	0.179	0.078	0.056	0.042	0.040	0.031	0.000
0.000	0.000	0.000	0.757	0.153	0.067	0.043	0.051	0.030	0.026
0.000	0.000	0.000	0.000	0.733	0.168	0.069	0.045	0.042	0.017
0.000	0.000	0.000	0.000	0.000	0.679	0.161	0.078	0.042	0.026
0.000	0.000	0.000	0.000	0.000	0.000	0.655	0.131	0.056	0.026
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.630	0.135	0.094
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.648	0.206
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.598

Table 3.2: Tag energy to real gamma energy conversion matrix

mentum) of the intermediate electron just before and after the photon production.

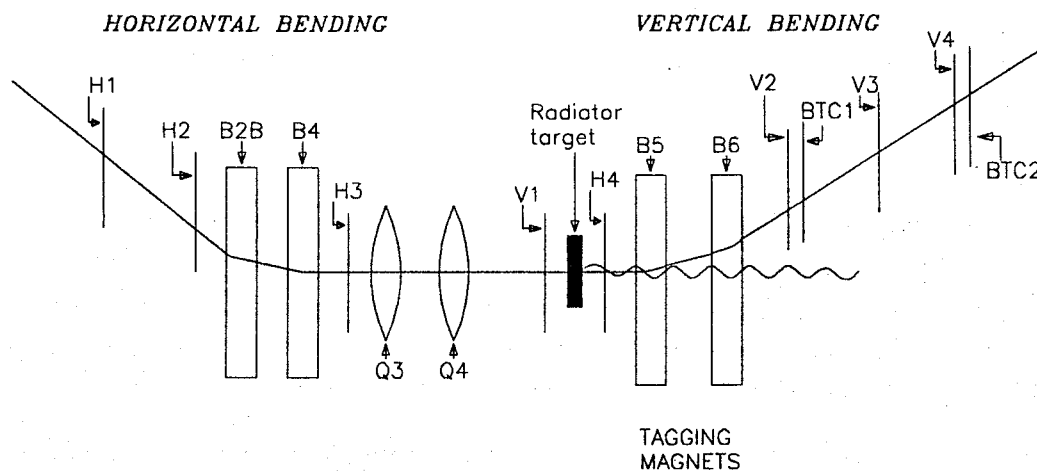
The photon beam energy is determined by subtracting the energy of the outgoing electron to that of the incoming electron, this method suffers from an intrinsic error, namely a single gamma emission is assumed. Actually one could consider the energy given by the tagging system as a good approximation to the real photon energy since the probability of emitting more than one energetic photon by bremsstrahlung when one uses a $0.1\% X_0$ target is less than 20 %. In any case this effect is not negligible (cf fig 3.5) and a correction must be applied if the energy is going to be involved in any analysis. Using MC techniques one such correction has been calculated [8] and is shown in table 3.2 using a 20 GeV bin size and considering a target of $0.125 X_0$.

The electron track before and after the radiation target, is reconstructed using a set of eight scintillator fingers named H1-H4 and V1-V4. The subset H1-H4 measures the horizontal coordinates (Y) of the incoming electron track. They have been constructed (see table 3.3) to optimize the precision in the coordinate determination and to minimize the beam degradation due to electromagnetic showers. V1-V4 measures the vertical coordinates (Z) of the outgoing electron track, here the beam degradation is not crucial, thus the thickness is larger than that of the Hodoscope. The different sizes of the scintillator fingers have been selected to keep the energy resolution constant.

Outgoing electrons with energy between 15 GeV and 80 GeV are kept. The lower energy cut imposed by geometrical constraints, the upper limit due to the little interest in gammas of low energy.

The choice of scintillator fingers and not of wire chambers as tracking elements

Figure 3.7: The Tagging system schematic layout



was basically made for faster response reasons. In fact, one wants to be able to track electrons at a rate of $10^8 e/\text{burst}$ or, in other words, one will require of the order of 10 ns to fully acquire the data belonging to one event. This timing requirement make the use of conventional wire chambers, almost impossible.

There are two extra hodoscope named BTC, for Back Tagging Counters, serving as a reference time for the experiment and included in the "pre-trigger". They are used by the tagging system in order to confirm the presence of a track in the V hodoscope.

The electron track reconstruction, and thus the photon energy measurement,

Table 3.3: Tagging system scintillator characteristics

HODOSCOPE	N. OF FINGERS	HEIGHT (Z, cm)	WIDTH (Y, cm)	THICKNESS (X, cm)
H1	80	100	1.5	6
H2-H4	64	100	1.5	6
V1	64	1.5	100	6
V2	34	3-10.5	100	8
V3	65	1.5-12	100	8
V4	72	1.5-12	100	8

takes place in an off-line program called, of course, Tagging. It is included in the NA14's standard program library NEPTUN. The program produces unambiguous solution in about 30% to 50% of the events and about 15% of ambiguous solutions. A very detailed description of the tagging system, both in hardware and software, can be found in ref [27]

3.2.4 Other beams.

Another advantage of the multi-step process employed to produce the experimental photon beam is the possibility to use different beams without modifying the beam production line. For instance, pion or muon beams can easily be produced.

These beams could be used either to align or calibrate the many pieces of the apparatus, or to be used as experimental beams in order to compare experimental results or to normalize physical quantities.

Muon Beam

A muon beam is produced by closing the neutral dump aperture and by eliminating the intermediate electron beam, (Fig 3.4). In this case only the muon halo will reach the experimental target. We will need to deactivate the muon veto from the trigger in order to be able to use the muon beam.

A muon beam, which covers the full size of the MWPCs, was used to calibrate the chamber timing.

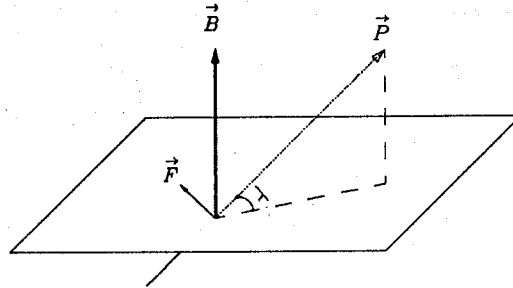
Pion Beam

Charged pions are abundantly produced in the initial interaction of the proton beam on the production target, but they are swept out of the beam line by the first bending magnets (Fig 3.4 : B1A,B1B). There is also pion production when neutral hadrons interact with the conversion target. These pions are eliminated by the tagging magnets (Fig 3.4 : B5,B6). Thus, if a pion beam is needed, it is sufficient to turn the B1A,B1B,B5 and B6 magnets off. The energy of the pion beam could be selected (usually 90 GeV) by reducing the neutral dump aperture.

Here as in the case of the photon beam, only the negative component of the beam is kept thus eliminating the non-interacted protons from the initial beam. Only a small contamination of k^- and p^- is expected.

In order to avoid the saturation of the detectors due to the high flux of the pion beam only 1% of the proton beam is used.

Figure 3.8: Track's dip angle



A pion beam was used for alignment of the microstrips telescope.

3.3 Magnets

When a particle of charge q and velocity $\mathbf{v}$ goes through a region of constant magnetic field $\mathbf{B}$ it feels a force given by

$$\mathbf{F} = q\mathbf{v} \wedge \mathbf{B}$$

The particle therefore follows a helical trajectory, having a straight line movement in the direction parallel to the beam and a circular movement of radius

$$R = \frac{p \cos \lambda}{Bq}$$

in the transverse plane, where λ is the angle of the direction of the particle relative to the projection plane (see fig. 3.8) and p is the particle's momentum.

So, if we have a constant magnetic field crossed by charged particles, the sign of the charge of the particle can be determined by observing the sense of the deflection they undergo and its momentum by measuring the radius of the circles they describe in the plane perpendicular to the field direction.

This is the most common method used in experimental particle physics to measure charged particles' momenta, generally one will have a bending magnet sandwiched into tracking devices, so that one will know the trajectory of the

particles before and after they cross the magnetic field region and thus one will be able to observe the sense of the deflection (measure the sign of their charge) and to calculate the radius of the arc connecting the projection of the tracks in the transverse plane before and after the bending magnet (momentum measurement).

In NA14, two magnets AEG and GOLIATH, serve the purpose described in the previous paragraph, in table 3.4 a summary of their main properties is given.

AEG

This magnet surrounds the active target and serves two functions, one is to get rid of the abundantly produced low energy pairs, as was mention in section 3.2.2. The second function is to measure the momentum of charged tracks produced at large angle or low energy which won't be able to reach the second magnet. The tracking is performed by the microstrips and the first set of wire chambers, the minimum momentum measurable is 1 GeV and the momentum resolution achieved is

$$\frac{\Delta p}{p^2} \sim 10^{-2} GeV^{-1}c$$

GOLIATH

This magnet provides a very precise momentum measurement

$$\frac{\Delta p}{p^2} \sim 10^{-4} GeV^{-1}c$$

for particles passing through the two set of chambers located before and after Goliath ($p > 3 GeV/c$).

3.4 The vertex detector.

SILICON DETECTORS

The development of high spatial resolution techniques and the high resistivity of silicon crystals produced nowadays, have permitted the use of high resolution tracking devices based on silicon in experimental particle physics. These detectors are made of silicon strips, which act as diodes. If a particle crosses the strip, a

Table 3.4: NA14 Magnets summary

	AEG	GOLIATH
DISTANCE FROM TARGET (<i>m</i>)	0.0	5.5
<u>APERTURE</u>		
Y (<i>cm</i>)	±65	±120
Z (<i>cm</i>)	±25	±60
<u>ACCEPTANCE</u>		
Y (<i>mrad</i>)	±650	±160
Z (<i>mrad</i>)	±250	±80
<u>MAGNETIC FIELD</u>		
B (T)	1.29	1.3
$\int B dL$ (Tm)	1.24	3.1
<u>MOMENTUM RESOLUTION</u>		
$\frac{\Delta p}{p^2} (GeV^{-1}c)$	10^{-2}	10^{-4}

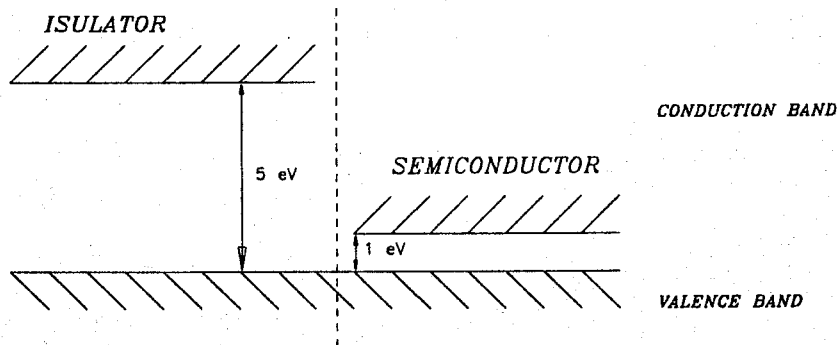
current is generated due to energy loss by ionization, this charge is collected on the electrodes of the diodes providing a measurable signal.

When one studies crystalline materials, the allowed energy levels are grouped into bands, in metals the highest energy band is not filled, so that any electron in that band can conduct. In other materials that band (Valence band) is completely filled, and conduction is only possible when electrons are promoted to the next higher energy band (Conduction band), within this kind of materials one can distinguish two different types, namely insulators and semiconductors. In insulators the energy gap, E_g , between the valence band and the conduction band (Band gap) is of the order of 5 eV, whilst for semiconductors the gap is only of the order of 1 eV, therefore the probability of having electrons (see eq. 3.1) in the conduction band, thus conduction, at room temperature is much higher than for insulators.

$$P \propto T^{3/2} e^{-(E_g/2kT)} \quad (3.1)$$

Among the semiconductors, with no doubt, silicon is the most widely used. Silicon is not used in its pure state, instead some impurities are added to it modifying the energy gap, depending on the effect of the impurity to the energy levels they are known as n-type or p-type. The n-type impurities are those which produce an energy level (Fermi level) close to the top of the band gap, since a loosely bound electron is provided by the impurity, the p-type produce just the opposite effect since they act as a source of holes (see Fig. 3.10).

Figure 3.9: Insulators and semiconductors relative band gap



When n-type doped silicon and p-type doped silicon are put together, in what is called a np-junction, a region of electric field is created in order to rearrange the energy levels of the two parts and produce a continuous band (see Fig 3.11), this region is known as the depletion layer. If one adds an external voltage (Bias voltage) the size of the depletion region can be modified as can be see in eq. 3.2, where $\epsilon\epsilon_0$ is the dielectric constant of the material, V is the bias voltage, V_0 is the proper voltage, N is the impurities density and e is the electronic charge.

$$d = \sqrt{\frac{2\epsilon\epsilon_0}{eN}(V - V_0)} \quad (3.2)$$

When connected to a bias voltage the np junction acts as a diode, permitting the flow of electrons from the p-type to the n-type but not in the reverse direction. The pass of a charged particle through the depletion layer will result in the creation of electron-hole pairs (only 3.6 eV are needed for an electron-pair creation in silicon) which then will drift towards the electrodes of the diode (see Fig. 3.12), given the small size of the depletion layer and the high drift velocity, the signal can be collected in a few nanoseconds, giving a very fast response time for this type of detectors as compare to conventional tracking detectors.

ACTIVE TARGET

Figure 3.10: n-type and p-type impurities

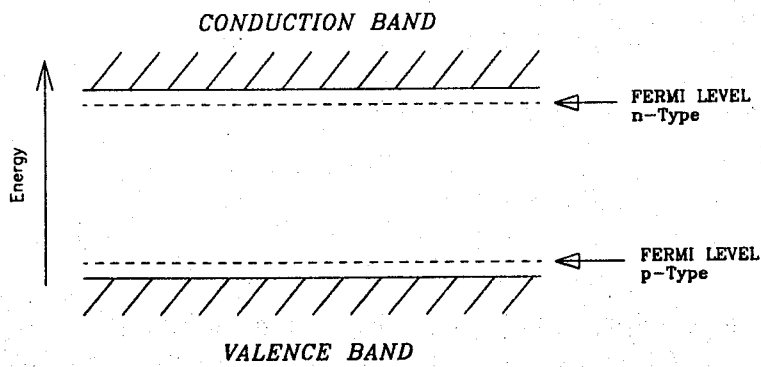


Figure 3.11: np junction

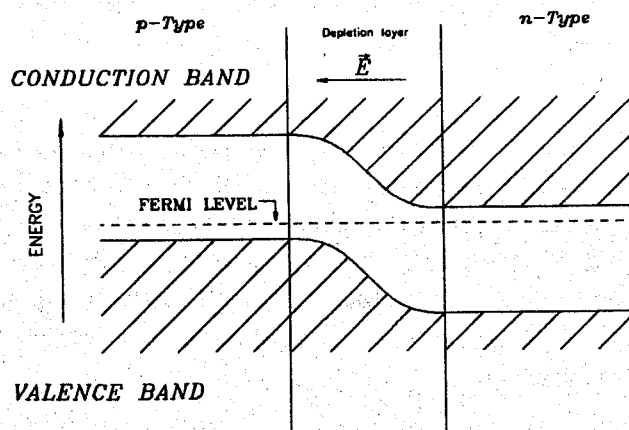
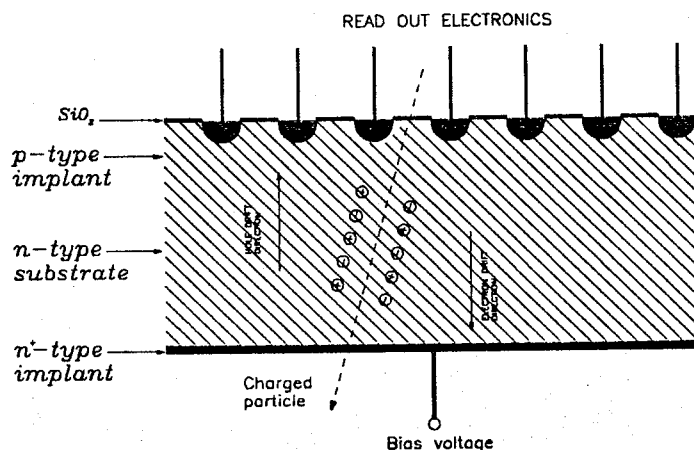


Figure 3.12: np junction as a tracking device



The NA14 experimental target, the *active target*, is made of 32 planes of silicon, with an active area of $5.04 \times 4.40 \text{ cm}^2$ and a thickness of $300 \mu\text{m}$ each, located in the AEG magnet.

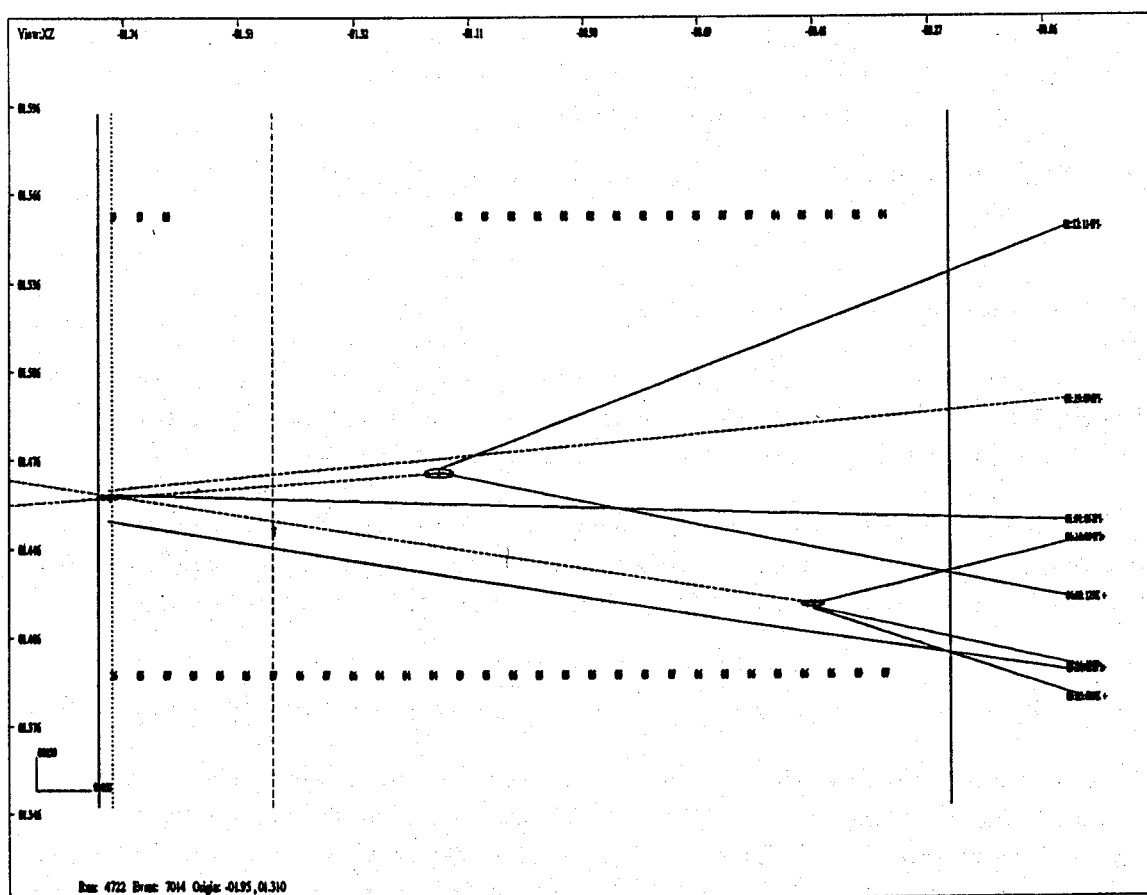
The planes are separated $512 \mu\text{m}$ along the beam axis ($300 \mu\text{m}$ plane thickness + $212 \mu\text{m}$ air), and are formed by parallel diode strips 2.1 mm wide each, the first 30 planes have 24 vertically oriented strips, measuring the Y coordinate, whilst the two last planes have 21 horizontally oriented strips and are known as Z planes.

The target segmentation was decided not only for tracking purposes but mainly to avoid saturation of each readout channel (maximum rate 20 MHz), its size was chosen to have of the order of 90% of the beam incident upon it. The whole assemble accounts for a 10% of a radiation length and 3.2% of a nuclear interaction length.

Each diode (strip) is connected to an analog readout channel, so that a direct measurement of the ionization deposited on it is made. The high energy products of a hadronic interaction are typically contained within one strip width along the length of the target. Thus, the measure of the ionization is directly a measure of the track multiplicity since all the produced particles can be considered minimum ionizing particles (mip) and each of them will deposit the same amount of charge when passing through the strip.

Figure 3.13 an example of a charm event is shown, the pulse height in units of 1 mip can be seen.

Figure 3.13: Charm event in the active target



THE MICROSTRIPS

Also located in the AEG magnet, the μ -strip telescope is used to give a very precise measurement of the production and decay vertices in the event.

It consists of 10 planes of silicon with dimensions $5 \times 5 \text{ cm}^2$, $450 \text{ }\mu\text{m}$ thick. Each plane is made of 1000 strips of $50 \text{ }\mu\text{m}$ pitch each. The planes are deployed as follows (see Fig. 3.14):

- Four sets of two planes separated by 9 mm . The first plane measures the Z coordinate (strips horizontally oriented) and the second plane measures the Y coordinate (strips vertically oriented).
- A fifth set similarly oriented as the previous but rotated 33 degrees about the beam axis (named U and V planes).

The different pairs of planes are separated by 15 mm .

The arrangement described above permits reconstruction of the tracks in two orthogonal views, Z and Y. The fifth set is used to have 3-dimensional information in order to eliminate ambiguities when matching hits to tracks.

The area of the planes was the maximum possible with the silicon technology available at the time they were made and provides an acceptance of $\pm 250 \text{ mrad}$, similar to the acceptance of AEG, the magnet where the telescope is located.

The strip width was selected after Monte Carlo simulation which showed that $50 \text{ }\mu\text{m}$ will lead to a resolution high enough to recognize charmed particle decays.

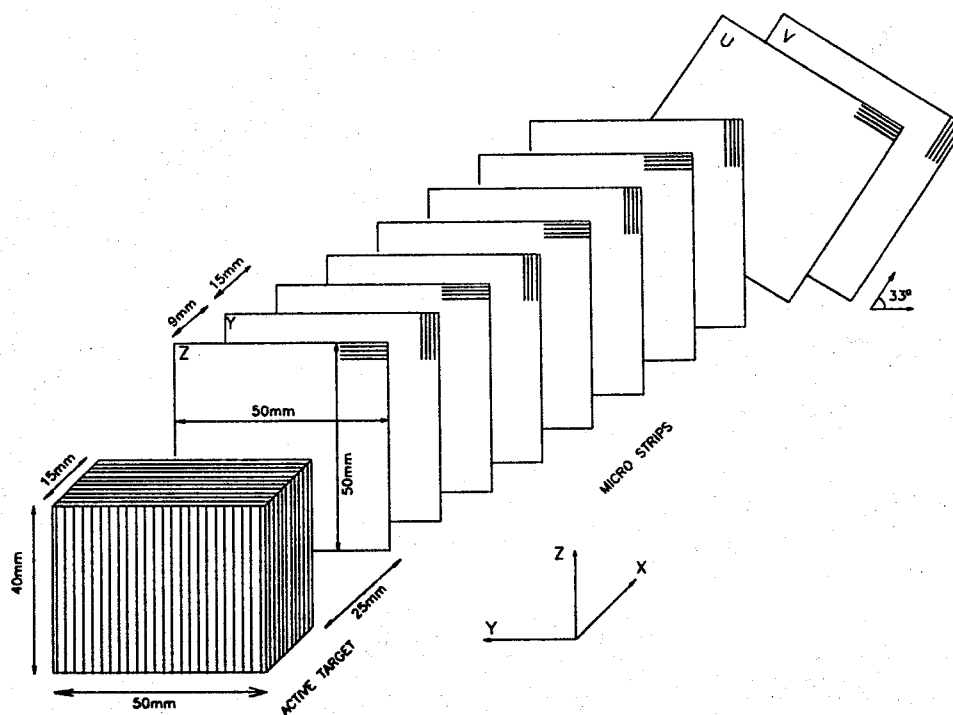
The separation within planes and the position of the planes is also a result of the Monte Carlo simulation. It represents a compromise between having the first plane as close as possible to the active target, in order to improve the main vertex reconstruction, and having the last set of planes as far away as possible in order to increase the lever arm and improve the track reconstruction (but without losing acceptance and permitting a straight line approximation to be made even in the bending plane).

Due to economic reasons the number of readout channels for the microstrips were reduced to half the number of needed channels by connecting two different strips to the same electronic channel. This will lead to the creation of an "OR" image of the hits making the track reconstruction step more complex. The connection was made in such a way that the two strips connected to the same channel can not belong to the same track.

A summary of the characteristics of the vertex detector (both active target and microstrips) is given in table 3.5.

A clear example of the use of the microstrip telescope is shown in figure 3.15. One can see in fig.3.15.1 the $k\pi$ mass spectrum when no vertex information is used. In fig. 3.15.2 one has the same mass spectrum but both vertices have been found using microstrip information and a minimum separation within them has been imposed. In this case the D^0 signal is clearly visible.

Figure 3.14: Vertex detector schematic layout



A more detailed description of the NA14's vertex detector, including the construction process, can be found in references [20],[21] and [30].

3.5 Multi Wire Proportional Chambers.

Wire chambers are one of the most often used position detectors in high energy physics experiments. Basically they consist of a pair of electrodes, an anode and a cathode, immersed in a gas. When an ionizing particle passes through the gas

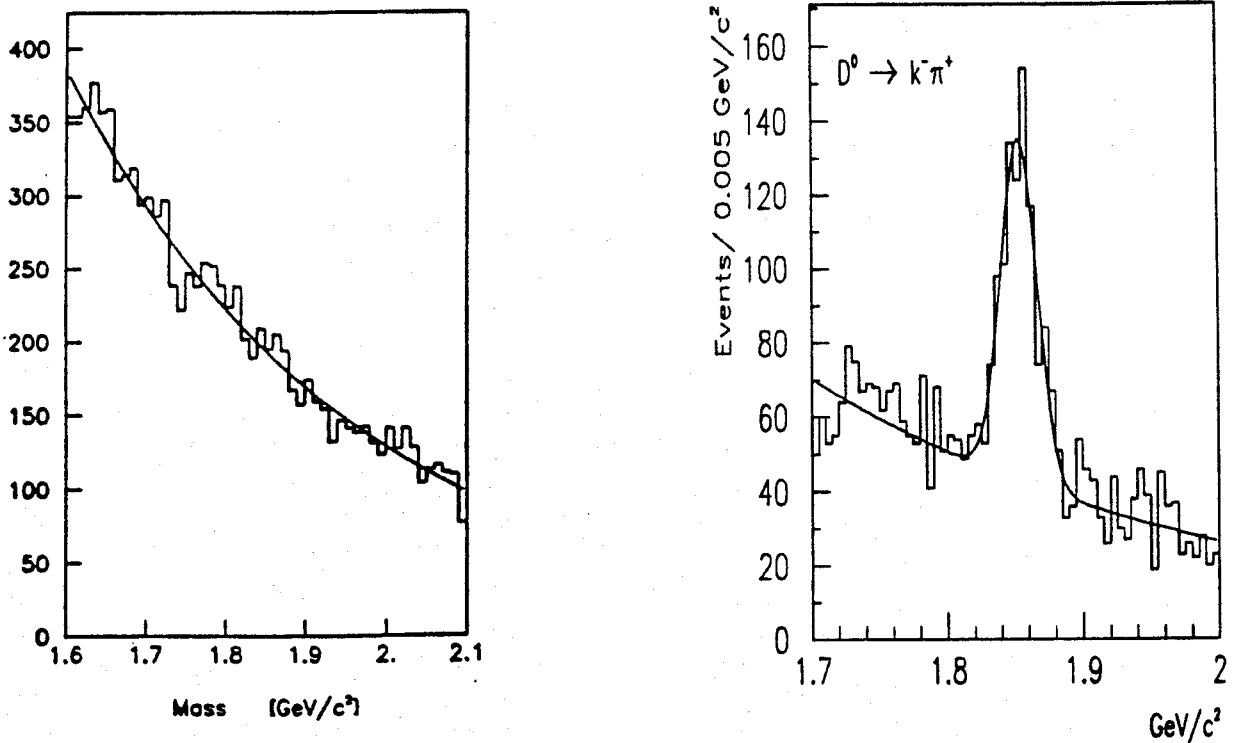
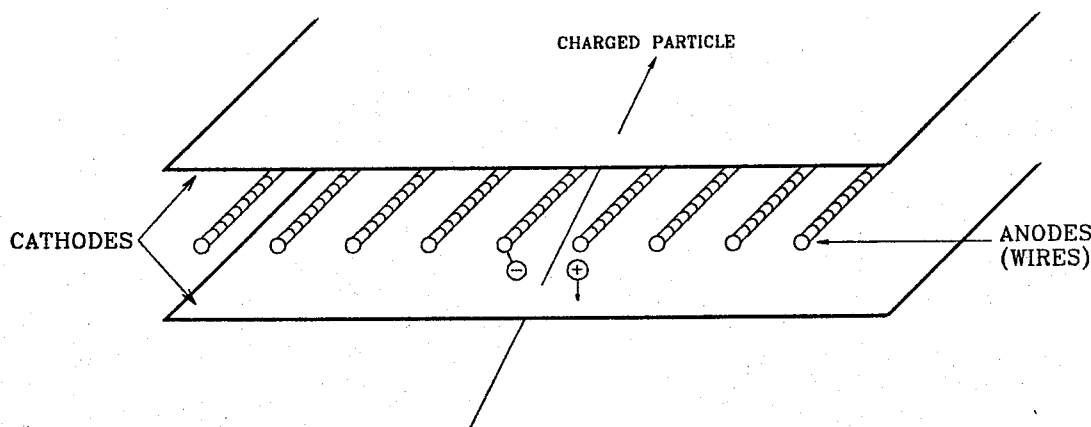
Figure 3.15: Effect of the vertex separation cut on the $k\pi$ mass spectrum

Table 3.5: Vertex detector characteristics

	ACTIVE TARGET	MICROSTRIPS
Number of planes	32	10
Plane orientation relative to the Y axis	Planes 1-30: 90 Planes 31-32: 0	Planes 1,3,5,7: 0 Planes 2,4,6,8: 90 Plane 9: 33 Plane 10: 123
Plane dimensions		
Y (mm)	50	50
Z (mm)	40	50
Si-Thickness (μm)	300	450
Strips/Plane	Planes 1-30: 24 Planes 31-32: 22	1000
Strip pitch (mm)	2100	50
Read-out type	analog	digital

Figure 3.16: Wire chamber schematic view



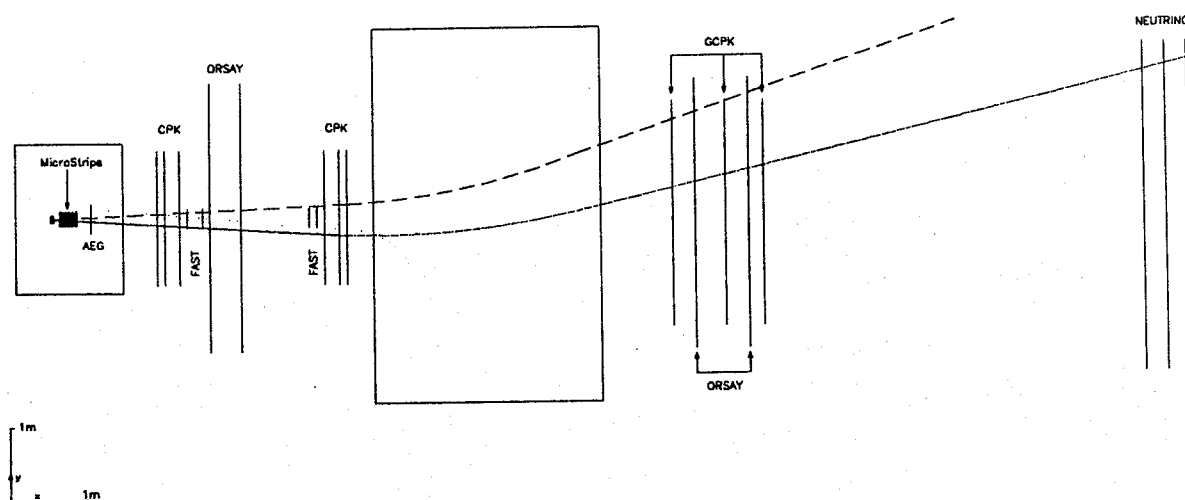
it liberates electrons. These electrons will drift towards the anode where they are collected and a signal is produced. Multiwire chambers are based on the principle just explained. However instead of a simple cell they have parallel planes of anode wires lying between conducting surfaces acting as cathodes. Each of the anode wires are read individually, so that the coordinate perpendicular to the wire can be determined. A simple layout of a multiwire chamber is given in figure 3.16.

Multiwire proportional chambers, MWPC for short, are abundant in the NA14 apparatus. There are 21 chambers and a total of 73 wire planes distributed in three stacks as shown in figure 3.17. All the NA14's wire chambers, except for the AEG one, are located in non magnetic field region to avoid problems of track reconstruction in high magnetic field regions.

Stack 1 contains two Orsay and six CPK chambers, all of which have a desensitized region around the horizontal plane to avoid the already mentioned high rate of pairs produced in a horizontal band around the beam axis. Four small chambers (called FAST) are provided to cover this region, they use fast electronic read out to cope with that high rate of e^+e^- . The AEG chamber is situated close to the active target providing a track coordinate as close as possible to the interaction point.

Stack 2 is made of five chambers and together with stack 1, will permit momentum determination by measuring the track direction before and after Goliath,

Figure 3.17: NA14's multiwire proportional chambers layout



the second NA14's magnet. The third stack is used to improve the momentum measurement for high momentum tracks¹.

Table 3.6 summarizes the main characteristics of the NA14's chambers.

3.6 Cherenkov counters.

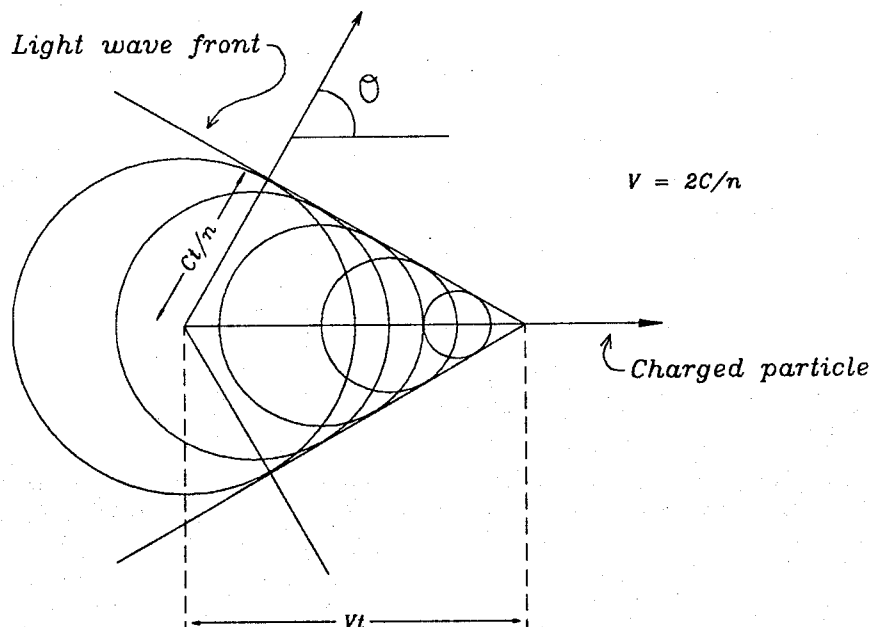
When a charged particle travels through a dielectric medium of refractive index n , with a velocity v larger than that of the light in the medium, it emits a coherent wave front of light in the form of a cone of aperture θ (eqs. 3.3 ,3.4 and fig. 3.18), known as Cherenkov radiation.

$$\beta > \frac{1}{n} \Rightarrow \text{Light} \quad (3.3)$$

$$\cos \theta = \frac{1}{\beta n} \quad (3.4)$$

¹Three large hexagonal chambers form the stack 1, they are called NEUTRINO only for historical reasons

Figure 3.18: Cherenkov radiation cone



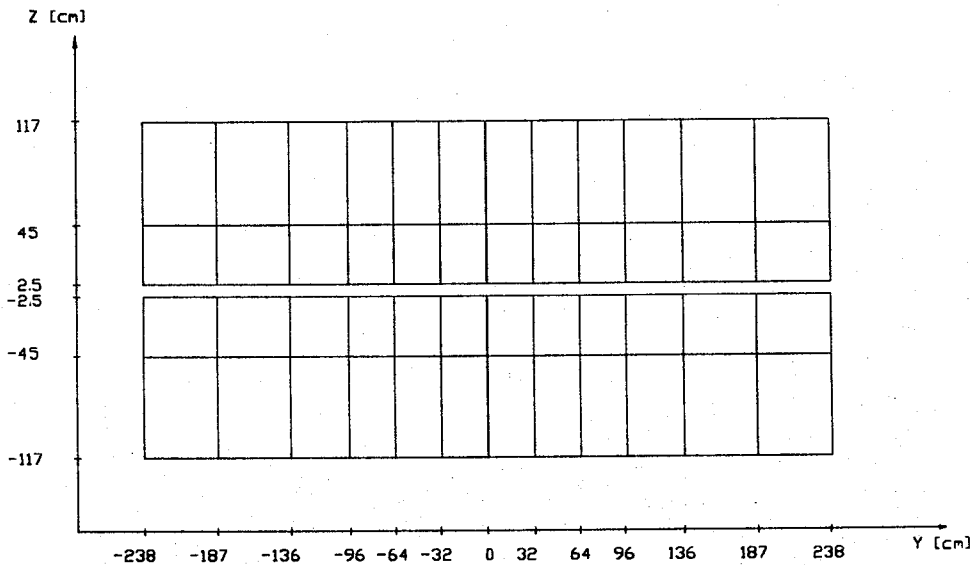
Eq. 3.3 shows us that the cherenkov effect is produced only above a momentum threshold, so cherenkov radiation can be used for particle identification. If the momentum of the particle is known and Cherenkov photons are generated, then some information about the mass of the particle is gained. This comes from the fact that in a given dielectric medium different particles will have different momentum thresholds to produce cherenkov light.

A Cherenkov counter is usually a box filled with some gas where particles traversing will emit light. This light will be reflected by mirrors, located at the end of the box, towards photomultipliers which serve as the measuring device.

There are two cherenkov counters, INDRA and ODYSSEUS, in NA14. A summary of their properties is given in table 3.7. Figures 3.19 and 3.20 show the mirror layout of INDRA and a schematic view of ODYSSEUS, respectively.

Odysseus was installed in the apparatus towards the end of the data taking period, so particle identification is only available from Odysseus for the last quarter of the data. Furthermore, it is located inside Goliath making it very difficult to determine the track direction, thus the light cone direction, when processing the data. For these reasons this cherenkov has not been used in the present analysis.

Figure 3.19: INDRA mirror layout



3.7 Calorimeters.

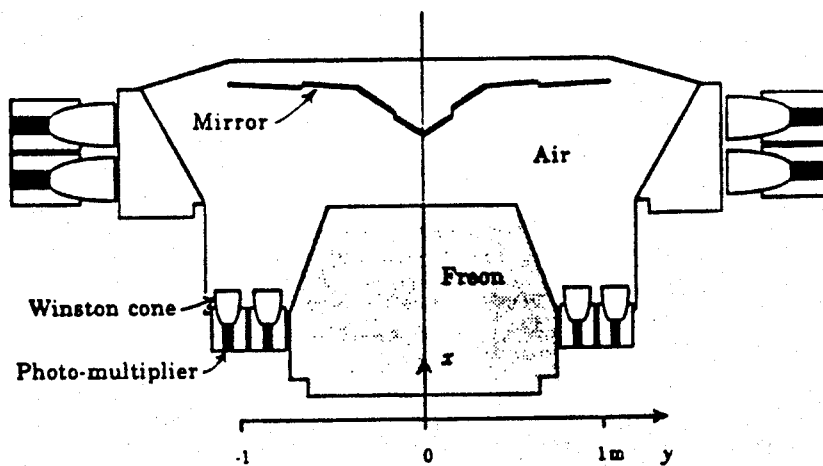
When a particle enters a dense medium part of its energy is deposited and used to create new particles (usually electrons and photons). These particles also lose energy creating more new particles in a process which is known as "showering".

A calorimeter is a piece of hardware especially designed to completely absorb, and thus measure, the energy of the incident particle.

NA14 has three electromagnetic calorimeters built to measure the energy of electromagnetically interacting particles such as π^0 , γ and e . All three calorimeters have a similar structure:

- **Charged veto:** permits a distinction between charged and neutral particles allowing us to reject charged particles in the photon analysis.
- **Pre-Converter:** Initiates the shower allowing the determination of the photon position at the entrance of the calorimeter. Its length is determined by the requirement that all photons must be converted but the size of the shower must be small enough not to disturb the position determination.
- **Position detector:** Determines the entry point of the particles in the calorimeter. In the three calorimeters it is made of crossed scintillator fingers.

Figure 3.20: ODYSSEUS schematic view



Finally one finds the calorimeter proper, for OLGA and CROWN, the chosen material is lead glass which has the advantage of acting as active and passive (converter) elements at the same time. ILSA is made of scintillator layers (active element) within lead blocks (passive).

Their position and sizes lead to an angular acceptance of $\pm 300 \text{ mrad}$. The angular acceptance for each of them can be seen in figure 3.21

Figure 3.21: Calorimeters angular acceptance

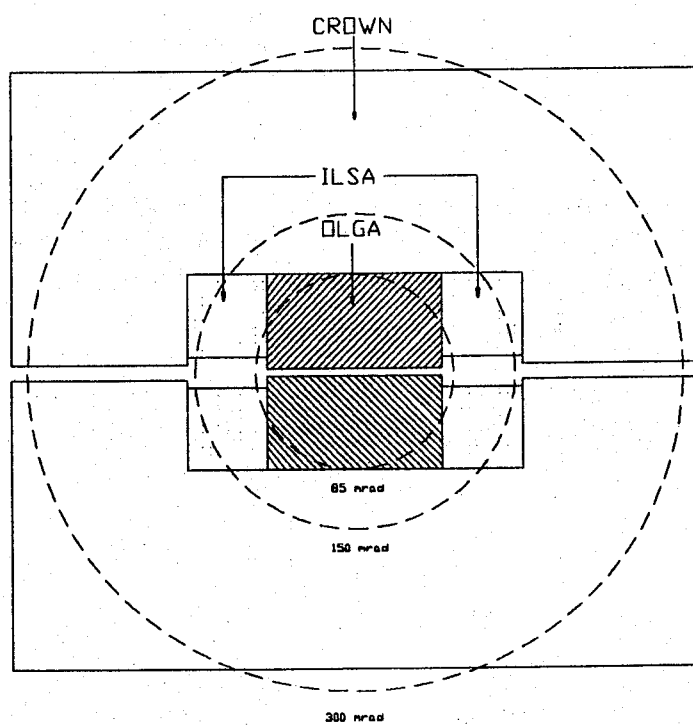


Table 3.6: Summary of NA14's wire chambers

Type	AEG	CPK	Fast	ORSAY	GCPK	NEUTRINO
Number	1	6	4	4	3	3
Distance from target (m)	0.13	1.0	1.4	1.7	7.8	14.0
		1.1	1.6	2.1	8.5	14.3
		1.3	3.0	8.1	9.0	14.6
		3.2	3.1	8.8		
		3.4				
		3.5				
Dimensions						
Y (m)	0.2	1.79	0.26	3.6	3.11	4.33
Z (m)	0.2	0.73	0.21	1.5	2.15	3.75
Desensitised region [cm]	-	5.0-12.0	-	5.0	-	-
Planes	4	4	2	4	4	3
Plane orientation 0°=Horizontal	0	104	90	90	104	60
	90	90	60	60	14	120
	45	0		120	90	0
	135	14		90	0	
Wires per plane	186	768	256	1792	1024	1232
		896		1536	896	
		368		1536	1024	
		576		1792	704	
Wire spacing (mm)	1.0	2.0	1.0	2.0	3.0	3.0
Read out gate (ns)	50.0	120.0	50.0	120.0	120.0	120.0

Table 3.7: NA14 Cherenkov counters

Counter	Gas	Refractive index	Momentum Threshold(GeV/c^2)					Desensitized cm
			e	μ	π	k	p	
INDRA	DRY AIR	1.000297	0.021	4.34	5.73	20.27	38.52	5
ODYSSEUS	FREON-12	1.001080	0.011	2.38	3.01	10.63	20.21	—

Chapter 4

Data acquisition

The NA14's data acquisition system was based on standard CAMAC modules read by a PDP 11/45 computer. The event selection, to be written to tape, was made using a two level trigger. Its main objective was to minimize the number of $\gamma \rightarrow e^+e^-$ events stored on tape, which, by far, is the most probable process to be produced in the target.

During the summer of 1985 and summer-autumn 1986 17 million triggers were registered on tape. The portion of hadronic interactions of this sample has been determined to be 95%.

4.1 The Trigger.

The experimental trigger for a high energy experiment is, generally, a combination of calculations using information from the detectors in the apparatus. The aims of a trigger are; first, obtain a data sample enriched with the physical process one would like to study; second, optimize the availability of the apparatus for event recording, and finally, minimize the amount of data written to tape. If all these requirements are fulfilled the off-line analysis (the physics analysis) will be highly simplified, and thus the computer requirements very much reduced.

The NA14 trigger was divided into two levels, a fast part called "pre-trigger", and a more complicated part called "final trigger". If the pre-trigger, PT, requirements are accomplished, then a $5 \mu s$ time gate is opened to read the CAMAC modules. During this time no new interaction is accepted. If no final trigger is produced after $0.6 \mu s$ following the PT signal a fast reset of the electronic modules is performed, and a new interaction can be accepted after $5 \mu s$, the time required

Table 4.1: Data acquisition parameters

SPS cycle	14 s
Burst	2 s
Protons	2×10^{12} p/burst
Photons	6×10^6 ($E_\gamma > 50$ GeV) γ /burst
Number of PT signals	220 /burst
Number of final triggers	95 /burst
Events written to tape	80 /burst
Triggers lost	$\sim 16\%$

to set the ADCs to zero.

If a final trigger signal is obtained, then the computer sends a "read" order to the CAMAC modules. The values are stored in intermediate memory blocks located in the CAMAC chassis, avoiding the dead time produced by the tape writing process. Immediately the "reset to zero" order is sent by the computer, leaving the electronics in a ready state for the next interaction. This whole process takes on the order of 5 ms.

A summary of the data acquisition parameters is given in table 4.1.

4.1.1 The pre-trigger.

The pre-trigger is made of the following requirements:

$$PT = BEAM \bullet ACT \bullet HODO \bullet DT$$

Where $\bullet$ indicates a logical AND and the meaning of the components follows:

- BEAM: The presence of a photon with energy larger than 40 GeV has been deduced from the tagging counters.
- ACT: An interaction has been detected in the active target. At least a hit with ionization of more than 2.5 mip deposited in each of the two last Y planes and the first Z plane of the active target, is imposed. For the Y planes only the central 15 strips are checked. In the vertical direction (Z

plane) the central 13 strips are used. The limit of at least 2.5 *mip* was imposed to eliminate the e^+e^- pairs, since they will deposit of the order of 2.0 *mip*. Only the central region was selected in order to avoid interactions taking place at the edge of the active target for which some tracks would be lost in the microstrips.

- HODO: This is formed by a combination of signals from the hodoscopes:

$$HODO = ((\overline{\mu V} \bullet G1 \bullet G2V \bullet G2H)_{TOP} \bullet G2H_{BOT}) OR ((\overline{\mu V} \bullet G1 \bullet G2V \bullet G2H)_{BOT} \bullet G2H_{TOP})$$

Where μV is the muon veto and $G1, G2H$ and $G2V$ are the hodoscopes mentioned in chapter 3. TOP and BOT indicate the top and bottom halves of the apparatus. HODO has been designed to improve the hadronic contents of the trigger.

- DT("dead time"): The "ready to read" signal provided by the PDP 11/45 computer.

4.1.2 The final trigger.

For the final trigger, FT, only an extra requirement is made:

$$FT = PT \bullet DARM$$

- PT: The pre-trigger signal.
- DARM: 'Double Arm', is a more complex requirement to ensure the presence of one track above and one below the central horizontal plane of the apparatus. This further enhances the hadronic content of the trigger.

$$DARM = (\overline{\mu V} \bullet G1 \bullet G2V \bullet G2H)_{TOP} \bullet (\overline{\mu V} \bullet G1 \bullet G2V \bullet G2H)_{BOT}$$

Fig. 4.1 illustrates the NA14 experimental trigger.

Monte Carlo studies indicate that the trigger described above enriches the charm content of the final sample by a factor of two, compared with all photon-induced hadronic interactions (See Fig. 4.2).

Figure 4.1: Schematic of the NA14 experimental trigger.

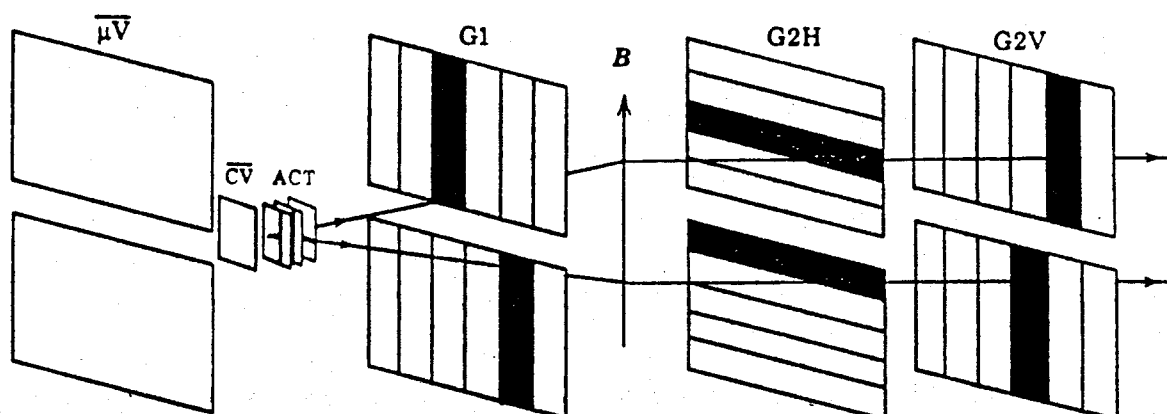
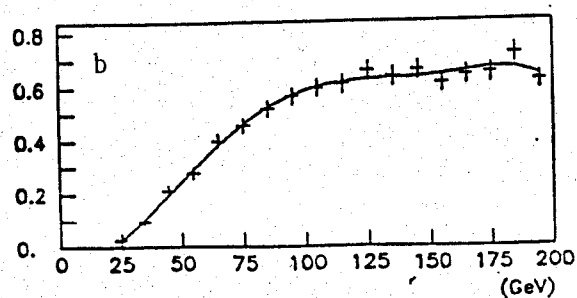
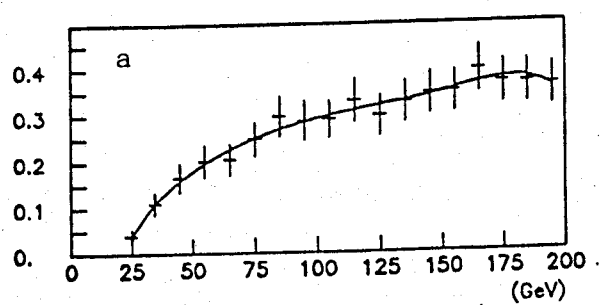


Figure 4.2: Trigger efficiency. a) Hadronic events. b) Charmed events.



4.2 Monitoring.

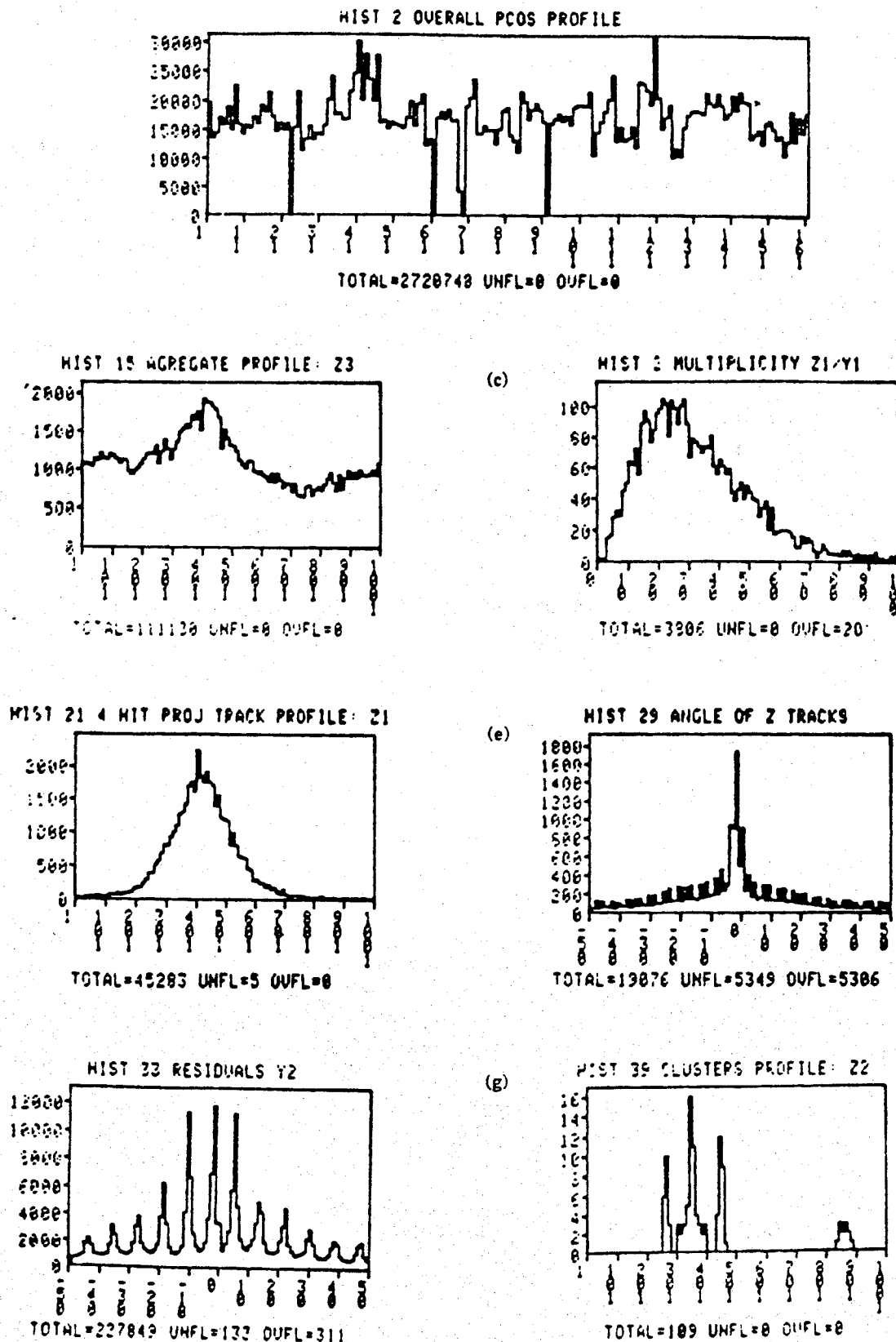
Monitoring the behaviour of the different parts of the apparatus is fundamental in all high energy physics experiments. It is done to guarantee the quality of the events stored on tape and to ensure the correct performance of all the pieces of the apparatus.

The NA14 PDP 11/45 computer was completely dedicated to read the CAMAC modules, format the data, and write it to tape. These tasks left little computer time available for a complete sub-systems monitoring. Only a limited degree (of monitoring) was provided by the 11/45, such as trigger rates and hit multiplicities, and little more. Two other computers (PDP 11/60) were dedicated to specific detectors monitoring, for instance, the microstrips telescope (was monitored by one of them). They would use the data stored in the intermediate memory blocks without disturbing the data acquisition system.

A complete monitoring of the NA14 apparatus was done by transferring (this was called the 'Bicycle shift') the data tapes to the main CERN computer, and IBM 3090. There standard monitoring jobs were run and the output returned to the counting room where a detailed evaluation was made by the two physicists on shift.

Some of the histograms produced by the microstrips detector on-line monitoring programs are shown in Fig. 4.3.

Figure 4.3: Example of the output of the Microstrips monitoring program.



Chapter 5

Data processing.

The data acquisition system writes the raw data onto magnetic tapes, as described in the previous chapter. This raw data consists in wire addresses, digitized pulse heights, counts from the TDC's and so on (DIGITISING). To analyze the events, it is necessary to reconstruct the kinematic variables of the tracks, and to identify the particles concerned. The process of transforming the raw data tape information into physical information is known as data processing. After the data processing step has been done the data analysis (physics analysis) can be performed.

It would be desirable to have the raw data sample completely reconstructed, so that the physical analysis could be done on very well selected samples. But, if one takes into account that the NA14's track reconstruction program, TRIDENT, takes 1.8 *s/event* (IBM 3090/600 TIME) and that 1.7×10^7 events were stored on tape, one will end up needing of the order of one year computer time to fully reconstruct the whole data sample. Thus, a full reconstruction approach could not be followed in our experiment. Fast algorithm were developed, called filters, to extract the preferred events using raw data or limited reconstruction information.

Besides track reconstruction, one needs particle identification, calorimetric information, etc... The job of transforming the digitized information into the quantities used in the analysis is performed by separate programs. All these programs are available in the form of program-libraries to the members of the collaboration. The modularity approach will reduce the time required for the physical analysis since only those parts of the detector needed will be reconstructed.

A general description of the programs and filters is given in this chapter with a more detailed description of the programs directly related to the thesis.

5.1 The NA14 Programs

Managing large amount of programming code used by various groups is better done by specific tools. Among the available tools, PATCHY was selected by the NA14 collaboration. PATCHY is fully supported by the CERN program library, so all the institutes involved in NA14 had access to it at their home computer.

PATCHY's basic structure is based on: PAM-FILEs, the Common-pool of code stored in a special format; PATCHES, the different parts of a PAM; and CRADLES, which are the user provided set of a cards to extract and modify the code in the PAM.

The most important PAM files used in NA14 are the following :

- GEANT:

It consists in the adaptation of the general CERN Monte Carlo program to the need of the NA14 experiment. In fact separate PAMS are used for the standard GEANT routines, the user-specific routines and the fragmentation routines.

- NEPTUN:

It is, more or less, almost everything but the Monte Carlo and the track reconstruction program. Neptun includes all the detector-related analysis programs. As an example, it contains INDANL, the piece of code providing information of particle identification given by INDRA, one of the Cherenkov counters

- TRIDENT :

The track reconstruction program.

- TYPHON :

A fast track reconstruction program used as an entry point to some of the filters mentioned below.

A block structure was used for the data tapes. When running a program, the information contained in the input tape will be copied to the output tape and a new block, with the results of the program, added. Two different tape formats were used. All tapes were kept in raw data format, the format used by the online PDP 11/45 computer, until Trident was run. EPIO, a machine independent format, tapes were produced by Trident. These tapes can be easily read in any computer where the CERN utilities are installed.

5.2 Filters

A brief description of some of the filters used by the NA14 collaboration is presented. A separated section is devoted to the microstrip filter (ORSAY filter) given its importance to this thesis.

Before discussing these filters, it is necessary to introduce Typhon, the NA14's fast reconstruction program. It is included in this section since some of the filters will use information provided by Typhon. The track reconstruction is performed using 12 MWPC (45 planes), the magnetic fields are approximated by a thin-lens formula, and the momentum calculated by computing the difference between the track directions before and after the magnets.

A momentum resolution of $\Delta p/p \sim 0.05 \cdot p \text{ GeV} \cdot C^{-1}$ is achieved.

THE KAON FILTER

With the momentum measurement of the tracks, and the information from the INDRA cherenkov, tracks with momentum in the range $6 - 50 \text{ GeV}/c$ and no light in the cherenkov were selected as kaons. The two requirements imposed were :

- AT LEAST TWO GOOD TYPHON TRACKS.
- AT LEAST ONE TYPHON IDENTIFIED KAON.

Here, "good typhon tracks" means tracks reconstructed in both sides of the goliath magnet. 7% of the events passed the filter. The study of the $D^\pm$ and D_s charmed mesons, carried out in ref. [21,20] was done using this filter. In ref. [21] a more detailed description of the filter can be found.

CLEAN TARGET FILTER

Only the active target information is used for this filter. Events with a clear main road and non-heavily ionizing tracks were selected. The aim of the filter was to study multiplicity steps in the target in order to look for secondary vertices. 8% of the data passed the filter. Further details about the filter itself and the analysis carried on the selected sample can be found in ref [23].

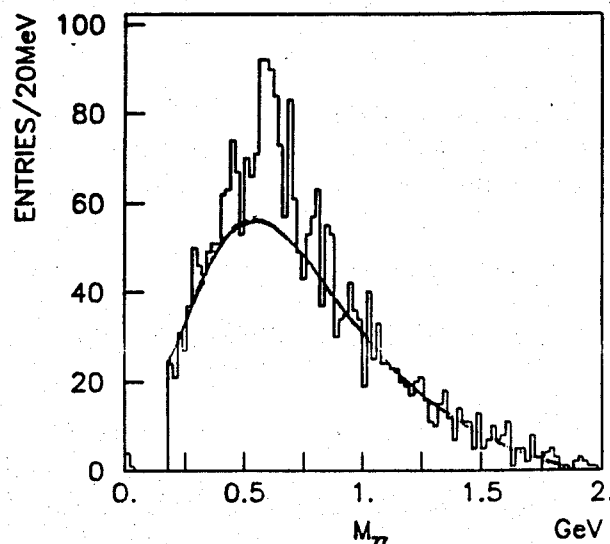
η FILTER

Events with a pair of photons, measured in OLGA, with a total energy larger than 2 GeV and an invariant mass not corresponding to the π^0 mass, were selected by this filter.

The aim of the filter was the study of channels containing an η in the final state. $D_s \rightarrow \eta\pi, \eta\pi\pi^0$. 6% passed.

A study carried out by M.P. Alvarez and the author [33], showed the limited usefulness of the filter. An $E > 25 \text{ GeV}$ cut has to be imposed on the η candidate in order to observe a small signal in the $\gamma\gamma$ invariant mass plot (see fig. 5.1). This reduces the usable sample of η candidates. Predictions, using standard efficiencies for the analysis chain, showed that less than one event was expected in the $D_s \rightarrow \eta\pi$ decay channel for the selected number of η candidates. Based in this result, the analysis was stopped .

Figure 5.1: η Study. $\gamma\gamma$ invariant mass



EMULATOR DATA

Available during 1987, a farm of up to 12 emulators (3081E) was used by the NA14 collaboration. The farm provided three times more power than the CERN central IBM 3090. A single user task would then run up to 10 times faster (real time) in the farm than in the multitasking system.

A subset (4.3 M-Events) of the raw data sample was completely reconstructed. This bias-free sample was used, among other things, to check the efficiency of the filters. A description of the analysis, performed on the "emulator sample", can be found in ref. [8]

5.3 The μ -Strips filter

The microstrip filter was developed with the aim of selecting charmed events without looking for any specific particle. The filter would use the vertex topology, rather than particle identification, to extract a charm-enriched sample. Since only geometrical criteria were used, this filter should provide a bias-free data sample.

Using the whole data sample, passed through the fast track reconstruction program TYPHON, a three step process was followed :

- Determine the interaction point within the active target.
- Track reconstruction in the vertex detector. Using the track parameters determined by TYPHON and the fact that tracks must originate from the interaction point or its neighbourhood.
- Select events which tracks having large transverse deviation from the interaction point.

The microstrips are needed since we are looking for short lived particles that will decay in the vicinity of the interaction point. A large precision in the transverse deviation is therefore needed. A more detailed description than the one given below can be found in ref [28].

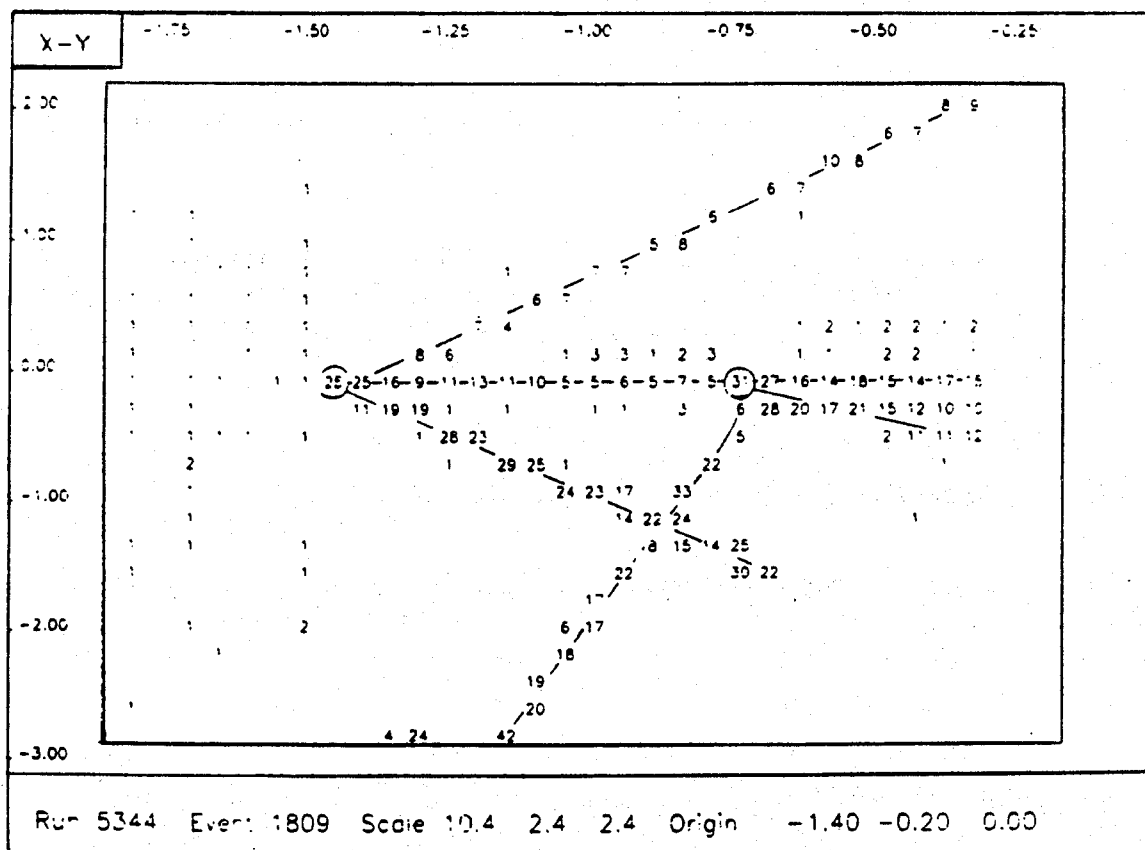
5.3.1 Searching for the interaction point

The longitudinal position of the interaction point, X_I , is obtained using the information from the active target. The transverse position, is fixed by extrapolating the "best track" reconstructed in the microstrips to the X_I coordinate obtained in the active target analysis.

Longitudinal position of the interaction point

The tracks from the microstrips are generally at a small angle to the beam, therefore resolution would be poor for the X coordinate of the vertex if determined using the microstrip tracks. Instead, the active target information was used. If one could determine the active target plane where the interaction has occurred the precision would be of the order of $\pm 150 \mu m$ (plane width = $300 \mu m$). Selecting this plane is not an easy task, due, mainly, to the complexity of the active target information (see Fig. 5.2).

Figure 5.2: Complex active target event.



A fast algorithm was developed to select the correct plane for the main vertex. The first step was to choose a "main road", where the event took place [28], and then a plane within this road as the interaction plane. A comparison between the X-position determined by the active target and the X-position calculated using the microstrips (using events with large-angle tracks), showed that the actual precision in the X-coordinate was $\sim 250 \mu m$, compared to the $500 \mu m$ that one would get using μ strips tracks in "normal" events.

Transverse position

The tracks with a momentum larger than 5 GeV/c and reconstructed before and after GOLIATH, were used in the following step. Using the track's parameters given by TYPHON, the tracks are extrapolated from the first point measured in the chambers to the third plane of the microstrip system. A $\pm 4 mm$ window is opened and any strip fired within that window investigated. A line parallel to the track direction is drawn passing through the selected strip, and smaller windows opened (centered on the line) in the other planes. The hits lying in these windows are used to fit a straight line. In the bend plane the circular shape of the track is taken into account by moving the position of the strips the appropriate quantity, so that a straight line fit can also be performed. Any combination of 4 fired strips is checked. The combination yielding the best probability of χ^2 is chosen. In the χ^2 test, not only is the hit position taken into account but also the compatibility between the MWPC and the found track parameters.

if any ambiguity remains after the two orthogonal projections are reconstructed, the "U" and "V" planes (rotated 23° and 123° respectively around the beam axis) are used.

Considering the probabilities of χ^2 in the Y, Z, U and V association and the two angles measured in the chambers, the best track is selected. The extrapolation of this track to the X_I -coordinate will give the transverse position of the interaction point (Y_I, Z_I).

5.3.2 Extra tracks reconstruction

Reconstruction of all the tracks not entering the previous step is then tried. Using the interaction point coordinates, previously determined, (X_I, Y_I, Z_I) as the starting point for the track, and the kinematic parameters from TYPHON a predicted position in the third plane of the microstrip is calculated. A window is opened, its size ($\pm 500 \mu m$) determined mainly by the fact that the track need not necessarily come from the interaction point. A track fitting method is performed much in the

same way as was described in the previous section. A χ^2 cut is imposed and any track not passing it, is not considered in the next step.

5.3.3 Event selection criteria

Three selection criteria are defined, the first one is called "LOCAL CRITERIA" and the last two known as "GLOBAL CRITERIA".

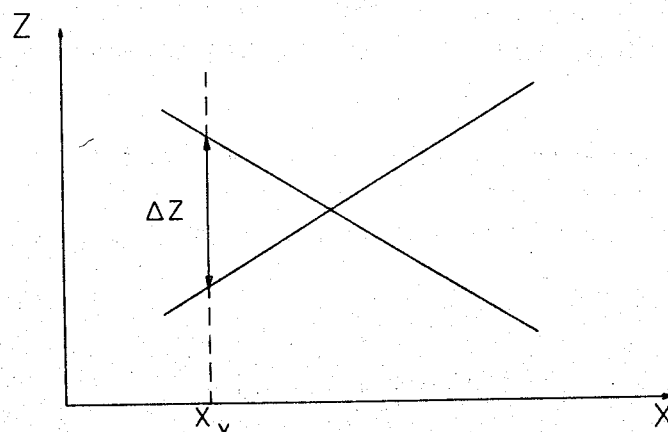
LOCAL CRITERIA

Two tracks crossing in space within 200μ , (D), at a X -coordinate downstream from X_I and having a transverse displacement, ΔL , greater than $60 \mu m$. Where the transverse displacement is defined as follows :

$$\Delta L = \sqrt{\Delta Z^2 + \Delta Y^2}$$

ΔZ and ΔY are respectively the distance, in the projections XY and XZ , between the two tracks, calculated at the X_I coordinate (see fig. 5.3).

Figure 5.3: Transverse distance definition.



In summary:

$$D < 200 \mu m \text{ AND } \Delta L > 60 \mu m \quad \text{Criteria A}$$

GLOBAL CRITERIA

One first finds all the pairs of tracks crossing in space within $150 \mu m$ (D). The mean value of the difference between each pair of tracks is calculated in the XZ projection (LX). In a similar way LY and LZ are calculated and LT is defined as :

$$LT = \sqrt{LY^2 + LZ^2}$$

Two other criteria are defined:

$$\begin{array}{ll} D < 150 \mu m \text{ AND } LX > 500 \mu m & \text{Criteria B} \\ D < 150 \mu m \text{ AND } LT > 150 \mu m & \text{Criteria C} \end{array}$$

All events satisfying the following condition :

$$A \bullet (B \bullet C)$$

where $\bullet$ stands for a logical OR, and A,B and C refers to the above defined criteria, were selected.

18% of the original sample passed the filter

Comparison to MC data and to the unfiltered emulator sample showed that the microstrip filter was bias free and that it had a selection efficiency between 50% and 60% for charm interactions. Only in one of the investigated channels, the long lived $D^\pm$, was a decrease in the filter acceptance observed. This is related to long proper-time candidates.

5.4 The Cherenkov analysis

INDANL is the patch of NEPTUN where the INDRA cherenkov information analysis takes place. Track reconstruction must have been done in advance. The charged track is extrapolated to the INDRA region. Association with the cherenkov data is performed in order to obtain the particle identification. Usually the result of the analysis is included in the track-bank created by Trident and is written to the output tape. Two different approaches are taken to provide particle identification, probability and threshold modes.

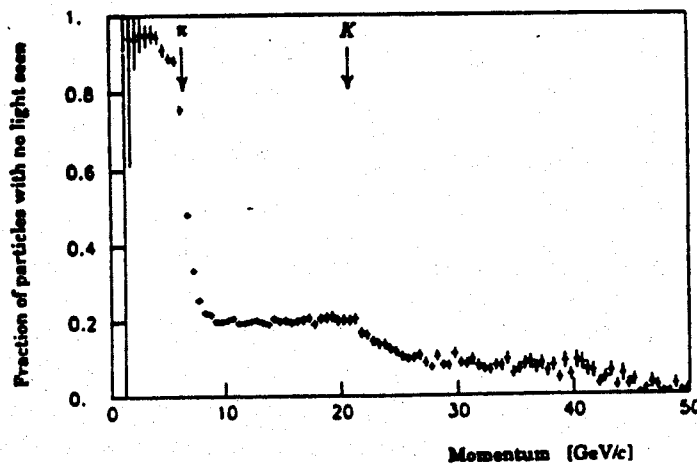
Threshold mode

Threshold mode is the simpler and faster of the two. The track is extrapolated, and the mirror through which it passes is identified. Once the mirror is selected its photomultiplier is checked to see whether light has been produced or not. Light is said to be produced when the ADC contents minus the pedestal, determined by calibration, is larger than 13 counts.

$$(ADC \text{ data} - \text{pedestal}) > 13 \text{ counts}$$

This roughly corresponds to imposing a cut at 0.5 photoelectrons. In section 3.6 it has been shown that light production depends on the particle's velocity (β), and that, for each particle type, a momentum threshold exists below which no light is produced. In fig. 5.4 the momentum thresholds in INDRA can clearly be observed for Kaons and Pions.

Figure 5.4: Momentum threshold in INDRA



The momentum ranges where the different particle types can be identified are given in table 5.1

For example, if a particle passing through INDRA has a momentum of 8 GeV/C , and gives no light, it will be considered as a kaon. Notice that a proton will also not produce light. However, since kaons are more abundantly produced than protons, kaon identification is assumed.

The identification of kaons is important for most of the charm decays studied in NA14. If one uses the "unambiguous" identification given in table 5.1, only a restricted momentum region can be used, therefore a limited number of kaons would

Table 5.1: Particle identification in INDRA

	Momentum threshold GeV/c			
	e	π	K	p
Light	0-4	6.5-19		
No-Light		0-5	6.5-20	21-38

be available for analysis. Extended momentum regions were defined to improve the K recognition efficiency. The "extended kaon" (See table 5.2) region includes a π/K ambiguous region. Further analysis showed that using these ambiguous tracks increases the number of charm candidates without significantly changing the signal to background ratio.

Table 5.2: Extended particle identification in INDRA

	Momentum threshold GeV/c				
	e	π	π/K	K	p
Light	0 - 6	6 - 20	> 20		
No-Light		0 - 5	5 - 6.5	6.5 - 21	> 21

Particles not entering the INDRA acceptance region are labelled Pions because they are the most abundantly produced particle type.

Probability mode

A Monte Carlo technique is used to predict the distribution of light produced, by a given track on the photomultipliers. The common particle types (e, μ, π, K, p) are used in turn. The observed signal is compared to the predicted one and a statistical analysis is performed yielding a probability for each particle type.

This method is much slower than the threshold mode, and no significant improvement in particle identification is obtained. Therefore the threshold mode was selected for the analysis presented herein.

5.5 TRIDENT

Trident is the NA14's program responsible for charged-track reconstruction (Particle trajectories and momentum measurement). It uses MWPC planes and microstrip information to produce all the parameters which define a track.

Originally written for the Omega spectrometer [31], it was then adapted to handle the "old" NA14 apparatus and eventually updated [20] to include the microstrips (NA14/2).

The full process of track reconstruction can be divided in three general steps:

- Wire chambers track reconstruction.
- Association in the microstrips.
- Vertex association.

These steps are briefly described in the following paragraphs.

MWPC tracks.

Space points (X, Y, Z) are formed by grouping the hits produced in adjacent MWPC's planes along the beam direction which have their wires in different spatial orientations. The space points are used to define "roads" in the apparatus. From these roads track segments could be determined.

In the magnetic-free regions of the spectrometer the particle trajectories are straight lines. These straight line segments are projected through the, well mapped, magnetic field regions using a Runge-Kutta method [32]. Association of the segments with one another, or with a vertex, will provide momentum measurement for each track.

Microstrip association.

The MWPC tracks are extrapolated to the microstrip region where three and four points tracks are formed in the two orthogonal projections (XY and XZ). A match in space is tried using the information of the U and V planes (See section 3.4). The matched tracks not pointing to the vertex are released, so that their hits can be used again, and a refit using looser cuts is performed.

At this point the non-matched tracks (only XY or XZ projections have been found) are dropped if they cross matched tracks or if they do not point to the vertex. The remaining track-projections (lying outside the U-V planes acceptance) are either matched in space using the parameters of the tracks coming from the MWPC fit or dropped.

A "goodness" flag is given to all the tracks processed. The different flag numbers are explained following:

- 2 Track segment found only in Stack 1. Momentum measurement done by association with the vertex using the bending of AEG.
- 3 Track segments found in Stack 2 and 3. Momentum measurement done by association with the vertex using the bending produced by both AEG and GOLIATH.
- 4 Track segments found in the 3 stacks. Momentum is measured by the bending produced in GOLIATH, and is further improved by association with the vertex using the bending of AEG.
- 12,13 Same as 2 and 3, but no vertex association has been achieved. Momentum measurement is not available.
- 22,23,24 The so called **FLAG-TWENTIES** tracks. Same as 2,3 and 4 but microstrip association was successful. They represent the best defined tracks because their parameters are very well defined.

Vertex association

The well measured tracks, types 22,23 and 24, are used to form a more precise vertex. An attempt is made to associate the remaining tracks to this new vertex. All associated tracks (main tracks) are labelled as fitted, the remaining are designated as extra tracks.

Table 5.3: Track types: Type-Fraction and Momentum precision.

Track flag	2	3	4	12	13	22	23	24
$\Delta p / p^2 [10^{-4} GeV^{-1} c]$	60	20	5	-	-	20	4	3
Fraction [%]	17	5	6	9	4	25	4	30

The results from Trident are written in the form of banks. The coordinates of the vertex (or vertices) and pointers to the main-tracks and to the extra-tracks banks, are stored in the Vertex bank. Both the main-track and the extra-tracks banks contain the parameters (and its errors) for each track.

Besides the track flag and some bank pointers, the following information is provided in the track bank (refer to figure 5.5 for a description of the angles mentioned):

X,Y,Z The coordinates of a point in the track trajectory. In types 22,23 and 24, the X coordinate of the first measured point in the microstrips, and the corresponding Y and Z, are given. For the rest of the tracks, the coordinates in the first measured point of the chambers are used.

λ The dip angle. The angle of the track to the horizontal plane.

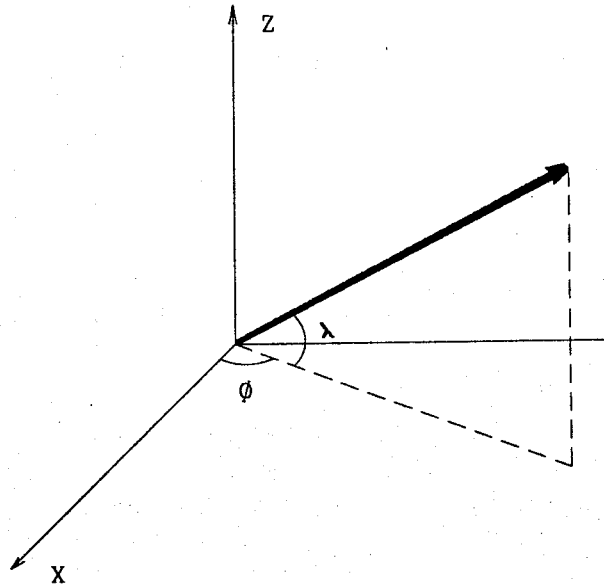
ϕ The azimuthal angle. The angle of the projection of the track in the horizontal plane to the beam (X) axis.

1/P The inverse of the momentum. This value is set to zero if the momentum has not been determined (Types 12 and 13).

With these parameters it is possible to completely determine the track trajectory in the apparatus. For any given X coordinate the corresponding Z and Y coordinates can be calculated, provided the value of any magnetic field encountered is known. The trajectory equations only depend on λ , ϕ , P and the magnetic field intensity B, at a given X. [20,21]

The errors in the parameters are given in the form of a square-matrix, each

Figure 5.5: Track angles



element of the matrix gives the error associated with any pair of parameters. $1/P$ is used instead of P since it is $1/P$ that has a Gaussian error.

5.6 Vertex finding

The Trident vertex is not suitable to be used in charm analysis since the cuts imposed are large enough to include tracks belonging to a secondary vertex. It is also important to freely select the tracks which are going to be used in a vertex calculation. For these reasons a vertex finding package was developed and is included in the NA14's program library.

N-TRACK VERTEX

The basic principle is that once N tracks have been selected as belonging to a vertex, they are constrained to pass through a common point in space. The coordinates of the common point are kept as free parameters, and become the coordinates of the vertex.

The parameters of the track are changed to force it to pass through the common

point. The amount of the change is controlled by the parameter's errors. The distance of the track to the common point with respect to its errors gives a χ^2 variable. χ^2 minimization then provides the coordinates of the common point.

A probability of chi-square ($P(\chi^2)$) cut is imposed in order to accept the vertex coordinates. Two different approaches are used depending on the type of vertex one is looking for.

- Secondary Vertex (Decay vertex):

All the selected tracks must be included in the vertex calculation, if the $P(\chi^2)$ cut is not passed then no vertex is considered to be found

- Primary vertex (Interaction vertex):

In this case the $P(\chi^2)$ is used in a different manner. If a common point is found but the cut in $P(\chi^2)$ is not passed then the track with the largest contribution to the χ^2 is dropped and the fit repeated. The iteration is stopped when the cut is fulfilled or only one track is left.

In both cases a starting point in space is initially selected. Using that point the vertex is calculated and the distance, in the X-direction, between the original point and the one resulting from the fit is measured. If this distance is smaller than a given cut the fitted point is taken as the vertex. If not, the result from the fit is taken as the new starting point and the process repeated. The procedure is iterated until the change in X is less than the chosen tolerance.

For the primary vertex calculation the Trident vertex is used as the first starting point. In the case of secondaries a simple intersection method is used to define a starting point.

The program also includes the possibility of forcing tracks to belong to the primary vertex. If this option is selected then the forced track(s) can not be dropped from the vertex fit, even if its contribution to the χ^2 is the largest one and the $P(\chi^2)$ cut not passed. The track with the next largest contribution to the χ^2 is dropped instead. This is of most use when including the "charm-tracks" in the vertex determination.

Chapter 6

Charm signals.

The μ -strip filter selected sample was used to extract a charm signal in the $D^0 \rightarrow K\pi$, $K3\pi$ and $D^+ \rightarrow K2\pi$ channels. Appropriate cuts were imposed in order to have a clear peak in the invariant mass plot of the decay products. A mass region was selected and all the events contained in it were written to tape. Three tapes were produced with 1,489 ($K3\pi$), 1,866 ($K2\pi$) and 3,644 ($K\pi$) events on each. They represent the so called *single-charm* sample. This sample was then passed through the *double-charm* selection process where a search was made for the second charm particle of the event.

In this chapter a description of both processes, the single-charm and the double-charm selections, is presented. The methods used and the cuts imposed are described in the following sections. Also, the mass plot for each decay channel studied is shown, and the total number of events given.

6.1 General concepts

6.1.1 Invariant mass

The relativistic expression

$$E^2 = m^2 + p^2 \quad (6.1)$$

is used to calculate the mass of a particle when its energy and momentum are known.

In order to determine the momenta of the parent particle we use the calculated

components of its decay products:

$$\begin{aligned} p_c^i &= \sum_d p_d^i \\ p_c &= \sum_i (p_c^i)^2 \end{aligned}$$

where d refers to all the decay products, i run over the spatial coordinates (X, Y, Z), and c stands for Charm.

Using energy conservation and Eq. 6.1 one can write

$$\begin{aligned} E_c &= \sum_d E_d \\ E_c &= \sum_d \sqrt{m_d^2 + p_d^2} \end{aligned}$$

where p_d is the momentum of the decay products (measured using the magnets, and given by Trident), and m_d its masses (fixed by particle identification). Finally, the mass of the parent particle is given by

$$m_c = \sqrt{E_c^2 - p_c^2}$$

The momenta of the decay products, p_d , is taken from Trident and its components are calculated using:

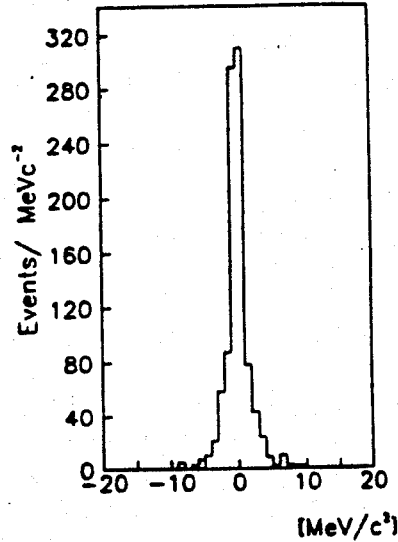
$$\begin{aligned} p_d^x &= p_d \cdot \cos \lambda \cdot \cos \phi \\ p_d^y &= p_d \cdot \cos \lambda \cdot \sin \phi \\ p_d^z &= p_d \cdot \sin \lambda \end{aligned}$$

here λ and ϕ are the track angles, as described in section 5.5 (See Fig. 5.5). These angles depend on the X coordinate (The particle trajectory is not a straight line so the angles will change at different X), therefore the momentum components of the decay products depend on X, and thus the mass of the parent particle must be given at a selected X coordinate.

The normal procedure is to calculate the mass of the charm candidates at the the Trident vertex and, once a secondary vertex has been found, recalculate the mass at that position.

This mass correction is generally very small, as can be seen in figure 6.1 where the difference of the mass calculated at the Trident vertex and at the secondary vertex is shown.

Figure 6.1: Mass correction



6.1.2 Charm-track

Once a secondary vertex position (X_S, Y_S, Z_S) has been found, and the momentum components of the parent particle have been calculated, one can define a set of parameters $(Y_S, Z_S, 1/P, \phi_S, \lambda_S)$ at the X_S coordinate which will define a track in the standard manner used by Trident. This *charm-track* could be used in the same way as any other track, if the errors in its parameters are also provided.

The two angles are calculated at the secondary vertex position (X_S, Y_S, Z_S) using the following expressions

$$\lambda = \arctan \frac{P_Z}{\sqrt{P_X^2 + P_Y^2}}$$

$$\phi = \arctan \frac{P_Y}{P_X}$$

The errors on Z and Y are taken from the secondary vertex fit, whilst the errors on λ and ϕ , are calculated propagating the errors in the angles of the decay products tracks.

When the parameters and their errors are known, the charm-track can be included in any new vertex determination. In particular they are quite useful in the interaction vertex calculation. The error in the transverse plane coordinates, (σ_Y, σ_Z) , are usually smaller than that of a "real" track, so the primary vertex determination is improved when the charm-track is used.

6.1.3 N_σ cut

One of the key points of the present analysis is the use of the *number of sigma* cut. Usually if one has a charm candidate, and has found the primary vertex, one would impose some minimum length in order to eliminate the possibility of the particle decaying at the main vertex. In this case one would not be able to say that a charm particle had been observed since the decay products could have been produced directly in the interaction.

In high energy fixed target experiments, the main spatial direction is fixed by the beam since all the events will be "boosted" in that direction. A cut in the separation between the two vertices along the beam direction is commonly use.

But since it is the distinguishability between the two vertices that is important, we have chosen to use the measured separation in terms of the error on the reconstructed vertices. The number of sigma, for any given two vertices (main and secondary), is defined as:

$$N_\sigma = \frac{\Delta X}{\sqrt{\sigma_{X_M}^2 + \sigma_{X_S}^2}}$$

$$\Delta X = X_S - X_M$$

where, S , stands for secondary, M , for main, and σ_{X_S} and σ_{X_M} are the errors in the X coordinates of the two vertices.

6.2 Single charm sample

This section is divided in two parts. In the first part the method followed to define a charm candidate is explained, and in the second part the selected sample is presented and its main features described.

6.2.1 Charm selection

Once an event has been read from tape, a loop over all of its tracks is performed. In order to use a track as a decay product of a charm candidate, the following constraints must be fulfilled:

λ cut

Many of the γ 's of the beam will convert into an e^+e^- pair. The opening angle,

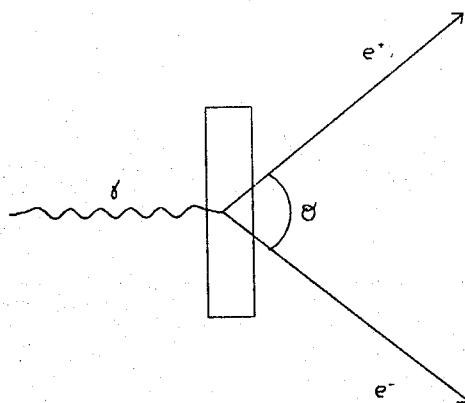
θ , between the two electrons (see Fig. 6.2) is given by

$$\theta \sim (m_e/E_\gamma) \cdot \log(E_\gamma/m_e)$$

this expression yields to

$$\theta < 7 \text{ mrad for } E_\gamma > 500 \text{ MeV}$$

Figure 6.2: Opening angle for $\gamma \rightarrow e^+e^-$



In figure 6.3 the dip angle for all the tracks in the events is represented, a narrow peak centered at zero, produced by the electromagnetic background, is clearly observed.

In order to eliminate most of the tracks produced by pair conversion, a $\lambda > 1.5 \text{ mrad}$ cut was imposed to any single track.

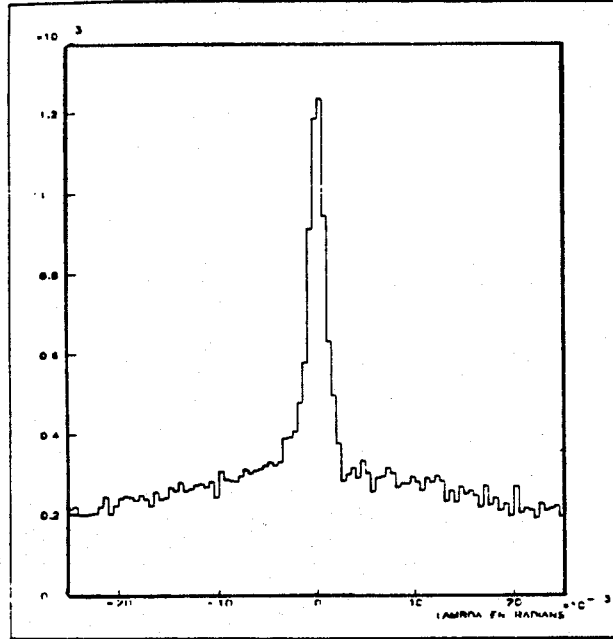
Minimum P cut

Multiple scattering in the active target would be of great importance for low momentum tracks. Multiple scattering leads to a large inaccuracy in the momentum determination on these tracks. In order to reduce this effect a $P > 1 \text{ GeV}/c$ constraint is used.

All tracks passing the previous criteria are used in the following steps.

Particle identification

The information of the INDRA cherenkov is used to find an *extended* kaon (See section 3.6 for the definition of extended kaon). Once a kaon has been found it is combined with pions (one, two or three pions are added to the kaon, depending

Figure 6.3: Dip angle (λ) of all tracks.

on the decay channel under investigation). The electric charge of the combination must be 0, +1 or -1.

Invariant mass

The invariant mass of the combination is calculated at the Trident vertex position. The set of tracks is passed to the secondary vertex calculation if its mass lies in the $1.7 - 2.0 \text{ GeV}/c^2$ region.

Secondary vertex

The vertex is said to be defined if the fit yields to a probability of χ^2 ($P(\chi^2)$) larger than 0.001. At this point the charm track is defined, and the mass of the combination recalculated at the secondary vertex position.

Main vertex

The charm-track is combined with all the remaining tracks in order to find the primary vertex. In this case the $P(\chi^2) > 0.001$ cut is used in a different way. If the cut is not passed, then that track (charm-track excepted), with the largest contribution to the χ^2 of the vertex is dropped and the process reiterated. No vertex is considered to exist when only the charm-track is left.

N_σ cut

Good primary and secondary vertices are now present. The number of sigma are calculated, and the following cuts are applied

$$\begin{array}{lll} k\pi & \text{channel} & - N_\sigma > 2 \\ k2\pi & \text{channel} & - N_\sigma > 4 \\ k3\pi & \text{channel} & - N_\sigma > 6 \end{array}$$

These cuts were selected in order to produce a signal over background, S/B, ratio, in the neighbourhood of the expected mass, of the order of one. Better defined signals, could be extracted by simply applying more severe N_σ cuts on the selected sample.

For the neutral channels ($K\pi$ and $k3\pi$) an extra criteria can be used in order to enhance the signal. In these cases the presence of a D^* was investigated through its decay mode $D^{*+} \rightarrow D^0\pi^+$. This decay is very well defined when one studies the mass difference between the D^0 and the D^* candidates

$$\Delta M = M(D^0\pi) - M(D^0)$$

If one adds a π of the right charge to the $k\pi$ or $k3\pi$ channels, and calculates the mass difference, a clear peak around $\Delta M = 145 \text{ MeV}$ will be obtained, even at low N_σ cut.

A 143. $< \Delta M < 149. \text{ MeV}/c^2$ region was used to tag the presence of a D^* . In this case the N_σ cuts used were the following:

$$\begin{array}{lll} k\pi & \text{channel} (D^*) & - N_\sigma > 0.5 \\ k3\pi & \text{channel} (D^*) & - N_\sigma > 4.0 \end{array}$$

Table 6.1 summarizes the number of sigma cut imposed to the different channels under study.

6.3 The selected single-charm sample

The selected sample contains not only charm particles, but also background. In order to determine the total number of charm candidates, a statistical analysis is carried out. For each of the decay channels investigated, the mass plot is used to determine the number of charm events available, and to calculate the statistical significance of the signal.

Table 6.1: N_σ cuts used in the single charm sample selection

Channel	N_σ
$K\pi$	2.0
$K\pi(D^*)$	0.5
$K2\pi$	4.0
$K3\pi$	6.0
$K3\pi(D^*)$	4.0

The cuts used to extract the sample are kept loose in order to select the largest number of charm events as possible. In the case of non-restrictive cuts, the main component of the background will be of combinatorial type. For this reason, when fitting the mass distribution of the sample, an exponential function is used for the background, and a gaussian distribution is used for the signal.

The function used is

$$Y = e^{a+b \cdot X} + c \cdot e^{-\frac{1}{2} \cdot \left(\frac{X-M}{\sigma_M}\right)^2}$$

Y represents the number of entries per bin of the histogram and X is the mass of the combination. From the fit of this function to the mass plot histogram one will determine a, b, c, M and σ_M .

A fit was performed on the histograms shown in figure 6.4 and a set of parameters extracted for each channel. The mass region used was $1.7 - 2.0 \text{ GeV}/C^2$ and the bin size was of 5 MeV .

The total number of entries in the mass region $1.835 - 1.875 \text{ GeV}/C^2$ was determined, both for the charm signal, S , and the background, B , using the Gaussian and exponential functions respectively. Using these values the signal over background ratio, S/B , was calculated. The relevant parameters of the fit, together with the number of charm candidates, background and the signal over background ratio are presented in table 6.2. The mass plot of the $k\pi$ and $k3\pi$ channels, been compatible with a D^* is given in figure 6.5. Notice the clearness of the signal.

Figure 6.4: Mass Plots. Single charm sample.

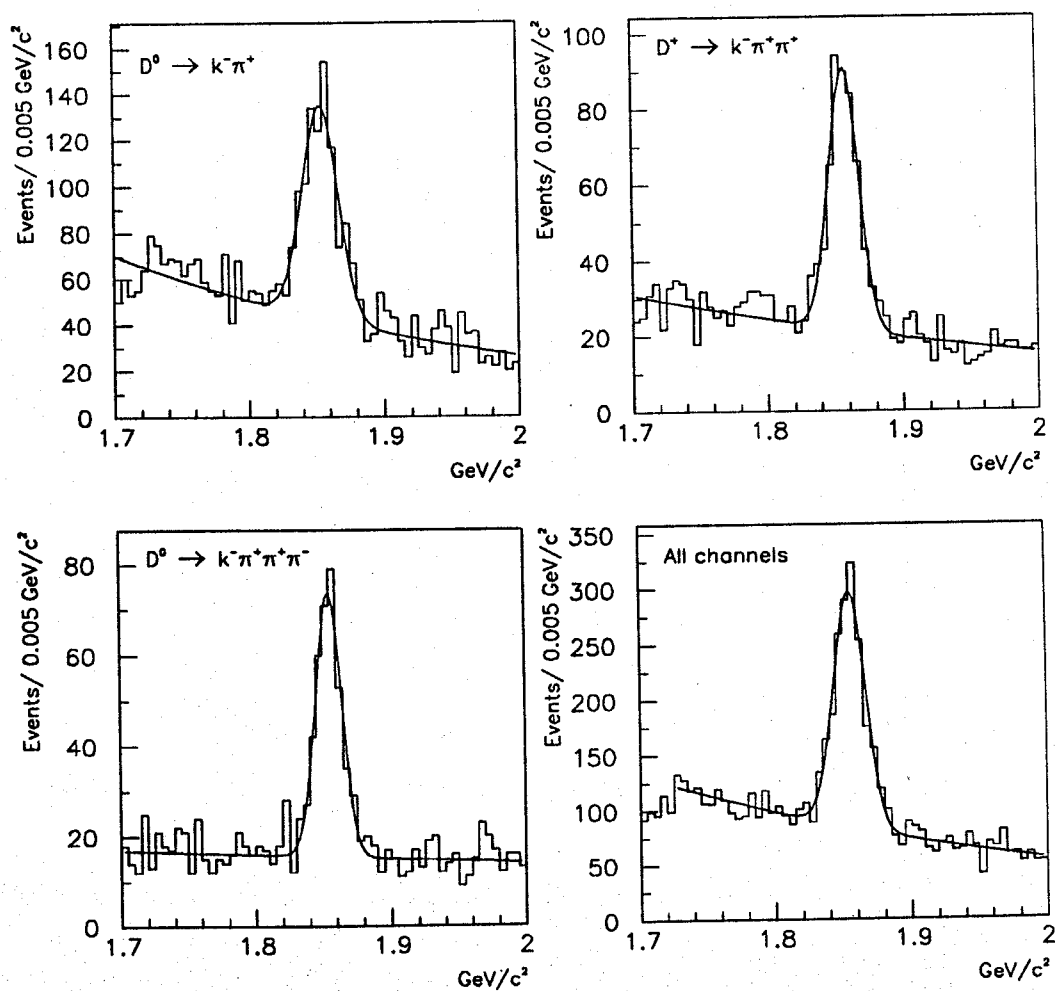


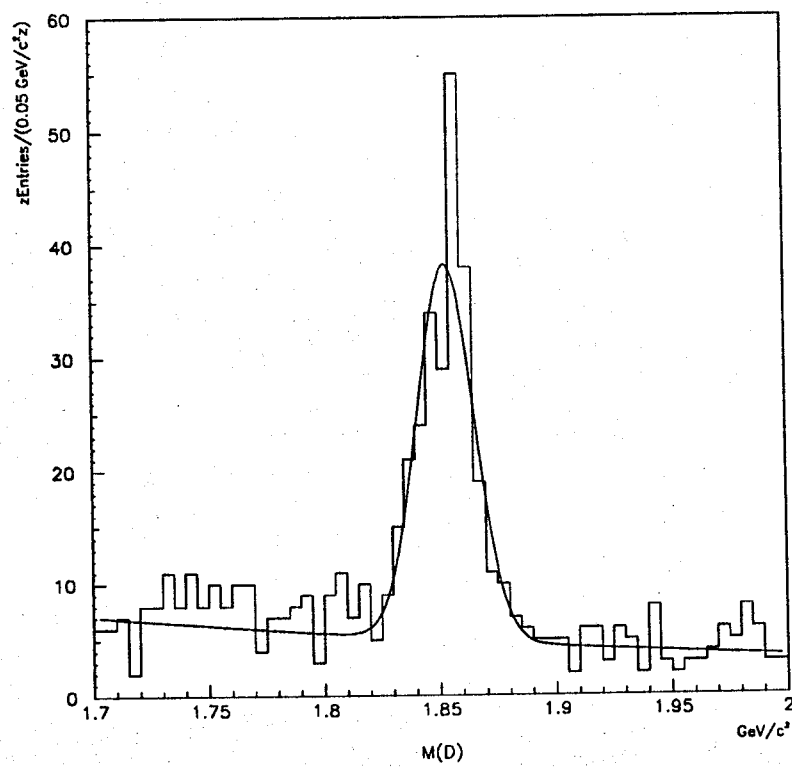
Figure 6.5: Mass plot. Single charm sample. D^* 

Table 6.2: Single charm sample. Summary

	CHANNEL			
	$k\pi$	$k2\pi$	$k3\pi$	All
Selection parameters				
N_σ	2	4	6	
Fit parameters				
a	9.8 ± 0.4	7.4 ± 0.6	3.8 ± 0.7	9.8 ± 0.3
b	-3.2 ± 0.2	-2.3 ± 0.3	-0.6 ± 0.4	-2.9 ± 0.2
c	92.3 ± 6.2	69.3 ± 5.7	58.4 ± 5.2	$213. \pm 10.$
$M(GeV/c^2)$	1.853 ± 0.0009	1.857 ± 0.0009	1.854 ± 0.0009	1.855 ± 0.0005
σ_M (GeV/c^2)	0.013 ± 0.0008	0.011 ± 0.0009	0.010 ± 0.001	0.012 ± 0.0005
χ^2/dof	1.2	0.77	0.85	1.2
Charm Particles				
S	534 ± 24	353 ± 20	271 ± 18	$1,134 \pm 35$
B	340 ± 20	173 ± 16	123 ± 15	671 ± 27
S/B	1.57 ± 0.12	2.04 ± 0.22	2.2 ± 0.3	1.69 ± 0.09

6.3.1 The clean single charm sample

In order to improve the S/B ration , a $N_\sigma > 7.0$ and a $P(\chi^2 > 0.002)$ cuts were used. In this case the number of sigma has been computed after the vertex refit.

This sample will be used for the inclusive analysis described in the following chapter. The parameters from the fit can be found in table 6.3. The mass plot with the fitted function superimposed is shown in figure 6.6.

6.4 Double charm sample

The single charm sample is used as input for the second charmed particle selection. First one presents the method followed to extract the sample and then the resulting the main parameters and the mass plots are given.

Figure 6.6: Mass plots. Clean single charm sample.

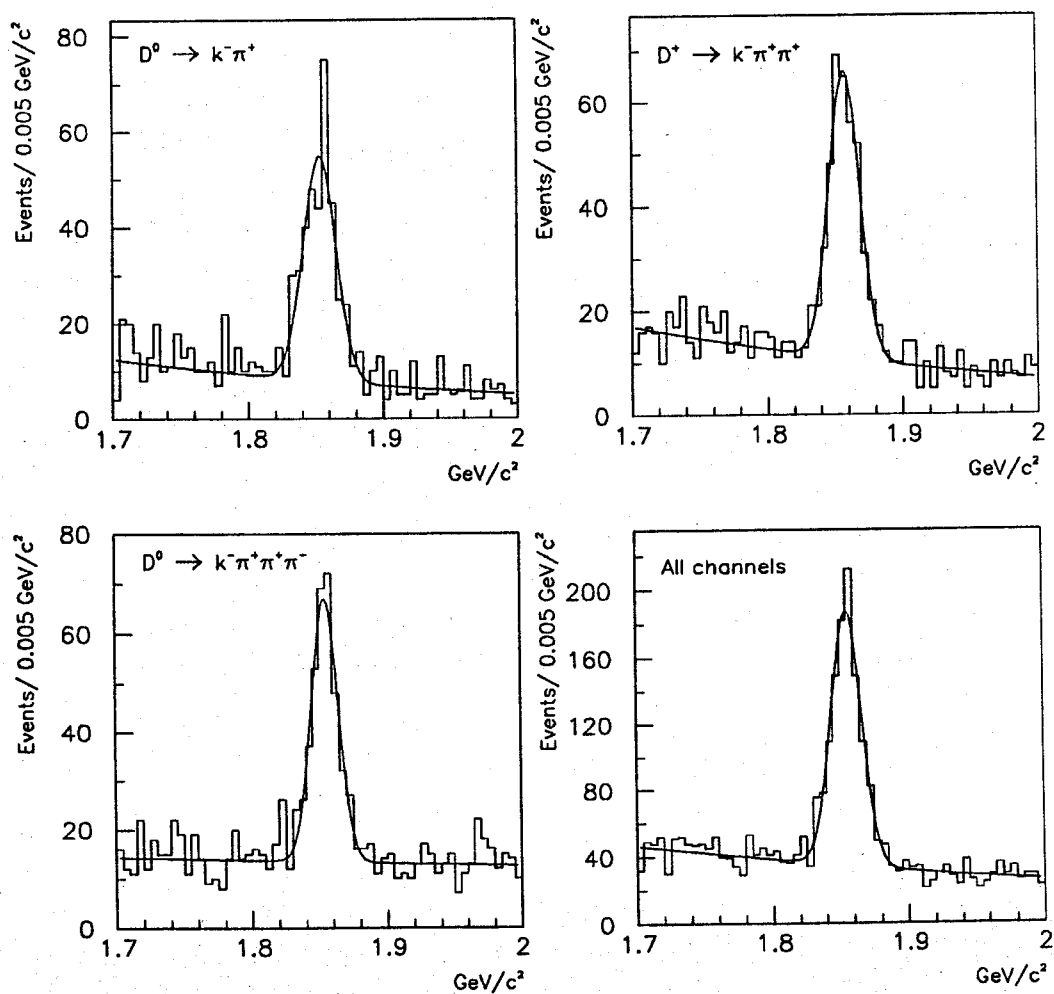


Table 6.3: Clean Single charm sample. Summary

	CHANNEL			
	$k\pi$	$k2\pi$	$k3\pi$	All
Selection parameters				
N_σ	7	7	7	
Fit parameters				
a	7.7 ± 0.9	7.9 ± 0.4	3.4 ± 0.7	7.2 ± 0.5
b	-3.0 ± 0.5	-2.9 ± 0.2	-0.5 ± 0.4	-2.0 ± 0.3
c	46.9 ± 3.9	55.2 ± 4.5	53.9 ± 5.3	154 ± 8
M (GeV/c ²)	1.853 ± 0.0008	1.858 ± 0.0009	1.854 ± 0.0008	1.855 ± 0.0005
σ_M (GeV/c ²)	0.012 ± 0.0008	0.011 ± 0.0008	0.010 ± 0.0008	0.011 ± 0.0005
χ^2/dof	1.5	0.8	1.0	1.3
Charm Particles				
S	258 ± 17	289 ± 17	256 ± 16	796 ± 30
B	62 ± 10	86 ± 10	107 ± 11	274 ± 18
S/B	4.2 ± 0.7	3.3 ± 0.4	2.4 ± 0.3	2.9 ± 0.2

6.4.1 Second charm selection

When an event has been decoded, a loop on the tracks banks is performed. The charm track is searched for, and the track number of the decay products is obtained. The particles "belonging" to the charm track are flagged as used. The remaining must pass the $\lambda > 1.5$ mrad and $p > 1$ GeV/c cuts in order to be considered in the following steps of the process.

Particle identification

The INDRA cherenkov is used to identify Kaons. For the double charm selection, two separated analysis were carried on. In the first one the unambiguous k identification was done. In the second, all particles momentum larger than 20 GeV/c and with light produced in INDRA were marked as kaon. This sample will be called the K20 sample, notice that this type of identification differs from the extended k criteria since the identified k are excluded.

The K20 was supposed to increase the number of final double charm selected. Actually the sample was finally not used since it introduced more noise than signal

in the selected sample.

Secondary vertex

One, two or three pions added in turn to the selected kaon. The invariant mass of the combination was checked to be in the $1.7 - 2.0 \text{ GeV}/c^2$ mass region.

The secondary vertices, one for each charm candidate, are searched for. The $P(\chi^2) > 0.002$ criteria is used to kill bad vertices. If the two vertices are found the charm track of each candidate is built and the main vertex process is started.

Primary vertex

Using the two charm tracks (forced to belong to the main vertex) together with the remaining charged tracks the primary vertex fit is performed. A $P(\chi^2) > 0.002$ cut is imposed, and the process of drooping the track with the largest contribution to the χ^2 is followed if the cut is not passed. Notice that the $P(\chi^2)$ criteria is tighter than for the single charm sample, this comes from the fact that now the two charms are present in the main vertex computation.

N_σ cut

At this point one has the three vertices well defined. The primary vertex is in principle different to the one found in the single charm selection. Therefore, one has to choose a new N_σ cut for both, the first-charm and the second-charm vertices. But, since our starting sample (the first-charm) has already a good signal to background ratio one can choose a fixed N_σ cut for it. The selected value was $N_\sigma > 1$, this ensures the distinguishability between the first-charm and the interaction vertices. Even if one fixes one of the two involved N_σ cuts, the process of selecting the other is still complex.

In the single charm selection, to chose a N_σ cut was a matter of looking at the mass plot, and to compute S/B ratios. The chosen value would be the one that yielded a large S/B ratio without reducing too much the signal.

Now the problem has gone 2-dimensional since there are two masses involved. One should use the mass scatter plot and determine the signal over background ratio on it. This method should work correctly for large statistics samples. But in the case of the present analysis where the different decay channel combinations are selected separately one is left with very few entries on each of the nine scatter plots ($M(k\pi)$ vs $M(k\pi)$, $M(k\pi)$ vs $M(k2\pi)$, etc), therefore a different approach must be followed.

The method chosen was to work with the two projections of the scatter plot and with the mass plot of each charm candidate when the mass of the other is

constrained to a $\langle M \rangle \pm 2\sigma_M$ mass region. The chosen values for the cut yielded good S/B ratios in the projections and a “large” number of entries on each of the mass-selected plots.

The final values are shown in table 6.4, the rows represent the first-charm decay channel and the columns the second, the second value given in the $k\pi$ and $k3\pi$ channels correspond to the D^* channel.

Table 6.4: Double charm selection. N_σ cuts

	$k\pi$	$k2\pi$	$k3\pi$
$k\pi$	$0.5 + 0.0$	4.0	$5.0 + 2.0$
$k2\pi$	$2.0 + 0.0$	3.0	$5.0 + 2.0$
$k3\pi$	$2.0 + 0.0$	4.0	$5.0 + 2.0$

6.4.2 The double charm signal

In order to extract the relevant parameters for the double charm signal, all the decay channels are added and a fit on the mass plots is performed. The scatter plot is given in fig. 6.7, the y-axis contains the mass of the second charm, while the x-axis represents the mass of the first charm. A clear accumulation of entries is observed in the neighbourhood of $M(1^{st}) \simeq M(2^{nd}) \simeq 1.85 \text{ GeV}/c^2$, and a very nice separation between “signal” and background is observed. This is more clearly seen in fig. 6.8 where the two projections of the scatter plot are presented, together with the mass plot of each of the two charms when the mass of the other is in the $1.82 - 1.88 \text{ GeV}/c^2$ mass region. The conclusion from these last plots is that as soon as one of the charm candidates is mass-selected the other presents an essentially background free distribution.

One extra refinement was introduced in order to avoid the “double-counting”. This consisted in selecting one combination per event. This process must be done very carefully since the selection criteria could introduce some bias in the final sample. For instance, it will not be difficult to define a selection mechanism including the mass of the two charm candidates, and selecting the combination which masses are closer to the accepted average mass value for the D meson. This would yield to a beautiful mass plot for the selected combination but the sample would be completely biased. The mass plot will be used to separate signal and background, and the background in this case would present large component in the signal region, which is not computable from the wings of the mass plot.

In our case we have used a more probabilistic method. The probability of χ^2 of

the three vertices is used to define a weight for each combination of a given event. Then the combination with the largest weight will be selected. In figures 6.9 and 6.10 the mass plots for this sample are shown.

Finally, table 6.5 summarizes the parameters of the double charm sample mass plots. The b parameter is missing for the mass plots where a constant (a) background and a Gaussian signal (c , M and σ_M) have been used. The binning is now 10 MeV , and a $1.82 - 1.88 \text{ GeV}/c^2$ mass region was used to obtain the quoted values of S , B and S/B .

Table 6.5: Double charm sample signal. Summary

	1 st Charm	2 nd Charm	1 st Charm $P(\chi^2)$ -selected	2 nd Charm $P(\chi^2)$ -selected
Fit parameters				
a	9.5 ± 2.7	5.7 ± 2.6	1.5 ± 0.3	1.7 ± 0.3
b	-4.8 ± 1.5	-2.6 ± 1.4	—	—
c	10.2 ± 2.6	10.5 ± 3.3	7.9 ± 2.2	8.1 ± 2.2
M (GeV/c^2)	1.850 ± 0.003	1.858 ± 0.003	1.847 ± 0.004	1.856 ± 0.003
σ_M (GeV/c^2)	0.010 ± 0.002	0.009 ± 0.003	0.014 ± 0.003	0.011 ± 0.003
χ^2/dof	1.5	1.5	1.2	1.3
Charm Particles				
S	26 ± 5	23 ± 5	26 ± 3	21 ± 3
B	12 ± 3	13 ± 4	9 ± 1	10 ± 1
S/B	2.2 ± 0.7	1.7 ± 0.6	3.0 ± 0.5	2.1 ± 0.5
Mass-selected				
a	0.32 ± 0.12	0.44 ± 0.13	0.28 ± 0.12	0.41 ± 0.13
c	7.5 ± 2.0	9.6 ± 2.6	6.3 ± 1.7	7.1 ± 2.0
M (GeV/c^2)	1.849 ± 0.003	1.858 ± 0.002	1.846 ± 0.003	1.857 ± 0.003
σ_M (GeV/c^2)	0.011 ± 0.002	0.009 ± 0.002	0.014 ± 0.003	0.012 ± 0.003
χ^2/dof	0.7	0.8	1.2	0.8
Charm Particles				
S	23 ± 5	23 ± 5	22 ± 5	22 ± 5
B	1.8 ± 1.4	2.4 ± 1.6	1.7 ± 1.4	2.3 ± 1.6
S/B	12.7 ± 5.3	9.6 ± 5.0	12.9 ± 6.0	9.6 ± 5.1

As an example of the kind of events one is working with, the vertices region of three selected double charm events are shown in figures 6.11, 6.12 and 6.12. The ellipses, centered on each vertex, represent the one sigma region.

Figure 6.7: Double charm sample mass scatter plot.

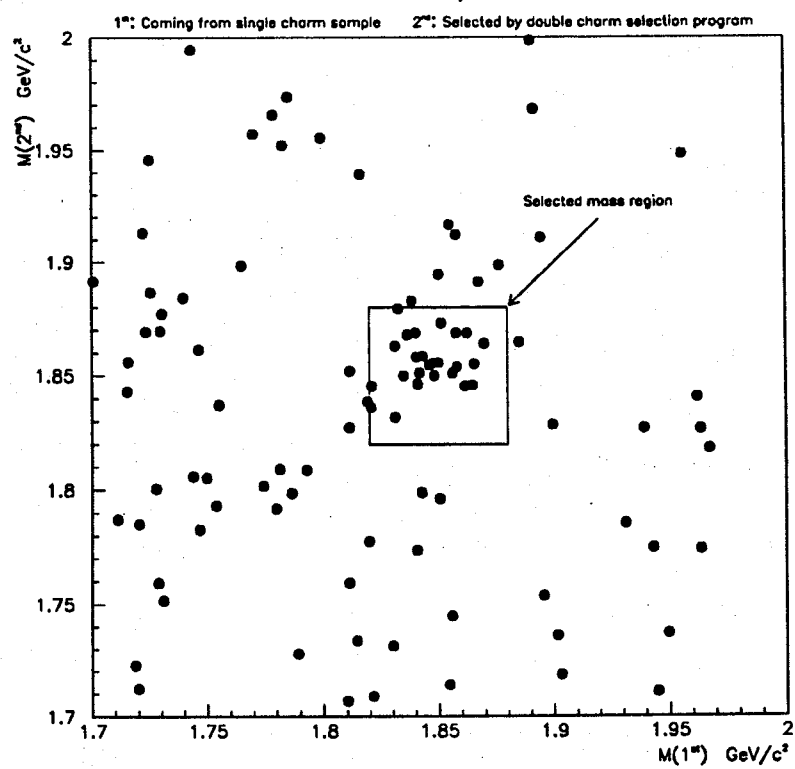


Figure 6.8: Double charm sample mass plots.

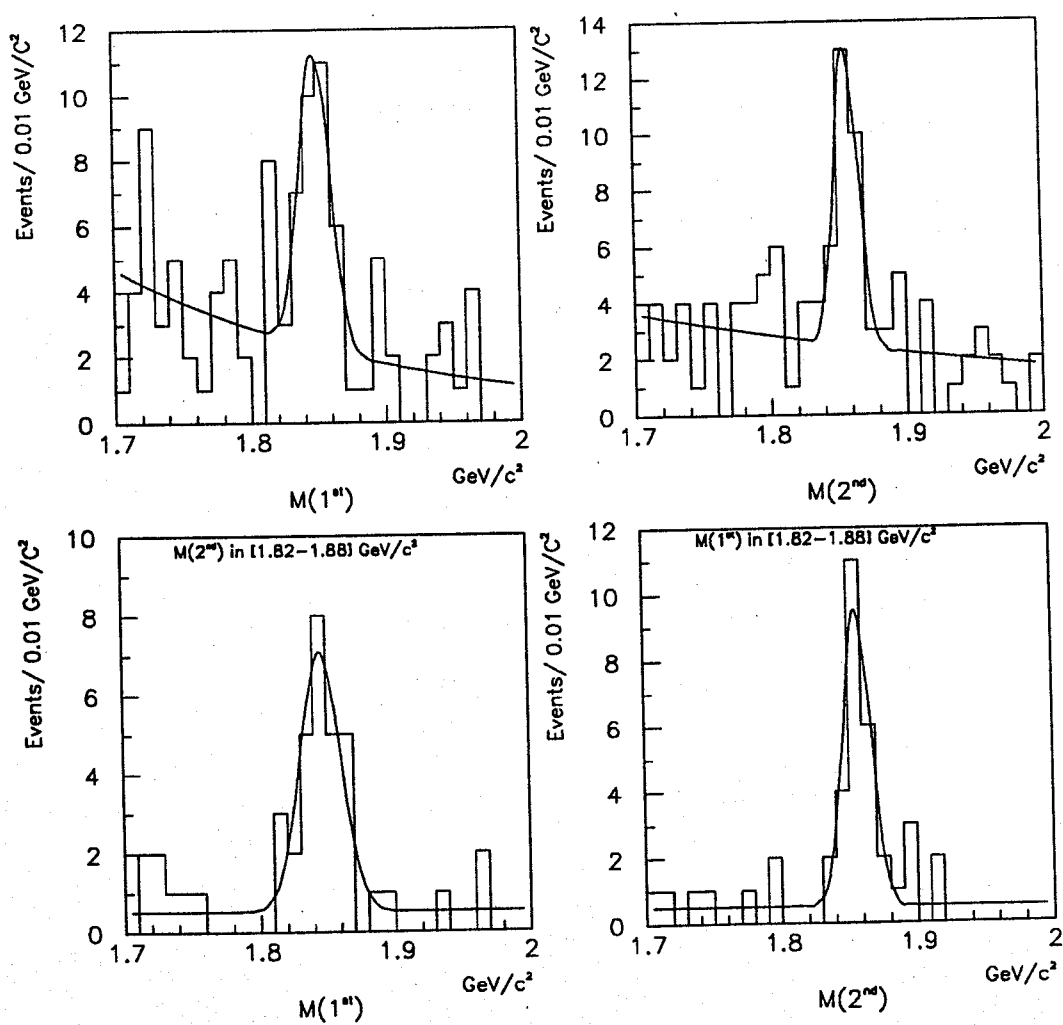


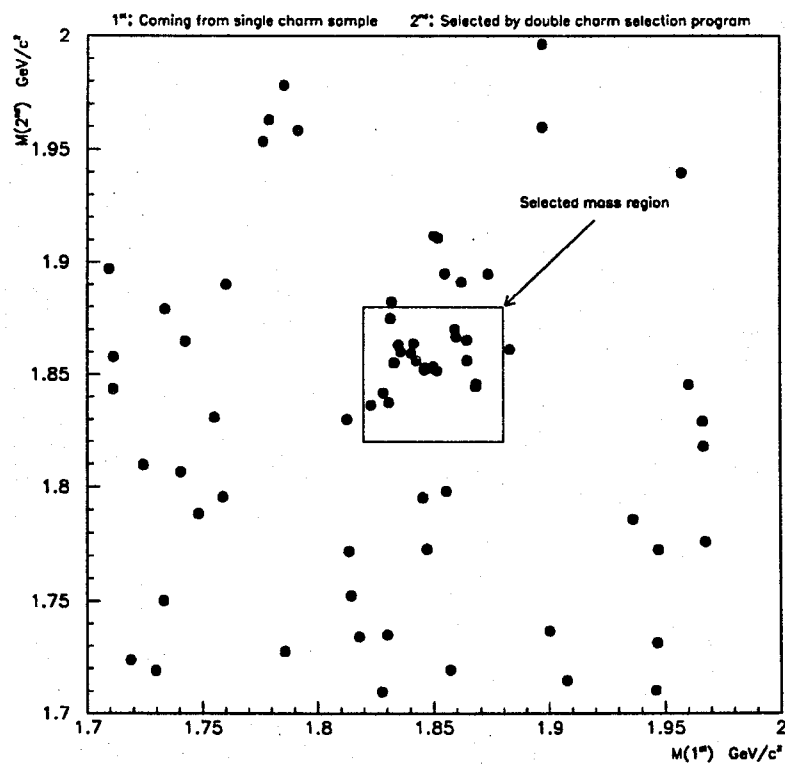
Figure 6.9: Double charm sample mass scatter plot. $P(\chi^2)$ -Selected sample

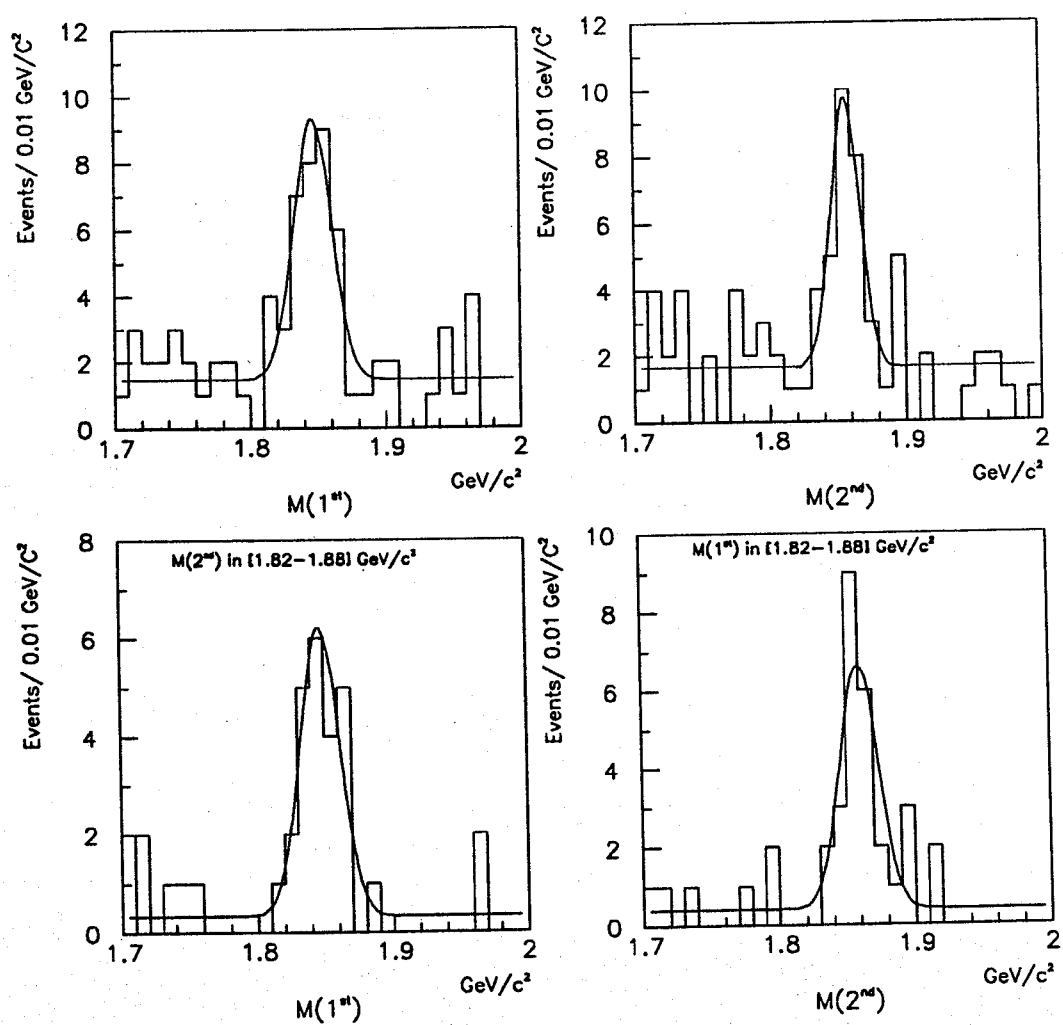
Figure 6.10: Double charm sample mass plots. $P(\chi^2)$ -Selected sample

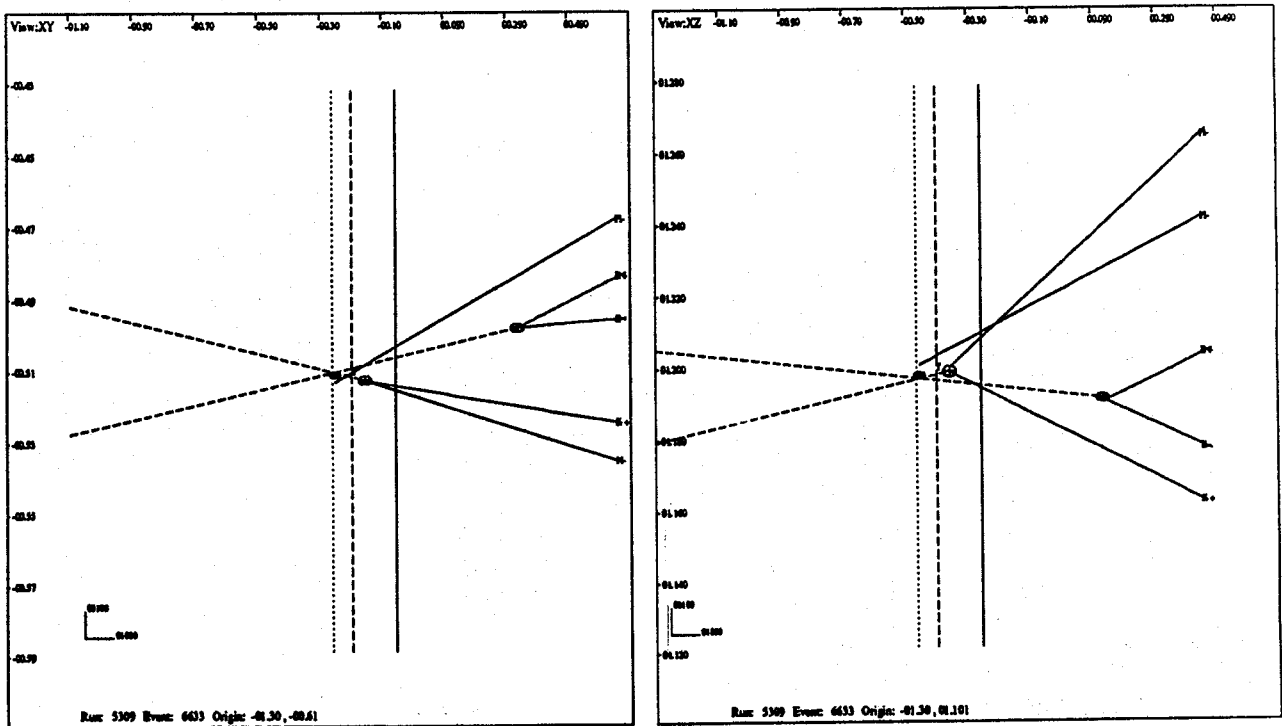
Figure 6.11: Double charm sample. Event display. $D^0 \rightarrow k\pi + D^0 \rightarrow k\pi$ 

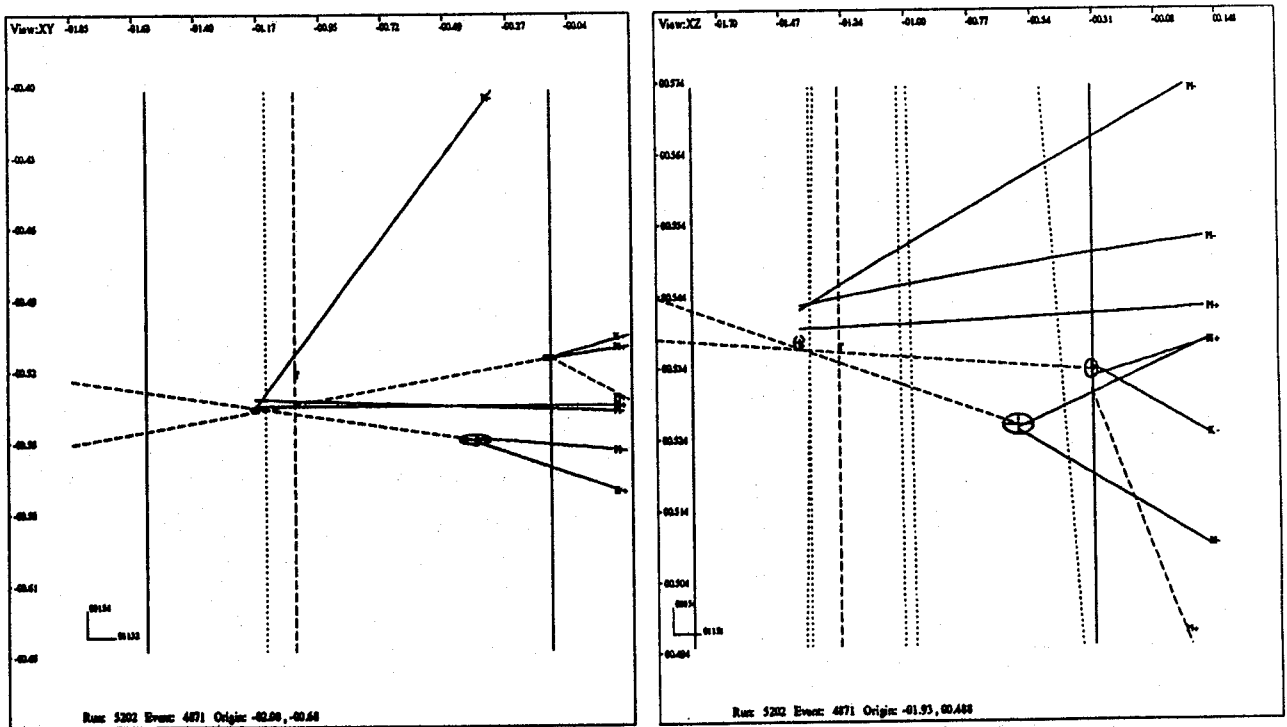
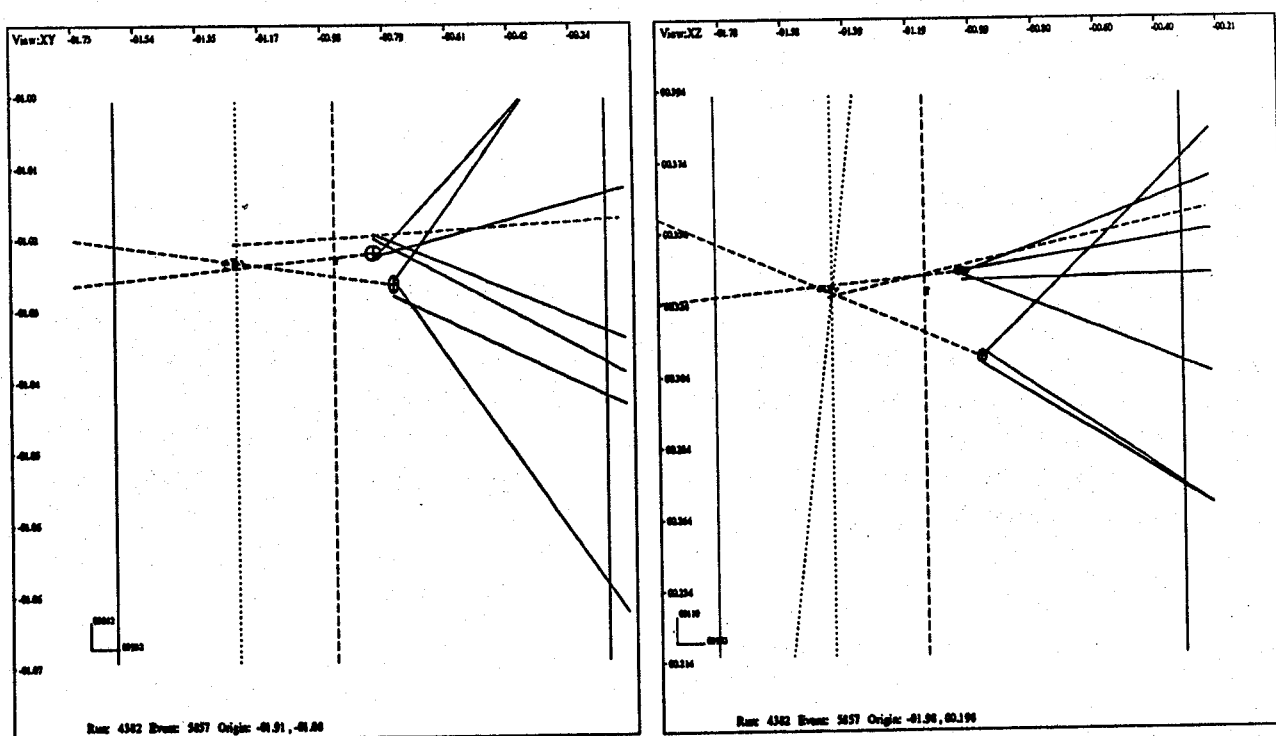
Figure 6.12: Double charm sample. Event display. $D^0 \rightarrow k\pi + D^+ \rightarrow k\pi\pi$ 

Figure 6.13: Double charm sample. Event display. $D^0 \rightarrow k\pi\pi\pi + D^+ \rightarrow k\pi\pi$ 

6.4.3 Other double charm events

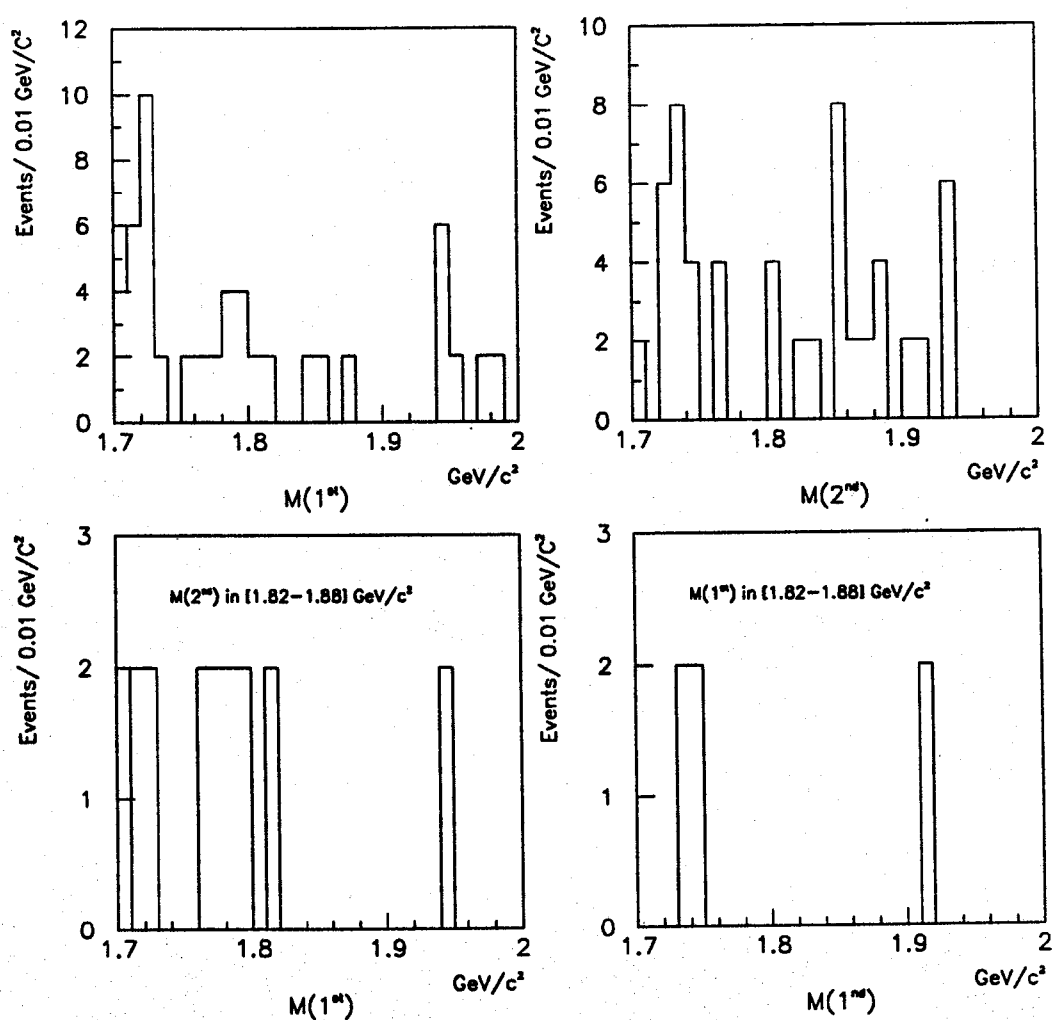
A search for double charm events containing $D_S \rightarrow kk\pi$, $D^+ \rightarrow kk\pi$ and $\Lambda_C \rightarrow kp\pi$ was performed using two complementary methods. The first method consisted in using the existing samples [20,21,26,25] of the new channels under investigation. This samples would be equivalent to the "single charm sample" used in the standard double charm selection process. The second method consisted in modifying the selection criteria (particle identification and mass windows) in the double charm selection program and passing it on the standard single charm sample in order to extract the Λ_C , D_S and $D^+ \rightarrow kk\pi$ signals.

The first method did not succeed in extracting any double charm event, when a $N_\sigma > 2$ cut was imposed on both charm candidates. The second method yielded two events for the $D^+ \rightarrow kk\pi$, one event for the D_S and no event was found for the Λ_C .

6.4.4 Multiple charm events

A search for events containing more than two charmed particles was also performed. In this case the tagging mechanism would be the detection of two particles with the same content of charm (DD or $\bar{D}\bar{D}$ as opposed to $D\bar{D}$). This could be achieved by searching for double charm events where the two identified k with the same electric charge. A flat distribution was obtain for the mass plot of each of the two charm candidates when the other was mass-selected in the $1.82 - 1.88 \text{ GeV}/c^2$ region (see fig. 6.14).

Figure 6.14: Multiple charm search. Mass plots.



Chapter 7

Physics results

7.1 Introduction

In this chapter a summary of the results obtained from the analysis of both the single charm and double charm samples is presented.

In general the results are not corrected for acceptance. The main interest is the comparison between the data and the theoretical expectations.

The layout of the chapter is as follows: First the quantities used are described, and their importance outlined. Comments about the Monte Carlo (MC) and the different parameters used are also given. Following one finds the results of the inclusive and correlation analyses. Finally, a summary of the results is shown.

7.2 Quantities studied

7.2.1 Inclusive Analysis

Transverse Momentum (P_T)

This is the momentum component perpendicular to the beam axis (X). The square of this magnitude is also studied.

The P_T distributions are included due to their importance on the correlation analysis. It contains information about the transverse momentum compensation of the Charm-Charm system. P_T has the advantage that is unchanged when boosted

to the γN CM.

Longitudinal Momentum (P_L)

(P_L) is the momentum component along the beam axis. As for all the longitudinal magnitudes, it contains useful information concerning the hadronisation process such as the fragmentation function.

Feynman-X (X_F)

The Feynman-X variable is defined as :

$$X_F = \frac{P_L}{P_{MAX}}$$

where P_L is the longitudinal momentum of the particle and P_{MAX} is the maximum available momentum. If P_c is the longitudinal momentum of a charmed particle, E_c its energy and E_γ is the beam energy. All measured in the LAB system then, X_F can be approximately written as :

$$X_F^{CM} = \frac{(1 + \frac{M_N}{E_\gamma})P_c - E_c}{M_N(1 + \frac{M_N}{2E_\gamma})}$$

where M_N is the mass of the interacting nucleon. The X_F variable measures the "forwardness" of a given particle (or particles system). Given the low efficiency of the tagging system and the difficulties of correcting for the tagging effects on the double sample, the X_F distribution will be given only for the single charm sample.

The computation of X_F is affected by the fact then the beam energy available for the real data (RD) sample is coming from the TAG answer. In order to compare to the MC prediction, either the TAG answer must be corrected by the multiple bremsstrahlung effect (cf section 3.2.3) or the E_{BEAM}^{MC} must be modified, so that it reproduces E_{BEAM}^{TAG} .

Rapidity (Y)

The rapidity, Y , of a particle is defined as :

$$Y = 0.5 \log \frac{E + P_L}{E - P_L}$$

under a boost in the longitudinal direction with velocity β , the rapidity is transformed as :

$$Y' = Y + \tanh^{-1} \beta$$

so the shape of the rapidity distribution remains unchanged.

7.2.2 Correlation Analysis

Momentum and Rapidity distributions

As for the inclusive analysis, the P_T , P_T^2 , P_L and Y distributions are also studied. In this case the Charm-Charm system values are taken, as opposed to the single particle ones used in the inclusive analysis.

Invariant Mass $M(D\bar{D})$

The invariant mass of the system

$$M(D\bar{D}) = \sqrt{E^2(D\bar{D}) - P^2(D\bar{D})}$$

Rapidity Gap ($|\Delta Y|$)

Is defined as the absolute value of the difference of the rapidities of two particles:

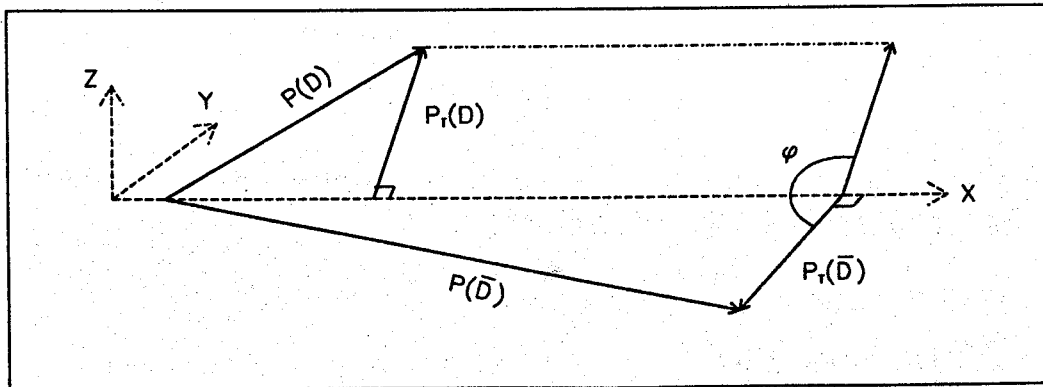
$$\Delta Y = |Y_1 - Y_2|$$

where Y_1 and Y_2 represents the rapidity of particle 1 and 2 respectively. This quantity is invariant under a relativistic boost along the longitudinal axis.

Angular Distribution

The angle, φ , between the two transverse components of the momentum of the two reconstructed charmed particles (see fig. 7.1). It is used to study the back-to-back behaviour of the charm-charm system.

Figure 7.1: Angle of the two charmed particles in the transverse plane



7.2.3 Montecarlo Sample

MC tapes were generated for the three decay channels of importance for this work. 20,000 $k\pi$ events, 20,000 $k2\pi$ events and 10,000 $k3\pi$ events were produced. These samples were passed through the charm selection programs (see section 6.2). The selected sample consisted of, 4,750 $k\pi$, 4,045 $k2\pi$ and 2,469 $k3\pi$ events. This correspond to an average 22% single charm selection efficiency. These events were passed through the double charm selection process which produced the MC double charm sample.

Both MC samples, single and double charm, were analysed by the same set of programs used for the real data (RD). The resulting distributions are compared without acceptance corrections.

MC Parameters

As mentioned in chapter 2, the theoretical expectation (MC predictions) depends on many parameters. Among them the fragmentation function and the intrinsic P_T of the target nucleon seem to be more closely related to the quantities under investigation.

The MC samples used in this analysis have been generated using the following fragmentation function ("hard") and mean value of intrinsic P_T^2 of the nucleon, $\langle P_T^2 \rangle_N$:

$$Z \cdot D(Z) = \frac{1}{\sqrt{1-Z}} e^{-0.7m_T^2/Z} \leftarrow \text{HARD}$$

$$\langle P_T^2 \rangle_N = 0.1 \text{ GeV}^2/c^2$$

weights have been included to account for the following fragmentation function ("soft") and intrinsic $\langle P_T^2 \rangle_N$:

$$Z \cdot D(Z) = (1-Z) e^{-0.7m_T^2/Z} \leftarrow \text{SOFT}$$

$$\langle P_T^2 \rangle_N = 1.0 \text{ GeV}^2/c^2$$

The relative importance of the two fragmentation functions and intrinsic P_T can be seen in figures 7.2 and 7.3 respectively

7.3 The Analysis

Here we explain the method followed to obtain the distributions. Separate sections are devoted to the inclusive and correlation analyses.

Figure 7.2: Relative importance of different fragmentation functions

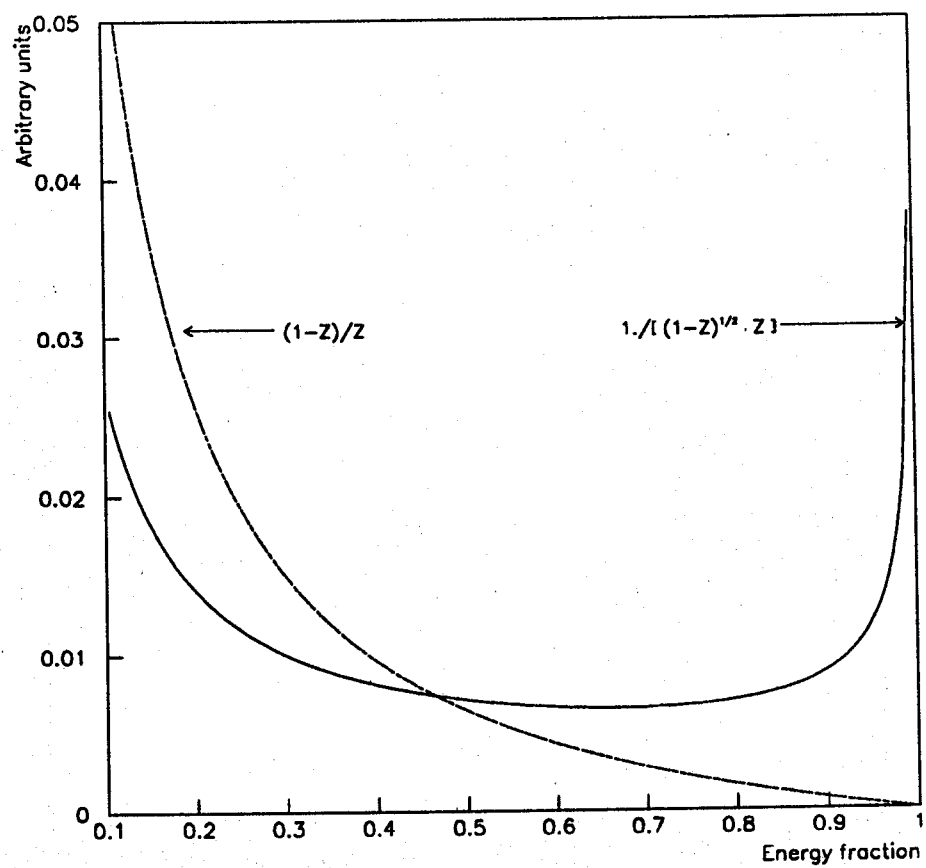
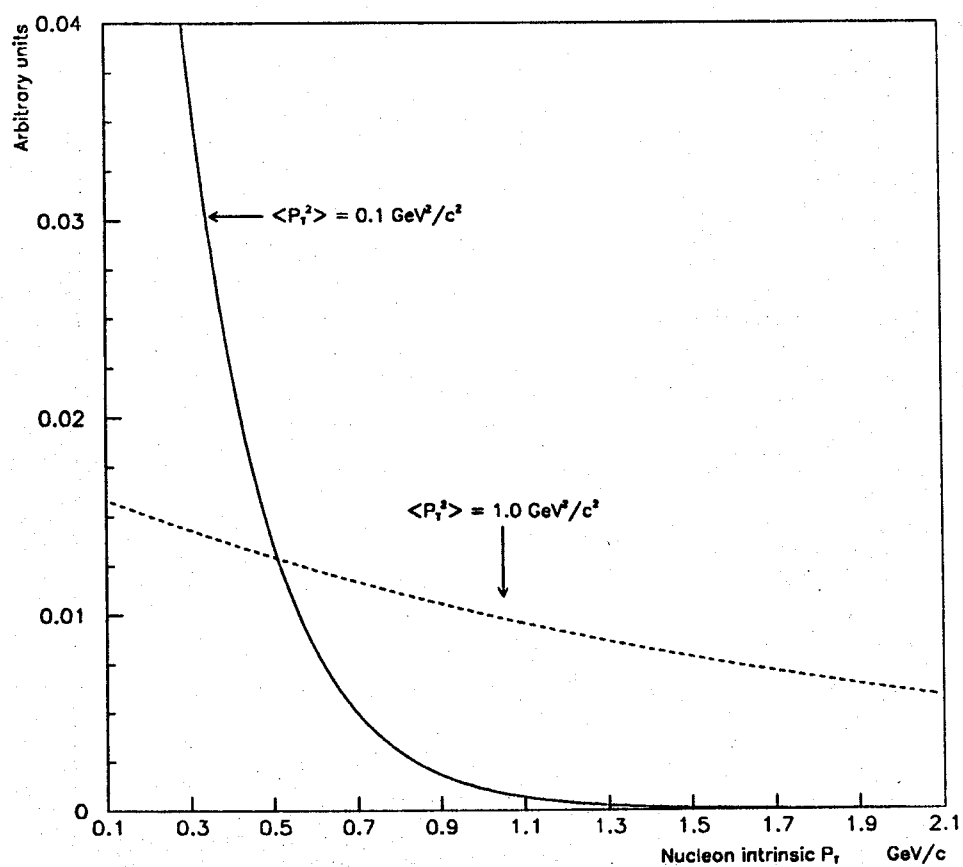


Figure 7.3: Relative importance of different intrinsic $\langle P_T^2 \rangle_N$ 

For each variable studied, three pieces of information are given. First, the plot of the distribution is shown. In addition to the real data points, one will find the theoretical predictions (dotted and dashed lines). Second, the mean values will be quoted together with their statistical and systematic errors. The mean values obtained from the different MC predictions are also given. Finally, the goodness of the theoretical prediction in reproducing the measured RD distributions is evaluated by computing the χ^2 per degree of freedom. The χ^2/dof is obtained by comparing, bin by bin, the MC and RD distributions.

Small values of χ^2/dof ($\chi^2/\text{dof} \leq 1.5$) will, in general, indicate a good agreement between the theoretical expectation and the measured quantities. The relative values of χ^2/dof , for a given distribution, will indicate which theoretical prediction is better in reproducing the data.

The final conclusion about the goodness of the MC predictions will be drawn by taking into account the visual inspection of the plot, the comparison of the mean values, and the computed χ^2/dof .

In the inclusive analysis the charmed particles are taken independently of their companions as opposed to the correlation analysis where the effect of the charmed particles on each other is studied. The later can be done only on the double charm sample whilst the inclusive analysis can be performed on both samples.

Usually the samples one uses to compute the different quantities under investigation are formed by two components. One is the real "signal" and the other the background. One way of separating the two contributions is with a mass plot. As shown in the previous chapter, the ratio of signal over background, S/B, is known. This ratio is used to subtract the background component from any measured variable.

7.3.1 Inclusive Analysis

In order to compute the background-free distributions the following steps were performed.

- a) Two mass windows were defined for the "signal" and background regions respectively

$$SIGNAL \begin{cases} M \in [1.835, 1.875] \text{ GeV}/c^2 & \text{SINGLE CHARM} \\ M \in [1.820, 1.880] \text{ GeV}/c^2 & \text{DOUBLE CHARM} \end{cases}$$

$$BACKGROUND \begin{cases} M \in [1.70 - 1.79] \text{ GeV}/c^2 \\ M \in [1.91 - 2.00] \text{ GeV}/c^2 \end{cases} \text{ BOTH SAMPLES}$$

- b) The distribution for the signal and background regions were obtained.
- c) Using the computed S/B ratio (one per decay channel), a background distribution, normalized to the number of background event under the signal region, was obtained.
- d) The subtraction of the "signal region" distribution minus the background distribution (normalized) produces the so called background subtracted or background free distribution.
- e) The same process is used to obtain the MC distributions.
- f) The final distributions are obtained by adding the contribution of each decay channel. In the case of the MC, they are weighted so that the relative importance of each channel is consistent with the real data.

7.3.2 Correlations

It has been shown (Chapter 6) that the expected number of background events in the signal mass region for the double charm sample was of the order of 2 out of 22 events. This enables us to consider this sample as essentially background free. So, for correlation magnitudes the events where the two charm candidates have the mass in the $1.82 - 1.88 \text{ GeV}/c^2$ region are taken and no background subtraction is performed.

7.3.3 Error Calculations

For each distribution the mean value will be quoted. On this mean value a statistical error is computed using the standard expression :

$$\epsilon(X) = \frac{\sigma_{N-1}(X)}{\sqrt{N}}$$

where σ_{N-1} is the standard deviation of the distribution and N the number of entries.

Systematic Error

The charm selection process and the definition of the signal region will introduce variation on the computed mean values of the distribution. These effects are quoted as systematic errors. In the present analysis the main source of systematics will be the probability of χ^2 , the N_σ cut and the mass window chosen. Below one can find the description of the method followed to determine the relative importance of each contribution together with the computed values.

In order to determine the relative importance of each contribution the following process was performed:

- First, the mean values, $\langle x \rangle_N$, of all the distributions were obtained using the selected (nominal) cuts (see previous chapter).
- Then, two of the selection criteria were fixed to their nominal values and the third was varied. The mean values, $\langle x \rangle'$, were recomputed. The differences, Δx , between the original mean values and the recomputed ones were calculated

$$\Delta x = | \langle x \rangle_N - \langle x \rangle' |$$

- The mean values of these differences, $\langle \Delta x \rangle$, were obtained. The relative contribution (quoted in the summary tables in percent), RI, was calculated as follows:

$$RI = \frac{\langle \Delta x \rangle}{\langle x \rangle_N} \times 100$$

In studying the effects of the selection criteria on the mean values there were no systematic effects observed which were larger than the expected statistical fluctuation of the mean values.

A summary of the total systematic effects is given at the end of the section.

- 1. $P(\chi^2)$

Samples corresponding to four different values of $P(\chi^2)$ were selected,

$$\begin{aligned} P(\chi^2) &= 1 \times 10^{-3} \\ P(\chi^2) &= 2 \times 10^{-3} \leftarrow \text{SELECTED} \\ P(\chi^2) &= 5 \times 10^{-2} \\ P(\chi^2) &= 1 \times 10^{-2} \end{aligned}$$

these samples were then pass through the whole analysis chain, and the variation in the mean value of all the distributions were investigated. The relative importance of the effect produced by the $P(\chi^2)$ is given in tables 7.1 and 7.2.

- 2. N_σ

The number-of-sigma cuts used to extract the different sample is another possible source of systematic error. The influence of this cut on the single

Table 7.1: Systematic effects of the $P(\chi^2)$ selection criteria. Inclusive Analysis

SINGLE CHARM			
P_T	P_T^2	P_L	Y
%			
0.5	0.6	0.4	0.1
DOUBLE CHARM			
P_T	P_T^2	P_L	Y
%			
3.7	6.8	1.4	0.6

Table 7.2: Systematic effects of the $P(\chi^2)$ selection criteria. Correlations

DOUBLE CHARM						
P_T	P_T^2	P_L	Y	ΔY	M	φ
%						
3.6	9.1	1.4	0.6	9.8	1.1	3.9

charm sample was determined using the following values:

$$\begin{aligned}
 N_\sigma &= \begin{cases} 2.0 & (k\pi) & 0.5 & (D^*) \\ 4.0 & (k2\pi) \\ 6.0 & (k3\pi) & 4.0 & (D^*) \end{cases} \\
 N_\sigma &= 7.0 & \leftarrow \text{SELECTED} \\
 N_\sigma &= 10.0 \\
 N_\sigma &= 15.0
 \end{aligned}$$

In the double charm sample the analysis of the effect of the N_σ cut is somewhat more complex. Here one has nine combinations of charm decay channels. For any given N_σ used to select the first charmed particle of the event, there will be three N_σ cuts, one per decay channel combination, to select the second charmed particle. In order to simplify the process, the approach of modifying all the N_σ cuts at once was chosen. If one calls N_σ^N to be the

selected (nominal) set of cuts, then the following values were used:

$$\begin{array}{l} N_{\sigma}^N - 0.5 \\ N_{\sigma}^N \leftarrow \text{SELECTED} \\ N_{\sigma}^N + 0.5 \\ N_{\sigma}^N + 1.0 \end{array}$$

The small variation of the N_{σ} cuts, as compared to those used in the single charm sample, are coming from statistical reasons. In fact when the sigma cut is reduced, the sample starts to get some contribution from the background and one must perform a background subtraction. In this case the analysis method would have been changed and the observed effects on the mean values can not be quoted as systematic errors. $N_{\sigma}^N + 0.5$ is close enough to N_{σ}^N , so that the method need not to be changed.

When one increases the cut, the statistical significance of the sample is very much reduced (10 events remains at $N_{\sigma}^N + 1.0$), and the observed variations could be purely statistical.

The contributions of the N_{σ} cut to the systematics are summarized in tables 7.3 and 7.4

Table 7.3: Systematic effects of the N_{σ} selection criteria. Inclusive Analysis

SINGLE CHARM			
P_T	P_T^2	P_L	Y
%			
1.2	2.7	1.2	0.2
DOUBLE CHARM			
P_T	P_T^2	P_L	Y
%			
6.0	9.1	4.2	0.6

• 3. Mass Window

The mass window is used to define the “signal” region. The systematic error is computed by using different mass windows on the same sample. Here two complementary approaches were followed, one consisting in keeping the central value unchanged and to expand or reduce the mass window width, the other in keeping the width and modifying the central value. The relative importances are given in tables 7.5 and 7.6.

Table 7.4: Systematic effects of the N_σ selection criteria. Correlations

DOUBLE CHARM						
P_T	P_T^2	P_L	Y	ΔY	M	φ
%						
3.6	10.3	3.6	0.3	2.4	2.3	6.1

Table 7.5: Systematic effects of the mass window. Inclusive Analysis

SINGLE CHARM			
P_T	P_T^2	P_L	Y
%			
0.9	1.3	0.7	0.1
DOUBLE CHARM			
P_T	P_T^2	P_L	Y
%			
4.6	6.8	3.1	1.2

Total Systematic Error

The total systematic errors are obtained by adding the three contributions in quadrature. In tables 7.7 and 7.8 the systematic effects are summarized.

7.4 The Results

The distributions of each of the studied variables are presented. They are compared to the MC predictions by superimposing the MC distribution after the analysis program chain.

In each part, a compilation of the mean values and their errors, both statistical and systematics, together with the computed value of χ^2/dof , are given.

Table 7.6: Systematic effects of the mass window. Correlations

DOUBLE CHARM						
P_T	P_T^2	P_L	Y	ΔY	M	φ
%						
6.0	11.5	2.3	0.6	8.9	0.5	5.1

Table 7.7: Total systematic effects . Inclusive Analysis

SINGLE CHARM			
P_T	P_T^2	P_L	Y
%			
1.6	3.1	1.4	0.2
DOUBLE CHARM			
P_T	P_T^2	P_L	Y
%			
8.4	13.2	5.4	1.5

7.4.1 Inclusive Analysis

Single Charm Sample

The final distribution for P_T , P_T^2 , P_L and Y are shown in figures 7.4 and 7.5.

In figure 7.4 the effect of changing the fragmentation function can be observed. The dashed line represents the MC prediction when a hard function is used, the dotted line corresponds to the results obtained with a soft fragmentation function, in both cases the intrinsic P_T is taken as $\langle P_T^2 \rangle_N = 0.1 \text{ GeV}^2/c^2$.

Figure 7.5 shows the effect of choosing different $\langle P_T^2 \rangle_N$. The dotted line corresponds to $\langle P_T^2 \rangle_N = 1.0 \text{ GeV}^2/c^2$, whilst the dashed one has been obtained using $\langle P_T^2 \rangle_N = 0.1 \text{ GeV}^2/c^2$. The soft fragmentation function was used for both predictions.

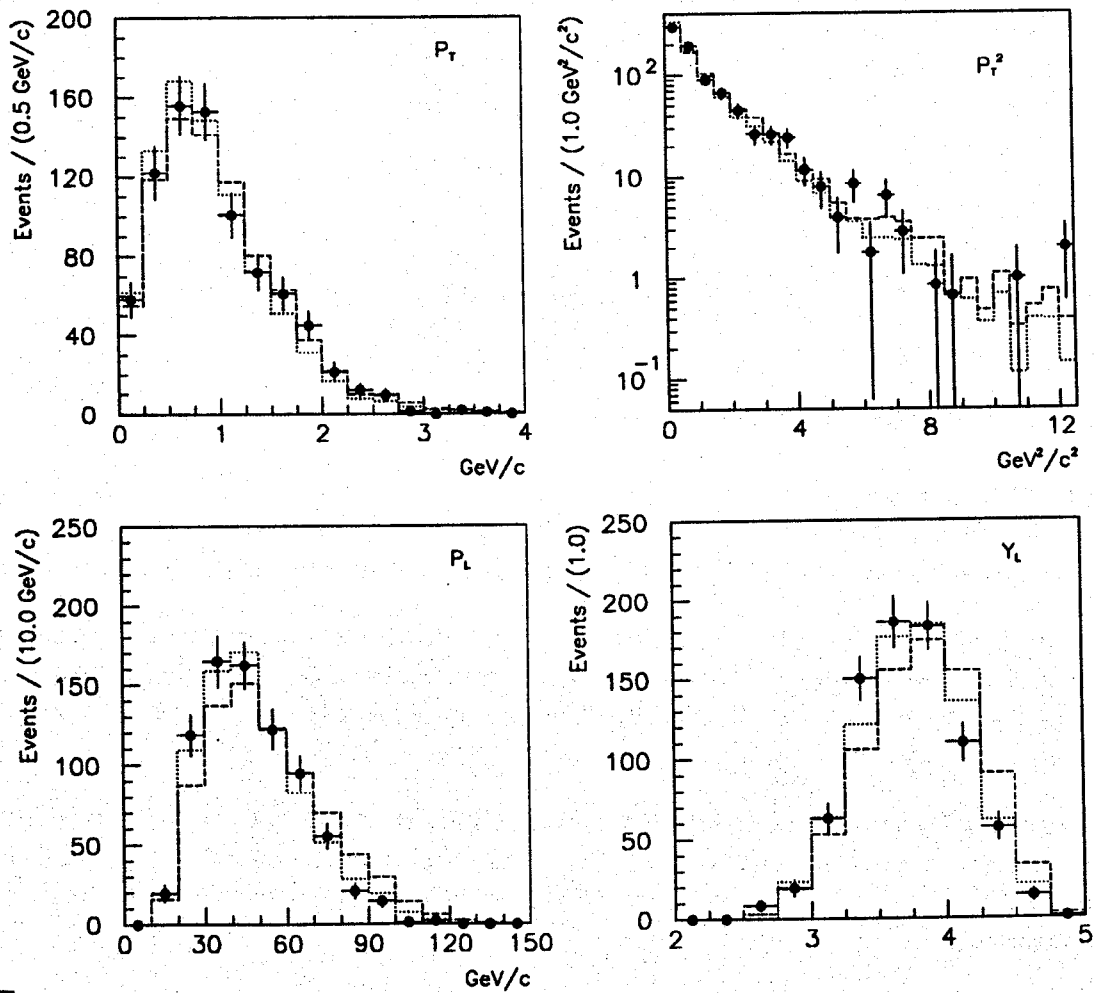
Table 7.8: Total systematic effects. Correlations

DOUBLE CHARM						
P_T	P_T^2	P_L	Y	ΔY	M	φ
%						
7.2	18.4	4.4	0.8	14.6	2.5	12.1

Figure 7.4: Effect of the fragmentation function on the P_T , P_T^2 , P_L and Y distributions. Inclusive analysis on single charm sample.

Dotted: Soft fragmentation function

Dashed: Hard fragmentation function



The mean values, and the χ^2/dof are summarized in table 7.9. Where MC(1), MC(2) and MC(3) mean:

- MC(1) Hard fragmentation function $\langle P_T^2 \rangle_{N=0.1 \text{ GeV}^2/c^2}$
 MC(2) Soft fragmentation function $\langle P_T^2 \rangle_{N=0.1 \text{ GeV}^2/c^2}$
 MC(3) Soft fragmentation function $\langle P_T^2 \rangle_{N=1.0 \text{ GeV}^2/c^2}$

the first error is statistical and the second systematic.

Table 7.9: Summary of results for the single charm sample. Inclusive Analysis

SINGLE CHARM				
	P_T	P_T^2	P_L	Y
	GeV/c	$(\text{GeV}/c)^2$	GeV/c	
MEAN VALUES				
RD	$0.98 \pm 0.03 \pm 0.02$	$1.33 \pm 0.06 \pm 0.05$	$48.0 \pm 1.0 \pm 0.7$	$3.72 \pm 0.02 \pm 0.008$
MC(1)	1.00	1.37	53.3	3.79
MC(2)	0.94	1.20	48.8	3.75
MC(3)	0.96	1.30	48.6	3.75
χ^2/dof				
MC(1)	0.88	1.24	7.1	6.0
MC(2)	0.88	0.97	1.4	1.2
MC(3)	0.60	0.85	1.3	1.3

Feynman-X (X_F) distribution

The X_F distribution, corrected for acceptance and tagging effects, is shown in figure 7.6. Superimposed on the data points one finds the predictions of the MC for the two fragmentation functions. A summary of the results is given in table 7.10.

From the displayed distributions, their mean values and the computed χ^2/dof one can conclude the following:

Table 7.10: Summary of results for the X_F distribution

	$\langle X_F \rangle$	χ^2/dof
RD	0.32 ± 0.01	
MC(1)	0.35	1.05
MC(2)	0.31	0.43

- The RD results are perfectly well reproduced by the MC.
- The use of soft fragmentation function seem to be preferred in order to reproduce the longitudinal distributions (P_L and Y).
- The transverse plane distributions (P_T and P_T^2) are not very sensitive to the change of the fragmentation function. None of the studied quantities seem to be sensitive to the choose of the intrinsic P_T of the nucleon. Nevertheless a slight effect is noticeable in the transverse distributions.

Double Charm Sample

The one-entry-per-event sample (see chapter 6) has been used to obtain the distributions presented in figures 7.7 (effect of the fragmentation function) and 7.8 (effect of the intrinsic P_T). The summary of the results is given in table 7.11

Table 7.11: Summary of results for the double charm sample. Inclusive Analysis

DOUBLE CHARM				
	P_T	P_T^2	P_L	Y
	GeV/c	$(GeV/c)^2$	GeV/c	
MEAN VALUES				
RD	$1.00 \pm 0.09 \pm 0.08$	$1.35 \pm 0.19 \pm 0.18$	$38.0 \pm 2.0 \pm 1.9$	$3.51 \pm 0.06 \pm 0.05$
MC(1)	0.97	1.22	44.0	3.65
MC(2)	0.92	1.10	40.8	3.59
MC(3)	0.93	1.20	40.7	3.59
χ^2/dof				
MC(1)	0.30	0.12	0.94	2.49
MC(2)	0.44	0.31	0.35	1.04
MC(3)	0.35	0.21	0.31	1.02

The conclusions can be summarized as:

- The main conclusion is that, even in a sample where the two charm candidates have been reconstructed the MC reproduces the measured distributions very well.
- The others points that one must notice is the reduction on the mean value of P_L and Y when compared to the single charm sample. Concerning P_L , one has to take into account the fact that in this sample the "second" charm has also been found. This produces a reduction in the acceptance (see figure

7.9) for large P_L 's, because if one of the particles is produced very forward (fast), the other will tend to be produced backward (slow) and therefore will be more difficult to detect. the different acceptance for P_L will also explain the modification in the values of Y .

General conclusions on the Inclusive Analysis

One has shown that the MC is able to reproduce the behaviour of the real data sample in the P_T , P_T^2 , P_L and Y distributions. A certain preference for a soft fragmentation function has also been noticed.

7.4.2 Correlations

One of the objectives of the present work is the study of the correlation of the two reconstructed charmed particles. The lack of a large statistic sample makes this study more difficult. In principle one would like to investigate the behaviour of one variable compared to another. This is usually done by plotting the two variables one against the other. This approach is not feasible in statistically limited samples. For this reason one has chosen to study the variables of the charm-charm system, that is the study of a system formed by the two charmed particles.

The distribution of P_T , P_T^2 , P_L , Y , $\cos \varphi$, φ , M and the rapidity gap, are shown in figures 7.10, 7.11, 7.12 and 7.13. The Monte Carlo expectation, drawn as dashed or dotted lines, has been superimposed on each plot. The one-entry-per-event sample has been chosen. Figures 7.10 and 7.11 show the effect of the fragmentation function, whilst in figures 7.12 and 7.13 the variation of the intrinsic P_T is represented.

A summary of the results is given in table 7.12.

General conclusions on the correlation analysis

From the presented distributions, the following conclusions can be drawn :

- One can observe that the agreement between the MC and the RD distributions is worse here than in the inclusive analysis.
- The invariant mass distribution is the only one where a clear agreement can be observed. The predictions for φ are also compatible with the data, but some flatter distribution will yield a better agreement.
- The effect of changing the fragmentation function has a noticeable effect only in the P_L distribution, the rest of them tend to be insensitive to this

Table 7.12: Summary of results for the double charm sample. Correlation Analysis

DOUBLE CHARM				
	P_T	P_T^2	P_L	Y
	GeV/c	$(GeV/c)^2$	GeV/c	
MEAN VALUES				
RD	$0.84 \pm 0.09 \pm 0.06$	$0.99 \pm 0.19 \pm 0.18$	$71. \pm 4. \pm 3.$	$3.48 \pm 0.07 \pm 0.03$
MC(1)	0.57	0.55	90.	3.65
MC(2)	0.55	0.51	82.	3.56
MC(3)	0.69	0.72	82.	3.56
χ^2/dof				
MC(1)	2.1	1.6	3.2	1.8
MC(2)	2.1	1.7	1.2	1.2
MC(3)	1.6	0.9	1.3	1.3
	M	φ	ΔY	
	GeV/c^2	degrees		
MEAN VALUES				
RD	$4.32 \pm 0.13 \pm 0.11$	$124. \pm 10. \pm 10.$	$0.42 \pm 0.06 \pm 0.05$	
MC(1)	4.38	143.	0.52	
MC(2)	4.32	142.	0.52	
MC(3)	4.32	139.	0.51	
χ^2/dof				
MC(1)	1.33	0.76	1.30	
MC(2)	1.08	0.74	1.29	
MC(3)	1.13	0.73	1.13	

parameter. However, even using a soft fragmentation function the MC is unable to predict a mean value of P_L as small as is obtained in the data.

- The only quantities sensitive to the intrinsic P_T of the quarks, are P_T and P_T^2 . To get a closer agreement between the MC and the measured mean values one must use a large intrinsic P_T ($\langle P_T^2 \rangle_N = 1.0 \text{ GeV}/c^2$) which is physically unrealistic.
- As a summary we observe that the RD presents a:
 - Slower behavior ($P_L^{RD} < P_L^{MC}$)
 - Less P_T compensation ($P_T^{RD} > P_T^{MC}$)
 than the MC distributions
- This is the first time that these kind of results are presented in a charm-photoproduction experiment. Similar results (with a smaller sample) were reported in hadro-production experiments [34,35]
- Concerning the angular distribution, the mean value measured here and the one obtained in ref. [34] both are smaller than the expected by the respective MC predictions. The shape is somewhat different since we do not observe a peak around 120° .
- Similar results have been recently presented by another hadro-production experiment [36]. In this case the comparison with the MC predictions was not available. But, the shapes of the distributions tend to agree with the ones presented here.
- One would need larger samples in order to determine if there is statistically significant difference between the Monte Carlo predictions and the data.

Figure 7.5: Effect of the intrinsic P_T on the P_T , P_T^2 , P_L and Y distributions. Inclusive analysis on single charm sample
Dotted: $\langle p_T^2 \rangle_N = 1.0 \text{ (GeV/c)}^2$
Dashed: $\langle p_T^2 \rangle_N = 0.1 \text{ (GeV/c)}^2$

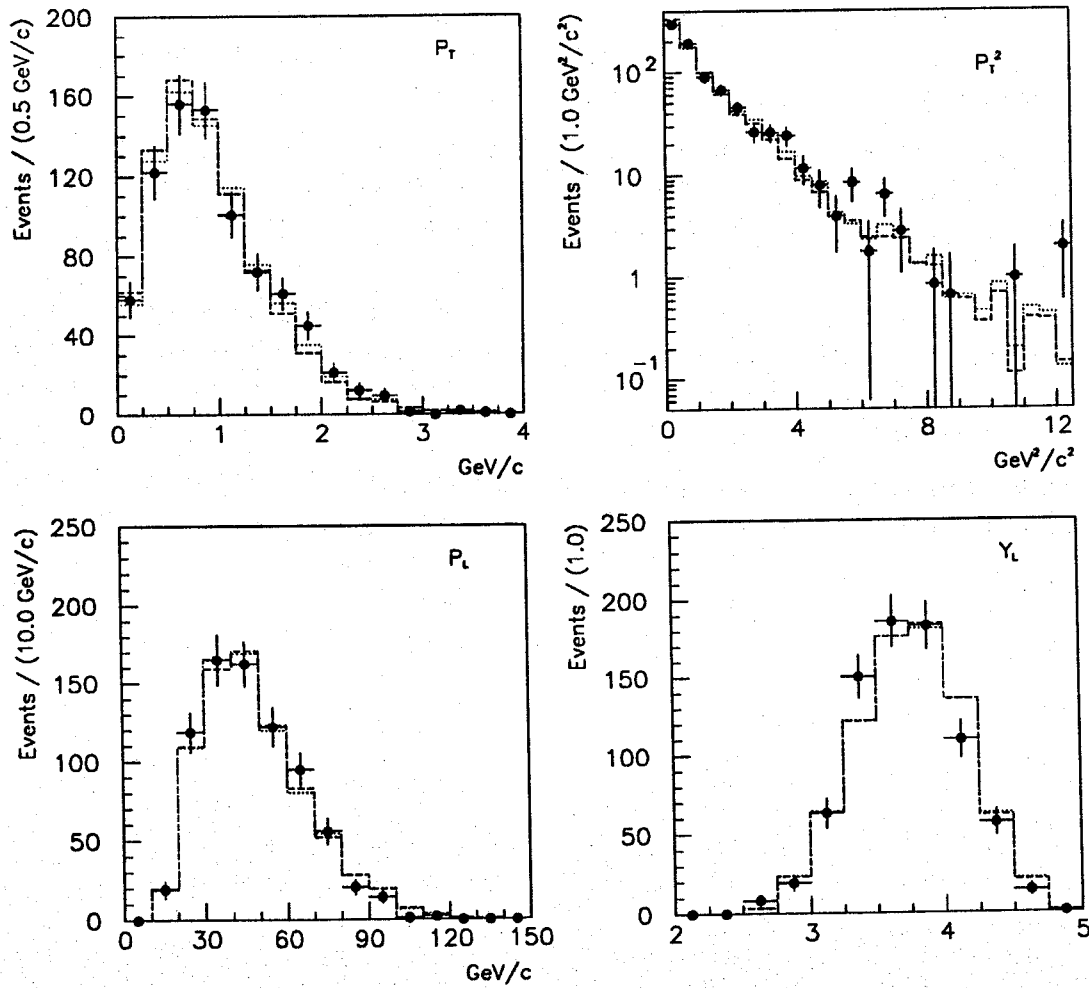


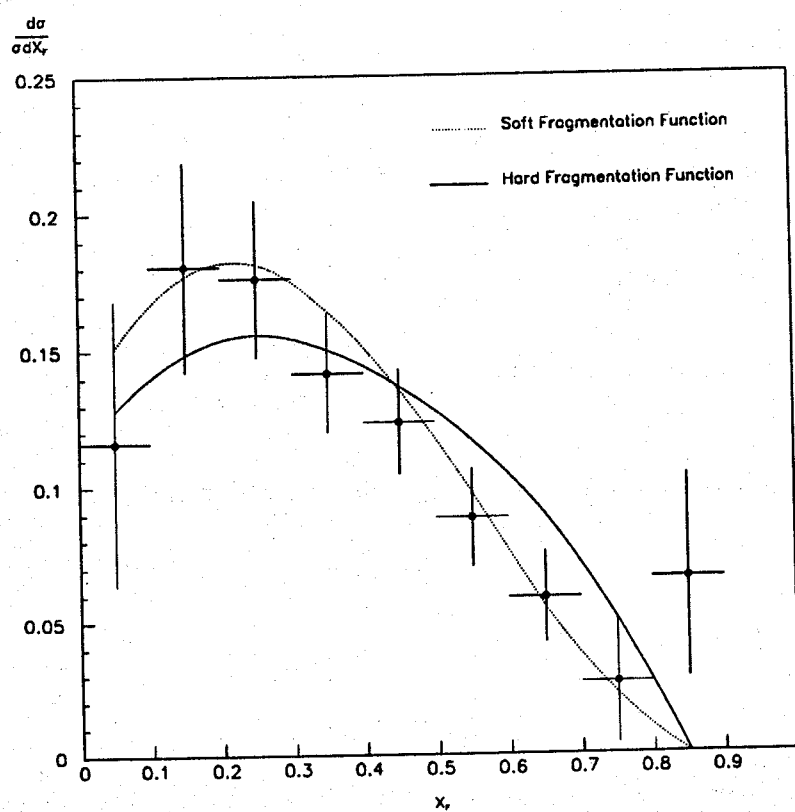
Figure 7.6: Effect of the fragmentation function on the X_F distribution.

Figure 7.7: Effect of the fragmentation function on the P_T , P_T^2 , P_L and Y distributions. Inclusive analysis on double charm sample

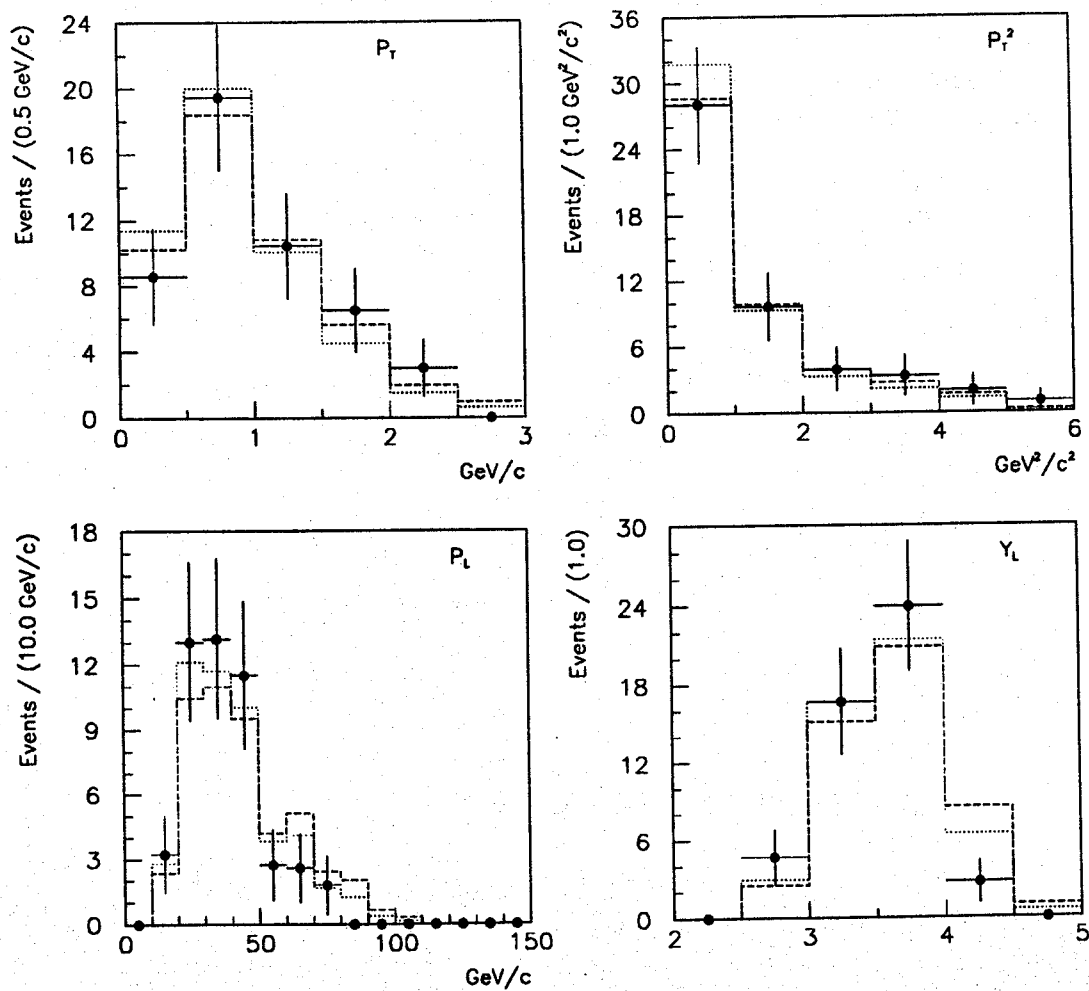


Figure 7.8: Effect of the intrinsic P_T on the P_T , P_T^2 , P_L and Y distributions. Inclusive analysis on double charm sample

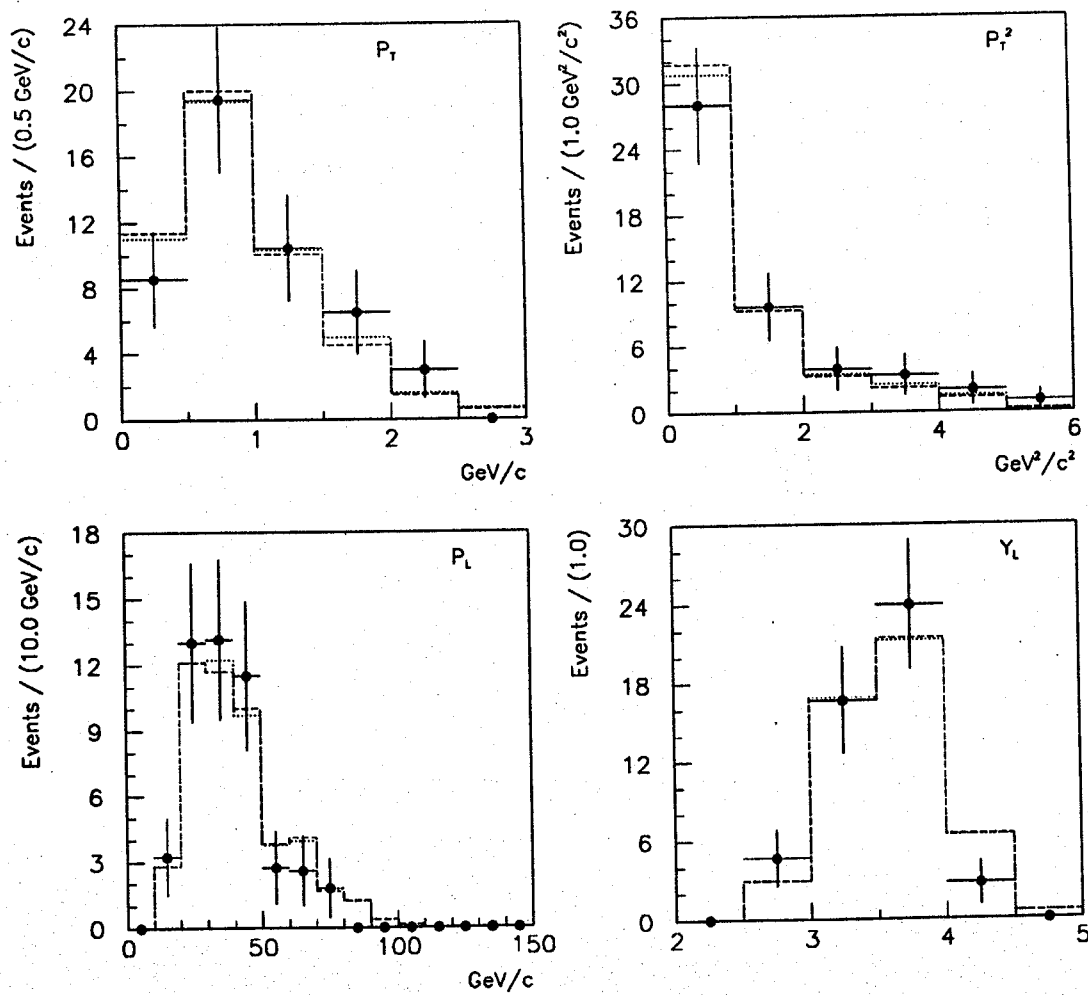


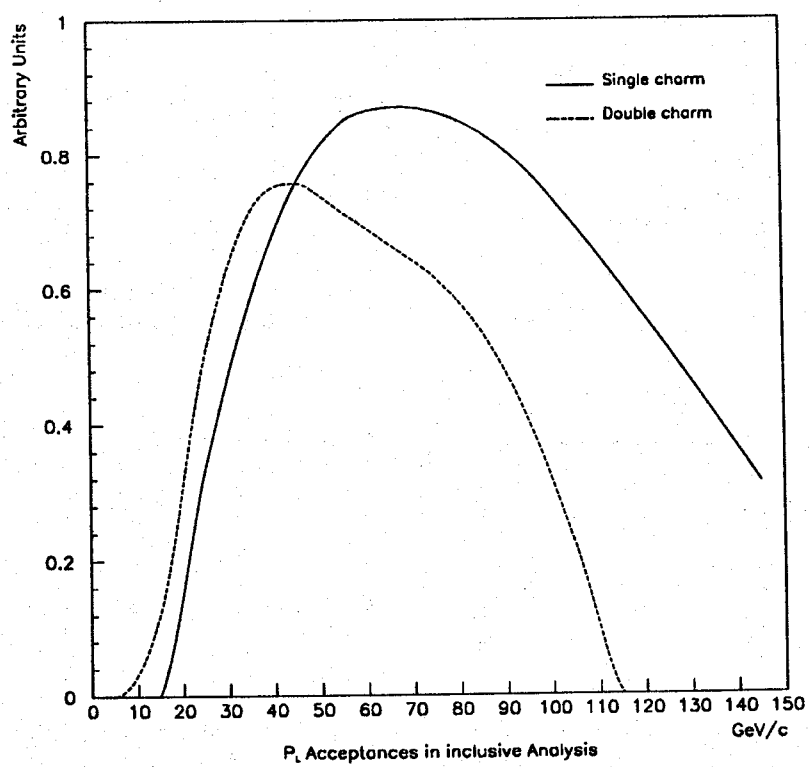
Figure 7.9: P_L acceptance in inclusive analyses.

Figure 7.10: Effect of the fragmentation function on the P_T , P_T^2 , P_L and Y distributions. Correlation analysis on double charm sample

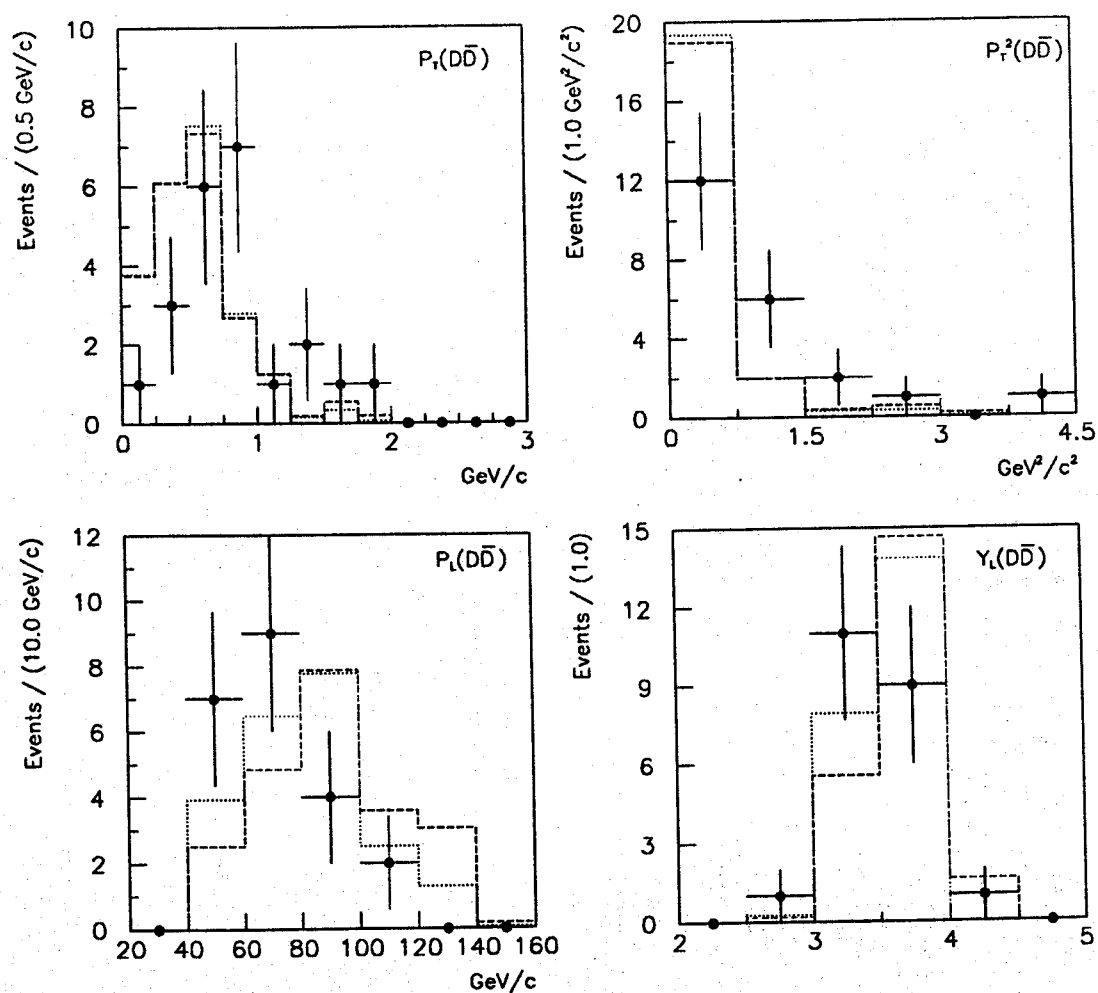


Figure 7.11: Effect of the fragmentation function on the M , φ , $\cos\varphi$ and ΔY distributions. Correlation analysis on double charm sample

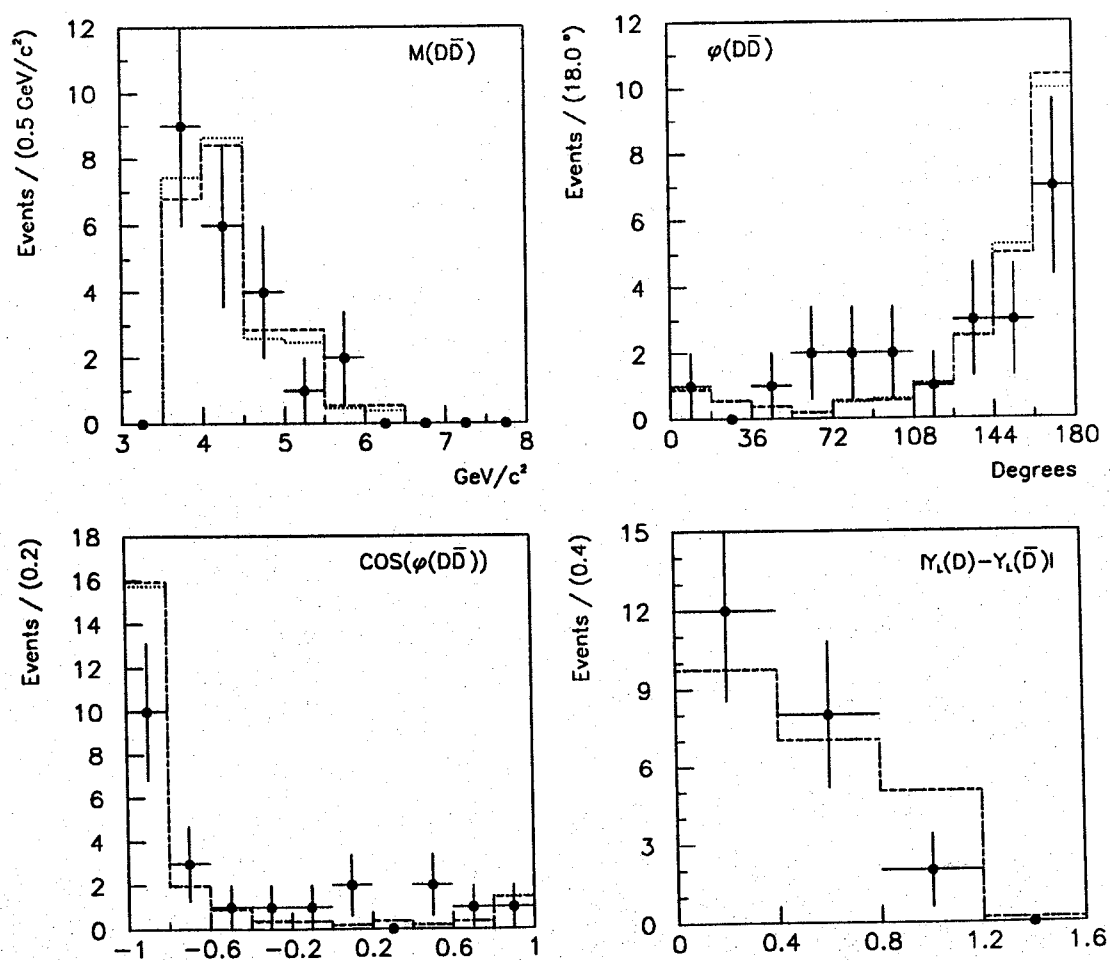


Figure 7.12: Effect of the intrinsic P_T on the P_T , P_T^2 , P_L and Y distributions. Correlation analysis on double charm sample

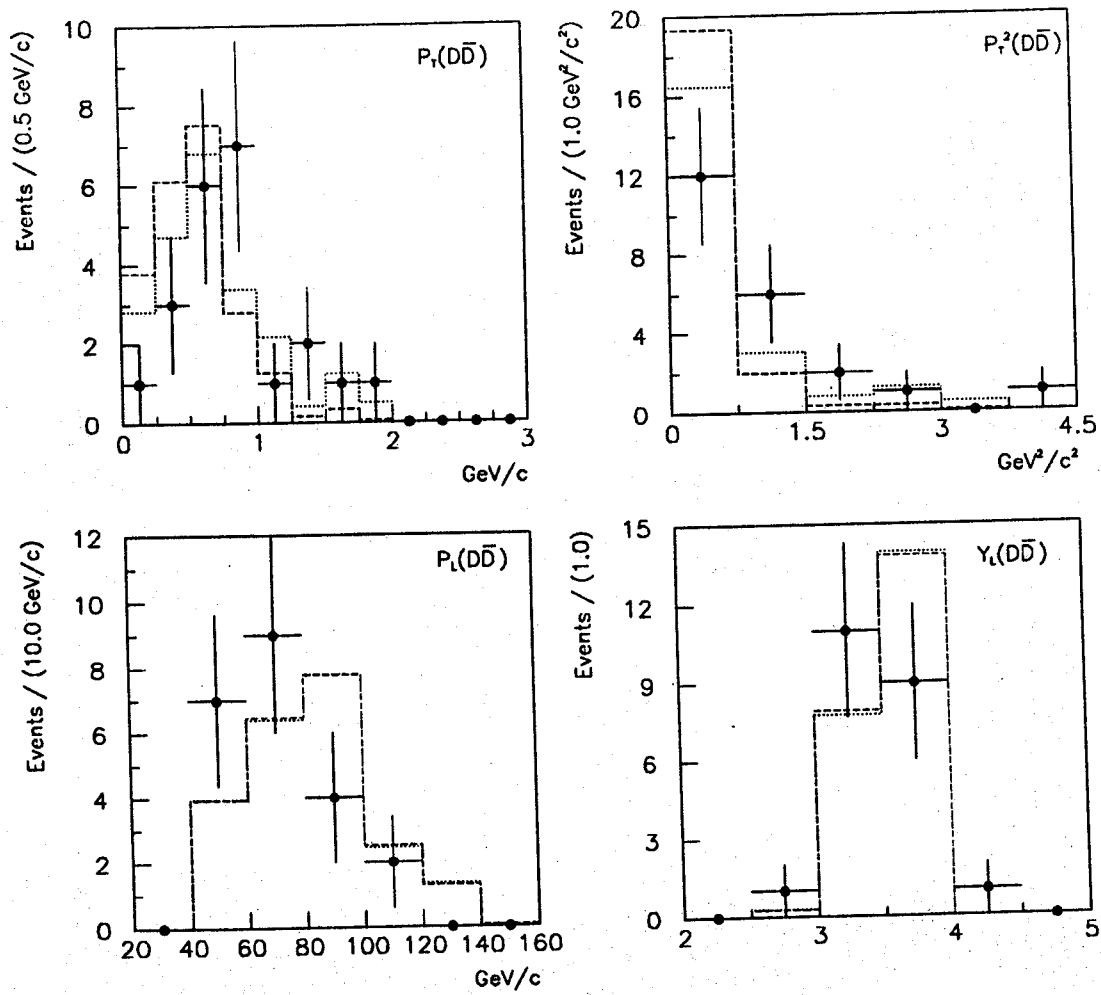
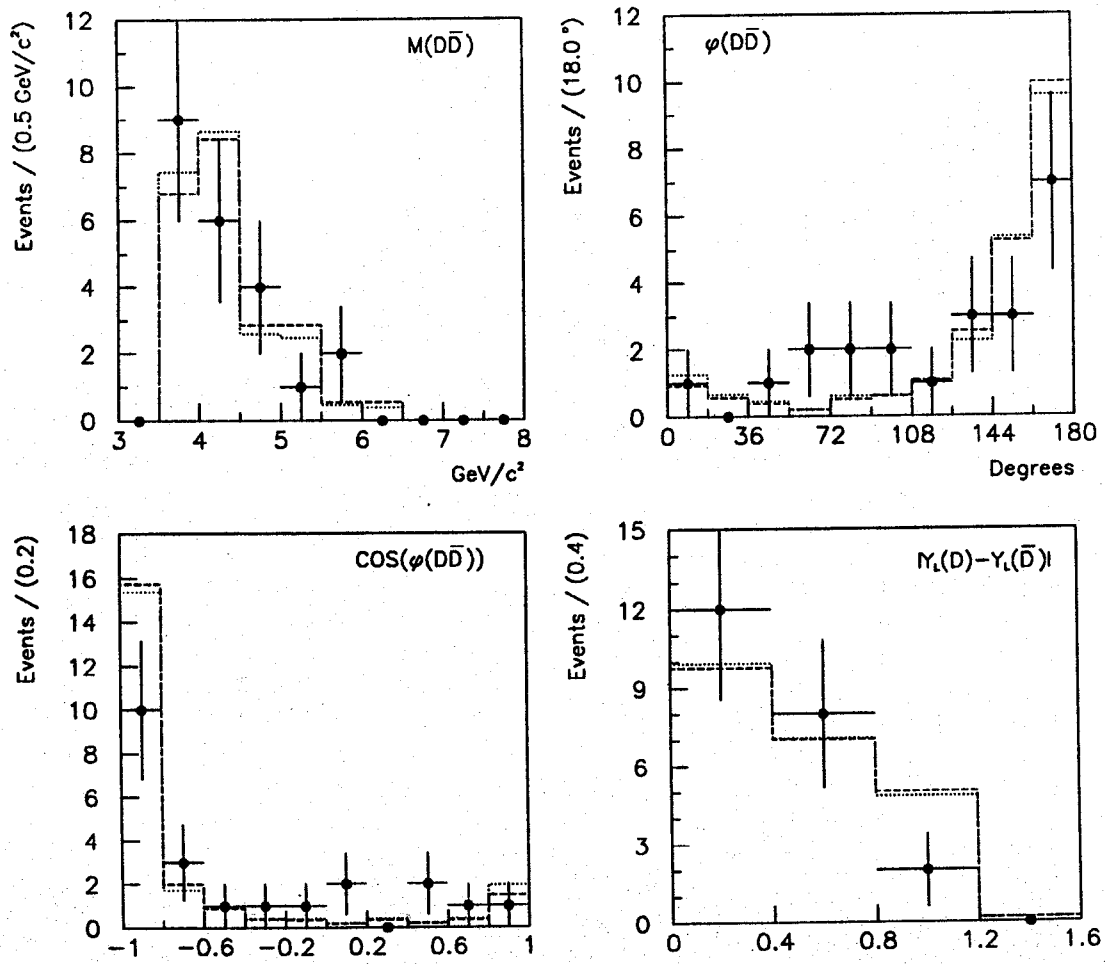


Figure 7.13: Effect of the intrinsic P_T on the M , φ , $\cos\varphi$ and ΔY distributions. Correlation analysis on double charm sample



Chapter 8

Summary and Conclusions.

8.1 Charm signal

- Using the NA14/2 spectrometer, 17×10^6 triggers were recorded during two data taking periods in 1985-1986.
- The raw data events were run through a fast selection filter aimed to increase the charm contents of the data sample. The output of this program consisted in some 850,000 events which were passed through the reconstruction program.
- Using the filtered sample a large sample of D mesons (D stands for both neutral and charged D mesons) was extracted. The main selection criteria being the separation between the interaction and the decay vertices, pondered by their errors,

$$N_\sigma = \frac{X(I) - X(D)}{\sqrt{\sigma_{X(I)}^2 + \sigma_{X(D)}^2}}$$

- Using different N_σ cuts for the three decay channels under investigation ($D^0 \rightarrow k^- \pi^+$, $D^+ \rightarrow k^- \pi^+ \pi^+$, $D^0 \rightarrow k^- \pi^+ \pi^+ \pi^-$) and taking into account that the presence of a D^* ($D^{*+} \rightarrow D^0 \pi^+$) can be easily tagged by computing the mass difference, $\Delta M = M(D^*) - M(D)$, we have extracted a sample of $1,134 \pm 35$ D mesons (called "single charm sample"), with a signal to background ratio, (S/B), of 1.69 ± 0.09 .

$$\left. \begin{array}{l} N_\sigma(k\pi) > 2.0 \quad N_\sigma(k\pi, D^*) > 0.5 \\ N_\sigma(k2\pi) > 4.0 \\ N_\sigma(k3\pi) > 6.0 \quad N_\sigma(k3\pi, D^*) > 4.0 \end{array} \right\} \begin{array}{l} 1,134 \pm 35 \text{ } D \text{ mesons} \\ S/B = 1.69 \pm 0.09 \\ M(D) \in [1.835, 1.875] \text{ GeV}/c^2 \end{array}$$

- Imposing a $N_\sigma > 7.0$ cut, without distinguishing among different decay channels we obtained the "clean single charm sample", made of 796 ± 30 D mesons,

and a signal to background ratio of $S/B = 2.9 \pm 0.2$

$$\begin{array}{l} 796 \pm 30 \text{ } D \text{ mesons} \\ N_\sigma > 7.0 \} S/B = 2.9 \pm 0.2 \\ M(D) \in [1.835, 1.875] \text{ } GeV/c^2 \end{array}$$

- A search for the second charm of the event (using the same decay channels as mentioned above) was performed on the single charm sample. Again, the main criteria to select candidates was the N_σ cut. Using the following cuts:

1 st charm	$k\pi$	$k2\pi$	$k3\pi$	$\leftarrow$ 2 nd charm
$k\pi$	$0.5 + 0.0$	4.0	$5.0 + 2.0$	
$k2\pi$	$2.0 + 0.0$	3.0	$5.0 + 2.0$	
$k3\pi$	$2.0 + 0.0$	4.0	$5.0 + 2.0$	

a sample of 71 double charm events was found lying in the mass region $1.7 - 2.0 \text{ } GeV/c^2$.

- An essentially background free sample of fully reconstructed double charm events was extracted. It consisted in 22 $D\bar{D}$ pairs with their masses in the $1.82 - 1.88 \text{ } GeV/c^2$ mass region. This represents the largest sample of double charm ever reconstructed in a photo-production experiment.
- A search was made for other charmed particles ($D_S \rightarrow kk\pi$, $\Lambda_C \rightarrow kp\pi$) and decay channels ($D^+ \rightarrow kk\pi$). It yielded two events for the $D^+ \rightarrow kk\pi$, one event for the D_S and no event was found for the Λ_C , within the selection cuts.
- A search for "multiple charm" events (events with more than two charmed particles) was undertaken yielding no signal in the selected mass region.

8.2 Physics results

- The following parameters:

$$\begin{array}{ll} m_c = 1.5 \text{ } GeV/c^2 & \text{Charm quark mass} \\ G(x) = 3(1-x)^5 & \text{Gluon distribution function} \\ Q^2 = 4m_c^2 & \text{Momentum transfer} \end{array}$$

were used together with the expression of $\sigma(\gamma g \rightarrow c\bar{c}X)$ calculated using perturbative QCD at order $\alpha_s\alpha_{em}$ to describe the $\gamma N \rightarrow c\bar{c}$ process.

The $\bar{c}$ is bound to a quark of the target nucleon forming a "Mesonic string", the remaining diquark bounds to the c to form a "Baryonic string". These two string are then independently hadronized using the LUND model.

The interaction products are passed through the detector simulation program and the whole selection chain. The resulting Monte Carlo sample will provide the theoretical expectations to which the measured quantities will be compared to.

- The analysis was separated in two parts, Inclusive and Correlations. In the inclusive analysis we studied the charmed particle characteristics independent of the presence of a second charmed particle. In the correlation analysis the influence of the charmed particles on each other was investigated.
- The Inclusive analysis consisted in the study of the P_T , P_T^2 , P_L and Y distributions of the D mesons. The same quantities were used for the Correlation analysis, now computed for the $D\bar{D}$ system. In investigating the correlation of the charmed particles we also used $M(D\bar{D})$, φ (the angle between the P_T 's of the two particles) and ΔY (rapidity gap).
- For each variable under study three Monte Carlo distributions were obtained:

- MC(1) Hard fragmentation function $\langle P_T^2 \rangle_N = 0.1 \text{ GeV}/c$
- MC(2) Soft fragmentation function $\langle P_T^2 \rangle_N = 0.1 \text{ GeV}/c$
- MC(3) Soft fragmentation function $\langle P_T^2 \rangle_N = 1.0 \text{ GeV}/c$

where the hard and soft and soft fragmentation functions were respectively:

$$Z \cdot D(Z) = \frac{1}{\sqrt{1-Z}} e^{(-0.7m_T^2/Z)}$$

$$Z \cdot D(Z) = (1-Z) e^{(-0.7m_T^2/Z)}$$

and $\langle P_T^2 \rangle_N$ is the mean value of the intrinsic P_T^2 of the nucleon.

- The inclusive analysis on the clean single charm sample yielded the following results:

SINGLE CHARM				
	P_T	P_T^2	P_L	Y
	GeV/c	$(\text{GeV}/c)^2$	GeV/c	
MEAN VALUES				
RD	$0.98 \pm 0.03 \pm 0.02$	$1.33 \pm 0.06 \pm 0.05$	$48.0 \pm 1.0 \pm 0.7$	$3.72 \pm 0.02 \pm 0.008$
MC(1)	1.00	1.37	53.3	3.79
MC(2)	0.94	1.20	48.8	3.75
MC(3)	0.96	1.30	48.6	3.75
χ^2/dof				
MC(1)	0.88	1.24	7.1	6.0
MC(2)	0.88	0.97	1.4	1.2
MC(3)	0.60	0.85	1.3	1.3

From these results and the displayed distributions (figures 7.4 and 7.5) one can conclude that the theoretical predictions perfectly agree with the data. One has observed that the use of a soft fragmentation function is preferred and that the effect of changing the intrinsic P_T is not noticeable at this level.

- The same analysis was carried on the double charm sample (there will be two entries per event, one for each charmed particle) and the following results were obtained:

DOUBLE CHARM				
	P_T	P_T^2	P_L	Y
	GeV/c	$(GeV/c)^2$	GeV/c	
MEAN VALUES				
RD	$1.00 \pm 0.09 \pm 0.08$	$1.35 \pm 0.19 \pm 0.18$	$38.0 \pm 2.0 \pm 1.9$	$3.51 \pm 0.06 \pm 0.05$
MC(1)	0.97	1.22	44.0	3.65
MC(2)	0.92	1.10	40.8	3.59
MC(3)	0.93	1.20	40.7	3.59
χ^2/dof				
MC(1)	0.30	0.12	0.94	2.49
MC(2)	0.44	0.31	0.35	1.04
MC(3)	0.35	0.21	0.31	1.02

we can conclude that even in sample were the two charmed particles have been reconstructed the inclusive analysis results are well reproduced by the Monte Carlo.

- Finally, we performed the correlation analysis on the double charm sample. The summary of the results follows:

DOUBLE CHARM				
	P_T	P_T^2	P_L	Y
	GeV/c	$(GeV/c)^2$	GeV/c	
MEAN VALUES				
RD	$0.84 \pm 0.09 \pm 0.06$	$0.99 \pm 0.19 \pm 0.18$	$71. \pm 4. \pm 3.$	$3.48 \pm 0.07 \pm 0.03$
MC(1)	0.57	0.55	90.	3.65
MC(2)	0.55	0.51	82.	3.56
MC(3)	0.69	0.72	82.	3.56
χ^2/dof				
MC(1)	2.1	1.6	3.2	1.8
MC(2)	2.1	1.7	1.2	1.2
MC(3)	1.6	0.9	1.3	1.3
	M	φ	ΔY	
	GeV/c^2	degrees		
MEAN VALUES				
RD	$4.32 \pm 0.13 \pm 0.11$	$124. \pm 10. \pm 10.$	$0.42 \pm 0.06 \pm 0.05$	
MC(1)	4.38	143.	0.52	
MC(2)	4.32	142.	0.52	
MC(3)	4.32	139.	0.51	
χ^2/dof				
MC(1)	1.33	0.76	1.30	
MC(2)	1.08	0.74	1.29	
MC(3)	1.13	0.73	1.13	

the main conclusion is that within the statistical significance of the data sample agreement has been found with the Monte Carlo predictions. But, the overall impression is that the Monte Carlo does not reproduce the P_T distribution in the correlation analysis as well as in the inclusive analysis.

- These results are in concordance with the one obtained in an earlier hadro-production experiment [34,35]. However, the statistical significance of our sample is larger.
- The relative abundance of single charm events have made possible the fine-tuning of the hadronisation models in inclusive production. But it is clear from this work (and other results) that more effort has to be put in the study of the correlations among the two produced charmed states. The information contained in double charm samples is larger than in single charm, even in the case of much smaller statistics.

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