A SEARCH FOR
PROMPT ELECTRONS WITH
LOW TRANSVERSE MOMENTUM
IN 630 GEV PROTON-
ANTIPROTON COLLISIONS

by

Kjell Fransson
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ABSTRACT


Prompt electrons produced in $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV have been studied in the $p_T$ range 0.5 – 2.0 GeV/c. A Ring Imaging Cherenkov (RICH) detector installed in the UA2 experiment at the CERN $p\bar{p}$ collider was used for the identification of the electrons. The production rate of electrons relative to charged hadrons was measured to be $e/h = [2.0 \pm 1.4 \text{ (stat)} \pm 0.6 \text{ (sys)}] \cdot 10^{-4}$.

Prompt electrons are produced in the semileptonic decay of charmed hadrons. Using the measured electron to hadron ratio, a value of the total charm production cross-section can be calculated. By assuming that all electrons originate from charm decay it is found that the total charm production cross-section can not exceed 1.9 mb at the 95% confidence level. The contributions from other prompt-electron sources to the electron to hadron ratio have been estimated to be 15%. Subtracting this background from the measured data results in a charm production cross-section, $\sigma(c\bar{c}) = 0.68 \pm 0.55\text{(stat)} \pm 0.32\text{(sys)}$ mb.

The thesis treats the development and performance of the RICH detector, the prompt-electron experiment in UA2 and the subsequent analysis and interpretation of the result.
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Doctoral dissertation to be publicly examined in Siegbahnsalen at the Department of Physics, Uppsala University, on Friday February 2 1990, at 14.00 h, for the degree of Doctor of Technology.

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Preface

The work described in this monograph is a result of the fruitful collaboration of a number of people.

The UA2-RICH experiment was carried out by Olga Botner, Lars Owe Eek, Tord Ekelöf, Allan Hallgren, and myself, from the University of Uppsala, Panos Kostarakis from the Nuclear Research Centre Demokritos, Athens, and Georg Lenzen from the University of Wuppertal, with the assistance of the UA2 collaboration.

The detector development was made in collaboration with Jacques Séguinot and Thomas Ypsilantis from College de France.

I have contributed in all the stages of the experiment that are described, starting with the measurements of the Quantum Efficiency of TMAE and followed by the development of the RICH detector and the realization of the UA2-RICH experiment. In the analysis, I have worked in particular with the prompt-electron search and the simulation of charm production.

The main results presented here, have already been published in the following articles:

The Time-Projection Ring Imaging Cherenkov (RICH) Counter New Experimental Results, L.O. Eek et al 84.


Preliminary Analysis of the Performance of a RICH Counter for Low-\(p_T\) Electron Identification at the CERN pp Collider, O. Botner et al 87.

Production of Prompt Electrons in the Charm region at \(\sqrt{s} = 630\) GeV, O. Botner et al 89.

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Uppsala 1989
# Contents

Chapter 1: INTRODUCTION ................................................................. 1
1.1 A short historical overview ..................................................... 1
1.2 Why study heavy quarks in hadronic interactions? .................... 3
1.3 The charm cross-section and prompt leptons ............................. 4
1.4 Electron identification .......................................................... 6
1.4.1 Ring Imaging Cherenkov detectors ..................................... 6
1.4.2 The UA2-RICH detector .................................................... 8
1.5 Outline of the thesis ............................................................ 8

Chapter 2: A RING IMAGING CHERENKOV DETECTOR FOR ELETTRON IDENTIFICATION ............................................... 10
2.1 Principles of Cherenkov ring imaging ...................................... 10
    2.1.1 Cherenkov radiation .................................................... 10
    2.1.2 Ring Imaging Cherenkov detectors ................................ 11
2.2 Photo-sensitive driftchambers .............................................. 13
    2.2.1 Basic principles ....................................................... 14
    2.2.2 Detection of single photo-electrons ................................ 15
    2.2.3 A photo-sensitive drift gas ....................................... 15
        2.2.3.1 Introduction ................................................... 15
        2.2.3.2 The quantum efficiency of TMAE ............................ 16
        2.2.3.3 The absorption length of TMAE ............................ 19
        2.2.3.4 The drift gas for the UA2-RICH detector .................. 21
2.3 The Multi Wire Proportional Chamber .................................... 21
    2.3.1 dE/dx ionization and the photon feedback problem ............. 21
    2.3.2 MWPC's with optical screens between the wires .................. 22
    2.3.3 The MWPC for the UA2-RICH ...................................... 25
2.4 The design of the UA2-RICH system ..................................... 28
    2.4.1 Mechanics ........................................................... 28
    2.4.2 The photon detector ............................................... 29
2.4.3 The mirror ................................................................. 31
2.4.4 The high voltage security system .................................. 32

2.5 Readout electronics ......................................................... 32
2.5.1 Pre-amplifiers ............................................................ 32
2.5.2 Amplifier discriminator units ....................................... 33
2.5.3 Drift time recorders ..................................................... 34

2.6 Radiator gas ................................................................. 34
2.6.1 A recirculating gas-system for C2F6 ................................ 36

2.7 Pion rejection ............................................................... 37
2.7.1 Test set-up and triggers .............................................. 37
2.7.2 Result and comments .................................................. 38

Chapter 3: THE UA2 RICH EXPERIMENT ..................................... 40
3.1 The Sp̅p̅S collider ........................................................ 40
3.2 The UA2 apparatus ......................................................... 43
3.2.1 The beam pipe .......................................................... 43
3.2.2 The vertex detector .................................................... 43
3.2.3 The central calorimeter .............................................. 45
3.2.4 The toroid magnets .................................................... 46
3.2.5 The forward-backward drift chambers ............................ 47
3.2.6 The converter and the proportional tubes ....................... 48
3.2.7 The forward-backward calorimeters .............................. 48

3.3 The position of the RICH detector .................................... 49
3.4 The scintillator hodoscope .............................................. 50
3.5 The triggers ................................................................. 51
3.5.1 The electron triggers .................................................. 51
3.5.2 The minimum bias trigger .......................................... 52
3.5.3 A multiplicity trigger for the RICH .............................. 52
3.5.4 Trigger efficiencies ................................................... 53

3.6 Data taking .................................................................. 55
3.7 Data processing and reduction ........................................ 56
3.7.1 UA2 track reconstruction ............................................ 56
3.7.2 Signal reduction for the RICH ...................................... 57
3.7.2.1 Conversion to wire and time ................................... 57
3.7.2.2 Finding the photon position, and correcting for the magnetic field ........................................ 57
3.7.2.3 Noise reduction ..................................................... 60
3.7.2.4. Identification of the Cherenkov photons and reconstruction of the ring image........................................61
3.7.3 Efficiency of the RICH analysis..................................................64
3.7.4 Raw data filtering and production.............................................65
3.8 The electron/pion separation by the RICH.....................................66
3.8.1 Delta electrons in UA2............................................................67
3.8.2 Random noise...........................................................................68
3.8.3 Pions above the Cherenkov threshold........................................69
3.9 The electron/pion separation by other detectors.............................69
3.9.1 The electromagnetic calorimeter...............................................69
3.9.2 Lead converter, proportional tubes...........................................71
3.10 Rejection of trivial electron sources...........................................71
3.10.1 Rejection of e+e- pairs from converted photons.......................71
3.10.2 Dalitz decays............................................................................74
3.10.3 Ke3 decays.................................................................................75
3.10.4 Electrons from Compton scattered photons.............................76
3.10.5 Single track requirement..........................................................76
3.10.6 The remaining event sample.....................................................77
3.11 Minimum bias sample....................................................................79
3.12 The electron to hadron ratio.........................................................80
3.12.1 Final electron and hadron samples..........................................80
3.12.2 Efficiency for the electron identification....................................81
3.12.3 Trigger acceptance.....................................................................83
3.12.4 The corrected electron to hadron ratio......................................83
3.13 Monte Carlo calculations of the residual background.....................84
3.13.1 The Monte Carlo program.........................................................85
3.13.2 Simulation of the RICH detector...............................................85
3.13.3 Generation of parent particles....................................................87
3.13.4 e+e- pairs from converted photons..........................................88
3.13.5 Dalitz decays.............................................................................89
3.13.6 Ke3 decays...............................................................................90
3.13.7 Compton scattering...................................................................90
3.13.8 Misidentified pions.................................................................91
3.13.9 Summary of the residual background.......................................91
3.14 The electron to hadron ratio after background subtraction................93
3.15 Comparison with e/h measurements at smaller $\sqrt{s}$....................93
Chapter 4: CHARM PRODUCTION

4.1 Introduction ................................................................................. 96
4.2 Charm cross-sections observed at lower energies ....................... 100
  4.2.1 Experimental methods ......................................................... 101
  4.2.2 Cross-sections for open charm-production ......................... 103
  4.2.3 Differential cross-sections .................................................... 107
4.3 Models of charm production in hadron-hadron interactions ......... 109
  4.3.1 Heavy quarks in perturbative QCD ....................................... 110
  4.3.2 Other charm production models ......................................... 115
  4.3.3 Higher order corrections to the fusion model ....................... 118
4.4 Monte Carlo simulations of $c\bar{c}$ production ......................... 121
  4.4.1 The Monte Carlo program Twister ....................................... 122
  4.4.2 The Lund string-fragmentation model .................................. 122
  4.4.3 Higher order corrections ...................................................... 123
  4.4.4 Comparison with measured differential cross-sections ........ 125
  4.4.5 Differential cross-sections at 630 GeV ................................. 126
  4.4.6 Particle ratios and decay properties ...................................... 129
  4.4.7 Predicted electron to hadron ratio ....................................... 131
4.5 Charm cross-section estimate at 630 GeV ................................. 131
  4.5.1 Conversion of the e/h ratio into $\sigma(c\bar{c})$ ......................... 132
  4.5.2 Acceptance of the prompt electrons from charmed particle decays ............................................................. 133
  4.5.3 An upper limit on the charm cross-section ......................... 134
4.6 Subtraction of beauty and vector meson contributions ............. 135
  4.6.1 Vector mesons ................................................................. 135
  4.6.2 Prompt electrons from semileptonic decays of beauty particles ............................................................. 138
  4.6.3 Estimate of $\sigma(c\bar{c})$ ........................................................ 139
4.7 Discussion of the results on $\sigma(c\bar{c})$ ..................................... 139

SUMMARY AND CONCLUSIONS ....................................................... 143

5.1 Detector aspects ....................................................................... 143
5.2 Physics aspects ....................................................................... 144

References ..................................................................................... 146

Acknowledgements ....................................................................... 153
Chapter 1

INTRODUCTION

1.1 A short historical overview.

Practically all so called "elementary particles", that we know today, interact via the strong interaction. They are usually referred to as hadrons. However, evidence is overwhelming that hadrons are in fact not truly elementary but made of constituents called partons. The partons are of two kinds, quarks and gluons. The quarks have spin $\hbar/2$, fractional electric charge and a new quantum number called colour. The gluons, mediators of the strong force have spin $\hbar$, no electric charge but like quarks, gluons carry colour. The three colours, e.g. red, green and blue and the corresponding anticolours, are sources of the strong force analogous to how positive and negative charges are sources of the electromagnetic force. Quarks and antiquarks are confined in colour-neutral (white) states that have an equal composition of red, green and blue quarks or a quark and an antiquark with a matching colour and anti colour. The states made from three quarks, e.g. a proton, are called baryons and those made from a quark and an antiquark are called mesons. Today we believe that interactions between quarks and gluons are described by a quantum field theory, known as Quantum Chromo Dynamics (QCD).

Three different types of quarks, up down and strange (u, d, s), were suggested by Gell-Mann (64) and Zweig (64) in order to explain the rapidly growing spectrum of different hadrons discovered in the 1950's and 60's (see e.g. Close 79). Around 1968 electron scattering experiments at Stanford gave the first hints of a point-like structure inside the proton. Subsequent
neutrino data from CERN strengthened the idea that quarks are really the fundamental building-blocks of matter. A fourth quark was suggested already in 1964 by Bjorken and Glashow to achieve symmetry with the 4 leptons which then were known to be electron, muon and two associated neutrinos (e, νe, μ, νμ). In 1970 Glashow et al showed that introducing a fourth quark could remedy the problem of the expected strangeness-changing neutral currents which were not observed in the experimental data. In addition the so called triangle anomaly, (Adler, Bell, Jackiew 69), a technical problem in field theories, spoil the renormalizability of QCD and could be avoided if the electrical charges of all fermions in the theory add up to zero. By predicting a fourth quark named charm, c, with charge $\frac{2}{3}$ the charges add up to zero since $Q (e^- + μ^- + 3 \cdot (u + d + s + c )) = 0$. The factor 3 accounts for the number of colours and $Q(\text{q})$ is the charge of q and given in table 1.1. The prediction of the existence of the charm quark was soon proved correct. In 1974 two experiments, Aubert et al (74) and Augustin et al (74), reported the observation of a narrow state at 3.097 GeV in proton-beryllium and electron-positron interactions respectively. This state now called J/ψ was interpreted as a bound state of a quark and an antiquark, c$\bar{c}$, of the earlier predicted charm flavour.

<table>
<thead>
<tr>
<th>Charge</th>
<th>1'st</th>
<th>2'nd</th>
<th>3'rd</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{2}{3}$</td>
<td>u</td>
<td>c</td>
<td>(t)</td>
</tr>
<tr>
<td>$\frac{1}{3}$</td>
<td>d</td>
<td>s</td>
<td>b</td>
</tr>
<tr>
<td>-1</td>
<td>e</td>
<td>μ</td>
<td>τ</td>
</tr>
<tr>
<td>0</td>
<td>νe</td>
<td>νμ</td>
<td>(ντ)</td>
</tr>
</tbody>
</table>

Table 1.1 Known or predicted, ( ), leptons and quarks grouped in 3 generations. A similar list can be made for antiquarks which have opposite charges.

The word flavour is used to differentiate between different quark types. In the following years mesons and baryons which had a net quantum number
of charm were discovered. The discovery of a new lepton, the $\tau$ by Perl et al 75 destroyed the newly obtained symmetry with the quarks. However, later evidence was found for yet another quark flavour $b$ which abbreviates bottom or beauty, Herb et al 77. Presently we await eagerly the discovery of number 6, the top quark. With the knowledge of today, the fundamental constituents of matter can be grouped in 3 generations as indicated in table 1.1.

1.2 Why study heavy quarks in hadronic interactions?

Quarks are confined inside hadrons and it is not possible to obtain a particle beam of free quarks. Thus, to study quark-quark and quark-gluon interactions it is natural to look at hadron-hadron scattering. However, hadron induced scattering is considerably more complicated than the previously mentioned lepton-hadron scattering since leptons are pointlike and hadrons are composite objects. Comparison with theory is complicated by the fact that so-far, the only practical way to make calculations in a field theory like QCD is to use the methods of perturbation theory. This is, in general, not possible since the strong coupling constant, $\alpha_s$, is quite large. Fortunately it was discovered, in lepton scattering experiments, that if a quark is struck sufficiently hard, implying a large transfer of momentum and energy, the quark behaves like a free pointlike particle. This can be explained in terms of QCD which possesses a property termed asymptotic freedom, (Politzer 73, Gross and Wilczek 73). Asymptotic freedom means that the strong coupling constant, $\alpha_s$, becomes smaller and smaller as the four-momentum transferred between the interacting partons increases. Similarly, if two quarks in the interacting hadrons come close enough for a hard scattering to occur, a perturbative QCD calculation can be expected to make sense. An important example of such a reaction is the so called high $P_t$ scattering. Another example of a hard scattering is the Drell-Yan process where a quark and an antiquark annihilate into a massive virtual photon which decays into a lepton pair (see e.g. Mueller 81).

However, in the overwhelming majority of the collisions, particles are created as a result of fairly soft interactions where the confinement effects dominate and perturbative calculations are not valid. In the case of heavy-quark ($c, b, t$) production through the fusion of two gluons or a quark and an antiquark, it is hoped that the occurrence of a mass, large compared to a
typical hadron mass-scale of a few 100 MeV, will make the interaction sufficiently hard to justify a perturbative approach and thus enable an experimental test of particle production in QCD. How large the mass has to be for the validity of such an approach is not completely clear.

To understand the production mechanisms of heavy particles is also important when we want to predict rates for new undiscovered particles such as supersymmetric hadrons, Higgs particles etc. (see e.g. Halzen 82). When we want to make these new discoveries we might also need to have a good knowledge of the production cross-section of heavy quarks since their semileptonic decays will appear as background in experiments using leptons as a probe to new physics.

1.3 The charm cross-section and prompt leptons

Experimental information on light meson production is abundant but it has turned out to be difficult to obtain useful data on production of particles containing heavy quarks. Considerable effort has been spent on measuring and interpreting data on charm and beauty production in hadronic interactions.

In 1973, about the time for the start of proton-proton collisions in the Intersecting Storage Rings (ISR) at CERN, Lederman and Saxon reviewed the possible sources of so called prompt leptons in hadron collisions. Possible sources include decays of the intermediate vector-bosons mediating the weak force, virtual photons from the Drell Yan process, pair-produced heavy leptons and charmed-particles. The term prompt implies that the electrons are produced close to the interaction vertex, a property well satisfied by the electrons from weak semileptonic decays of charmed particles since the decay time is about $10^{-13}$ s. Since then, prompt leptons have become an important experimental tool particularly in the search for particles containing heavy-quarks.

At the end of 1981, when the CERN proton- antiproton collider came into operation, the maximum available energy for hadronic collisions, took a leap by about a factor from 10 to 540 GeV. Here the use of prompt leptons met its greatest success with the discovery of the intermediate vector bosons at the CERN pp collider (Banner et al 83, Bagnaia et al 83, Arnison et al 83a, Arnison et al 83b). Muons and electrons with transverse momenta above ~10 GeV/c were looked for as signatures of the new vector bosons.
Measurements at the ISR ($\sqrt{s} = 63$ GeV) had indicated that the total cross-section for charm hadro-production, $\sigma(c\bar{c})$, was at least a few hundred microbarns, though values exceeding 1 mb had also been reported. In comparison, $\sigma(c\bar{c})$ observed at the CERN SPS and in the FNAL fixed target experiments was an order of magnitude smaller. At this time we proposed an experiment, at the $p\bar{p}$ collider, to measure the yield of prompt electrons at relatively small transverse momenta in the region around 1 GeV/c. In the $p_T$ region around 1 GeV/c charmed particles, mostly D mesons, decaying into an electron, a neutrino and a hadron (normally a kaon) are expected to dominate the prompt $e^{\pm}$ spectrum. Figure 1.1 shows a compilation of the observed rate of prompt electrons at the ISR, presented in terms of an $e/\pi$ ratio.

![Figure 1.1](image.png)

Figure 1.1 Measured values of the $e/\pi$ ratio at the ISR. Taken from Baillon et al 82.

This ratio is often used since it is fairly constant as a function of the transverse momentum $p_T$ and many systematic uncertainties can be expected to cancel if the yield of electrons and pions are measured at the same time. The measured values of $e/\pi$ are between 1 and 2 times $10^{-4}$ as can be seen in the figure. From this value, $\sigma(c\bar{c})$ can be estimated if the
contributions from other sources of prompt electrons are known, as
exemplified by the superimposed curves in figure 1.1. Such an estimate
requires however a knowledge of the production and decay characteristics
of the charmed particles. Estimated values or upper limits of $\sigma(c\bar{c})$
from prompt electron production are typically about 100 - 300 $\mu$b (Tavernier 87).

In collider experiments, looking for leptons from charm decay, electrons
are normally preferred in comparison to muons due to the large muon
background coming from decaying pions. The search for prompt $e^\pm$ is
however also subject to copious and varied background from non-prompt
sources, like converting photons, Compton scattering, and weak decays of
kaons. Furthermore there are large contributions from prompt $e^+e^-$ pairs
coming mainly from Dalitz decays of $\pi^0$ and $\eta$ mesons. These processes are
not regarded as interesting and care has to be taken, in the design of
experiments and in the analysis, to suppress their contributions to the
measured rate of prompt $e^\pm$. Residual backgrounds must be calculated by
Monte Carlo methods and subtracted from the measurement.

1.4 Electron identification.

An important aspect in an experiment searching for prompt electrons is
the particle identification. As stated earlier prompt electrons occur at a level
of only about $10^{-4}$ of the rate of charged hadrons. A detector system with
ability to reject hadrons to such a level, that their contamination in the final
electron sample is well below 1 in 10000, normally has to rely on a
combination of different particle identification methods, like electro-
magnetic calorimetry, dE/dx measurements, time-of-flight measurements
and Cherenkov- and transition-radiation detection.

1.4.1 Ring Imaging Cherenkov detectors.

The detection of Cherenkov light has played an important role for
identification of different particle species in high energy physics
experiments. An early example is provided by the discovery of the anti-
proton in 1955 (Chamberlain et al). Cherenkov detectors can be applied to a
wide range of experimental situations simply by choosing the radiating
medium and it is often possible to reach a high level of certainty in the
identification. However when separation of e.g. $\pi$ / K / p is needed in a wide
momenutm range, it has usually been necessary to combine several Cherenkov counters of the type that registers the presence of Cherenkov light when the particle velocity exceeds a threshold velocity. Over the past 15 years, the trend in particle physics experiments has been towards a frequent use of colliding beams in order to reach the highest possible energies and multi-purpose detectors with full solid-angle coverage and high granularity for the study of rare and complicated events. The large space and high cost of threshold Cherenkov-counter systems in this environment has attracted the attention to alternative solutions.

![Figure 1.2](image.png)

**Figure 1.2.** The principle of a RICH detector having a large phase space acceptance. The Cherenkov light is focused by a spherical mirror of radius R forming a circular image at R/2 where it is detected on a spherical, or close to spherical, detector surface. (From Séguinot and Ypsilantis 77).

The most important development along these lines is the Ring Imaging CHerenkov (RICH) detector. The angle of the Cherenkov light is measured by focusing the light into a ring of photons This idea was suggested by Roberts (60) and enables a direct measurement of the velocity from the ring radius in quite a wide momentum range above the threshold. The RICH principle is illustrated in figure 1.2. The Cherenkov photons are detected by means of, e.g., a drift-chamber separated from the radiator by a UV-
transparent window. The photons liberate electrons in the drift-chamber gas doped with a photo-sensitive vapour, as proposed by Séguinot and Ypsilantis (77). Presently a number of large scale applications of the RICH technique are about to come into operation in the near future, e.g. in the DELPHI detector at LEP and in the SLD detector at the SLC.

1.4.2. The UA2-RICH detector.

In 1982 we (Baillon et al) proposed the installation of a RICH detector in one of the magnetic spectrometer arms of the UA2 detector at the CERN pp collider to improve the ability to separate electrons from hadrons. The RICH module for UA2 was similar to one module of the large forward (gaseous) RICH detector planned for the DELPHI experiment. The purpose of this proposal was twofold: to enable a measurement of prompt electron production at momenta around 1 GeV/c and to gain experience in operating a RICH detector in a collider environment.

Among particles with low momenta, hadrons could be discriminated in the UA2 detector by typically a factor of 10. An additional factor of the order $10^4$ had to come from the RICH. The separation of electrons from hadrons is inherently a threshold problem. Naively one might expect an infinite separation when the threshold for Cherenkov-photon emission is below the pion mass yielding a 100% clean electron sample. In practice the rejection is limited by events where the hadron is accompanied by a low momentum electron that avoids the tracking detectors, e.g. a delta electron created in the RICH radiator or the material preceding it. The fact that the RICH detector also measures the angle of the radiating particle is important in order to establish the connection to the tracks measured by the other detectors. In the following we shall demonstrate that it is indeed possible to construct a compact RICH detector with the required rejection capability.

1.5 Outline of the thesis.

In chapter 2 we discuss some important considerations for the design of a RICH detector, the development work and the detailed construction of the UA2-RICH. In chapter 3 the prompt electron experiment and the analysis at $\sqrt{s} = 630$ GeV is presented.
Finally, in chapter 4 we summarize the experimental and theoretical situation regarding charm production in hadronic interactions, and using our measured prompt electron rate we estimate the $c\bar{c}$ production cross section at a collision energy of $\sqrt{s} = 630$ GeV.
Chapter 2

A RING IMAGING CHERENKOV DETECTOR FOR ELECTRON IDENTIFICATION

2.1 Principles of Cherenkov ring imaging.

A short overview is given of the phenomenon of Cherenkov radiation and the technique of Cherenkov ring imaging.

2.1.1 Cherenkov radiation.

A charged particle traversing a transparent dielectric medium polarizes surrounding atoms or molecules at each point along its trajectory resulting in the emission of a short electromagnetic pulse. Normally the intensity of this radiation falls quickly as a function of distance with no observable result except for a small energy loss of the particle. However if the particle velocity exceeds the light velocity in the medium, constructive interference takes place and Cherenkov light is emitted at a specific angle with respect to the charged particle trajectory (Cherenkov 34) The effect is similar to the shock wave created by an aeroplane moving faster than the velocity of sound. Due to azimuthal symmetry, a cone of light emerges around the particle. The necessary condition for Cherenkov light emission is illustrated by the construction of waves according to Huygens principle (figure 2.1).

From the simple constructive interference seen in figure 2.1, the Cherenkov angle \( \theta_c \) can be found to be

\[
\cos \theta_c = \frac{1}{\beta n}
\]  

(2.1)
where $n$ is the refractive index of the medium and $\beta$ is the particle velocity relative to the speed of light in vacuum. The threshold condition is seen to be $\beta_{th} = 1/n$, and the maximum Cherenkov angle will be $\theta_{c \text{ max}} = \arccos(1/n)$ at $\beta = 1$.

![Figure 2.1 Huygens construction drawn at a few points along the charged particle track.](image)

The velocity of the particle is below that of light and no constructive interference takes place. b) A wave front is formed, for particles moving faster than light. The wave front moves away from the particle direction at an angle $\theta$.

The number of Cherenkov photons emitted in the energy interval $dE$ over a pathlength $dL$ in the radiating medium was derived by Frank and Tamm (37).

$$\frac{d^2N_{ph}}{dLdE} = \left(\frac{Ze^2}{\hbar c}\right) \sin^2\theta_c = 370 Z^2 \sin^2\theta_c \text{ [cm}^{-1}\text{ eV}^{-1}], \quad (2.2)$$

where $Ze$ is the particle charge. Notice that for a constant $\theta_c$, eq. 2.2 is independent of energy implying that most Cherenkov photons are emitted with short wavelengths in the ultraviolet since

$$\frac{dE}{d\lambda} \propto \frac{1}{\lambda^2}.$$  

2.1.2 Ring Imaging Cherenkov detectors.

The principle of the Ring Imaging Cherenkov (RICH) detector is that Cherenkov photons are focused into a ring at a surface of a photon-detector
where the position of individual photons are measured. This enables the
determination of $\theta_c$ from the ring radius, as well as the direction of the
particle from the position of the ring.

The focusing can be achieved e.g. by a spherical or parabolic mirror or by
so called proximity focusing. The latter method can be utilized in the case of
dense radiators like solids or liquids where a sufficient number of photons is
emitted over a short distance. The light is then allowed to travel over a
distance without radiator, to let the cone expand into a ring.

Here we shall only consider RICH detectors with gaseous radiators and
spherical mirrors (corresponding to the UA2-RICH). The principle of this
type of detector is illustrated in figure 1.2. In the case of a flat detector surface,
$\theta_c$ is obtained from the relation $r = f \cdot \tan \theta_c$ where $r$ is the measured ring
radius and $f$ is the focal distance of the mirror. The photon detector should
be able to localize light quanta in two dimensions with sufficient efficiency
and precision, of the order (1 mm$^2$). For use at colliding beam facilities (see
section 1.4.1), the cost should be sufficiently low to make large surface area
(typically several m$^2$) detectors feasible. (This was not a critical point for the
UA2-RICH since the solid angle coverage was limited to a sector of the UA2
magnets, see the next chapter).

The important parameters characterizing a RICH system (radiator plus
photon detector) is the average number of photons that can be detected, $N_{ph}$,
and the resolution of the Cherenkov angle $\Delta(\theta_c)/\theta_c$.

$N_{ph}$ can be be obtained by multiplying formula 2.2 with the efficiency, as
a function of energy, for a photon to be detected and then integrating over
the energy interval where the detector has a sensitivity $> 0$. Observe that in
general $\sin^2\theta_c$ is a function of $E$ due to the chromatic dispersion of the
radiating medium, $n = n(E)$. At wavelengths far from the absorption bands
of the radiator the variation of $n$ with energy is slow, and the number of
detected photons is often expressed as

$$N_{ph} = N_0 \cdot L \cdot \sin^2 \theta_c$$  \hspace{1cm} (2.3)

where $N_0$ is a quality factor. For the case $Z = 1$ we have

$$N_0 = 370 \text{ eV}^{-1} \text{ cm}^{-1} \cdot \int_{E_{min}}^{E_{max}} Q(E) \prod_{i} \xi_i(E) \, dE.$$  \hspace{1cm} (2.4)
Here $Q$ is the quantum efficiency of the photon detector and the $\varepsilon_i$ summarize all other efficiency factors between emission and detection of Cherenkov photons. The losses normally occur during the transmission through the radiator gas and entrance window of the photon detector and when reflected in the mirror. The lower limit $E_{\text{min}}$ is usually determined by the quantum efficiency while $E_{\text{max}}$ is set by the optical transmissions and reflectivity.

The resolution, $\Delta(\theta_c)$ of the Cherenkov angle $\theta_c$ limits the ability of the RICH detector to separate different particles of a given momentum. The resolution of the relativistic $\gamma$ factor \( \gamma = 1/\sqrt{1 - \beta^2} \) is given by

\[
\frac{\Delta \gamma}{\gamma} = \frac{\gamma^2 \beta^2 n}{\sqrt{N_0 L}} \Delta \theta_c ,
\]

(see Séguinot, Ypsilantis 77).

The factors contributing to $\Delta(\theta_c)$ were analyzed in detail by Ypsilantis (81). The most important ones are the error from the chromatic dispersion in the radiator (often substantial for ultraviolet wavelengths) and the position resolution of the photon-detector. If the detector is displaced relative to the interaction point or if a magnetic field is present, particles do not always come from the centre of curvature of the mirror, as presumed in figure 1.2. As a consequence there will be optical aberrations depending on the impact parameter i.e. the distance from the track to the centre of curvature of the mirror and the size of the area on the mirror illuminated by the Cherenkov light. Optical aberrations were negligible in the case of the UA2-RICH detector.

2.2 Photo-sensitive drift chambers.

To solve the problem of single photon detection over large areas with good spatial resolution, Séguinot and Ypsilantis proposed the use of drift chambers where the drift gas had been doped with a photo-sensitive vapour. The development of RICH counters with this type of photon detector has been described in a number of papers, (e.g. Séguinot, Ypsilantis 77, Séguinot et al 80, Ekelöf et al 81, Barrelet et al 82 and Eek et al 84). In the following sections we will concentrate on the problems relevant for the UA2-RICH detector.
2.2.1 Basic principles.

The principle of the photo-sensitive drift chamber is illustrated in figure 2.2. The Cherenkov photons enter from the radiator into the drift chamber through a window and ionize the photo-sensitive vapour M through the reaction $hv + M \rightarrow M^+ + e^-$ with a certain probability (quantum efficiency). Thus single electrons are liberated for some of the Cherenkov photons.

![Diagram of a photo-sensitive drift chamber](image)

**Figure 2.2** The principle of the photo-sensitive drift chamber.

The electrons then drift in an electric field to a multi-wire proportional chamber (MWPC). In the strong field close to one of the wires, each electron is accelerated, creating a charge avalanche which has to be of sufficient magnitude to be detectable by the electronics connected to the wire.

By recording the wire number as well as the drift time for each of the detected signals, a two-dimensional image can be reconstructed. Sometimes also a third coordinate is measured through the induced signal on the MWPC cathode, providing a measurement of the depth coordinate of the photo-conversion. This information can help improve the resolution of the Cherenkov ring in the case where the photons enter the detector at an angle.
2.2.2 Detection of single photo-electrons.

Due to the charge avalanche in the detector gas and the drift of the created ions (see e.g. Sauli 77), a signal is induced on the sense wire. To achieve single electron detection with high efficiency and good time resolution a mean amplification in the gas of the order of a few $10^5$ is necessary. That a gas-gain of this size could indeed be reached was first demonstrated by Charpak and Sauli (78) using a multistep avalanche chamber (MSAC), in which the electrons first encounter a region of strong field, the pre-amplification step, with a gain of about $10^3$ before reaching the MWPC. Later, Ekelöf et al (81) showed that a sufficient gain could be reached without the pre-amplification step if the detector gas was methane (CH$_4$) or a mixture of CH$_4$ and other hydrocarbons like isobutane (C$_4$H$_{10}$) or ethane (C$_2$H$_6$).

2.2.3 A photo-sensitive drift gas.

2.2.3.1 Introduction.

Of critical importance for the design of a RICH detector is the matching of the optical properties of the different components; the radiator, the mirror, the window, the drift gas and the photo-sensitive agent. The transmission and reflectivity limit the photon energy to the ultraviolet and hence the gases for the photo-ionization process must have a cut-off below the typical energies of the photons being absorbed. The photo-sensitive gas should also have a high quantum efficiency for photo-ionization and a vapour pressure that gives a short mean free path, at most of the order of a few cm.

The photo-ionization process was investigated by Sequinot and Ypsilantis and it was found that efficient photon detection could be achieved using organic vapours like benzene (C$_2$H$_6$). However benzene, with a photo-ionization threshold of $E_{pi} = 9.25$ eV is not compatible with e.g. CH$_4$ which has a transmission cut-off at about $E_t = 8.5$ eV. Benzene would require an entrance window made by expensive and delicate single-crystals of the alkali-halides like MgF$_2$ or LiF$_2$. Later work has concentrated on the substances TEA (Tri Ethyl Amine), (Charpak et al 77) and TMAE (Tetrakis-(di-Methyl Amino)-Ethylene), (Anderson 80) with $E_{pi} = 7.5$ eV and $E_{pi} = 5.5$
eV respectively. The TEA and TMAE molecular structures are shown in figure 2.3.

![Molecular structures of TEA and TMAE](image)

Figure 2.3 The molecular structures of TEA and TMAE.

The threshold for TMAE vapour is among the lowest of all known organic compounds and enables the use of fused quartz ($E_t \sim 7.5$ eV) and a wide selection of radiators. Consequently all large scale applications so far have been based on the use of TMAE (see however Lund-Jensen et al 88).

2.2.3.2 The quantum efficiency of TMAE.

In order to understand the response of a RICH system it is essential to know the quantum efficiency as a function of photon energy for the photosensitive compound used. A measurement of this property of TMAE was therefore an early step in the development of RICH detectors. (Ekelin and Fransson 81)

The equipment used for the quantum efficiency measurements consisted of a monochromator with a deuterium light source having a maximum light output around 160 nm (7.7 eV). The light passed via a CaF$_2$ window into a stainless-steel compartment filled with CH$_4$ and the photosensitive vapour. In the middle of the compartment was a small drift-chamber of the approximate dimensions $5 \times 5 \times 8$ cm$^3$ and the elongation being in the direction of the light beam. After having passed through the centre of the drift gap, the light beam was collected, behind a second CaF$_2$ window, by a photo-multiplier tube (PMT) coated with a wavelength shifter (p-terphenyl) giving a flat response to photons above an energy of 4 eV (Baillon et al 75). The photo-electrons produced in the drift-gap moved vertically in a field of about 0.8 kV/cm to a MWPC with 37 wires of 20 $\mu$m.
diameter separated by 2 mm and positioned perpendicularly to the light beam. The anode wires were on ground potential and the cathode planes, made from a woven mesh, were ~5 mm above and below the anode plane at a potential of ~2 kV. The uniformity of the response from the individual wires was investigated using 40 keV electrons from a Ruthenium source (Ru\textsuperscript{106}) and a central group of 9 wires was selected.

During the quantum efficiency measurements, the 9 wires were connected together and the total current to ground was measured using a Keithley Picoammeter (Model 410A). Under the above conditions, the current was about 0.5 nA at 160 nm. Since the current had substantial short time-fluctuations particularly outside the region of maximum intensity of the deuterium lamp, the analogue output of the picoampmeter was connected to a digital voltmeter (Schlumberger) and integrated for a period of 10 s at each measured wavelength. Simultaneously the current measured by the PMT was recorded. After completion of a wavelength scan the container was evacuated and the PMT current was measured again as a function of wavelength. This procedure enabled the calculation of the relative quantum efficiency

\[
Q(\lambda) \propto \frac{I_W}{I_{PM}} \cdot \frac{1}{\left( e^{-(l_1/l_0)} - e^{-(l_2/l_0)} \right)}
\]

(2.6)

where the mean free path \(l_0\) is obtained from

\[
l_0(\lambda) = L \cdot \left\{ -\ln \left( \frac{I_{PM}}{I_{PM}^0} \right) \right\}^{-1}
\]

(2.7)

In 2.6 and 2.7 \(I_W, I_{PM}\) and \(I_{PM}^0\) are the measured currents on the wires, the current on PMT and the PMT during the reference scan, respectively. \(L\) (11.3 cm) is the total distance, traversed by the light-beam in the compartment filled with the photo-sensitive vapour and \(l_1\) and \(l_2\) are the distances corresponding to the beginning and the end of the selected group of wires.

The calculation of \(Q(\lambda)\) assumes that the transmission, \(T\) through the second CaF\(_2\) window and the ratio of detection efficiencies, \(\varepsilon_{PM}\) and \(\varepsilon_{MWPC}\) of PMT and MWPC are independent of wavelength and light intensity during the measurement. This independence should be valid for the detection efficiency of the PMT because of the wavelength shifter. In the case of the
efficiency of the MWPC, the amount of light from the monochromator was varied, at a constant wavelength, by a slit in front of the monochromator window, to make sure that the current from the MWPC did not saturate but was proportional to the amount of light. The CaF$_2$ window was only 2 mm thick and should therefore be almost fully transparent down to the CH$_4$ cutoff, however, no measurement of the transmission was made.

![Graph showing quantum efficiency of TMAE as a function of photon energy.](image)

**Figure 2.4** The quantum efficiency of TMAE as a function of photon energy. The compilation is due to Arnold et al. 88.

All measurements were performed with CH$_4$ as the detector gas. Different concentrations of TEA and TMAE were added to the CH$_4$ by bubbling part of the gas through a container with liquid TEA or TMAE. The measurements were performed with the TEA at 4°C and the TMAE at 20°C. In the case of TMAE, container, tubing and CH$_4$, had to be heated to a temperature of 30°C to avoid condensation. An additional component of pure CH$_4$ was added so that the mean free path of photons in the mixture would not be too short and a reasonable current in the drift chamber could be achieved. In the case of TMAE, the concentration was reduced in this way typically by a factor 2-4 resulting in a TMAE concentration of about 100-
200 ppm. In the case of TEA a reduction by a factor of \( \sim 20 \) was needed to give a concentration of 1400 ppm.

The measured quantum efficiency of TMAE is shown in figure 2.4 and compared to two other measurements.

The agreement between the measurements is reasonable. It should be noted that the data by Nakato et al was for photon energies \( E < 7.3 \) eV. The quick drop in our data below 8.5 eV is due to the transmission limit of CH\(_4\). The absolute normalization of the curves in figure 2.4 was obtained by Holroyd et al (86) from a comparison with the known benzene and the cis-2-butene quantum efficiencies, and by us and Nakato et al from Ring Imaging measurements as described in Arnold et al (88) Similar quantum efficiency measurement for TEA are shown in figure 2.5.

![Graph](image_path)

**Figure 2.5** The relative quantum efficiency of TEA, \( Q/Q_{\text{max}} \) as a function of wavelength. The compilation is due to Lund-Jensen et al 88.

**2.2.3.3 The absorption length of TMAE.**

In figure 2.6 the inverse mean-free-path, \( \mu \), is plotted for TMAE (20°C) in CH\(_4\) as obtained during the measurements described above. In the region 160-200 nm the mean-free-path is about 2 cm. This is in good agreement
with the measurement by Anderson (80) while the measurements by Arnold et al (88) and Ashford et al (87) give $\mu^{-1}$ more like ~3 cm. The difference is believed (Lund-Jensen et al) to be due to contaminations since different methods of purifying the TMAE had been used. For the measurement described above and for that of Anderson, the TMAE was purified by exposing the liquid to vacuum and allowing a small portion to boil away, while in the two other measurements, the TMAE was also "washed" with distilled water. The procedures are described in Anderson (80).

![Graph showing absorption coefficient vs wavelength](image)

**Figure 2.6** The inverse absorption length $\mu$ from the measurements by Ekelin and Fransson

The reason for the relatively long $\mu^{-1}$ is the low partial pressure of TMAE, 0.345 torr at 20°C. In comparison, TEA has a partial pressure of 52 torr (Anderson 88) giving a mean-free-path of 0.6 mm at 20°C. To make the mean conversion depth in the photon detector shorter the TMAE is normally heated and all parts of the detector must consequently also be heated to avoid condensation. TMAE is non-transparent if deposited on e.g. a window and TMAE oxide is electrically conducting.
2.2.3.4 The drift gas for the UA2-RICH detector.

Since we want to separate electrons from pions it is advantageous to choose the radiator gas such that pions are below the threshold for emission of Cherenkov photons over most of the momentum region to be investigated. When the pions do not radiate it is more important to maximize the number of photons from the electrons than to get the best possible resolution on the ring image. Therefore a combination of TMAE in CH$_4$ with a CaF$_2$ window was chosen. In this way the RICH detector was optimized for Cherenkov photons between 5.5 and 8.7 eV. The properties affecting the resolution that can be improved upon is the position error from the diffusion of the electrons, which can be made smaller by adding e.g. C$_2$H$_6$ or iso-C$_4$H$_{10}$ to the CH$_4$, and the chromatic dispersion in the radiator which will be less important if the photon detector is sensitive only in a more narrow energy interval.

The temperature of the TMAE was kept at 27°C during the UA2-RICH experiment and most of the test measurements. This gave a partial pressure of ~0.55 torr of TMAE corresponding to a mean free path of about 2 cm according to Arnold et al. Both methods of purification (distilled water and evaporation) were applied on the TMAE.

2.3 The Multi Wire Proportional Chamber.

A short account is given of the design considerations behind the construction of the MWPC, and a few of the investigated designs are discussed. The MWPC for the UA2-RICH experiment is presented.

2.3.1 dE/dx ionization and the photon feedback problem.

In a typical experiment using a RICH detector with a photo-sensitive drift chamber, signals will be generated, not only by the Cherenkov photons, but also by the ionization from charged particles traversing the drift volume. In contrast to a single photo-electron, a charged particle can generate a signal of several hundred electrons depending on the depth of the drift-volume. Figure 2.7 compares a photon-detector "image" where about 200 beam particles (10 GeV/c η) has passed perpendicularly through the detector for the case a) without TMAE and b) with TMAE present in the chamber (from Eek et al 84).
Figure 2.7 Photon-detector "image" showing about 200 overlaid events of a beam of 10 GeV/c negative pions (Eek et al 84). a) No TMAE present. b) 0.7 torr partial pressure of TMAE added to the drift gas. The beam had an extent of about 5 mm and the wire pitch was 1.27 mm. The filaments around the spot in a) was due to δ-rays.

A large increase of the noise around the beam spot can be seen in b) where the partial pressure of TMAE was 0.7 torr. This phenomenon is explained by the large number of electrons which are created by the pions These electrons reach the MWPC sense wires where photons in the ultra-violet are created in the charge avalanches around the wires. The photons come from de-exitations of atomic states in carbon and hydrogen atoms that were exited close to the wire by the impact of the accelerated electrons (The phenomenon was recently investigated in detail by Lund-Jensen et al 88). In the presence of TMAE, the photons liberate electrons over a distance of a few mean-free-paths. In this particular example about 20 background points per pion were created.

This so called photon feedback is obviously an undesirable background that can easily destroy a Cherenkov image. Avalanches may also be created by the photo-electrons from Cherenkov light which can cause feedback that deteriorates the resolution.

2.3.2 MWPC's with optical screens between the wires.

In an effort to limit the spread of the feedback photons we tried (Eek et al 84) to place UV-absorbing screens between the wires of a small test chamber. It was found that efficient single-electron counting could be achieved if the screens were made from small printed circuit boards, having narrow conducting strips at different levels relative to the sense wire. A suitable
voltage had to be applied between the strips and optimized to reach the desired efficiency and avoid losses of electrons drifting on to the screens. An example of this type of design is shown in figure 2.8.

![Diagram](image)

**Figure 2.8** a) MWPC with PC-board screens. b) Transverse cut showing the layout the individual cells. (From Dulinski et al 86.)

The mounting of the screens between the sense wires poses a difficult mechanical problem since small mis-alignments can result in local gain variations (this limits the maximum average gain that can be obtained) if the distance between the strips and the wires becomes too short. The solution to this problem in an early prototype design for the UA2-RICH is shown in figure 2.9. Instead of the strips, a double-fence of stainless steel wire pairs (4, 35 μm diameter) on top of each other was positioned between the 10 μm diameter anode wires. A small screen was kept in place by the wire pairs. Figure 2.9 illustrates how the screen wires and the anode wires were mounted in the MWPC.
Figure 2.9  Detail of the MWPC prototype (published in Eek et al 84). The optical screens are referred to as cloisonnes.

The overlaid images of 300 events in figure 2.10 shows optical screens are able to absorb photons and suppress the photon-feedback. The beam-spot above the Cherenkov ring looks similar to that of figure 2.8 a) except for the vertical line of signals which is caused by remnant ionization or feed-back photons created by earlier beam particles.

Figure 2.10  The first 300 overlaid events recorded with optical screens between the sense-wires
A few different designs of the optical screens have been tested. It is necessary to have a mechanically stable construction with sufficient precision in the mounting of all details to avoid gain variations as mentioned earlier. Such variations can make the MWPC less high voltage stable. Care had to be taken in order to minimize the electric cross-coupling between the sense wires, since the large signal from the ionization after a charged particle which is a few hundred times stronger than the signal from a single electron must not be allowed to propagate across the MWPC.

In the case of TMAE detectors it is desirable to measure also the 3rd coordinate, i.e. the conversion depth, since the long mean-free-path of TMAE will give a parallax error on the Cherenkov ring when the photons enter at an angle to the window. This coordinate can be measured by dividing the cathode plane below the sense-wires into strips and record the induced signals and their drift time as for the wires. However, the amplitude of the cathode-strip signals are always smaller than the anode signals and an increase in gain is required in order to obtain full efficiency of the 3rd coordinate. In practice an increase in gain may be difficult to achieve since more feedback-photons are created and these photons can eventually lead to the development of sparks (see Lund-Jensen et al 88 for a discussion). Another method of limiting the photon feedback is based on the MSAC type of chamber mentioned in section 2.2.2. See e.g. Breskin et al 83)

2.3.3 The MWPC for the UA2-RICH.

The finally selected MWPC for the UA2-RICH experiment consisted of a cathode with a tubular structure where each tube contained one of the sense wires. The signal electrons were focused through a slit in the tube on the side facing the drift-chamber. The tubular design is illustrated in figure 2.11.
Figure 2.11 a) Structure of the MWPC for the UA2-RICH experiment. b) Cross-section of the tubular structure.

The tubular cathode was realized with 8 stainless-steel bars, 5 mm wide, placed parallel to each other and perpendicular to the sense wires as can be seen in figure 2.11a) for two bars. To produce the cathode, the structure in figure 2.11 b) was cut out from a stainless-steel plate by the method of electro-erosion and the plate was then cut into eight slices. The distance between the centre of the tubes was equal to the anode wire distance and was 2.54 mm and the number of tubes was 80. Thus the bars were ~20 cm.
Figure 2.12 Counting efficiency relative to the efficiency plateau as a function of cathode voltage. Upper curve for the anodes and lower curve for the cathodes.

The 80 sense wires were made of 20 µm diameter gold-plated tungsten wire and were about 50 mm long. Above the cathodes, centred between the anode wires, were 70 µm diameter potential wires with the purpose of focusing the drifting electrons through the 0.5 mm slits. Typical operating voltages were between −1.7 and −1.8 kV on the cathodes and about −3 kV on the focusing wires. The anode wires were on ground potential.

The MWPC was tested extensively both with Cherenkov light, ionization from particles and UV-light from an H₂ flashlamp. The conclusion was that the photo-electrons could be focused through the cathode slits without any detectable losses and that fully efficient photo-electron counting could be achieved. Figure 2.12 shows as a function of the cathode voltage, the number of detected anode signals arising from flash-lamp generated UV-photons which enter through a small hole in a mask covering the drift-volume (normalized to 1 at the plateau). The constant number reached at about 1.75 keV indicates that efficient counting is achieved.

Also shown is the corresponding efficiency relation for the cathode signals recorded from the 8 individual cathode bars. At e.g. 1.8 kV the efficiency is
80%. To reach full cathode efficiency, an increase in gain corresponding to about 100–150 V, relative to the start of the efficiency plateau for the anode, would be necessary. By moving the position of the mask in front of the drift-volume window in small steps, it was checked that the detection efficiency did not depend on the exact position of the mask above the cathode i.e. the light entered just above a slit or in between. The tubular cathode design was abandoned in the development work for the DELPHI forward RICH detector at LEP since it was shown by us (Dulinski et al 86) that substantial losses of photoelectrons occur in the presence of a strong magnetic field parallel to the wires. However, in UA2 the main magnetic field component is perpendicular to the wires.

The motives for selecting the tubular design are that the stainless-steel cathode is rigid and comparatively simple and provides a very efficient screen against feedback photons. Also the tendency for large ionization signals to propagate through the MWPC was found to be less for the tubular design than for any of the other investigated solutions resulting in a beam-spot of small size. Finally, efficient single-photo-electron counting could be achieved without any severe high-voltage instability and the 3rd coordinate readout reasonable efficient (the best of the tested MWPC’s).

In UA2, the gain was reduced to keep the rate of sparks as low as possible, resulting in a ~30% efficiency for the 3rd coordinate. The corresponding efficiency of the anodes was between 90 and 95%.

2.4 The design of the UA2-RICH system.

An overview of the components in the detector system is given.

2.4.1 Mechanics.

The complete RICH is shown schematically in figure 2.13. The outer dimensions of the radiator container which was made of aluminium were determined by the requirement that it should fit between the magnetic spectrometer and the drift chambers in UA2. The length of the radiator and the focal distance of the mirror were determined as a compromise between the desires to maximize the number of photons, i.e. to make the radiator as long as possible, and to minimize the bending, for the interesting tracks (p > 1 GeV/c), in the part of the magnetic field that
extended into the radiator (see chapter 3). Also the component of the field that could cause a drift of photo-electrons into the CaF$_2$ window had to be as small as possible. The focal length of the mirror was finally chosen to be 600 mm.

![Diagram of RICH radiator container with spherical mirror and photon detector.]

Figure 2.13 The RICH radiator container with the spherical mirror and the position of the photon detector.

2.4.2 The photon detector.

A cut through the middle of the drift volume and the slot were the MWPC enters is shown in figure 2.14.

![Diagram of MWPC and field shaping electrodes.]

Figure 2.14 A cut through the middle of the drift volume.
The CaF$_2$ window was 5 mm thick and 200 x 200 mm$^2$ in area which was obscured by the support about 2.5 mm on all sides. The back-wall of the drift box was 40 mm away from the CaF$_2$ window.

The drift box was made from glass-fibre reinforced epoxy. To maintain a uniform drift field, both the in- and the outside was covered by a layer of parallel printed circuit lines with a spacing of 2.54 mm. The window had 70 µm diameter potential wires aligned to and connected with the printed circuit lines. The wires were placed on both the in- and the outside so as to polarize the crystal and avoid charge build-up as observed by Barrelet et al (82). A resistor chain on the side of the drift volume was fed by a constant current during the measurements, thus creating a succession of decreasing negative potentials towards the MWPC. The drift field used during the UA2-RICH experiment was 0.5 kV/cm giving a drift velocity in the CH$_4$–TMAE mixture of 9.5 cm/µs. This drift field required a voltage of about -14 kV at the far end. The uniformity of the drift field was checked by shooting a narrow particle beam through the side of the drift volume, parallel to the window, in the manner described by Barrelet et al.

![Graph showing transmission vs wavelength](image)

**Figure 2.15** Transmission of the CaF$_2$ window measured before mounting, and after completion of the experiment.
Figure 2.15 shows the transmission of the CaF$_2$ window as measured before the assembly of the drift volume but after the potential wires had been applied to the surface. The same window was measured before the mounting of the wires and had then a 10% better transmission at all wavelengths. Also shown (lower curve) is the transmission measured after the final UA2-RICH running period.

2.4.3 The mirror.

The 600 mm focal-length mirror was made at CERN by slumping and polishing of a 3 mm thick glass plate. The glass was coated, by vacuum evaporation, with 80 nm Al and 35 nm MgF$_2$. Due to it's large size it was not possible to measure the reflectivity of the detector mirror. Therefore a number of small plane test-mirrors were coated at the same time as the detector mirror. A mean value of the measured reflectivity of the test mirrors is shown in figure 2.16, upper curve together with the actual reflectivity of the detector mirror as measured after the UA2-RICH experiment, by cutting the mirror into smaller pieces.

![Graph showing reflectivity vs. wavelength](image)

**Figure 2.16** Mean reflectivity of the test mirrors together with the reflectivity of the actual detector mirror as measured after the completion of the experiment (by dividing the mirror in pieces).
After the coating the mirror was cut into its final shape. The mirror in the plane of figure 2.14 measured about 75 cm.

2.4.4 The high voltage security system.

In a system with a MWPC operating close to its maximum gain it is important to monitor all high-voltage currents and automatically detect an increase above some pre-set threshold since otherwise the MWPC might be damaged by sparks. An automatic system for over current detection was developed and this system could switch off all the MWPC high-voltages simultaneously. In the beginning of the data taking with the RICH inside UA2 the current detection system was modified so that it could detect also small constant currents of the order of a few micro ampere.

2.5 Readout electronics.

A short description of the electronics designed to register the MWPC signals is given.

2.5.1 Pre-amplifiers.

The pre-amplifier circuit was built with the Philips NE 592 D video amplifier. The chips were soldered between two 16 pin sockets, forming a box of approximate dimensions $10 \times 20 \times 17$ mm$^3$ containing 8 channels. A drawing of such an amplifier box is shown in figure 2.17 a).

![Diagram of pre-amplifier circuit and amplifier box](image)

Figure 2.17 a) A unit of 8 amplifiers to be mounted directly on the MWPC circuit board. b) The circuit diagram.
The box was mounted directly on the circuit board of the MWPC thus minimizing the external parasitic capacitance by keeping the distance between the sense wires and the input of the amplifier as short as possible. In this design it was only ~1 cm.

In figure 2.17b the circuit diagram is shown. The anode wires are connected to ground over a 4.7 kΩ resistance. The two diodes protects the amplifier from large signals, e.g. due to sparks. The transconductance of the circuit was measured to be about 7 mV/fC and the dispersion in gain between the different channels in a sample of several hundred was found to be less than 1 dB. The input capacitance with the amplifier mounted on an MWPC anode was measured to be about 6 pF (i.e. the capacitance of the amplifier, the resistor and the diodes as well as the capacitance of the MWPC). The noise charge of the circuit was measured and found to be equivalent to about 3200 electrons.

Though the number of wires was only 80 the number of channels mounted on the MWPC was actually 160 thus only every second channel was used during the UA2-RICH experiment. The main reason was to allow chambers with a shorter wire spacing to be used with the same electronics during the development stage. Since the extra channels provided an opportunity to monitor the electronic cross-talk there was no reason to change the design before the start of the experiment.

2.5.2 Amplifier discriminator units.

The differential outputs of the pre-amplifiers were taken from the 16 pin sockets on top of the box in figure 2.17 via 4 m twisted-pair flat-ribbon cables to the Amplifier-Discriminator (A-D) units. The A-D's amplified the analogue signals and converted them to logic output pulses, if they exceeded a certain adjustable threshold.

The input sensitivity, i.e. the lowest possible threshold, was 5 mV, corresponding to a charge of 4300 electrons at the input of the pre-amplifiers. During the data taking in the UA2-RICH experiment a threshold of 10 mV was used for the anodes signals and 7.5 mV for the cathode signals.
2.5.3 Drift time recorders.

The outputs of the A-D were transferred to the Drift Time Recorder units of type DTR 247 CERN (Van Köningsveld 77) in 82 m long twisted pair cables.

The DTR digitizes the time interval between an input pulse and a stop pulse using a clock frequency of 125 MHz. With the 9 bits used per channel the maximum drift-time memory is 2048 ns. A time bin of 4 ns is obtained by interpolation of the 8 ns clock period. Each 16 channel unit is able to collect up to 256 pulses and thus the DTR can register multiple hits on the MWPC wires.

In the UA2-RICH experiment the maximum drift time slightly exceeded 2 µs which meant that it was not possible to register the information from a complete event with one DTR channel. In addition, it is desirable to register also the signals in a time interval before and after an event to get a good definition of the start time and to monitor the level of background signals. This problem can be avoided in a test-beam measurement since with parallel particles all the Cherenkov photons appear in a limited time slice of the detector. Each data channel was recorded by two different DTR channels: the stop time of the second had been delayed by 1.5 µs with respect to the first. The stop time of the first set of DTR channels was generated by the pp bunch-crossing signal in the presence of a valid trigger. To avoid event-to-event fluctuations in the relative stop-time between two channels both stop times were registered by a TDC.

The DTR information was transferred to the data-acquisition computer via a CAMAC-based system.

2.6 Radiator gas.

The choice of the gas mixture CH₄ + TMAE with a CaF₂ window allows a large number of possible radiators as can be deduced from figure 2.18. This compilation due to Arnold et al (88) compares the transmissions of possible radiators and windows with the quantum efficiency of TMAE.
Figure 2.18 Quantum efficiency for TEA and TMAE and window transmissions together with the transparency range and Lorentz factor at the threshold (η) for different radiators. In this compilation, due to Arnold et al, the arrows indicate that the radiators are transparent enough at short wavelengths to be used with TEA.

The radiator chosen for the first UA2-RICH run in 1984 was CH\(_4\) which obviously matches well the transmission properties of the drift gas. CH\(_4\) has a Cherenkov-radiation threshold for pions of \( p = 4.4 \text{ GeV}/c \) and \( \theta_c \_{\text{max}} = 32 \text{ mrad} \). In the second run (1985) it was desired to increase the number of produced photons which lead to the choice of the fluoro-carbon C\(_2\)F\(_6\) as radiator. As can be seen in figure 2.18 this gas has a threshold just below CH\(_4\) and good transmission properties down to short wavelengths. C\(_2\)F\(_6\) also has a smaller chromatic dispersion than CH\(_4\). The pion threshold in C\(_2\)F\(_6\) is \( p = 3.5 \text{ GeV}/c \) and \( \theta_c \_{\text{max}} = 40 \text{ mrad} \). From formula 2.3 we can expect a 60% increase in the number of photons for a \( \beta = 1 \) particle by using C\(_2\)F\(_6\) instead of CH\(_4\).
2.6.1 A recirculating gas-system for C$_2$F$_6$.

C$_2$F$_6$ is a relatively expensive gas and consequently it was decided to circulate the gas. The advantage was also that a more rapid flow of gas through the radiator was possible which should reduce the amount of impurities in the system since the gas was circulated through a purifying cartridge that was able to remove oxygen and water. A schematic drawing of the regulating system is shown in figure 2.19.

![Diagram](image)

**Figure 2.19** Schematic drawing of the system for recirculating the C$_2$F$_6$ (see text for explanations).

The gas was led from a reservoir with ~0.4 bar over-pressure via an adjustable needle valve and a flow-meter to the radiator. At the outlet of the radiator a compressor sucked the gas back into a reservoir through a back valve. A by-pass from the reservoir was connected to a pressure regulator positioned after the radiator and adjusted to keep the pressure 2 mbar above atmospheric pressure. In the case of a fault in the pressure regulation, the compressor was automatically stopped. During normal operation about 1 l/h
of C₂F₆ was replaced by letting this quantity escape through the ventilation valve.

After installation of the C₂F₆ system in UA2 the O₂ and H₂O contamination was measured to be about 16 ppm and 5 ppm respectively. To monitor a possible accumulation of nitrogen, from a small air leak, that might effect the refractive index, the N₂ level was monitored during the full running period and was never found to exceed 0.5%.

2.7 Pion rejection.

Though some investigations of the electron identification capability of the RICH detector had been performed prior to the UA2-RICH data taking periods, the C₂F₆ radiator had not been tried earlier. In addition it turned out to be impossible to keep all parameters from the tests unchanged during the p̅p̅ experiment. After the termination of the data taking, it was therefore decided to make a detailed determination of the probability for a pion to be misidentified as an electron by the RICH. This work has been described in detail by Eek (89) and we shall give only a short resume.

2.7.1 Test set-up and triggers.

The investigation was carried out in π⁻ beam at the CERN proton synchrotron (PS). There was also a substantial component of other negative particles in this beam and the exact particle composition was very momentum dependent. The pions were identified by two threshold Cherenkov counters, 4 m and 5 m long, respectively with a combined probability for mistaking an electron as a pion of about 2 · 10⁻⁷. The arrangement of the beam line after the last bending magnet is shown in figure 2.20.

The RICH detector was mounted on a movable and turnable support and could thus be adjusted in a desired angle and position.

A trigger was formed from a coincidence of signals in the scintillators S₁-S₄. S₁ is not shown in figure 2.20 but was placed just upstream of the first Cherenkov counter. An anti-coincidence signal was taken from the scintillator V₁ in which a circular hole of diameter 8 cm had been cut out. The pion event sample was defined as events with absence of signals from the two Cherenkov counters and the muon-veto counter, V₄. Signals from
the scintillators V2 and V3 and the lead-glass blocks Pb1 and Pb2 were not included in the pion selection but were used for the interpretation of misidentified events.

Figure 2.20 Schematic drawing of the set-up in the PS beam-line.

Correspondingly an electron sample was selected by demanding a signal in the Cherenkov counters. The electron sample was used to determine both the expected location of the ring images and the efficiency of the electron identification. The pions were then analysed in exactly the same way as the electrons and the fraction of pions misidentified as electrons were determined.

2.7.2 Result and comments.

The misidentification probability as a function of momentum is shown in figure 2.21.

A constant $e/\pi$ ratio of about $5 \cdot 10^{-5}$ was observed below the pion Cherenkov threshold of 3.5 GeV/c. The efficiency in electron identification was found to be about 60%. The application of the clustering algorithm described in chapter 3 reduced the misidentifications by a few percent and the efficiency by about 5%. The inefficiency in electron identification resulted from events having less than 3 detected photons and the requirement that the fitted radius should be between 22 and 28 mm. The mean number of detected photons was found to be about 5.
Monte Carlo simulations were performed in order to understand the constant $e/\pi$ ratio measured below the pion threshold. It was found that the dominant source was knock-on electrons created by the traversing pion in the material of the RICH detector or in the material between the Cherenkov counters and the RICH detector. The contribution of knock-on electrons is also plotted in figure 2.21 as open circles. As can be seen these electrons correspond to about 80% of the misidentified pions below the pion threshold. By examining the remaining events, some images were found with a pattern of hits characteristic of electronic noise (several hits on the same wire) or a cluster from an ionizing track in a combination which gave the correct radius when fitted to a circle. This explanation was valid for about 20% of the misidentified pions below the Cherenkov threshold.

To conclude, we have measured the desired degree of certainty in the electron identification prior to the UA2-RICH experiment and found that better than $10^{-4}$ can be reached. The misidentified events are understood in terms of knock-on electrons and noise.
Chapter 3

THE UA2 RICH EXPERIMENT

3.1 The SppS collider.

The CERN $p\bar{p}$ collider was proposed by Rubbia et al 1976 with the primary goal of producing the intermediate vector bosons $W^\pm$ and $Z^0$ which are predicted by the gauge theory of the electro-weak interaction. It was suggested that bunches of antiprotons could be injected, accelerated and stored simultaneously with bunches of protons circulating in the opposite direction in the already existing Super Proton Synchrotron (SPS). Rubbia et al recognized that high intensity $\bar{p}$ bunches could be made by using cooling techniques. Of the methods initially suggested, electron-cooling (Budker 67) and stochastic cooling, (van der Meer 72), the latter was finally chosen.

![Diagram of stochastic cooling](image)

**Figure 3.1** The principle of stochastic cooling is illustrated for the case of a horizontal deviation from an equilibrium closed-orbit particle. A position error at the pick-up electrode transforms into an angular error at the kicker electrode which corrects the particle. Figure from Möhl (1983).
Stochastic cooling is achieved by measuring the time averaged fluctuations about the mean momentum of a beam of particles and generating from these measurements, corrections to the beam trajectory. The procedure is repeated until the spread in momentum and phase-space is reduced, see figure 3.1.

$p\bar{p}$ collisions are achieved in a four-step procedure as illustrated in figure 3.2. Bunches of $10^{13}$ protons are extracted from the CERN Proton Synchrotron (PS) at an energy of 26 GeV and with 2.4 s intervals. The protons hit a beryllium target producing $10^7$ antiprotons per bunch with a typical momentum of $\sim 3.5$ GeV/c. The antiprotons are injected into the Antiproton Accumulator (AA) and cooled stochastically during 2.4 s before the next bunch is injected. They are added to the existing stack of previously stored antiprotons. The stack is cooled further and the product of the 3D momentum and coordinate phase-spaces of the beam can be reduced by a billion times. The stacking capacity is about $5 \cdot 10^9$ $\bar{p}$'s per hour. Intense $\bar{p}$-stacks have been maintained in the AA for as long as a month.

Figure 3.2 Schematic diagram of the proton and antiproton accelerating machines at CERN and their connecting beam lines.
The SPS receives 3 bunches of about $10^{11}$ protons from the PS of an energy of 26 GeV. Then 3 bunches of $10^{10}$ antiprotons are successively extracted from the AA, accelerated in the PS to 26 GeV and injected into the SPS. In the SPS the 6 bunches are accelerated to 315 GeV and kept circulating for typically 24 hours. Each bunch is then about 2 $\mu$s long and extend 1 mm transversally. They are allowed to collide along the ring at 6 points of which two are used for the experiments UA1 and UA2. At these collision points the beams are focused strongly to give as high an event rate as possible. The luminosity, i.e. the count rate divided by the cross-section, is a measure of the quality of a collider. The maximum integrated luminosity achieved up to the 1985 run was $3.5 \times 10^{29}$ cm$^2$/s. The good performance of the collider resulted in the discovery of the intermediate vector bosons in 1983. For a summary of collider physics see e.g. Bagnaia (88).

Figure 3.3 A schematic cross-section of the UA2 experiment where the position of the RICH counter in one of the azimuthal sectors has been indicated. Notice also the position of the scintillator hodoscope, indicated as a black bar, in front of the magnet in the RICH sector.
3.2 The UA2 apparatus.

The UA2 apparatus was designed mainly to search for the intermediate vector bosons. Figure 3.3 shows a cross-section of the UA2 apparatus through the plane were the RICH detector was added.

The main components are a central detector for reconstruction of the vertex point and the emanating tracks. A central calorimeter covers the polar angles 40° – 140° and 360° in azimuth. In the polar regions 20° – 37.5° and 160° – 177.5, the "Forward-Backward" (F/B) regions, were toroidal magnetic fields followed by drift chambers, for momentum measurements. The RICH detector was located in front of one group of drift chambers, covering a 30° azimuthal angle. The F/B regions were also covered by calorimeters. In addition all calorimeters, both F/B and central, were preceded by converters and shower detectors. For an overview of the UA2 detector see Mansoulie (83).

3.2.1 The beam pipe.

After an interaction, the emanating particles encountered the wall of the beam-pipe. The wall was located at a radius of 138 mm and was made of 0.15 mm of corrugated stainless-steel. The amount of material traversed will depend on the vertex position and on the polar angle (θ). The typical spread of the vertex points along the beam directions was ± 11 cm. Averaging over the locations of vertex points we find an increase of 30% in the amount of traversed material relative to the case of an uncorrugated wall. The number of radiation lengths traversed was

\[ X_0 \text{ (Beam pipe)} = 1.25 \% \cdot \frac{1}{\sin \theta} \]

3.2.2 The vertex detector.

The beam pipe was surrounded by a cylindrical vertex chamber with full azimuthal coverage and covering 20° – 160° in polar angle, see figure 3.4.

This detector was composed of four proportional chambers (VS1 – VS4) having a helicoidal arrangement of cathode strips equipped for readout (Dialinas 83), see figure 3.5, and two drift chambers, (VJ1 , VJ2) with charge
division readout and similar in construction to those of the JADE detector (Prevot 82, Heintze 78).

![Diagram of vertex detector]

Figure 3.4 A transverse view of a quarter of the vertex detector. See the text for explanations of the notation. A straight line has been drawn to represent a track emanating from the vertex. The drift path of the ionization-electrons produced in the drift chambers VJ1 and VJ2 has been indicated as arrows pointing at the wires. Figure from Mansoulie (83).

The drift chambers filled the space between the proportional chambers, VS2 and VS3, and, VS3 and VS4, respectively. In addition, a 5th proportional chamber was positioned after a tungsten converter which had a thickness of 1.5 radiation lengths. However, only the region corresponding to the central calorimeter was covered, see figure 3.4, and was not used in the analysis discussed in this thesis. In figure 3.4, VS1 and VS2 are followed by a vertex hodoscope, designated by VH. This hodoscope was removed for the 1985 run and replaced by a prototype silicon detector covering a limited solid angle including that of the RICH detector. Due to a large number of dead channels the silicon detector was not used in the present analysis except to check the ability of the remaining system to reject converted photons.
The vertex was found with an efficiency of better than 97%. The precision in the longitudinal direction was about ± 1.5 mm. In the transverse plane it was about ± 0.9 mm for a single event which was larger than the expected variation from event to event which was ~ 0.2 mm. Therefore only the average value for the run was used in the analysis.

3.2.3 The central calorimeter.

The central calorimeter was not used in the present e/h measurement and will only be dealt with briefly. See Beer et al (1984). It is divided into 24 "orange slices" in $\phi$ and 10 cells along $\theta$. Each of the 240 cells is a tower segmented in 3 compartments, one electromagnetic (lead/scintillator) and two hadronic (iron/scintillator). The depth of the electromagnetic part is 17 radiation lengths and the total depth of all compartments is 4.5 absorption lengths. The resolutions obtained were $\frac{\Delta E}{E} = 0.15$ (E in GeV), for electrons and about
\[ \frac{\Delta E}{E} = \frac{0.32}{4\sqrt{E}} \] for single hadrons of 1 GeV.

### 3.2.4 The toroid magnets.

The magnetic spectrometers were located in the F/B regions, approximately 1 m from the interaction point. Azimuthally they were divided into 12 sectors in the forward part and into 12 sectors in the backward part, see figure 3.6.

![One of the toroid magnets before mounting. Picture from UA2 handbook.](image)

In each 30° sector about 20% of the angle was obscured by iron and coils. The magnetic field was shaped like a torus with a radius of 1.6 m around the colliding beams, The main field component was in the azimuthal direction. The field integral was approximately given by:
\[ \int B \, dl \approx 0.38 \cdot \frac{1}{\tan \theta} \text{Tm.} \]

### 3.2.5 The forward-backward drift chambers.

The magnets were followed by a set of 3 drift chambers, see figure 3.7, each having 3 wire planes. One plane had the wires directed in the magnetic-field direction and the other two were tilted by +7° and -7° respectively. A resolution of 300 μm was obtained in the drift direction resulting in an angular resolution of the measured track segment of \( \sigma_\theta = 0.47 \) mr in the bending plane.

![Exploded view of the F/B detectors in one sector. Figure from Mansoulie (83).](image)

Together with the measured vertex and a matched track-segment in the vertex detector, the bending in the magnetic field enabled the momentum \( p \) to be determined with a precision of

\[ \frac{\Delta p}{p} = \sqrt{(1.8)^2 + (2.5)^2} \% \quad (p \text{ in GeV/c}). \]
A more detailed account of the construction and performance of the F/B chambers can be found in Conta et al (1984).

### 3.2.6 The converter and the proportional tubes.

Behind the F/B chambers, a 1.5 radiation-length converter initiated electromagnetic showers. These showers were detected by four layers of 20 mm diameter proportional brass tubes, Borer et al (1983). In the present investigation they were only used as a check on other detectors.

### 3.2.7 The forward-backward calorimeters.

The last detector in each F/B sector was a calorimeter composed of two compartments. The electromagnetic part had 24 radiation lengths and was followed by a hadron veto of 6 radiation lengths, see figures 3.7 and 3.6. This detector was a sandwich of 4 mm lead plates and 4 mm scintillators where each of the 24 F/B sectors were divided into 10 cells, 2 in the azimuthal and 5 in the polar direction.

![Figure 3.8 Schematic drawing of 2 symmetric modules from one F/B calorimeter sector. From the UA2 handbook.](image)

The light from the scintillators was collected, for each cell and compartment, by two light guides doped with BBQ wavelength shifter in the
part facing the calorimeter. The ratio of the PM-tube pulse-heights from the right and left side could be used to determine the impact point in the direction across the cell to a precision of about 6 cm at low momenta. This was used in the matching of calorimeter clusters to tracks in the F/B chambers and showers detected in the proportional tubes. It also enabled an impact-point dependent energy correction to be applied. The energy resolution for electrons was
\[
\frac{\Delta E}{E} = \frac{0.17}{\sqrt{E}}, \text{ (E in GeV)}.
\]

3.3 The position of the RICH detector.

The RICH detector covered one 30° sector of the magnetic spectrometer system on the side of the interaction region from where the anti-proton beam was approaching. Of the 30°, about 20% were shadowed by iron and coils. A transverse cut through the RICH sector is shown in figure 3.9.

![Diagram](Image)

**Figure 3.9.** Transverse cut through the magnet sector with the RICH, showing how the photons radiated by a passing particle are reflected by the spherical mirror and focused into the photon-detector volume.
The photon detector and the first part of the radiator were located in the fringe-field of the magnet, with the drift volume about 1.9 m from the interaction region. The residual field integral in the radiator was about 0.03 Tm, corresponding to $\Delta \theta \sim 0.3^\circ$ for a particle with a momentum of 2 GeV/c. Since this bending occurred mainly over the first 10 cm, the distortion of the ring images by this effect was negligible.

In the photon detector, the main component of the toroidal magnetic field essentially had the same direction as the electric drift field. There was, however, also a component of the magnetic field perpendicular to the drift volume. This had a different sign for long and short drift distances respectively, and was zero in the middle. This component made the photoelectrons follow a curved path which had to be corrected for in the analysis. The field component was $\sim 0.07$ T at the entrance of the MWPC. The 3rd magnetic-field component caused a displacement perpendicular to the CaF$_2$ window of, at most, a few millimetres. The two transverse field components could give some losses of drifting electrons created close to the walls of the drift volume and the CaF$_2$ window, depending on their polarity. The drift into the window was important only in a short region at long drift distances (1 ~ 2 cm) where the Cherenkov rings were less likely to occur.

3.4 The scintillator hodoscope.

The scintillator hodoscope covered most of the opening of the sector of the magnetic spectrometer where the RICH detector (indicated in fig 3.3) was located.

The purpose of the hodoscope was twofold:
- To provide a trigger on charged particles in the RICH sector.
- To give information on the number of tracks entering the spectrometer.

The second point was motivated by the need to reject the background from converted photons and Dalitz decays. An electron positron pair could be identified as a single electron or positron if one of the particles had a momentum, small enough to be swept away by the magnetic field and thus avoid detection in the RICH detector and the drift chambers. In the case of pairs, from conversions, with very small opening angles and looking like a single track in the vertex detector, the presence of a double track was detected by the pulse-height information from the hodoscope.
The hodoscope is illustrated in figure 3.10. It consisted of two planes, each with five fingers of 1 cm thick plastic scintillators. The somewhat larger first plane covered approximately 24° in azimuth and 15° in polar angle while the second plane was limited to 23° and 11.3° respectively. The light was carried by 3 m long light guides to the PM-tubes placed outside the magnetic field. The PM-tube signals were then after shaping used in the trigger and recorded by a 12 bit ADC.

3.5 The triggers.

3.5.1 The electron triggers.

The electron trigger demanded a charged particle in the RICH sector and electromagnetic energy deposited in the calorimeter behind the RICH. This condition was realized by a coincidence between the UA2 minimum-bias trigger, the signal from the scintillator hodoscope described in section 3.4 and the added calorimeter pulses provided they were sufficiently large.

The UA2 minimum-bias trigger was formed from a coincidence of two scintillator hodoscopes close to the beam on both sides of the collision region (Battistoni et al 82). They covered the polar angle interval from 0.42°
to 5.7° with respect to the beam. This trigger gave a signal for more than 98% of all non diffractive events (Banner et al 85).

To form the trigger signal from the RICH hodoscope an OR of the five fingers in each plane was made using the shaped signals. A coincidence between the two planes was then required in the trigger.

The transverse energy was obtained as a sum of the calorimeter PM-tube pulse heights. This sum was approximately proportional to the total transverse energy in the sector since the gain of the PM-tubes had been adjusted to be proportional to \( \sin \theta \), \( \theta \) being the polar angle at the centre of the calorimeter cell.

Three different energy thresholds were used in the data taking, henceforth designated by \( E_1, E_2 \) and \( E_3 \). The nominal thresholds are given in table 3.1.

Table 3.1. Nominal energy thresholds for the different triggers.

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Minimum ( E_t ) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB</td>
<td>0</td>
</tr>
<tr>
<td>E1</td>
<td>0.8</td>
</tr>
<tr>
<td>E2</td>
<td>1.4</td>
</tr>
<tr>
<td>E3</td>
<td>2.5</td>
</tr>
</tbody>
</table>

During normal UA2 data taking the RICH-trigger rate was reduced with a prescale factor.

3.5.2 The minimum bias trigger.

Data were also recorded with a "minimum-bias" trigger for the RICH sector (designated by MB). This trigger was equivalent to the electron triggers above but with no requirement on the deposited energy.

3.5.3 A multiplicity trigger for the RICH.

A RICH detector with a drift chamber for photon detection is not well suited to provide a trigger signal. Firstly, Cherenkov radiation is not the only source of signals which can also be generated by charged particles
passing the drift volume. To identify the Cherenkov rings at the trigger
level will thus be a difficult task in most practical cases. Secondly, a
relatively long time is needed to collect the information so that a fast trigger
is excluded for this reason.

In the case of the UA2-RICH experiment, the small size of the detector
and the high drift-velocity in pure CH$_4$ limits the total drift time to about
2µs. Since the interval between bunch-crossings was about 7µs there was
enough time to generate a late second level trigger and reset the electronics
if no signals were detected by the RICH in the corresponding 2µs interval. To
make use of this possibility a second-level trigger unit was designed (Jonsson
83). This unit was able to sum all the signals occurring at the DTR inputs
during the time between a bunch-crossing and 2µs after. If the sum did not
exceed a threshold which was set in our experiment to correspond to one
detected signal, a clear-signal was generated to the data-acquisition system. In
this way events without any detected signals in the RICH could be discarded
already at the trigger level. This resulted in a reduction of the trigger rate by
a factor of two, corresponding mainly to the probability that a charged
particle crossed the drift-volume.

(Due to some difficulties in implementing this trigger together with the
normal set of UA2 W$^\pm$ and Z$^0$ triggers it was used mainly during the
dedicated RICH data-taking periods, see section 3.6)

3.5.4 Trigger efficiencies.

The response of the different triggers to an energy deposition in the
electromagnetic calorimeter is illustrated in figure 3.11, where the trigger
rate as a function of transverse energy has been plotted. The rates of the
different triggers have been multiplied by their respective prescale-factors.
Figure 3.11. Trigger rate for the 3 different electron triggers and the RICH minimum bias trigger.

From the above measurements, the probability of having a trigger for some deposited amount of $E_T$ can be calculated. In order to estimate the efficiency of detecting an electron of a certain $p_T$ the response of the calorimeter was simulated using the UA2 Monte Carlo program and including the measured trigger efficiencies. The result for the single electron efficiency as a function of $p_T$ is shown in figure 3.12.
Figure 3.12. Trigger efficiencies for single electrons as a function of $p_T$ for the 3 electron triggers.

As can be seen the efficiency of E3 is small below $p_T$ of 2 GeV/c. Since the probability to misidentify a pion as an electron starts to grow rapidly for momenta above 4 GeV/c (corresponding to $p_T \sim 2$ GeV/c) this trigger was not used in the present analysis.

3.6 Data taking.

In the autumn of 1985 data with the RICH in UA2 was collected in a parasitic mode during most of the $p\bar{p}$ running period. In addition there were two short periods of dedicated running, in total $\sim 28$ h, during which about $2/3$ of our data were collected.

For most of the time the four triggers were recorded simultaneously and prescaled to give approximately the same rate, except for the MB triggers which were collected at a slower rate. Table 3.2 summarizes the integrated luminosities and event samples obtained for the different triggers.
Table 3.2. Integrated luminosities and collected number of triggers

<table>
<thead>
<tr>
<th>Trigger</th>
<th>$\int L , dt [\mu b^{-1}]$</th>
<th>Number of triggers</th>
</tr>
</thead>
<tbody>
<tr>
<td>E1</td>
<td>1660</td>
<td>$0.6 \cdot 10^6$</td>
</tr>
<tr>
<td>E2</td>
<td>2720</td>
<td>$0.35 \cdot 10^6$</td>
</tr>
<tr>
<td>E3</td>
<td>5590</td>
<td>$0.13 \cdot 10^6$</td>
</tr>
<tr>
<td>MB</td>
<td>7.83</td>
<td>$0.06 \cdot 10^6$</td>
</tr>
</tbody>
</table>

(During the dedicated running periods, the difference in the prescale factors between the three triggers were smaller explaining the unequal number of total triggers.)

The full information from the UA2-detector was recorded for all triggers.

3.7 Data processing and reduction.

In this section we shall go through the most important steps in finding the charged particles that produce Cherenkov light in the RICH radiator. These steps will be the base of a fast filter to reduce the relatively large data sample to a less CPU-time consuming size.

3.7.1 UA2 track reconstruction.

The reconstruction of the tracks entering the RICH sector was performed by the normal pattern-recognition program for the UA2 detector. The essential steps were:

- Reconstruction of the tracks in the vertex detector.
- A fit of the vertex position using the vertex detector tracks.
- Reconstruction of the tracks in the drift-chambers behind the RICH.
- Association of the drift chamber tracks to the vertex detector tracks.
- A momentum fit to tracks in the drift chambers and magnetic field.

The last step could be performed either using only the information on the vertex position or including the track segment measured by the vertex detector. For the prompt-electron search in the UA2-RICH data it was necessary to use the information on the vertex track in order to suppress particles, such as electrons from kaon decays, that did not originate at the vertex. In the analysis, the vertex detector track-segment was required to
point at the vertex within ~1 cm. This type of fit had an efficiency of about 60%.

3.7.2 Signal reduction for the RICH.

3.7.2.1. Conversion to wire and time.

The first step in the RICH analysis was to find the wire and cathode coordinate and the corresponding drift time. As mentioned in chapter 2, each data channel was measured by two time delayed DTR channels. The average start-time for the data channels was determined off-line. For each event this time was subtracted and an event dependent correction was calculated using the stop times measured by the TDC. If the same wire had recorded pulses in the overlapping time region of the two DTR channels only those of the first DTR channel were kept.

3.7.2.2. Finding the photon position, and correcting for the magnetic field

In the case of zero magnetic field the x (wire) and y (time) coordinates of the photon-detector signals could be found just by multiplying the wire number with the wire spacing and the drift time with the drift velocity. With the magnetic field present a correction was necessary since the photo-electrons followed a curved path as discussed in section 3.3.

The Lorentz-angle (the angle of the drifting electron relative to the electric field in the presence of a magnetic field) of a CH4-TMAE mixture was not well known as a function of the magnetic and electric field-strengths and was investigated using the ionization-electrons from charged particles passing the drift volume. Such ionization clusters could easily be found by looking for track segments using the cathode-bar coordinates. Where a track had passed, all 8 bars had been hit close in time providing the y coordinate of the track cluster. The x coordinate was found using a cluster finding algorithm applied within a time-slice corresponding to the time measured on the cathodes. Figure 3.13 shows the RICH information in an event interpreted as an e+ e- pair. The rectangular area to the right shows the hits on the 8 cathode-bars. In the top of this area the passages of the two particles are clearly visible as straight tracks on the cathodes. The corresponding wire-time clusters can be seen among the (x,y) coordinates to the left.
Figure 3.13. An $e^+ e^-$ pair as seen by the RICH. Wire-time ($x,y$) coordinates to the left and cathode-time ($z,y$) coordinates to the right. (See the text for further explanation.)

The cluster coordinates were compared to the extrapolated tracks from the drift chambers. The resulting deviations in the $x$-coordinate plotted with the $y$-coordinate of the track, along the $y$-axis, are displayed in figure 3.14.

The drift velocity and direction in a gas, in the presence of an electric field in the $y$ direction and as a function of the transverse magnetic field, can be parametrized as:

$$
\bar{V}_D = \frac{V_0}{1 + \alpha^2 (F_x^2 + F_z^2)} \cdot (\alpha F_z, 1, -\alpha F_x),
$$

(3.1)

$F_x$ and $F_z$ are the magnetic field components in $x$ and $z$ directions,

$V_0$ is the drift velocity for 0 transverse magnetic field,

$\alpha = \frac{1}{\sqrt{F_x^2 + F_z^2}} \cdot \tan(\theta_1),$

$\theta_1$ is the Lorentz angle.
To first order $\alpha$ and $V_0$ are independent of the transverse magnetic field while $\theta_1$ is not. This approximation should be sufficient since $F_x$ and $F_z$ are relatively small.

![Graph](image)

**Figure 3.14.** The difference between the x-coordinates of the track clusters found in the RICH and the extrapolated drift-chamber tracks plotted with the y-coordinate of the drift-chamber track. a) before magnetic field correction and b) after magnetic field correction.

Since the precision in the determination of the position of the particle passages were fairly independent over the drift volume, a fit was made with $V_0$ and $\alpha$ as free parameters in the following way. For each value of $V_0$ and $\alpha$ that was tried a (wire,time) → (x,y) map was calculated by stepping through the measured map of the magnetic field in the opposite direction to the drifting electrons. Starting at a wire, a 60 ns step was taken in the direction predicted by (3.1) until the maximum drift time observed in the data had been reached. The wire and time coordinates of the identified clusters were then translated to x and y by a quadratic interpolation in the (wire,time) → (x,y) map. The squared residual deviations to the extrapolated tracks were calculated for each event and summed over an event sample of
a few thousand tracks. Then new values of \( V_0 \) and \( \alpha \) were tried until a minimum was found. The result for the final corrected cluster-sample can be seen in figure 3.14 b. The \( x \)-width of the distribution represents mainly the uncertainty in the extrapolated track positions. A similar plot was made for the \( y \)-deviations but the effect is much less pronounced in this case since \( V_0 \) was relatively well known from the beginning.

The average final values were \( V_0 = 0.096 \pm 0.001 \) mm/ns, \( \alpha = 1.7 \pm 0.02 \text{ T}^{-1} \). This is rather close to what is obtained if the mean time between collisions in the drift gas is assumed independent of the magnetic field. This gives (see e.g. Peisert, Sauli 82 for formulas) \( \alpha = V_0 / E = 1.9 \text{ T}^{-1} \), were \( E \) is the electric field. The observed value of \( \alpha \) implies that \( \theta_1 \) was never larger than 15° in the drift volume.

3.7.2.3. Noise reduction.

Noise signals in the photon detector could have a pure electronical origin or correspond to ionization in the drift gas from a track or from the photon feedback process. In order to identify the Cherenkov photons, the noise signals had to be removed in each event or the noisy events excluded from the analysis.

![Figure 3.15. The frequency of events with a certain number of unexplained signals (see text).](image-url)
The track clusters were located by a cluster-finding algorithm looking for a sequence of signals on consecutive or almost consecutive wires close in time (see figure 3.13). A signal occurring close after (within 5 ns of) a candidate Cherenkov photon on a nearby wire was also discarded. In this way most of the electronic cross-talk could be removed. Feed-back photons could not be identified on an event by event basis but should give only a small contribution with this type of tubular-cathode chamber.

Figure 3.15 shows a typical distribution of the number of unexplained signals in the events, i.e. signals that were not removed by the clustering algorithm or could be explained as Cherenkov photons or cross-talk. As can be seen the distribution has a long tail. It had been observed that events with many unexplained signals had a high probability of having signals that were misinterpreted as Cherenkov photons. Therefore events containing more than 3 unexplained signals were excluded in the analysis. This resulted in a loss of events with real Cherenkov rings by ~ 10%.

3.7.2.4. Identification of the Cherenkov photons and reconstruction of the ring image.

The first step in finding the Cherenkov photons associated with a particular track was to extrapolate the track segment, as measured in the drift chambers behind the RICH, to the RICH mirror. It was then reflected in the mirror and extrapolated to the photon-detector drift volume and 20 mm inside (corresponding to the mean photon absorption distance). The point found in this way constituted the expected centre of the ring image.

The next step was to locate the signals, if any, in an annulus around the expected centre. If three or more photon candidates were found the centre \((x_c, y_c)\) and radius, \(r\), of a ring was fitted to the \((x, y)\) coordinates. (It was necessary to fit also the centre since those predicted from the UA2 drift-chambers were not accurate enough to enable a measurement of the radius as the mean distance to the photons, with enough precision, thus at least 3 coordinates were required.) In the fit, the deviation in the square of the radius was minimized using the method of least squares. The motivation for using \(r^2\) instead of \(r\) itself was that in this case an analytic solution can be found according to:

\[
x_c = \frac{\sigma_{yy} (\sigma_{xx} \sigma_{yy} - \sigma_{xy} (\sigma_{yx} + \sigma_{yy}))}{2 (\sigma_{xx} \sigma_{yy} - (\sigma_{xy})^2)}
\]
and

\[ y_c = \frac{\sigma_{xx} (\sigma_{yy}^2 + \sigma_{yx}^2) - \sigma_{xy} (\sigma_{xy}^2 + \sigma_{xx}^2)}{2 (\sigma_{xx} \sigma_{yy} - (\sigma_{xy})^2)} \]

where \( \sigma_{uv} = \frac{\sum_{i=1}^{n} u_i \cdot v_i}{n} - \frac{\sum_{i=1}^{n} u_i \cdot \sum_{i=1}^{n} v_i}{n^2} \)

now the radius can be calculated as

\[ r = \sqrt{(x - x_c)^2 + (y - y_c)^2} = \sqrt{\frac{\sum_{i=1}^{n} \left[ (x_i - x_c)^2 + (y_i - y_c)^2 \right]}{n}} \]

---

**Figure 3.16.** The fitted-radius distribution for conversion electrons with momenta between 1 and 2 GeV/c, open squares. The black squares are from a Monte Carlo simulation described in section 3.13.
This procedure was illustrated in figure 3.13 where a ring (dotted circle) had been fitted to the photon coordinates shown as large dots and found inside the annular region (full circles) for the $e^+$ and the $e^-$ respectively.

In figure 3.16 the distribution of fitted radii for a sample of selected conversion electrons with momenta between 1 and 2 GeV/c are plotted. A sharp peak can be seen at $r = 24$ mm which is exactly what is expected for a $\beta = 1$ particle.

To choose a suitable width of the annular region the number of events with at least 3 detected photons were plotted together with the number of events with a fitted radius between 22 and 26 mm for different widths. The most narrow region had an inner radius of 20 mm and outer radius of 28 mm; the widest had 6 mm and 40 mm respectively. The result is shown in figure 3.17.

![Figure 3.17. For a sample of conversion electrons is shown the number of events with at least 3 detected photons (open triangles) and those which had a fitted radius between 22 and 26 mm (black boxes) as a function of the width of the annular region around the expected centre.](image)

No particular gain in the number of events with a correct radius can be seen when the width was increased beyond ~20 mm. Consequently an inner radius of 14 mm and an outer of 34 mm was selected for the analysis.
The fitted radius was selected to be between 22 - 26 mm to minimize the risk of misidentifying a pion as an electron and at the same time have a reasonable efficiency.

3.7.3 Efficiency of the RICH analysis.

The mean number of photons observed in the test-beam measurements was about 5 while in UA2 we observed an average of 4.5 photons corresponding to a specific detector response, \( N_0 = 47 \text{ cm}^{-1} \). The only differences to the test-beam measurements, performed after the last UA2 running period, consisted in the presence of a magnetic field and less well collimated particles. The effect of the magnet on the detection efficiency was tested inside UA2 before the 1985 running period. Ultraviolet light was created by a deuterium flashlamp mounted inside the radiator. A mask in front of the CaF$_2$ window allowed the photons to enter the drift volume at specific positions and the detection efficiency was determined as a function of the magnetic field. Except for some edge effects the loss at maximum field strength was found to be constant over the detector area and equal to about 10%, explaining the difference with the test beam data. Figure 3.18 shows a distribution of the number of photons in a sample of events with two tracks within 3° in azimuth which is a topology expected for conversion electrons. Stringent cuts on the calorimeter and a detected shower in the converter were used to select the electrons. No cuts on the RICH were applied. As can be seen there is an over-representation of events with zero hits which most likely correspond to misidentified pions. A fitted Poisson curve with the mean value 4.5 has been superimposed. The zero bin was not included in the fit.

The detection efficiency was also studied in the Monte Carlo simulations of the RICH, described in more detail in section 3.13. If a realistic distribution of Cherenkov photons was generated, the distribution of detected photons was found to deviate from a true Poisson distribution. The distribution of photons should in fact be understood as a superposition of several Poisson distributions with different mean values determined by the track length inside the radiator. This resulted in a somewhat larger loss of electrons from the requirement of 3 detected photons than would have been expected from a poisson distribution with a mean of 4.5 (17%). The observed loss in the Monte Carlo simulations, adjusted to give a mean of 4.5 detected photons,
was after the cuts imposed in the analysis equal to 23%. The extra loss could be explained partly by the above mentioned shape of the distribution and partly by by ionization from passing particles which spoiled the information about the Cherenkov photons. The fitted radii were selected in the given intervals with an efficiency of 65%.

![Distribution of the number of photons in a sample of conversion electrons. The fitted Poisson curve has a mean of 4.5.](image)

3.7.4 Raw data filtering and production.

Since it was clear from the start of the off-line processing that we could expect at most some ten prompt electrons among the sample of $10^6$ collected events, a filter was designed with the aim of reducing the data sample to a manageable size and at the same time leave as many options open as possible for the continued analysis.

To avoid the time consuming UA2 track-finding in the vertex detector and the F/B drift-chambers the RICH detector was analyzed first, followed in the 2nd step if the event survived by the drift-chambers behind the RICH and in nearby sectors. The vertex detector track-finding was performed in the 3rd step and in the 4th step the momentum analysis was made.
The cuts that applied in each step were:

**Step 1**
- At least 3 signals detected in the RICH.

**Step 2**
- At least 1 track observed in the drift chambers behind the RICH.
- At least 3 photon candidates in a 24 mm wide annulus around the expected ring centre in the RICH.

**Step 3**
- At least one track in the vertex chamber within the transverse projection within 30 mrad in azimuth to the candidate electron track through the RICH.
- This vertex track should have a hit in either of the two first proportional-chamber planes in the vertex detector.

**Step 4**
- The candidate electron track should point at the vertex sufficiently well to enable a momentum fit having a probability of $\chi^2 > 1\%$.

This filter reduced the data sample by a factor of 10 when the RICH signals had been used in the trigger (see section 3.5.3) and by a factor of 20 otherwise.

In addition to these prompt electron candidates, a sample of conversion electrons were selected by requiring at least two tracks in the drift chambers within 3 degrees in azimuth, of which at least one should have a fitted momentum.

### 3.8 The electron/pion separation by the RICH.

The ratio of prompt electrons to pions observed at the ISR was of the order of $10^{-4}$. Consequently the probability to identify a pion as an electron must be at least an order of magnitude smaller or of the order of $10^{-5}$. This rejection must be achieved to a large part using the RICH detector.

As was already discussed in the preceding chapter, the RICH underwent extensive testing shortly after the UA2 running period to certify the rejection power using the same running parameters as inside UA2.

The result of the test-beam measurements were presented in figure 2.21. Below the pion threshold, the misidentification probability was about
constant, $5 \cdot 10^{-5}$. This level of the electron/pion ratio was explained mainly in terms of delta electrons created by pions traversing the material of the RICH or the beam tube and by "random" noise in the photon detector.

3.8.1 Delta electrons in UA2.

We do not have to concern ourselves with delta-electrons created before the RICH since they are swept away by the magnetic field or in the rare case of a very high momentum delta both particles should have a good chance of being detected in the drift chambers.

![Graph](image)

Figure 3.19. Momentum distribution of delta electrons from a from a 2 GeV pion, misidentified as an electron. From a Monte Carlo calculation for the pion rejection tests. (Eek 89).

The average amount of material encountered by a particle traversing the photon-detector was about the same, $\sim 7\%$ of a radiation length, as in the specific beam-position used in the tests. However, during the tests there was, in addition, $\sim 3\%$ of a radiation length in the beam before the RICH.

As mentioned in section 3.3.1 there was a residual field of about 0.03 Tm present in the radiator in UA2. This deflects a 200 MeV delta electron by about $2.6^\circ$ which meant that the corresponding Cherenkov ring would not overlap with the 34 mm fiducial region around the expected centre from the
pion track. In figure 3.19 the momentum distribution of delta electrons from a 2 GeV/c pion that were misidentified in the RICH, according to the Monte Carlo calculation performed for the test-beam case, are shown. Many of these would not be observed in UA2 due to the field in the radiator.

Of course a delta created in the RICH might also be detected in the drift-chambers. In conclusion the rejection of the pion- delta-electron events should improve in UA2.

3.8.2 Random noise.

A further possible difference concerns the noise in the photon detector which might have a different frequency and distribution in UA2, as compared to the fixed position test-beam situation. This problem was investigated in an analysis briefly reported in Botner et al 87. In a sample of real events "expected" image-centres were generated randomly over the photon detector surface following the distribution observed in the data. The number of signals in an annulus around the image centre was searched for photons however this region was not allowed to overlap either with a corresponding ring-region belonging to a track actually present in the event used, or with an area where a charged particle were predicted to have passed. The cuts used were less stringent than those applied in this analysis and no clustering was performed, however the misidentification probability was still found to be below $10^{-4}$. A visual inspection of the few remaining events showed no sign of Cherenkov rings due to typical random noise, rather they seemed to be good electron rings picked up by accident. It is tempting to explain these events as being delta electrons, in this case with lower momenta and larger emission angle (these should be more frequent) than those appearing close to the primary pion. It could also be a converted photon were one of the $e^+ e^-$ pair was not detected in the drift chambers, since in this investigation the pulshight information from the scintillators were not used.

In conclusion there are not more misidentifications due to random noise inside UA2.

The fact that the recorded image in a RICH detector can be scanned visually, at least for a limited sample of events, should result in an improved rejection power. Though the effect from this possibility is difficult to quantify it is clear that the pattern of signals originating from noise is in
most cases easy to recognize for the human eye, also when the software has
made a different interpretation.

3.8.3 Pions above the Cherenkov threshold.

Above a momentum of 3.5 GeV/c the charged pions start to radiate
Cherenkov light. This results in a drop of the rejection power as can be seen
in figure 2.21. At a momentum of 4 GeV/c the misidentification probability
has risen to 2 \times 10^{-3}. Though this is still a very good rejection in most cases it
is marginal to what was needed in the UA2-RICH experiment and consequently we decided not to use electrons with momenta of more than
4 GeV/c in the final analysis.

3.9 The electron/pion separation by other detectors.

3.9.1 The electromagnetic calorimeter.

The calorimeter contributed to the electron pion separation both by the
requirement of electromagnetic energy in the trigger and through the cuts
applied in the data analysis.

Two properties were demanded of a track in the calorimeter. First the
leakage of electromagnetic energy into the hadron veto compartment had to
be less than 2\%, second, the measured momentum was required to match
the energy deposited by a track within 4 standard deviations, calculated from
the resolution of the calorimeter and the spectrometer. The second property
was important also in rejecting events with associated photons (see section
3.10).

A further requirement that was important for the performance of the
calorimeter was that we allowed no neutral clusters, i.e. energy depositions
which could not be associated to a track in the drift chambers. This rejected
many pions that had undergone a nuclear interaction since that type of
shower had a larger transverse extension than the electromagnetic clusters.

To evaluate the pion rejection a sample of minimum-bias triggers in the
RICH sector were studied. No identified electrons were allowed in the RICH
and the sample was subjected to the electron-background rejecting cuts
described in section 3.10, however this selection was not important for the
observed performance except for the cut on neutral calorimeter energy.
Of the remaining sample, the tracks that passed the hadron veto cut and the momentum energy matching were histogrammed as a function of momentum. This gave an average probability for misidentification of 10% between 2 and 5 GeV/c. Below 2 GeV/c this probability increases to about 40% at 0.5 GeV/c, however if the threshold of the E1 trigger was imposed and the result corrected with the trigger efficiency for electrons (see figure 3.12), the misidentification probability instead decreases down to $p \sim 1$ GeV/c ($p_T \sim 0.5$ GeV/c) where the efficiency of E1 becomes zero.

Since the statistical significance of this investigation was not so good above a momentum of about 3 GeV/c the same procedure was repeated with a Monte Carlo generated pion sample. A good agreement was found within the errors. Figure 3.20 shows the misidentification probability found in the minimum-bias sample and the Monte Carlo generated pion sample. Also the data points after application of the E1 trigger are shown.

![Figure 3.20](image)

**Figure 3.20** Probability to misidentify a pion as an electron in the electromagnetic calorimeter, deduced from the minimum-bias sample and from the Monte Carlo. The boxes are after the application of the E1 trigger threshold.

The calorimeter with the requirements discussed above had an efficiency of ~98% for single electrons (discussed further in section 3.12.2). The cut against neutral energy (which anyway had to be applied in the analysis) was efficient on a level of about 95%.
3.9.2 Lead converter, proportional tubes.

An additional rejection factor of about 5 could be obtained by demanding a cluster in the proportional tubes behind the 1.5 radiation-length lead converter. However, at an expense of a ~40% inefficiency at a $p_T$ of about 1 GeV/c. Due to the low efficiency we did not require this signal for the prompt electrons. In the final sample 57% of the electrons between 0.5 < $p_T$ <2.0 GeV/c had a detected cluster. (For candidates with higher momenta a clear drop was observed in this fraction indicating the presence of pions misidentified by the RICH.)

3.10 Rejection of trivial electron sources.

The interest in prompt electrons at the ISR were, in the beginning, mainly focused at observing various heavy particles, including open and hidden heavy quarks. Later also the fast increase of the $e$ to $\pi$ ratio at very low transverse momenta, explained in terms of hadronic brems-strahlung and a low-mass continuum of virtual photons (Åkesson et al 85), attracted a lot of attention. The approach taken here was to try to suppress the contributions from well known sources as much as possible. The main contributions (in the remainder of this chapter they will be referred to as backgrounds) considered in these experiments were:

**Electron-positron pairs from**,
- converted photons,
- Dalitz decays of $\pi^0$ and $\eta$ mesons.

**Single electrons from**,  
- semileptonic decays of kaons (Ke3),
- Compton scattering of photons (only $e^-$).

In the following we will discuss the cuts devised to suppress the backgrounds in the UA2-RICH experiment.

3.10.1 Rejection of $e^+e^-$ pairs from converted photons.

Already at the planning stage of the experiment $e^+e^-$ pairs from converted photons was anticipated to be the most important background because of the presence of a magnetic field without any tracking elements inside it.
A real photon has zero mass which results in an extremely small opening angle between the electron and the positron when a conversion takes place, thus it will in general be impossible to distinguish the two tracks in the vertex detector. The fraction of the photon energy carried by the $e^+$ and the $e^-$ respectively is an essentially flat distribution, somewhat peaked at the two extreme ends as can be deduced from figure 3.21

![Figure 3.21](image)

**Figure 3.21** The differential probability for a conversion of a photon into an $e^+ e^-$ pair per radiation length in lead. Plotted as a function of the fraction of the photon energy transferred to either the $e^+$ or the $e^-$ after a conversion has taken place. (From Rossi 52).

Thus an asymmetry in the two momenta of the pair is quite probable. Thus a substantial number of low momentum $e^+$ or $e^-$ partners will could be swept away by the magnetic field before reaching the RICH and the drift chambers.

Fortunately most of the overlapping tracks entering the magnet were detected by the scintillator hodoscope (see section 3.4). Figure 3.22 a) shows a scatterplot of the pulse-height distribution for minimum ionizing particles. Figure b) is the same type of plot but now for a sample of conversions where two tracks were found within 3° in azimuth in the drift-chambers and where both were predicted to have crossed the same hodoscope finger both in the first and the second plane. The pulse heights are expressed in MIP
units, i.e. normalized to the value expected for a minimum-ionizing particle.

![Graph](image)

**Figure 3.22.** The pulse height in the hit finger in the first plane of the scintillator hodoscope is plotted on the x-axis versus that found in finger of the second plane. a) is made from a sample of single minimum-ionizing tracks and b) from a sample of conversions with both particles traversing the same fingers in both planes. (The size of the peaks is not visible on the plot but the total number of entries is about 300 and 200 in a and b respectively)

In figure b there is a clear clustering around a value of 2 by 2 MIPs indicating overlapping tracks.

For a prompt electron candidate the pulsheight was required to be between 0.5 and 1.35 mips for the traversed finger of each plane. If the track were within 15 mm from the border between two fingers the same cut was applied instead to the sum of their pulse heights. The probability that a double track would survive this cut was only 2% while the inefficiency for single tracks was about 30%.

A category of conversion which were not rejected by this cut had one particle of so small momentum that the pair opened up sufficiently, due to multiple scattering in the vertex detector, for the low momentum track to be detected by a different scintillator finger or not at all. Therefore events were rejected if a pulsheight, exceeding 0.5 mips, were found in any finger that could not be associated to a track in the drift-chambers. Those events where the low momentum track was lost outside the hodoscope, e.g. in the magnet iron, could not be rejected.
The source of the conversion background discussed here was the material in the beam pipe and the vertex detector. Up to the position of the first hodoscope plane this amounted to \( \left( \frac{3.33}{\sin\theta} + 0.3 \right) \% \) of a radiation length, i.e. between 6 and 7\%. By requiring that the candidate prompt-electron track had generated a signal in both of the innermost proportional chambers, VS1 and VS2 (see section 3.2.2), conversions occurring in the material after VS2 was rejected. The material in the beam pipe (see section 3.2.1) and in the proportional chamber wall before the first plane contributed only

\[
(1.1 + 0.12)\% \cdot \frac{1}{\sin\theta}.
\]

Since almost all real photons in hadron collisions originate from the decays of \( \pi^0 \) and \( \eta \) mesons into two \( \gamma \), the second non-converted \( \gamma \) could sometimes be detected in the calorimeter behind the RICH. In the prompt electron search we allowed no events with neutral energy in our sector of the calorimeter, i.e. a cluster that could not be associated to a track in the drift chambers before them. This rejected \( \gamma \)'s with energy exceeding the calorimeter read-out threshold of \(~50\) MeV. If the \( \gamma \) entered the same calorimeter module as the electron it could be rejected by the requirement of matching energy and momentum in the electron identification (see section 3.9).

When both the \( e^+ \) and the \( e^- \) reached the RICH and the drift-chambers the event was rejected if both tracks were identified as electrons either in the RICH or in the calorimeter. In this case the calorimeter requirement was only the presence of an electromagnetic energy associated to the track.

Finally the event was rejected if two tracks were found within 3 degrees in azimuth. This was effective against conversions since charged tracks were not deflected azimuthally by the magnetic field and could therefore be expected to remain essentially in the same plane. (The opposite of this cut was in fact found to be a useful method of selecting conversions.)

These cuts on charged tracks in the RICH sector were modified in a later stage of the analysis (see section 3.10.5).

### 3.10.2 Dalitz decays.

A Dalitz decay can be described as an internal conversion of a virtual photon. Consequently there are some similarities between the conversion of
a real photon from a $\pi^0$ or $\eta$ meson and the Dalitz decay of these mesons, e.g., also in this case there is an associated $\gamma$ together with the $e^+e^-$ pair. The difference is that now the $e^+e^-$ pair is generated promptly at the interaction vertex and the mass of the virtual photon is not zero implying a non-zero opening angle between the two particles. However the non-zero mass also means that the momentum is more evenly shared within the $e^+e^-$ pair than for the conversions in the material, so that both tracks stood a better chance of being detected after the magnet. The branching ratios of the two decays are:

- $\pi^0 \rightarrow \gamma e^+e^-$, \hspace{1cm} $1.198\pm0.032\%$
- $\eta \rightarrow \gamma e^+e^-$, \hspace{1cm} $0.50\pm0.12\%$

The cuts used to reject the Dalitz background were essentially the same as those against conversions described in the preceding section. (Only the demand of hits in VS1 and VS2 did not reduce the Dalitz decays.)

Most effective in the Dalitz case were the requirements that a second $e^+$ or $e^-$ should not be present in the RICH sector, and that no $\gamma$ should be seen in the calorimeter. Also the rejection of events with an unexplained hit in the scintillator hodoscope was important for the reduction of the Dalitz background.

The $e^+$ or $e^-$ or $\gamma$ from a Dalitz decay could also sometimes enter a neighbouring magnet sector or the central calorimeter. However, we found in the Monte Carlo calculations described below that the set of cuts described above were able to suppress the Dalitz decays sufficiently and in order not to introduce additional inefficiencies the information from the neighbouring sectors was not used.

3.10.3 K$_e^3$ decays.

The semileptonic decays of $K^\pm$ and $K_L^0$ mesons were potentially important sources of backgrounds since they give rise to single electrons or positrons. The relevant decay parameters are:

<table>
<thead>
<tr>
<th>Branching ratio (%)</th>
<th>$c \cdot \tau$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L^0 \rightarrow \pi^- e^- \nu_e$</td>
<td>$38.6\pm0.4$</td>
</tr>
<tr>
<td>$K^\pm \rightarrow \pi^0 e^+ \nu_e$</td>
<td>$4.82\pm0.05$</td>
</tr>
</tbody>
</table>
This means that a $K_L^0$ of e.g. 2 GeV/c will have a mean decay distance of \(\sim 6\) m so that the demand of hits in the two inner proportional chambers was a very effective cut, since the distance to the VS1 plane was only 15 cm.

The charged kaons could of course not be rejected in this way. Instead the most important identification criterion for the $K^\pm$ as well as for the $K_L^0$'s decaying before VS1 was that of an $e^+$ or an $e^-$ not coming directly from the vertex. The rejection of these events was effected by demanding that the candidate prompt-electron should belong to the best quality class of fitted tracks, i.e. matching tracks in the F/B drift-chambers and the vertex detector (see also section 3.7.1) and a vertex track was pointing at the vertex within \(\sim 1\) cm.

### 3.10.4 Electrons from Compton scattered photons.

This type of single electron background differs from the kaon decays in that only negatively charged particles, $e^-$, are produced. Thus, a presence of such events in the final sample could be expected to give rise to a charge asymmetry.

The cuts that were effective against the $e^-$ from Compton scattering were the same as those rejecting the $K_L^0$ decays, hit in VS1 and VS2 and a good fit. In addition, some events would be rejected as the scattered $\gamma$ was sometimes detected in the calorimeter.

### 3.10.5 Single track requirement.

After applying the cuts described so far on the sample of electron triggers it was found that the probability of survival for events, where the prompt-electron candidate was accompanied by a hadron, was small. In fact only 2 events of this type was found in the final sample one having with an electron $p_T$ of 0.5 GeV/c and 2 extra tracks and one event, where the electron had $p_T = 0.92$ GeV/c, having 1 extra track.

In view of this we decided to reject all events with more than one charged track detected in the drift chambers. This was important particularly for the Monte Carlo calculations since a dependence of the amount of background on the structure of multi-track events, e.g. due to a variation in the track finding efficiency, or the exact amount of multiple scattering, would be difficult to reproduce exactly and could result in an additional
systematic error. This cut also enabled simplified calculations where the probability to detect an electron from a prompt source, e.g. a charmed particle decay, could be found by demanding an isolated electron in the correct region of space and weighting with the efficiency for a single track to be detected.

3.10.6 The remaining event sample.

After application of all the above cuts 19 events remained. No event was found with an electron $p_T$ below 0.5 GeV/c (as expected from the trigger efficiency), 7 events of the E1 trigger had a $p_T$ of less than 0.9 GeV/c and 9 events had a $p_T$ between 0.9 and 1.5 GeV/c. Of the E2 triggers 4 events survived one of which had also triggered the E1 and 3 with momenta in the range 1.5-2.0 GeV/c. This division into 3 bins was motivated by the fact that the trigger was about 75% efficient above 0.9 and 1.5 GeV/c for the E1 and the E2 trigger respectively.

The remaining events were inspected visually. Of the 9 events in the $p_T$ bin 0.9-1.5 GeV/c one was found to have two clear ionization clusters created in the photon detector which could not be associated to any track in the drift chambers. On account of the single track requirement this event was rejected. For a second event in this bin the signal pattern in the photon detector is shown in figure 3.23a.

A delta electron has been knocked out by the candidate "electron" track within the area expected to contain the Cherenkov photons. The delta has traveled some distance ionizing the photon-detector drift gas. By accident a consistent set of signals has been left by the clustering algorithm for the event to be accepted. This event was rejected. In general, events where the ionization from a charged particle overlap with the annular region around an expected Cherenkov ring have a larger probability of being a misidentified hadron. Therefore we decided to reject this type of event. In the bin with $p_T < 0.9$ GeV/c, 3 events where the "photons" could be associated to an ionization cluster were found and they were consequently dropped in the continued analysis.
Figure 3.23 Signals in the photon detector a) from an event removed because of track ionization in the Cherenkov-ring area and b) an accepted prompt electron.
Figure 3.23b shows the RICH signals in an event that was accepted as a prompt electron candidate. In total 14 events remained with equal number of electrons and positrons.

3.11 Minimum bias sample.

The minimum bias (MB) triggers, recorded simultaneously with the electron triggers, provided a sample of charged particles mainly hadrons going through the RICH sector. As mentioned in the introduction the rate of prompt $e^\pm$ at the ISR was often expressed in terms of the ratio of $e^\pm$ to charged or neutral pions. It was observed that this ratio was nearly constant as a function of $p_T$ for $p_T \geq 0.5$ GeV. We shall follow this idea also at $\sqrt{s} = 630$ GeV by expressing the prompt electron rate in terms of the ratio $\frac{e^+ + e^-}{h^+ + h^-}$ where h stands for a hadron. This is useful since the phase-space acceptance of charged tracks and some detection efficiencies will cancel when forming the ratio. The ratio will have a considerably smaller systematic error than the corresponding prompt $e^\pm$ production cross-section.

The rate of charged hadrons in the UA2-RICH experiment was obtained from the MB sample. The events recorded with the MB trigger were subjected to the same set of requirements as the events recorded with the electron triggers, excluding the cuts explicitly designed to identify the electrons. This meant e.g. that the expected Cherenkov-ring centre, calculated from the hadron track, had to fall within the region allowed for an electron image, but without any demand on the number of Cherenkov photons. In fact, no identified electrons were found in the MB sample after application of the background-rejecting cuts discussed in section 3.10. The cut against $\gamma$'s in the calorimeter had to be corrected for separately since the inefficiency introduced by this cut in the MB sample was different to that for the electrons. The about 5 to 10% extra loss for the hadrons could be understood from the fact that hadron showers tend to spread over several calorimeter modules as opposed to electron showers.

The $h^\pm$ cross-section calculated from the charged hadron sample is shown as a function of $p_T$ in figure 3.24 together with the corresponding cross-section calculated from the fit by UA2 (Banner et al 85) and normalized to the spatial acceptance of the RICH scintillator hodoscope.
Figure 3.24 The differential cross-section of charged according to a UA2 fit (circles) and for the charged hadrons remaining after the track cuts in this experiment (crosses), multiplied by a factor of 10.

The observed efficiency is fairly constant between $p_T \sim 0.85$ and 1.75 GeV/c. The drop above 1.75 GeV/c is explained by the demand that the momentum should be less than 4 GeV/c. Below 0.85 the acceptance of the F/B spectrometer and the angular acceptance of the RICH starts to decrease.

3.12 The electron to hadron ratio.

In this section we will use the final sample of electrons and hadrons to calculate an uncorrected electron to hadron ratio. We will then discuss and apply the various efficiency corrections.

3.12.1 Final electron and hadron samples.

The number of electrons remaining after the application of all cuts for the triggers E1 and E2 are given in table 3.3, grouped in 3 different $p_T$ bins together with the corresponding number of charged hadrons. From these values we can calculate an uncorrected electron to hadron ratio by
normalizing to the integrated luminosity of the respective triggers according to:

\[
e^+ + e^- \over h^+ + h^- \over = \frac{N(E_i)}{N(MB)} \int L(MB) \, dt \over \int L(E_i) \, dt \over , i = 1,2
\]

Table 3.3. Final sample of electrons and hadrons and the uncorrected electron to hadron ratio. In the central \( p_T \) bin the ratio is given for the trigger E1. The errors are statistical.

<table>
<thead>
<tr>
<th>( p_T )</th>
<th>Number of events</th>
<th>( e^+/h^+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 - 0.9</td>
<td>E1: 4, E2: 0</td>
<td>MB: 482</td>
</tr>
<tr>
<td>0.9 - 1.5</td>
<td>E1: 7, E2: (1)</td>
<td>MB: 241</td>
</tr>
<tr>
<td>1.5 - 2.0</td>
<td>E1: 0, E2: 3</td>
<td>MB: 37</td>
</tr>
</tbody>
</table>

3.12.2 Efficiency for the electron identification.

The inefficiency introduced by requiring at least 3 photons and by the demand that the fitted ring should have a correct radius was discussed in section 3.7.3. The efficiency of the electron identification from the Cherenkov ring reconstruction was found to be \( \varepsilon_{\text{ring}} = 50\% \). In addition the efficiency of the cut on the number of noise signals had to be evaluated since this cut was not made on the MB sample. The number of unexplained signals might be expected to be different for particles below the Cherenkov threshold as compared to those radiating Cherenkov light, the observed difference was, however, very small. The efficiency of this cut was \( \varepsilon_{\text{noise}} = 90\% \). Finally we should consider the inefficiency introduced by the rejection of some events by visual scanning. If we define this cut as the removal of events having a track close to the predicted ring centre, this cut effected 5% of the tracks with a 34 mm fiducial. However most of this inefficiency was already accounted for by the inefficiency of the ring fit, since most of the events of this type did not have a correctly fitted ring or too few photons if some had been removed by the clustering algorithm. I view of this we do not correct for this effect but allow for a 2% systematic error.
The second part of the electron identification procedure concerned the calorimeter. Here we also include the cut against detected neutrals since this cut was of importance for the performance of the calorimeter. As discussed in section 3.11 this cut could not be corrected for through the normalization due to a substantial difference in the effect between hadrons and electrons. The efficiency in the $e^\pm$ case had to be evaluated by Monte Carlo since there were no suitable data sample for this purpose. The result was $\varepsilon_\gamma = 95\%$. After the application of this cut, the efficiency of the momentum-energy matching and the hadron veto requirement (see section 3.9) was $\varepsilon_{\text{cal}} = 98\%$. This was also based on a Monte Carlo but the result was cross-checked on a sample of conversion electrons.

The systematic error in the efficiencies was estimated by varying the parameters of the Monte Carlo program and by comparing with the corresponding efficiencies observed in the conversion electron sample. The latter was then normally taken as a lower limit on the efficiency for single electrons. Table 3.4 lists the efficiencies in the electron identification and the corresponding systematic errors.

<table>
<thead>
<tr>
<th>Analysis step</th>
<th>Efficiency (%)</th>
<th>Systematic error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 3$ photons</td>
<td>77</td>
<td>+6 −1</td>
</tr>
<tr>
<td>Ring fit</td>
<td>65</td>
<td>+1 −4</td>
</tr>
<tr>
<td>Noise rejection</td>
<td>90</td>
<td>+4 −4</td>
</tr>
<tr>
<td>Visual scan</td>
<td>100</td>
<td>0 −2</td>
</tr>
<tr>
<td>$\gamma$ rejection</td>
<td>95</td>
<td>+2 −5</td>
</tr>
<tr>
<td>Calorimeter</td>
<td>98</td>
<td>+2 −8</td>
</tr>
<tr>
<td>Total</td>
<td>42</td>
<td>+4 −5</td>
</tr>
</tbody>
</table>
3.12.3 Trigger acceptance.

The requirements on the trigger level of a p̅p interaction and a signal in the scintillator hodoscope in the RICH sector were common for electron and hadron triggers and thus to cancel in the formation of the e/h ratio.

The efficiency of the calorimeter trigger was discussed in section 3.5.4 and presented as a function of \( E_T \) and \( p_T \) in figures 3.11 and 3.12. Due to the small number of events in the final sample we have chosen not to correct for the trigger efficiency of each event individually but to calculate the acceptance for each of the three \( p_T \) bins assuming the e/h ratio to be constant over the bin. In this way we could calculate a total trigger acceptance for the bin using the measured hadron spectrum and the efficiency as a function of \( p_T \) according to figure 3.12. The result, \( \epsilon_{\text{trigger}} \), is presented in table 3.5.

**Table 3.5 Trigger efficiency correction for the triggers E1 and E2 in the relevant \( p_T \) bins, and the estimated systematic error.**

<table>
<thead>
<tr>
<th>( p_T )</th>
<th>Trigger</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 - 0.9</td>
<td>E1</td>
<td>28±6</td>
</tr>
<tr>
<td>0.9 - 1.5</td>
<td>E1</td>
<td>90±4</td>
</tr>
<tr>
<td>1.5 - 2.0</td>
<td>E2</td>
<td>79±7</td>
</tr>
</tbody>
</table>

The acceptance in the lowest \( p_T \) bin is small and the uncertainty in the correction will contribute a large systematic error.

3.12.4 The corrected electron to hadron ratio.

We can now arrive at a final observed electron to hadron ratio according to:

\[
\frac{e^\pm}{h^\pm} = \left( \frac{e^\pm}{h^\pm} \right)_0 \cdot \epsilon_{\text{ring}} \cdot \epsilon_{\text{noise}} \cdot \epsilon_{\gamma} \cdot \epsilon_{\text{cal}} \cdot \epsilon_{\text{trigger}} \cdot \frac{1}{\epsilon_{\text{trigger}}}. \quad (3.2)
\]

The result of this calculation can be found in table 3.6.
Table 3.6 The electron to hadron ratio before and after the corrections according to 3.2. Statistical errors only.

<table>
<thead>
<tr>
<th>$p_T$</th>
<th>$e^\pm/h^\pm \cdot 10^4$</th>
<th>$e^\pm/h^\pm \cdot 10^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>uncorrected</td>
<td>corrected</td>
</tr>
<tr>
<td>0.5 - 0.9</td>
<td>0.4±0.2</td>
<td>3.4±1.7</td>
</tr>
<tr>
<td>0.9 - 1.5</td>
<td>1.4±0.5</td>
<td>3.7±1.4</td>
</tr>
<tr>
<td>1.5 - 2.0</td>
<td>2.3±1.3</td>
<td>7.2±4.3</td>
</tr>
</tbody>
</table>

The systematic error on the corrected $e/h$ ratio was found by combining in quadrature the errors on the different efficiencies. In addition, a 5% normalization error was included on the ratio of the luminosities since the triggers were not recorded with the same relative frequency during all data taking periods. Due to the small statistics available it was not possible to normalize each period separately.

The statistical error was evaluated according to $\sigma_{e/h} = \frac{e}{h} \sqrt{\frac{1}{N_e} + \frac{1}{N_h}}$

(Since the number of hadrons is reasonably large the error in the ratio should have an almost gaussian distribution, see e.g. James 82.)

3.13 Monte Carlo calculations of the residual background.

There are a number of possible background sources which can contribute to the $e/h$ ratio. Of these, the "true" prompt single-electrons from the semileptonic decay of charmed particles and particles containing beauty will be discussed in chapter 4.

Due to the relatively large masses of the vector mesons $\rho$, $\omega$, $\phi$, and $J/\psi$, their decays into $e^+e^-$ pairs will normally have a large opening angle for the cases where one $e^\pm$ is found in the range $0.5 < p_T < 2.0$, and hence vector mesons were not rejected by the cuts against pairs in our analysis. The contribution of vector mesons was normally not subtracted in experiments on prompt-electrons at other accelerators. At 630 GeV the total cross-section to produce these mesons is not known experimentally so we shall postpone further discussion of vector meson decays to the next chapter.

Further we can expect a contribution from the sources of $e^+e^-$ pairs and $K_{e3}$ decays designated as background in section 3.10. This residual
background has to be estimated by Monte Carlo simulation and this will be the topic of the following sections.

3.13.1 The Monte Carlo program.

The first step in simulating a background process was to generate a distribution in $p_T$ and rapidity of the parent particle. For this we used the information obtained by measurements at the $p\bar{p}$ collider when available. The Monte Carlo program generated the position of the interaction vertex where the parent was created. The parent particle was then allowed to decay, if required by the lifetime, and the decay products, or the undecayed parent, were tracked through the UA2 and the RICH detectors using (for most cases) the full UA2 detector simulation program complemented with a simulation of the RICH and the scintillator hodoscope. The physical effects that were simulated included energy loss from ionization, bremsstrahlung, multiple scattering, and gamma conversions. A few extra charged pion tracks were generated in other directions than the RICH sector so that the vertex position could be reconstructed in the analysis program but no realistic underlying event-structure was simulated.

The Monte Carlo generated signals in raw-data format which could be read by the analysis program and subjected to the same requirements as real data. However since this was a time consuming procedure it was necessary, in order to get enough statistics in the samples that survived all cuts, to impose some requirements already at the detector simulation level. For instance cuts on the pulsheight in the scintillator and the number of photons in the RICH.

The sample of remaining background electrons was then corrected for the efficiencies of the electron identification and the single-track reconstruction efficiency as given by the Monte Carlo. Finally the number of background electrons were normalized to the number of parent particles, entering the space region defined by the overlap of the scintillator fingers, divided by the $p_T$ dependent ratio of parents to charged hadrons.

3.13.2 Simulation of the RICH detector.

The simulation of the RICH-detector response followed essentially the ideas described in Lund-Jensen et al (88). For each particle that was tracked
through the RICH radiator a number of Cherenkov photons were generated according to a Poisson distribution with a mean value computed from:

\[
<N>_{\text{generated}} = \frac{\alpha}{n_c} L \cdot (Q T \cdot R) \cdot \int_{E_{\text{min}}}^{E_{\text{max}}} \left(1 - \frac{1}{\beta^2 n^2(E)}\right) dE. \tag{3.3}
\]

\(E_{\text{max}}\) and \(E_{\text{min}}\), the maximum and minimum photon energy considered, were determined by the CH\(_4\) transmission and the TMAE quantum efficiency to be 8.7 and 5.5 eV respectively (see also equations 2.2-4). L is the track length through the radiator, the constant \(Q T\) is the maximum of the TMAE quantum-efficiency times the CH\(_4\) transmission, and R is the reflectivity of the mirror which was approximately 65% independent of the photon energy.

The variation of the refractive index with energy, \(n(E)\), has been measured for C\(_2\)F\(_6\) in the liquid phase by Séguinot and Ypsilantis (Séguinot 89) to be \(n(E) = 1.1956 + 7.46\cdot10^{-3}E\) (E in eV). This can be related to the refractive index in a gas using the Lorentz equation:

\[
\frac{n^2 - 1}{n^2 + 2} = \left(\frac{4\pi}{3} r_B \frac{N_A \cdot \rho}{M}\right) \cdot f(E)
\]

where the constant factor contains \(r_B\), the Bohr radius, \(N_A\), Avogadros number, \(\rho\), the density and \(M\), the molecular weight. The molar refractivity function \(f(E)\) is independent of the phase of the medium in question and thus \(n(E)_{\text{gas}}\) can be easily derived.

Evaluation of equation 3.3 gave an \(<N>_{\text{generated}} = 0.5\) photons/cm assuming \(QT = 52\%\).

The particle was tracked through the radiator, taking into account the curvature of the trajectory due to the toroidal field. The photon-creation points were distributed uniformly along the track in the radiator and the photons were emitted at an angle with respect to the track given by formula 2.1 and with a uniform azimuthal distribution. The photon energy was generated uniformly between \(E_{\text{max}}\) and \(E_{\text{min}}\). Each photon was then tracked to the mirror, reflected and tracked into the photon detector drift-volume. The photons were absorbed individually with a probability calculated from the length of radiator gas traversed, according to a measured loss of 13% over 15 cm in the C\(_2\)F\(_6\) (Herbst 88). Finally the photons detected in the drift-volume were selected taking into account the transmission of the CaF\(_2\)
window, measured as a function of energy, and an energy dependent parametrization of the TMAE quantum efficiency, following the spectral distribution measured by Ekelin and Fransson 81, normalized to 100% at the peak (see figure 2.4).

For each surviving photon, a photo-electron signal was generated at a depth, according to an exponential distribution with a mean free path of 15 mm and with a smearing of the x and y coordinates of $\sigma = 2$ mm, chosen to reproduce the resolution observed in the data. This choice was necessary in order to take effects of diffusion and magnetic field distortions into account. The curved drift paths of the electrons due to the magnetic field in the drift volume were not simulated.

The absolute normalization of the quantum efficiency, 52% at the peak, was adjusted so that the number of photons surviving corresponded to that observed in the UA2-RICH data. Previous determined values like e.g. 65% (Arnold et al 88) and 58% (Holroyd et al 87) indicate that we have an additional loss of photons of about 10-20%.

In addition to the signals from Cherenkov photons, signals due to ionization of traversing tracks were generated on a number of consecutive wires according to a gaussian distribution with the mean number of hit wires equal to 6 and $\sigma = 2$ wires. A gaussian spread in the drift direction with $\sigma = 1$ mm was applied around the cluster centre. Finally one of the generated signals was dropped at random. This procedure was found to give an acceptable representation of the typical clusters observed in real data.

Figure 3.16 compared the distributions of fitted radii from a data sample with conversion electrons to a Monte Carlo generated sample. The agreement is good except for a slightly larger tail in the measured data.

3.13.3 Generation of parent particles.

All parent particles were generated according to a parametrization of the inclusive charged particle $p_T$ spectrum as measured by UA2 (Banner et al 85):

$$ E \frac{d^3\sigma}{dp^3} = \frac{A}{\left(1 + \frac{p_T}{P_{th}}\right)^n} $$

(3.4)
where $n = 7.66$, and $p_{T0} = 0.865$ GeV/c. The constant $A$ cancels in the formation of the $e/h$ ratio.

Even for $\pi^0$'s, the fit to the $p\bar{p} \rightarrow h + X$ data was used rather than the $p\bar{p} \rightarrow \pi^0 + X$ measurement since this data extend to lower $p_T$ values. The $\pi^0$ data starts at about 1.5 GeV/c. To find the correct number of charged hadrons for the normalization we used the measured ratio $2\pi^0/(h^+ + h^-) = 0.68\pm0.13$, obtained by Banner et al (85) by a common fit to the two data sets in the overlapping $p_T$ range 1.5-8.9 GeV/c. This ratio is compatible with the ratio of $\pi^\pm$ to $h^\pm$ measured by UA2 (Banner et al 83 in the polar-angle region around $90^\circ$, which was approximately constant down to about 0.6 GeV/c. At 0.55 GeV/c the ratio $\pi^\pm/h^\pm$ was measured to be $0.80\pm0.03$. However, the generated $\pi^0$'s in this $p_T$ region do not contribute to the background of electrons with $p_T$ above 0.5 GeV/c.

$\eta$ production has been measured by UA2 in the $p_T$ range $3.25 \leq p_T \leq 6$ GeV/c where $\eta/\pi^0$ ratio was determined to be $\eta/\pi^0 = 0.60\pm0.04\text{(stat)}\pm0.15\text{(sys)}$, (Banner et al 85). To extrapolate the $\eta$ production to the momentum range of our experiment, the $\eta/\pi^0$ ratio was assumed to be constant as a function of transverse mass $m_T = \sqrt{m^2 + p_T^2}$ and equal to 0.6 for large $p_T$. This type of scaling (suggested by Borquinn and Gaillard 76) was used by several ISR experiments for similar calculations.

$m_T$-scaling was also assumed to be valid for kaon production. For charged kaons the $K/\pi$ ratio was found to be well described by a constant as a function of $m_T$, $0.39 \pm 0.02\text{(stat)} \pm 0.03\text{(sys)}$ (Banner et al 83). The $p_T$ of the kaon data, measured by UA2 in the $90^\circ$ region, was between 0.45 and 1.05 GeV/c.

All the parent particles were generated with a flat rapidity distribution.

3.13.4 $e^+e^-$ pairs from converted photons.

Converted photons were found to be the most important source of electron background in this experiment. The photon sources considered were the decays of $\pi^0$ and $\eta$ mesons with branching ratios:

$\pi^0 \rightarrow \gamma\gamma$, $(98.80\pm0.03)\%$ and
$\eta \rightarrow \gamma\gamma$, $(38.9\pm0.4)\%$

The parent particles were generated with $0 < p_T < 5$ and over a pseudo-rapidity and azimuthal range around the trigger hodoscope large enough to include all decays giving a gamma of at least 0.5 GeV/c pointing towards the
RICH sector. The γ's were converted in the material up to the first proportional chamber plane according to an exponential probability with a mean free path given by the fraction of a radiation length traversed. New mesons were generated until a γ conversion occurred and the p_T spectrum of the parents pointing inside the trigger hodoscope were recorded.

The energy of a converted gamma was divided between the e^+ and the e^- according to the Bethe-Heithler cross-section as given e.g. by Rossi (52). If at least one e^± with a p_T exceeding 0.5 GeV/c had been created the full Monte Carlo processing was performed for all particles in the event.

Before the event was recorded for later processing by the analysis program the signals generated in the scintillator hodoscope and the RICH were investigated and the cuts that did not depend on the track information were imposed, i.e. no pulse height > 1.5 Mip and at least 3 signals in the RICH detector.

3.13.5 Dalitz decays.

The second most important source of background were the Dalitz decays of the π^0 and η mesons. The relevant branching ratios were:

\[ \pi^0 \rightarrow \gamma e^+ e^- , \quad (1.20\pm0.03)\% \quad \text{and} \]
\[ \eta \rightarrow \gamma e^+ e^- , \quad (0.50\pm0.12)\% \]

The mesons were made to decay isotropically in their rest system into a real and a virtual photon with a mass according to the Kroll-Wada formula (Kroll and Wada 55). The virtual photon was then decayed into an e^+e^- pair. The shape of the distribution used to generate the virtual photon of mass M and the angle between the electron and the photon, θ, was given by:

\[ \frac{d^2N_{e^+e^-}}{dM d\cos\theta} \propto \frac{1}{M} \left(1 - \frac{M^2}{\mu^2}\right)^3 \cdot \sqrt{1 - \frac{4m_e^2}{M^2}} \cdot \left(1 + \frac{2m_e^2}{M^2}\right) \cdot (1 + \cos^2\theta), \]

where m_e was the electron mass and μ the mass of the decaying meson.

If an electron of 0.5 < p_T pointing at the RICH sector had been created the Monte Carlo processing was allowed to continue in the same fashion as described for the conversions of real photons.
3.13.6 Ke₃ decays.

The Ke₃ decays were potentially considered to be an important background source since single electrons are produced.

The branching ratios and the decay lengths for βγ = 1, were given in section 3.10.3. For each parent kaon, a decay length was generated and the particle tracked through the UA2 detector and decayed, taking the correct V-A matrix element into account. Kaons that were predicted to decay outside the detector were discarded already in the generation step.

It was found that the cuts described in section 3.10.3 were able to reject the kaons with high efficiency and the residual background from Ke₃ decays could be neglected in comparison to conversions and Dalitz decays.

3.13.7 Compton scattering.

Since this process was anticipated to be a less important background source for pₜ > 0.5 GeV/c a simplified calculation was performed without the use of the detector simulation. A photon spectrum from π⁰ → γγ and η → γγ was generated and each γ was forced to Compton scatter at the interaction point. Each Compton electron was given a weight of 1 − e⁻ᵃ where a was the probability for Compton scattering in the material between the interaction point and the first proportional chamber plane. The expression for a was taken from a parametrization by Rossi (52):

\[
P(E) = π N_A r_e^2 \cdot X \cdot \frac{Z}{A} \cdot \frac{\ln(2\varepsilon)+0.5}{\varepsilon},
\]

where \( N_A \) is Avogadros number, \( r_e \) is the classical electron radius, \( X \) is the thickness in g/cm², \( Z \) is the atomic number, and \( A \) is the mass number of the material respectively. \( \varepsilon \) is equal to \( E/m_e \) where \( E \) is the incident photon energy and \( m_e \) the electron mass.

To find the angular distribution after the scattering, the differential cross-section according to the Klein-Nishina formula was used (see e.g. Brun 84):

\[
\frac{d^2N}{dE_dE'} \propto \frac{m_e}{E^2} \cdot \left( \frac{E'}{E} + \frac{E}{E'} - \sin^2\theta \right),
\]

where \( E' \) and is the energy of the scattered photon and \( \theta \) is the scattering angle. From this formula the energy and direction of the Compton electron
could be obtained and the momentum vector could be calculated by assuming an elastic collision.

Events where the scattered photon also entered the calorimeter behind the RICH where discarded if the energy was above the calorimeter threshold. No other cuts were made.

Since the resulting background falls rapidly and becomes negligible in comparison to the conversions and the Dalitz decays in the $p_T$ range of interest a more detailed analysis was not performed. As already noted there was no charge asymmetry observed in the final data sample, consistent with a negligible Compton background.

3.13.8 Misidentified pions.

The probability to misidentify a pion as an electron was discussed in section 2.7, 3.8, and 3.9. The corresponding background level below the pion Cherenkov-threshold, 3.5 GeV/c, was calculated to be constant and less than $4 \times 10^{-6}$.

Above the pion momentum of 3.5 GeV/c, the contribution to the background was more uncertain. The background from misidentified pions was calculated using the observed hadron momentum spectrum and the misidentification probabilities from the test beam measurement (figure 2.21).

3.13.9 Summary of the residual background.

In figure 3.25 the variation with $p_T$ of the residual e/h ratio from the dominant electron backgrounds is plotted. The $\pi^0 \rightarrow \gamma\gamma$ is seen to be the dominant background source both at all $p_T$.

From the sum of the contributions in figure 3.25 and the background from misidentified pions, an e/h ratio was calculated and subtracted from the measured e/h ratio. Since the measured ratio was corrected for the trigger efficiency under the assumption of a constant e/h, which was not fulfilled by the background, the residual background was weighted with the shape of the trigger efficiency and integrated over each of the $p_T$ bins. Table 3.7 gives the background of the various sources of electrons and the misidentified pions separately.
Figure 3.25 The Monte Carlo calculated remaining electron background expressed in terms of an e/h ratio as a function of $p_T$.

Table 3.7 The residual background expressed as an electron to hadron ratio and integrated over each of the 3 $p_T$ bins for background electrons and misidentified pions respectively.

<table>
<thead>
<tr>
<th>$p_T$ (GeV/c)</th>
<th>$e^\pm/h^\pm \cdot 10^4$</th>
<th>$e^\pm/h^\pm \cdot 10^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 - 0.9</td>
<td>4.5±0.9</td>
<td>0.04±0.01</td>
</tr>
<tr>
<td>0.9 - 1.5</td>
<td>1.7±0.4</td>
<td>0.07±0.03</td>
</tr>
<tr>
<td>1.5 - 2.0</td>
<td>0.8±0.3</td>
<td>1.0±0.3</td>
</tr>
</tbody>
</table>

The total error given in table 3.7 includes the uncertainties in the branching ratios and the ratios of parents to hadrons for the different processes given in the previous sections. For the background from converted photons, the effect of varying the amount of material in the
beam-pipe and the vertex detector within reasonable limits was studied with a simplified Monte Carlo including the conversion process and taking into account multiple scattering. The error in the calculated conversion background was estimated to be 5% and 2% due to the uncertainty in the amount of material in the beam pipe and the vertex detector respectively.

The different contributions to the error were considered to be independent and were combined in quadrature together with the statistical error in the Monte Carlo calculations. The statistical error was small in comparison to the total systematic error.

3.14 The electron to hadron ratio after background subtraction.

The prompt electron to hadron ratio was calculated by subtracting the residual background from the non-prompt sources and the Dalitz decays according to table 3.7. The result is shown in table 3.8 where the systematic errors on the measured e/h and the background have been combined in quadrature.

Table 3.8 The electron to hadron ratio after subtraction of the residual background for the 3 \( p_T \) bins. Also given is the mean \( p_T \) of the detected electrons.

<table>
<thead>
<tr>
<th>( p_T ) ( (\text{GeV/c}) )</th>
<th>( &lt;p_T&gt; ) ( (\text{GeV/c}) )</th>
<th>( e^+/h^\pm \cdot 10^4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 - 0.9</td>
<td>0.6</td>
<td>-1.0±1.7±1.4</td>
</tr>
<tr>
<td>0.9 - 1.5</td>
<td>1.1</td>
<td>2.0±1.4±0.6</td>
</tr>
<tr>
<td>1.5 - 2.0</td>
<td>1.8</td>
<td>5.4±4.3±1.0</td>
</tr>
</tbody>
</table>

In the bin \( 0.5 < p_T < 0.9 \) the signal cannot be distinguished from the background. We shall not consider this bin in the discussion about \( c\bar{c} \) production in chapter 4.

3.15 Comparison with e/h measurements at smaller \( \sqrt{s} \).

A large number of experiments measured of prompt electron production at the ISR. The results are expressed in terms of the ratio

\[
\frac{e^+ + e^-}{\pi^+ + \pi^-} \quad \text{or} \quad \frac{e^+ + e^-}{2\pi^0},
\]

which are typically in the range \( 1 - 3 \cdot 10^{-4} \) for
\( p_T > 1 \text{ GeV/c} \) and \( \sqrt{s} > 50 \text{ GeV} \). (See e.g. Kernan, Van Dalen 84.). Büsser et al (76) measured the energy dependence in the range \( 23.5 < \sqrt{s} < 62.4 \) and found an increase by about a factor of two.

If we convert the results of this experiment into an \( e/\pi \) ratio using the UA2 measurement of \( \pi/h = (68\pm13)\% \) we obtain the values of table 3.9.

Table 3.9 The electron to pion ratio calculated using \( \pi/h = 0.68 \pm 0.13 \).

<table>
<thead>
<tr>
<th>( p_T ) (GeV/c)</th>
<th>( e^\pm/h^\pm \cdot 10^4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9 - 1.5</td>
<td>3.0\pm2.1\pm1.3</td>
</tr>
<tr>
<td>1.5 - 2.0</td>
<td>9.3\pm6.3\pm2.5</td>
</tr>
</tbody>
</table>

The error of 13% in the \( \pi/h \) ratio has been included in the systematic error. The results are compatible with no increase over the order of magnitude step in centre of mass energy between the ISR and the collider.

Figure 3.26 shows a compilation due to Heiden (81) of measurements of the \( e/\pi \) ratio as a function of \( \sqrt{s} \) together with our measured point at \( \sqrt{s} = 630 \text{ GeV/c} \). The data are from Appel (74), Ballam (78), Basile (81), Barone (76), Barloutaud (80), Beier (76), Büsser (74), Guy (77), Muirhead (77), and Rangaswamy (79).
Figure 3.26 A compilation of $e/\pi$ data at different center of mass energies. Data for $p_T < 0.4$ GeV/c are plotted with crosses while daggers are used for $p_T < 1$ GeV/c and the open boxes have $p_T > 1$ GeV/c. Our data point with a mean of 1.1 GeV/c was plotted with a filled box.
Chapter 4

CHARM PRODUCTION

4.1 Introduction.

In this chapter we will use the measured electron to hadron ratio from the previous chapter to draw some conclusions concerning the production of charmed particles.

Charmed particles can be produced by strong, electromagnetic, and weak interactions. They have been studied at $e^+ e^-$ colliders, in beams of neutrinos, electrons, muons, photons and hadrons interacting with hadronic targets, and at $pp$ and $p\bar{p}$ colliders. A summary of properties of known charmed particles are given in table 1, 2, and 3. More detailed information can be found in e.g. Trilling (81).

All experimental methods used to observe a charm signal, rely in some way on the decay of the charmed particle. This is characterized by the fact that the states with the lowest masses can decay only weakly with lifetimes of the order $10^{-13}$ s and that the $c$ quark decays preferentially into an $s$ quark due to the Cabibbo mechanism, see e.g. Aitchison and Hey (82). Thus kaons are normally among the decay products.
Figure 4.1 Signal to background ratio for charm production in different types of interactions as a function of number of events per day. Figure from Halzen 82a

In $e^+ e^-$ collisions, at energies above the charm threshold but below that for beauty, about 40% of the hadronic final-states contain a charmed particle-pair. The small number of final-state particles provides for a relatively easy reconstruction of the charmed-particle decay. Total cross-sections are at the nanobarn level. In contrast, charm cross-sections in hadron-hadron interactions, at the CERN SPS fixed-target experiments, are at least 3 orders of magnitude larger and steeply rising with energy. They constitute, however, only about 1% of the total cross-section and the final-state multiplicity is large. Demands on triggers and experimental equipment are therefore challenging. Figure 4.1 illustrates the relation between cross-section and signal to background ratio for charm production in various types of interactions.
Table 4.1. Charmed pseudoscalar mesons \((J^P = 0^-)\). Data from Review of Particle Properties (88). (The \(D_S\) mesons were previously called \(F\).) The number in italics is not known experimentally but has been assumed in the Monte Carlo calculations described in section 4.4.

<table>
<thead>
<tr>
<th>Name</th>
<th>Quark content</th>
<th>Isospin ((I,I_3))</th>
<th>Mass (MeV)</th>
<th>Mean lifetime ((\text{sec}))</th>
<th>Branching to (e^\pm + X(%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D^+)</td>
<td>(\bar{c}d)</td>
<td>(\frac{1}{2};\frac{1}{2})</td>
<td>1869.3±0.6</td>
<td>((10.69^{+0.34}_{-0.32}) \times 10^{-13})</td>
<td>19.2±^2.3_1.6</td>
</tr>
<tr>
<td>(D^0)</td>
<td>(c\bar{u})</td>
<td>(\frac{1}{2};\frac{1}{2})</td>
<td>1864.5±0.6</td>
<td>((4.28±0.11) \times 10^{-13})</td>
<td>7.7±1.1</td>
</tr>
<tr>
<td>(D^+_s)</td>
<td>(c\bar{s})</td>
<td>(0;0)</td>
<td>1969.3±1.1</td>
<td>((4.36^{+0.38}_{-0.32}) \times 10^{-13})</td>
<td>10</td>
</tr>
<tr>
<td>(\eta_c)</td>
<td>(c\bar{c})</td>
<td>(0;0)</td>
<td>2979.6±1.7</td>
<td>(10.3^{+3.8}_{-3.4})</td>
<td>–</td>
</tr>
<tr>
<td>(D^0_s)</td>
<td>(c\bar{s})</td>
<td>(0;0)</td>
<td>1969.3±1.1</td>
<td>((4.36^{+0.38}_{-0.32}) \times 10^{-13})</td>
<td>10</td>
</tr>
<tr>
<td>(\bar{D}^0)</td>
<td>(u\bar{c})</td>
<td>(\frac{1}{2};\frac{1}{2})</td>
<td>1864.5±0.6</td>
<td>((4.28±0.11) \times 10^{-13})</td>
<td>7.7±1.1</td>
</tr>
<tr>
<td>(D^-)</td>
<td>(d\bar{c})</td>
<td>(\frac{1}{2};\frac{1}{2})</td>
<td>1869.3±0.6</td>
<td>((10.69^{+0.34}_{-0.32}) \times 10^{-13})</td>
<td>19.2±^2.3_1.6</td>
</tr>
</tbody>
</table>

a) For \(\eta_c\) we give the full width in (MeV).

Table 4.2 Charmed \(J^P = 1^-\) mesons. Quark content and isospin are the same as for the corresponding pseudoscalar. The decays shown are those of interest for the present investigation. Data from Review of Particle Properties (88).

<table>
<thead>
<tr>
<th>Name</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Decay mode</th>
<th>Branching fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D^{<em>+}/D^{</em>-})</td>
<td>2010.1±0.6</td>
<td>&lt; 2.0</td>
<td>(D^0/\bar{D}^0 + \pi^+ + \pi^-)</td>
<td>49±8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(D^+ / D^{*-} + \pi^0)</td>
<td>34±7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(D^+ / D^{*-} + \gamma)</td>
<td>17±11</td>
</tr>
<tr>
<td>(D^{*0}/\bar{D}^{*0})</td>
<td>2007.1±1.4</td>
<td>&lt; 5</td>
<td>(D^0/\bar{D}^0 + \pi^0)</td>
<td>52±7</td>
</tr>
<tr>
<td>(D^{<em>+}_{s}/D^{</em>-}_{s})</td>
<td>2112.7±2.3</td>
<td>&lt; 22</td>
<td>(D^0/\bar{D}^0 + \gamma)</td>
<td>48±7</td>
</tr>
<tr>
<td>(\psi)</td>
<td>3096.9±0.1</td>
<td>0.068±0.01</td>
<td>(D^+_s / D^-_s + \gamma)</td>
<td>Dominant</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(e^+ + e^-)</td>
<td>6.9±0.9</td>
</tr>
</tbody>
</table>
Charm production

Table 4.3 \(J^P = \frac{1}{2}^+\) baryons. The brackets [qq'] and (qq') indicate a symmetric and anti-symmetric combination of the respective qq' pairs. The \(\Xi_c\)'s have both a symmetric and an anti-symmetric state of the respective non-charmed quarks. The mass given is for the antisymmetric member (previously called A'). The quantities in italics are not known experimentally but has been assumed in the Monte Carlo calculations described in section 4.4. \(A'\) - in the branching column means that this particle is not expected to have any appreciable branching to \(e^+ + X\). Data from Review of Particle Properties (88).

<table>
<thead>
<tr>
<th>Name</th>
<th>Quark content</th>
<th>Isospin ((I, I_3))</th>
<th>Mass ((\text{MeV}))</th>
<th>Lifetime ((\text{sec}))</th>
<th>Branching to (e^+ + X)(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Lambda_c^+)</td>
<td>c(ud)</td>
<td>0; 0</td>
<td>2284.9±1.5</td>
<td>((1.79^{+0.23}_{-0.17}) \times 10^{-13})</td>
<td>4.5±1.7</td>
</tr>
<tr>
<td>(\Sigma_c^+)</td>
<td>cuu</td>
<td>1; 1</td>
<td>2452.2±1.7</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(\Sigma_c^0)</td>
<td>cud</td>
<td>1; 0</td>
<td>2452.9±3.4</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(\Sigma_c^+)</td>
<td>cdd</td>
<td>1; -1</td>
<td>2450</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(\Xi_c^+)</td>
<td>csu</td>
<td>(\frac{1}{2}, \frac{1}{2})</td>
<td>2460±19</td>
<td>((4.3^{+1.7}_{-1.2}) \times 10^{-13})</td>
<td>–</td>
</tr>
<tr>
<td>(\Xi_c^0)</td>
<td>csd</td>
<td>(\frac{1}{2}, -\frac{1}{2})</td>
<td>2460</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(\Omega_c^0)</td>
<td>css</td>
<td>0; 0</td>
<td>2740</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>(\Xi_{cc}^{++})</td>
<td>ccu</td>
<td>(\frac{1}{2}, \frac{1}{2})</td>
<td>3630</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>(\Xi_{cc}^{+})</td>
<td>ccd</td>
<td>(\frac{1}{2}, -\frac{1}{2})</td>
<td>3630</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>(\Omega_{cc}^+)</td>
<td>css</td>
<td>0; 0</td>
<td>3810</td>
<td>–</td>
<td>0.15</td>
</tr>
</tbody>
</table>

A lot of effort has been spent over the past decade to utilize the copious production of charm (and also beauty) particles in hadronic interactions. With the narrow monochromatic beams available at the CERN-SPS and at the FNAL in principle \(\sim 10^7\) particles with the charm quantum-number could be produced per day, potentially permitting high-statistics studies of decay properties and searches for rare states. The desire to improve the small signal to noise ratio has stimulated the development of methods for high-resolution vertex-detection like silicon-microstrip detectors, and high-resolution bubble chambers.

As was mentioned in the introduction the order of magnitude increase of \(\sigma(\text{pp} \rightarrow c\bar{c} + X)\), that was observed between SPS (fixed target) and ISR energies, triggered a lot of interest in the dynamics of charm production. This was one of the prime motives, when the UA2-RICH experiment was proposed in 1982 (Baillon et al 82) and we shall discuss the measured cross-
sections and theoretical interpretations in some more detail in the following sections.

The rest of the chapter will be organized as follows:

- The cross-sections that have been observed at the ISR and at fixed-target experiments, and the transverse and longitudinal momentum distributions, of charmed mesons and baryons, will be discussed in section 4.2.

- Section 4.3 gives a brief overview of the basic results and assumptions in the theoretical calculations of $\sigma(\bar{c}c)$, within perturbative QCD, and a few examples of different theoretical ideas are discussed.

- Section 4.4 describes the Monte Carlo simulations of charm production and decay.

- In section 4.5 we calculate a rough estimate and an upper limit of $\sigma(\bar{p}p \rightarrow \bar{c}c + X)$, using the measured electron to hadron ratio.

- In section 4.6 we discuss the remaining sources of prompt electrons other than charm, and try to estimate their contribution by Monte Carlo.

- Finally in section 4.7 we summarize the results on $\sigma(\bar{c}c)$ and compare with some recent QCD estimates.

### 4.2 Charm cross-sections observed at lower energies.

Charmed particles were most probably first detected in hadronic collisions but this was not realized at the time. A number of cosmic-ray emulsion experiments detected decays of presumably short lived heavy particles, Niu (71). Intensive search followed the first observation of hidden charm (J/ψ) in 1974 (Aubert et al 74, Augustin et al 74), and open charm was soon discovered, the $\Lambda_c$ in neutrino-hadron interactions (Cazzoli et al 75) and the $D^0$ and $D^+$ (Goldhaber et al 76, Peruzzi et al 76) at the $e^+e^-$ storage ring SPEAR at SLAC. During the same time a large number of unsuccessful charm searches were performed with hadron beams.

Though some indirect evidence had been found in prompt-lepton experiments (e.g. Büsser et al 76, Barone et al 78), it was only in 1979 that the first generally accepted proof for the production of charm in hadronic collisions was obtained. Drijard et al (79 a) observed a peak, see figure 4.2, at the mass of the $D^+$ meson in pp collisions at the ISR. Shortly afterwards
evidence was also found for the production of the $\Lambda_c$ baryon, (Drijard et al 79 b).

![Figure 4.2](image)

**Figure 4.2** First direct evidence for $D^+$ meson production in hadron interactions. A peak was observed by Drijard et al (79 a) in the invariant mass distribution of $K^-\pi^+\pi^+$ at the $D$ meson mass.

In this section we will briefly discuss the hadro-production properties of charmed particles. We only discuss the data obtained with proton beams. For production with other primary particles or for more detailed information we refer the reader to some of the many useful reviews that exist on the subject. Early experience is summarized in Müller 80, Treille 81, Geist and Reucroft 82, Reucroft 83, Putzer 83, and in Kernan and Van Dalen 84. More recent reviews and conference summaries are given in Tavernier 87, Weilhammer 88, Gasparini 89 and Purohit 89.

### 4.2.1 Experimental methods.

The methods used to detect the decays of charmed particles may crudely be divided into three classes.

- **Direct observation of the decay vertex.**
  This has so far required visual detection methods like emulsions or high-resolution bubble chambers, to observe the charm production and decay vertices. These are typically separated by a distance of a few hundred $\mu$m. The method has the advantage of being essentially background free, and having almost constant acceptance for $x_F > 0$. 
The problem is to obtain enough statistics. The continuous improvement of silicon microstrip detectors seems to be able to remove this limitation and, maybe in the future, make this method for heavy-flavour search useful also at colliders.

• Invariant mass-peaks.

In exclusive hadronic decay-modes of charmed particles, mass-peaks are looked for in the Cabbibo-favoured c to s quark decays, like \( D^+ \rightarrow K^- \pi^+ \pi^+ \). The narrow width of these decays in principle enables a direct measurement of the particle mass. In practice the signal to noise ratio grows quickly worse with increasing energy. This has necessitated the use of selective triggers and methods to reduce the combinatorial background from all the possible invariant-mass combinations. Triggers e.g. on leptons and diffractively produced kaons have been used. Another trick is to look for the vector meson decay \( D^* \rightarrow D \pi \). The elaborate means required to extract the signal, introduce systematic effects that might influence the evaluation of cross-sections.

• Prompt leptons.

Detection of leptons from the semileptonic decay-mode was pioneered at the ISR by the measurement of prompt electrons at large angles. Prompt-lepton pairs can also be used for this purpose, in particular e\( \mu \) pairs offer a very good signal to background ratio. Another type of prompt-lepton measurement is the beam dump experiments at the CERN SPS and at the FNAL. Here a hadron beam is dumped into a dense target. The target contains enough material to absorb all the produced particles and decay products except for muons and neutrinos from prompt decays occurring before the parent particle is absorbed. The muons or neutrinos can then be detected in a small-angle forward cone.

The lepton experiments actually measure an integral over all heavy-flavoured states weighted by their production cross-sections and branching ratios. The determination of the total cross-sections consequently requires a detailed knowledge of the respective semileptonic branching fractions and the relative probability for the production of different particle types. Due to the statistical nature of the method it is normally not regarded as a definite proof of heavy-
quark production but it has often been used to derive stringent upper limits.

4.2.2 Cross-sections for open charm-production.

In fixed-target experiments from around 1980 the measured total cross-sections were typically in the range 10 – 20 \( \mu \text{b} \). Simultaneously several experiments at the ISR found cross-sections in excess of 100 \( \mu \text{b} \). The most dramatic and confusing results came from experiments searching for \( \Lambda_c \) production close to the beam where, after extrapolation to the full phase space, cross-sections of more than 500 \( \mu \text{b} \) were deduced.

![Graph showing cross-sections as a function of square root of energy](image)

Figure 4.3 A compilation of cross-sections from various experiments using proton beams as a function of \( \sqrt{s} \). See table 4.4 for references. The curve is a lowest order QCD calculation. (From Tavernier 87)

Table 4.4, and fig 4.3 shows a compilation of cross-sections from various experiments using proton beams (some older and more doubtful measurements were left out). Part of the data has been recalculated with new branching ratios by Tavernier (87), from whom most of the results in table 4.4 were collected. As can be seen not all the experiments are mutually compatible. These discrepancies can partly be attributed to difficulties in directly comparing the calculated cross-sections between different types of
experiments when the model parameters used to correct the data are not so well established, e.g.:

- Most experiments are only sensitive in a certain, often rather restricted range of kinematic variables. Thus the extrapolation of the cross-section to the total phase-space is influenced by the assumed dependence on longitudinal and transverse momenta.
- Experiments performed with heavy targets have to correct their cross-sections for the dependence on the atomic number A.
- Many measurements have relied on the observation of exclusive final-states for which, particularly in the early days of charm-searches, branching ratios were not well known.
- In the case of prompt leptons, the exact identities of the parent heavy particles are unknown so an assumption as to the relative abundance of such particles is needed.

During the last five years high-statistics data from fixed-target experiments, with good coverage of the complete forward hemisphere, have become available. Particularly the NA27 (see e.g. Aguilar-Benitez et al 88) experiment using the bubble-chamber LEBCC together with the EHS - spectrometer, has presented cross-section measurements with small statistical and systematic errors (see table 4.4) at $\sqrt{s} = 27$ GeV. Preliminary data from the FNAL 800 GeV proton beam, also with the bubble-chamber LEBCC now together with the MPS spectrometer, indicate a rise by a factor of $1.7^{+0.7}_{-0.5}$ between $\sqrt{s} = 27$ GeV and $\sqrt{s} = 39$ GeV (Ammar et al 87). Taken together with the limits from lepton experiments at the ISR it seems unlikely that $\sigma($DD$)$ exceeds $\sim 100 \mu b$ at $\sqrt{s} = 63$ GeV.

The two experiments that observed a large $\Lambda_c$ signal repeated their measurements before the ISR was closed down. Even though both experiments now measured a smaller signal, the CBF collaboration (R422, Cifarelli et al 88) by a factor of 3 and the R608 (Chauvat 87) by more than a factor of 10 for $x_F > 0.75$ (the $x_F$ range of the old R603 experiment), the conclusion, that there is a large forward $\Lambda_c$ component at the ISR, still stands. If one tries to extrapolate the $\Lambda_c$ production cross-section to the full $x_F$ range, the smallest values are obtained assuming a flat $x_F$ distribution, $\sigma(\Lambda_c \bar{D}) = 56 \pm 34 \mu b$ for R422. However, the data from both experiments behaves more like $(1-x_F)^2$ giving in the case of R422, $\sigma(\Lambda_c \bar{D}) = 285 \pm 171 \mu b$. The same procedure for R608 gives a similar result. The quoted values do not include the uncertainty in the branching ratio for $\Lambda_c \rightarrow pK^-\pi^+$, taken to be $2.2 \pm 1.1\%$. 

Charm production

This value also seems to be the subject of some controversy since the LEBC-EHS experiment recently published the limit BR(Λ\textsubscript{c}→pK⁻π⁺) > 4.4% (90% C.L.), (Aguilar-Benitez 88).

At √s=630 GeV the UA1 collaboration (Albajar 88) has estimated the contribution from charmed-particle decays to their inclusive muon spectrum for p\textsubscript{T}'s larger than 10 GeV/c. In events with an associated jet of E\textsubscript{T} > 10 GeV UA1 finds that (24±8±9)% of the heavy flavour decays into muons are due to charm. They do not make any attempt to extrapolate to a total cross-section for c\overline{c} production.

The only other data from energies above √s = 63 GeV come from cosmic ray experiments. Data collected before 1980 are reviewed by Gaisser and Yodh (80). In experiments with emulsion chambers one can look for events, with energies of the order of 10 ~ 20 TeV (√s ~140 GeV), having pairs of tracks with lifetimes in the range 10\textsuperscript{-14} ~ 10\textsuperscript{-12} s. The expected background in this case is very small, of the order ~10\textsuperscript{-4}. From 7 events, coming from different experiments, a σ(c\overline{c}) of 300 ~ 600 \mu b is deduced, using a linear A dependence. With A\textsuperscript{2/3} the result is 0.75 ~ 1.5 mb.

Another effect, interpreted as charmed particle production by cosmic rays, is the two component behaviour of the hadron attenuation length in lead. This effect, observed in the large lead- ionization-chamber calorimeter at Tien Shan, consists in a significant increase in the attenuation length around 50 ~ 100 TeV. The explanation, in terms of copious production of charmed particles, is discussed in detail by Dremin and Yakovlev (86). Using a Monte Carlo they find a σ(c\overline{c}) of 3 ~ 5 mb at 100 TeV (√s = 430 GeV).

A final point to mention is that several experiments, e.g. WA78 and WA82 (Cobbaert et al 87, and 88, Adamovich et al 89), have studied the A\textsuperscript{α} dependence of σ(c\overline{c}). The collected information now seems to indicate that α is a smoothly decreasing function of x\textsubscript{F}, (see e.g. Gasparini 89), compatible with α = 1 in the central region and about 30% lower at x\textsubscript{F} = 1, similar to the behaviour for light hadrons.
Table 4.4 A compilation of production cross-sections for charmed particles from experiments using proton beams. This presentation follows mainly that of Tavernier (87) were some of the original results have been reevaluated with new branching ratios. The comments indicate the method used, prompt lepton, specific trigger particle, beam dump (BD), bubble chamber (BCh), invariant mass combinations(i.m.c.). If only a specific charmed particle state has been looked at this is indicated. When known, the $x_p$-region where the experiment is sensitive, as well as the distribution (n, corresponding to $f(x_p) = (1-x_p)^n$) used to extrapolate to the full phase space have also been included. In all cases a linear A dependence has been assumed.

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>Beam-target</th>
<th>$\sigma$ (µb)</th>
<th>Reference</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.5</td>
<td>p-Fe</td>
<td>5±4</td>
<td>Asratyan 78</td>
<td>v, BD</td>
</tr>
<tr>
<td>19.4</td>
<td>p-C₃F₈</td>
<td>3.9±1.9</td>
<td>Erriques 86</td>
<td>1µ trigg, BCh.</td>
</tr>
<tr>
<td>&quot;</td>
<td>p-Si</td>
<td>0.75±0.35±0.05</td>
<td>Barlag 88</td>
<td>Si-µstrip, n=5.5, $x_F&gt;0$.</td>
</tr>
<tr>
<td>25.7</td>
<td>p-Fe</td>
<td>22±9</td>
<td>Ritchie 80/Bodek 84</td>
<td>1µ.</td>
</tr>
<tr>
<td>&quot;</td>
<td>p-Fe</td>
<td>11.3±1.1±1.8</td>
<td>Ritchie 83</td>
<td>1µ, &gt;0.3, n=5</td>
</tr>
<tr>
<td>26.0</td>
<td>p-p</td>
<td>15.5±8.2</td>
<td>Aguilar-Benitez 83,84</td>
<td>BCh+spect., D→.</td>
</tr>
<tr>
<td>&quot;</td>
<td>p-C₃F₈</td>
<td>24.6±12±3</td>
<td>Erriques 86</td>
<td>1µ trigg, BCh.</td>
</tr>
<tr>
<td>27.4</td>
<td>p-Cu</td>
<td>39±10</td>
<td>Abramowicz 82</td>
<td>v, BD, $&lt;x&gt;=0.8, n=3-5$.</td>
</tr>
<tr>
<td>&quot;</td>
<td>p-Cu</td>
<td>17±4</td>
<td>Fritz 80</td>
<td>v, BD, $&lt;x&gt;=0.8, n=4$.</td>
</tr>
<tr>
<td>&quot;</td>
<td>p-Cu</td>
<td>15±5</td>
<td>Jonker 80</td>
<td>v, BD, $&lt;x&gt;=0.8, n=4$.</td>
</tr>
<tr>
<td>&quot;</td>
<td>p-W</td>
<td>15.5±0.8±2.3</td>
<td>Ball 83/Duffy 85,86</td>
<td>v, BD, $&lt;x&gt;=0.45, n=4$.</td>
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<tr>
<td>&quot;</td>
<td>p-Cu</td>
<td>~17</td>
<td>Grässler 86</td>
<td>v, BD, n=5-6.</td>
</tr>
<tr>
<td>&quot;</td>
<td>p-Cu</td>
<td>15.5±2.6±1.2</td>
<td>Dorenbosch 86</td>
<td>v, BD, n=5.</td>
</tr>
<tr>
<td>&quot;</td>
<td>p-Cu</td>
<td>~20</td>
<td>Debu 86</td>
<td>v, BD, n=5.</td>
</tr>
<tr>
<td>&quot;</td>
<td>p-Cu</td>
<td>7±20</td>
<td>Diamant-Berger 79</td>
<td>2µ+missing energy.</td>
</tr>
<tr>
<td>&quot;</td>
<td>p-Fe</td>
<td>31±29</td>
<td>Brown 79</td>
<td>1µ.</td>
</tr>
<tr>
<td>&quot;</td>
<td>p-W</td>
<td>&lt;10</td>
<td>Fisher, Geist 83/Kenyon 82/Ito 81</td>
<td>$\mu^+\mu^-$ mass spect</td>
</tr>
<tr>
<td>&quot;</td>
<td>p-p</td>
<td>15.1±1.7</td>
<td>Aguilar-Benitez 87</td>
<td>BCh, D→.</td>
</tr>
<tr>
<td>&quot;</td>
<td>p-emul.</td>
<td>91±35</td>
<td>Aziz 85</td>
<td>BCh+spect.</td>
</tr>
<tr>
<td>38.8</td>
<td>p-p</td>
<td>29±1±1</td>
<td>Ammar 86</td>
<td>i.m.c., $\Lambda_c$ and D</td>
</tr>
<tr>
<td>63</td>
<td>p-p</td>
<td>150±450</td>
<td>Drijard 79,83/Geist 82</td>
<td>i.m.c., $\Lambda_c$ n=0.</td>
</tr>
<tr>
<td>53-62</td>
<td>p-p</td>
<td>1390±180</td>
<td>Lockman 79</td>
<td>i.m.c., $\Lambda_c$ n=0.</td>
</tr>
<tr>
<td>63</td>
<td>p-p</td>
<td>840±320</td>
<td>Irion 81/Giboni 79</td>
<td>e trigg, i.m.c., $\Lambda_c$ (n=0), D (n=3).</td>
</tr>
<tr>
<td>62</td>
<td>p-p</td>
<td>650±222</td>
<td>Basile 81a</td>
<td>e trigg, i.m.c., $\Lambda_c$, $x_F&gt;0.35,n=2$.</td>
</tr>
<tr>
<td>62</td>
<td>p-p</td>
<td>285±171</td>
<td>Basile 88</td>
<td>l.m.c., $\Lambda_c$, $x_F&gt;0.5$.</td>
</tr>
<tr>
<td>63</td>
<td>p-p</td>
<td>101±18±26</td>
<td>Chauvat 87</td>
<td>Opposite sign e µ.</td>
</tr>
<tr>
<td>53-62</td>
<td>p-p</td>
<td>70±36</td>
<td>Clark 78</td>
<td>e$^+e^-$ pairs.</td>
</tr>
<tr>
<td>53-62</td>
<td>p-p</td>
<td>73±21</td>
<td>Chilingarov 79</td>
<td>Analysis of $\mu^+\mu^-$ mass spect.</td>
</tr>
<tr>
<td>63</td>
<td>p-p</td>
<td>&lt;100</td>
<td>Antreasyan 80/Fischer Geist 83</td>
<td></td>
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</table>
Charm production

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>Beam-target</th>
<th>$\sigma$ (µb)</th>
<th>Reference</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>53-63</td>
<td>p-p</td>
<td>&lt;300</td>
<td>Drijard 83</td>
<td>Reanalysis of all e/π data at the ISR.</td>
</tr>
<tr>
<td>~140</td>
<td>p-emul.</td>
<td>300-600</td>
<td>Niu 78/Gaisser 80</td>
<td>Cosmic rays.</td>
</tr>
<tr>
<td>~430</td>
<td>p-Pb</td>
<td>3000-5000</td>
<td>Dremin,Yakovlev 86</td>
<td>Cosmic rays.</td>
</tr>
</tbody>
</table>

To summarize, the subject of charm cross-sections in hadronic collisions has often appeared confusing, especially in the early eighties when the UA2-RICH experiment was initiated. Clearly an indication of its behaviour at an order of magnitude larger cms energy is an important constraint on some of the ideas developed.

4.2.3 Differential cross-sections.

These are commonly discussed in terms of the transverse momentum $p_T$ and the scaled longitudinal momentum $x_F = 2p_T/\sqrt{s}$. Experimental data on charm production are often parametrized

$$\frac{d^2\sigma}{dp_T^2 \, dx_F} \sim (1-|x_F|)^{n_2} e^{-a p_T^2} \quad (4.1)$$

or

$$\frac{d^2\sigma}{dp_T^2 \, dx_F} \sim (1-|x_F|)^{n_1} e^{-b p_T}. \quad (4.2)$$

If the value of the parameter $n_1$ is about 5 or larger the production is said to be central, while a value of less than 3 is normally expected for diffractive production or if there is a leading-particle effect. Central production is sometimes instead fitted to the invariant differential cross-section

$$E \frac{d^2\sigma}{dp_T^2 \, dx_F},$$

For $x_F \neq 0$ this corresponds to

$$\frac{d\sigma}{dx_F} \sim \frac{1}{x_F} (1-|x_F|)^{n_2} \quad (4.3)$$
Central behaviour is expected when quarks from the colliding hadrons undergo a hard scattering process (this will be further discussed in section 4.3), and if the created $c\bar{c}$ pair is converted into charmed hadrons independently of the remaining quarks from the initial hadrons. Conversely if a charmed hadron is formed by a combination of the $c$ or $\bar{c}$ with a quark or anti-quark from one of the colliding particles, it can be expected to emerge at larger $x_F$ values (leading-particle effect), especially if this partner is one of the primary constituents (valence quarks), carrying a substantial part of the initial hadron momentum. On the basis of the number and type of constituents that take part in the scattering or are contained in the final state particle, simple counting rules for the parameter $n$ in the case $x_F \to 1$ can be derived. Such rules have been compared in detail to data on light particles (see e.g. chapter 6 in Collins and Martin (82)) and a qualitative agreement is found in many cases, even though the above picture is modified e.g. by the fact that many of the observed final state particles are in fact decay products of higher mass states. Table 4.5 gives an example of counting rule predictions for charmed particles due to Gunion (79).

**Table 4.5.** Predictions due to Gunion (79) for the parameter $n$ (see text). Observe the decrease of $n$ when the number of transferred valence quarks increases.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$n$</th>
<th>Reaction</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p\ (uud) \to D^+ (\bar{c}\bar{d})$</td>
<td>5</td>
<td>$\pi^- (\bar{u}\bar{d}) \to D^+ (\bar{c}\bar{d})$</td>
<td>3</td>
</tr>
<tr>
<td>$D^0 (c\bar{u})$</td>
<td>5</td>
<td>$D^0 (c\bar{u})$</td>
<td>1</td>
</tr>
<tr>
<td>$\bar{D}^0 (u\bar{c})$</td>
<td>3</td>
<td>$\bar{D}^0 (u\bar{c})$</td>
<td>3</td>
</tr>
<tr>
<td>$D^- (d\bar{c})$</td>
<td>4</td>
<td>$D^- (d\bar{c})$</td>
<td>1</td>
</tr>
<tr>
<td>$\Lambda_c^+ (cud)$</td>
<td>1</td>
<td>$\Lambda_c^+ (cud)$</td>
<td>2</td>
</tr>
</tbody>
</table>

Of course it is plausible that a heavy quark should move more independently than the lighter flavours. However data on charmed particles indicate that the $c$ quark is not heavy enough to rule out effects from
recombinations with the quarks from the initial state hadrons (e.g. $\Lambda_c$ production at the ISR and a leading particle effect observed in $\pi^- p$ interactions, see e.g. Tavernier 87 for a discussion). (The exact production mechanism assumed can also affect the central behaviour, see paragraph 4.3).

At fixed target energies the most detailed data comes from the LEBC-EHS p–p experiment (Aguilar-Benitez 88). Fitting their D meson data to the form $(1 - |x_F|)^{n_1}$ they find a central behaviour with $n_1 = 4.9 \pm 0.5$. These data have a tendency opposite to table 4.5 in that for $D^+ + D^0$ $n_1 = 4.2 \pm 0.8$ is found, and for $D^- + \bar{D}^0$, $n_1 = 6.6 \pm 1.1$. Though, obviously, both are compatible with the central value of 4.9. (Thus, in contrast to $\pi^- p$ interactions, there seems to be no clearly observed leading particle effect.)

At $\sqrt{s} = 63$ GeV the situation is less clear. As already mentioned in the study of $\Lambda_c^+$ one finds that the production is forward, with $n_1 \sim 2$. For the D, the production is probably more central. The BCF collaboration (Basile et al 81b, 82) finds, when comparing 3 different models to their $D^0$ data, that the central form, according to 4.3 with $n_2 \sim 3$, fits their data better than a flat distribution in $x_F$, or rapidity. (This agrees with the above mentioned LEBC-EHS data since the invariant distribution, here, gives $n_2 = 3.2 \pm 0.6$.) Geist (82), finds, putting all data together, a good agreement with a flat rapidity distribution.

Most data on the $p_T$ dependence seems to agree fairly well with a mean $p_T$ of about 900 MeV. LEBC-EHS finds $<p_T> \sim 0.86 \pm 0.09$, and a fit to the function 4.1 gives $a = 0.99 \pm 0.09 \ (\text{GeV}/c)^{-2}$. At ISR Basile et al (82) fitted the function 4.2 and found $b = 2.35 \pm 0.47 \ (\text{GeV}/c)^{-1}$. The $\Lambda_c^+$ data tends to give slightly lower momenta, $b = 2.6 \pm 0.5 \ (\text{GeV}/c)^{-1}$, (Cifarelli 88), $b = 3.4 \pm 0.4 \ (\text{GeV}/c)^{-1}$, (Chauvat 87).

4.3 Models of charm production in hadron-hadron interactions.

Before Quantum Chromo Dynamics appeared as the most promising candidate for a field theory of the strong interactions, predictions for the probability of producing heavy particles were characterized by exceptionally small values. (See discussion Halzen 82a) For example, in the thermodynamic statistical model, the probability to create a particle of mass $m$ behaves like
\[ P \sim e^{-2 \frac{m}{T}} \]

where \( T \) is a universal temperature of the order 160 MeV. This implies a relative abundance of different particles like \[ \pi : K : D \sim 1 : 10^{-1} : 10^{-5}. \]

A similar example is provided by the string model where the creation of a quark is viewed as a tunneling phenomenon. The probability that a string breaks into a quark-antiquark pair with a quark mass \( m_q \) is

\[ P \sim e^{-am_T^2} \tag{4.4} \]

where \( m_T = \sqrt{p_T^2 + m_q^2} \), \( a = \frac{\pi}{k} \) and \( k \) is the string constant. This gives

\[ u, d : s : c \sim 1 : \frac{1}{3} : 10^{-11}. \]

The small numbers for c and b quarks reflect the difficulty to localize enough energy to create a heavy quark. The exponential drop with \( m_q \) is absent in QCD because the couplings of quarks to gluons are independent of their flavour. A look at fig 4.4 seems to supports QCD. As the energy increases the ratio \( \sigma(\text{charm})/\sigma(\pi^+\pi^-) \) seems to reach a value of about \( 10^{-2} \sim 10^{-3} \) and still increasing.

Encouraged by this qualitative support we will continue to examine the possibilities for quantitative calculations in QCD and to see how they compare with experiments.

### 4.3.1 Heavy quarks in perturbative QCD.

QCD is a non-abelian gauge theory based on the local symmetry SU(3) colour. Such theories have the unique property of being asymptotically free. This means that the effective coupling becomes smaller as the interaction distance decreases. The behaviour of the strong coupling constant \( \alpha_s \) to lowest order is given by
Figure 4.4 Comparison between $\sigma(c\bar{c})$, $\sigma(\pi^{\pm})$, and $\sigma(K^{\pm})$ as a function of the centre-of-mass energy squared, (from Halzen 82a).

$$\alpha_s(Q^2) = \frac{12\pi}{(33-2n_f) \ln(Q^2/\Lambda^2)}.$$ (4.5)

$n_f$ is the number of quark flavours, above threshold, in the interaction, and $\Lambda$ represents the energy scale where the confinement of the quarks becomes important, typically a few hundred MeV. The momentum scale, $Q$, at which $\alpha_s$ is evaluated, corresponds to the inverse of the interaction distance.

Figure 4.5 shows the lowest order, $\alpha_s^2$, Feynman diagrams for heavy quark creation in QCD, quark-antiquark annihilation and gluon-gluon fusion.
Figure 4.5 Lowest order Feynman diagrams for heavy quark creation in QCD through quark-antiquark annihilation and gluon-gluon fusion.

Here the internal quark and gluon lines must have a virtual mass, $Q^2$, at least of the same order of magnitude as the heavy quark mass. Thus for a sufficiently heavy quark, it should be possible to compute such a process by perturbation theory. In the case of charm, we shall have to worry about whether $m_c$ is actually heavy enough. If we compute $\alpha_s$ for the case $\Lambda \sim 400$ MeV and $Q^2 = 4m_c^2$ we find $\alpha_s \sim 0.3$ which seems fairly encouraging if we want to neglect terms proportional to $\alpha_s^4$. The so-called flavour creation diagrams, of figure 4.5, have been evaluated by several authors before 1980. (Combridge 79, Babcock et al 78, Carlsson and Suaya 78, 79, Jones and Wyld 78, Glück et al 78) As an illustration we reproduce the formulas obtained by Combridge. After integration of the differential cross-section he obtains for the subprocess cross-sections

$$
\sigma_{qq \rightarrow c \bar{c}}(\hat{s}) = \frac{8\pi \alpha_s^2(Q^2)}{27 \hat{s}} (\hat{s} + 2M^2) \sqrt{1 - \frac{4M^2}{\hat{s}}}
$$

and

$$
\sigma_{gg \rightarrow c \bar{c}}(\hat{s}) = \frac{\pi \alpha_s^2(Q^2)}{3 \hat{s}} \left(- \left(7 + \frac{31M^2}{\hat{s}}\right) \frac{1}{4} \chi + \left(1 + \frac{4M^2}{\hat{s}} + \frac{M^4}{\hat{s}^2}\right) \ln \left(\frac{1+\chi}{1-\chi}\right)\right)
$$

where $\chi = \sqrt{1 - \frac{4M^2}{\hat{s}}}$. 

(4.6)
Here $M$ is the mass chosen for the heavy quark and $\hat{s}$ is the centre-of-mass energy squared of the colliding partons.

Now we need to take into account the fact that we do not have free quarks and gluons colliding but two hadrons. The parton model approach is to convolute the hard scattering cross-sections above with the fractional momentum distributions of the partons within the hadrons according to

$$
\sigma_{ab \to cc + X}(\hat{s}) = \sum_{i,j} \int dx_1 \int dx_2 \, f^a_i(x_1, Q^2) \, f^b_j(x_2, Q^2) \hat{\sigma}_{ij}(\hat{s}, Q^2)
$$

(4.7)

The summation indices, $i$ and $j$, run over all the different parton types present in the colliding hadrons, $a$ and $b$. $x_1$ and $x_2$ are the momentum fractions for the 2 partons in each subprocess.

The functions $f$ are extracted from deep-inelastic scattering experiments (DIS) in the case of $u$ and $d$ quarks. Since the DIS experiments have an electromagnetic or weak interaction probe the gluons show up only as missing momentum when the quark distributions are compared to the total momentum of the investigated hadrons. Typically a large number of low momentum gluons carry a total of about 50% of the hadron momentum. As the collision energy, $\sqrt{s}$, increases, the threshold of a reaction at the parton level, $x_1 \cdot x_2 \cdot s > \frac{\hat{s}}{2}$, GeV$^2$, will decrease if expressed in terms of the momentum fractions $x_1$ and $x_2$, $(x_1 \cdot x_2 > \frac{\hat{s}}{5})$, and the gluon initiated subprocesses will start to dominate. As indicated in formula 4.7 the probability distributions $f$ depend also on the scale $Q^2$ of the interaction. The $Q^2$ dependence comes about because the partons are interacting particles surrounded by a cloud of virtual gluons and quark-antiquark pairs. As $Q^2$ increases more details of the "dressed" partons become observable as the resolving power, according to the Heisenberg principle, increases and the $f$-functions will contain more partons at small $x$ values. This dependence can be calculated in QCD, resulting in the so called Altarelli-Parisi equations (Altarelli, Parisi 77). Using the $Q^2$ behaviour the gluon distribution can also be extracted from DIS data, though notably, with a larger uncertainty, particularly at small values of $x$ and $Q^2$. Recent parametrizations of parton distribution functions can be found in e.g. Diemoz et al (88) (DFLM), Martin et al (87) (MRS), and Eichten et al (84) (EHLQ)

The validity of formula 4.7, where the scattering process has been "factorized" into a hard scattering part $\hat{\sigma}$ and the functions $f$, incorporating
all the soft and non-perturbative parts of the interaction, is not obvious, and one has to prove that the functions \( f \) are not process-dependent. In the case of hadron-collisions such factorization theorems exists for the Drell-Yan process and for high Pt-scattering. (Politzer 77, Radyushkin 78, Amati et al 78, Libby and Sternman 78, Ellis et al 79)

Recently at least a partial proof has been obtained also for heavy quark production (Collins, Soper, Sternman, 1986). They find that the corrections to 4.7 are of order \( \Lambda/M \), which again raises the question of whether \( m_c \) is a heavy enough quark-mass for the model to apply.

Figure 4.6 from Combridge (79) shows the behaviour of \( \sigma(q\bar{q}) \) in pp and \( p\bar{p} \) collisions, separately for the gg subprocess with \( m_q = m_D \) and \( m_B \). Note that the \( gg \rightarrow q\bar{q} \) dominates already at ISR energies in the case of charm with no difference between pp and \( p\bar{p} \) as a consequence.

![Figure 4.6](image)

Figure 4.6 \( \sigma(q\bar{q}) \) in pp and \( p\bar{p} \) collisions for the gluon fusion and quark-antiquark annihilation subprocess respectively with \( m_q = m_D \) and \( m_B \). (Combridge 79)

The mass dependence exhibited in figure 4.6 points at a further source of uncertainty in the predicted \( \sigma(q\bar{q}) \), the exact choice of the heavy quark mass. In the case of charm, changing \( m_c \) from 1.8 to 1.2 GeV will increase the cross-section with an order of magnitude at SPS fixed-target energies.
In QCD one should in principle use the so called "current mass" which is $Q^2$ dependent. For a $Q^2 \approx 1$ GeV$^2$, the corresponding charm-quark mass is $m_c \approx 1.3$ GeV, (Gasser and Leutwyler, 1982). This is much smaller than the "constituent mass" ($m_c \approx 1.65$ GeV) as obtained from bound-state calculations for charm quarks. What value to choose is not so clear since the produced $c\bar{c}$ pair has to be converted into 2 final state hadrons with a total mass of at least $2 \cdot M_D$ for open charm and this additional energy must possibly also be provided by the charm quarks. In short we find an interval in the effective $m_c$ between $\sim 1.3$ and 1.8 GeV.

To conclude the list of uncertainties in connection with the $\sigma(c\bar{c})$ calculations, the choice of scale $Q^2$ is not unambiguous. For quark-antiquark annihilation a simple and natural choice is $Q^2 = 4m_c^2$. For gluon fusion different values are possible e.g. $Q^2 = \frac{\Lambda}{2} = 2m_c^2$. According to Combridge varying $Q^2$ between $2m_c^2$ and $4m_c^2$ changes $\sigma(c\bar{c})$ by 20%. Finally a variation of $\Lambda$ between 100 and 400 MeV will affect the cross-section by a factor of 3. In practice the choice of $\Lambda$ should be correlated with the quark and gluon momentum distributions used.

4.3.2 Other charm production models.

The lowest order calculation above, was compared to data on charm hadro-production in figure 4.3. As can be seen the fusion model falls below the measured values by a substantial factor. This observation together with the unexpectedly large forward production of $\Lambda_c$, and to some extent $D$ mesons, not anticipated in the fusion model predictions, led to the invention of a number of different models that could boost the cross-sections and generate charmed hadrons with a hard $x_F$ distribution. As an example we will briefly consider the flavour excitation mechanism (Combridge 79, Barger et al 82, Halzen 82b, Odorico 82) and intrinsic charm production (Brodsky et al 80, Brodsky et al 81).

Combridge first suggested that, in addition to the flavour creation diagrams in fig. 4.5, one should also consider the diagrams of fig. 4.8, the so called flavour excitation diagrams.
Figure 4.7 The Feynman graphs for the flavour excitation process.

Here a charm quark, that is already present in the sea of virtual quark-antiquark pairs in one of the incoming hadrons, is brought onto the mass-shell by an interaction with a quark or a gluon in the other hadron. This approach suffers from large uncertainties due to, among other things, our ignorance of the charm structure function in the hadrons. However, Combridge showed that it is possible to get substantial contributions, exceeding those from lowest order fusion. Later Halzen and Odorico showed, by using a charm quark distribution with a hard $x_F$ component, that the large forward production observed at the ISR could be reproduced, see figure 4.8.

Figure 4.8 Predictions of the fusion and flavour excitation process compared to data (of early 1980's). a) Total cross-sections, from Halzen (82a).b) $x_F$ dependence (Barger et al 82).
Observe the steep rise of the cross section in fig. 4.8a. Extrapolating out to collider energies, this curve seems to predict cross-sections of the order 5 to 10 mb. An interesting point, concerning the $x_F$ distributions, is that the model, according to Barger et al, predicts a more central behaviour of $c\bar{c}$ production at 630 GeV/c.

In their paper from 1986 Collins et al argue that, at least for heavy enough quarks, the flavour excitation diagrams are already part of higher order corrections to the gluon fusion term. The difficulty to separate the two processes is illustrated in figure 4.9.

![Figure 4.9](image)

**Figure 4.9** The same process a) interpreted as a flavour creation b) or flavour exitation c). (From Combridge 79).

Ellis (1986) calculated the lowest-order contributions ($\alpha_s^2$) of flavour excitation and concluded that they contributed negligibly to the charm cross section or were part of the higher order corrections to charm creation. In the light of these results, a large contribution from charm-excitation, to the total charm production cross-section, seems less convincing.

The intrinsic charm approach assumes that there are higher Fock-states in the hadron wave function that may contain a $c\bar{c}$ pair. This is different from the flavour-excitation case where the $c\bar{c}$ pair was generated perturbatively. A 1-2% admixture of such a state has important consequences. The intrinsic heavy quark is assumed to exist long enough within the bound state hadron so as to attain the same velocity as the lighter constituents. This means that they will carry most of the hadron-
momentum, see figure 4.10a. As a result all the charmed hadrons will be produced at large \( x_F \) independent of whether they are the result of a recombination with a valence quark or not. This feature is not supported by data. Fig. 4.10 b shows the predicted \( x_F \) dependence for \( \Lambda_c \) and \( D^- \) production.

![Graph showing distributions](image)

**Figure 4.10** a) \( x \) distribution of the intrinsic charm component compared to that of a light quark b) \( \Lambda_c \) and \( D^- \) production as a function of \( x_F \) predicted by the intrinsic charm model.

Though the intrinsic charm model can give rise to large cross sections it does not reproduce the steep rise of the cross-section between SPS and ISR energies since the charm component should be present at the same level independent of collision energy. It is also in disagreement with photo and neutrino production data (Philips 82). In short the case for a large intrinsic charm component does not seem too convincing either, though it might still be present at a lower level.

### 4.3.3 Higher order corrections to the fusion model.

About a year ago the first complete next to leading order (\( \alpha_s^2 \)) calculation of heavy-quark production was published (Nason, Dawson and Ellis 88) Based on these calculations estimates of total cross-sections for charm, beauty and top production have been obtained (Altarelli et al 88, Berger 88). The contributions from the next to leading order are found to be substantial. The K factor defined as

\[
K = \frac{\sigma(\alpha_s^2) + \sigma(\alpha_s^3)}{\sigma(\alpha_s^3)}
\]
was calculated by Berger. Using $Q^2 = 4m_c^2$ he found a K factor of about 3 for charm and about 2 for bottom, at fixed target energies. The large size of the corrections is explained by the observation (Nason et al 88, Benakker et al 89) that the next-to-leading order cross-section for gluon fusion does not go to zero at the threshold $\hat{s} \to 4m^2$ which is the case in lowest order. This is very important since the gluon distribution increases steeply at small $x$ values. Another interesting difference, in next to leading order, is the appearance of new types at processes like quark gluon interactions and gluon splitting, (see figure 4.11), where cross sections approach a constant as $\hat{s} \to \infty$. Thus they will be important mainly at high $p_T$ and can be expected to modify the differential distributions.

![Diagram](image)

**Figure 4.11** New processes contributing to heavy-quark production in the next-to-leading order.

Figure 4.12 shows the next-to-leading order $\sigma(c\bar{c})$ as evaluated by Altarelli et al (88). The data are the same as in figure 4.3.
Figure 4.12 $\sigma(c\bar{c})$ as evaluated by Altarelli et al to order $\alpha_s^3$, compared to data from figure 4.3.

Unfortunately the uncertainties in the cross-section determination, discussed earlier, still prevail. We do not know what value to choose for the common factorization and renormalization scale $Q^2$, see equation 4.7. (To order $\alpha_s^3$ the hard scatter cross section, $\hat{O}$, will also depend explicitly on $Q^2$). It is difficult even to investigate the $Q^2$ dependence of the cross-section below $-m_c^2$, since the evaluation of the gluon structure function becomes very uncertain at the small values of $x$ and $Q^2$ needed. Further our poor knowledge of the gluon structure function will have even greater influence at $\sqrt{s} = 630$ GeV as the threshold moves to smaller $x$ values, according to:

$$(x_1 \cdot x_2)_{\text{Threshold}} \sim \frac{4m_c^2}{s}.$$ 

This corresponds to a "mean" $x$ threshold of order $5 \times 10^{-3}$. Another source of worry at high $\sqrt{s}$ is the presence of unknown logarithmic corrections of the type $\log(s/m_d)$ (see e.g., Nason 88).

In spite of this it is clear that the inclusion of the next to leading order contributions helps to bridge the gap between the old fusion model calculations and the data. If we disregard the highest values from the ISK the
band with $m_c = 1.5$ in figure 4.12, seems to reproduce the general trend of the measurements. A value of $m_c = 1.5$ is also in good agreement with photoproduction of charm (see Ellis and Nason 88, and Altarelli et al 88).

In conclusion, considerable progress has been made within the theory for hadro-production of charm, though it is still difficult to make more than an order of magnitude comparison with data due to the large theoretical uncertainties in the predicted cross-sections.

4.4 Monte Carlo simulations of $c\bar{c}$ production and hadronisation.

If we believe that our measured rate of prompt electrons evaluated in the preceding chapter is dominated by decays of charmed particles, an estimate of the corresponding charm cross-section requires a detailed understanding of the spectrum of these electrons. With this we will be able to calculate the acceptance in the limited region of phase space available in this experiment. As was mentioned in section 4.2 a prompt lepton experiment measures an integral over all the different semi-leptonically decaying heavy particles. Thus we have to make assumptions about their relative frequency and kinematic distributions and convolute with the respective semi-electronic decay distributions.

At present there exist no experimental information about the $p_T$ and $x_F$ dependence of charm production at higher energies than $\sqrt{s} = 63$ GeV. There is no reason to believe that these distributions would stay constant with a factor of ten increase in energy. For example, the mean $p_T$ for light particles observed at the $p\bar{p}$ collider is larger than at the ISR. (See e.g. discussion in Collins and Martin 82.) The distributions in "absolute" momentum of the interacting partons will, of course, be different at at 630 GeV. This can affect the $p_T$ distributions of the charmed quarks since in a process like quark or gluon fusion into heavy quarks, the centre-of-mass energy of the interacting partons $x_1 \cdot x_2 \cdot s$ has to exceed the threshold $(2m_q)^2$ where $m_q$ is the heavy-quark mass. For quarks emerging with a certain $p_T$ this threshold will instead be $4(m_q^2 + p_T^2)$. Thus at high $\sqrt{s}$ the available $x$ range, for the initial partons that can create a quark of mass $m_q$ and transverse momentum $p_T$, will have increased. To overcome our ignorance a model is needed. This will be discussed in the following two sections. We will compare the kinematic distributions generated for ISR conditions with
data, and in section 4.4.4 we will discuss the corresponding results at $\sqrt{s} = 630$ GeV.

### 4.4.1 The Monte Carlo program Twister.

A Monte Carlo program to simulate the kinematics of charm production should be based on the relevant matrix-elements for heavy-quark production, convoluted with the parton momentum-distributions of the initial-state hadrons. The produced quarks should then be fragmented into final-state hadrons, and the produced charmed mesons and baryons should be allowed to decay semileptonically so that the expected prompt-electron yield can be calculated for a given total cross-section. Preferably, an underlying event-structure of light particles should also be present, reflecting the structure of events containing heavy particles.

These tasks are fulfilled by the program Twister (Ingelman 87). In this program it is possible to simulate separately the events containing heavy quarks of a specified flavour. The lowest order fusion processes, $q\bar{q}$ and $gg$ into a heavy-quark pair, are included using the matrix elements of Combridge 79, discussed earlier in section 4.3. The matrix elements include explicit quark masses and are therefore not singular even at zero momentum transfer. The structure functions used can be chosen among a set of available parametrizations. Finally the hadronisation of the produced quarks are achieved using the Lund string-fragmentation model in it's implementation Jetset 6.3. This program also performs the decays of all short-lived particles.

### 4.4.2 The Lund string-fragmentation model.

An important step in the simulation of hadronic collisions is the conversion of the produced quarks into hadrons, as required by the property of confinement. A model which describes these essentially soft and non-perturbative strong interactions, is the Lund string-fragmentation model, Andersson et al 83 with the Monte Carlo implementation, Jetset 6.3, Sjöstrand 86. In this model the quark and antiquark, or more generally a colour triplet or anti-triplet charge, are connected via a tube-like colour-field, with transverse dimensions of approximately 1 fm. A causal and Lorentz-invariant description of the flow of energy and momentum between the
quark and antiquark is achieved by treating the colour field as a massless relativistic string with no transverse degrees of freedom. This picture automatically leads to a linear confinement along the string. The string constant i.e. the amount of energy per unit length is known phenomenologically to be of the order 1 GeV/fm. Now if the q and \( \bar{q} \) move apart the potential energy of the string increases and the string may break to produce a new q'\( \bar{q} \) pair so that the system splits into two new strings in colour-singlet states, q'q' and q'\( \bar{q} \) This occurs typically when the q and \( \bar{q} \) are 2 - 5 fm apart. The strings may continue to split until there is not enough energy left to produce a new pair and the remaining pairs have masses of known hadrons. The string breaking procedure is illustrated in figure 4.13.

![Figure 4.13 Production of quark anti-quark pairs in the breaking of the colour-flux tube.](image)

The end-points can be associated with diquarks thus enabling the representation and production of baryons as well as mesons. Gluons correspond to momentum and energy-carrying kinks on the string. As already noted in section 4.3 the creation of heavy flavours in the string-breakups is heavily suppressed \( \sim 10^{-11} \) for charm compared to light particles due to the tunneling mechanism (see equation 4.4). Consequently charm will not be produced in the fragmentation process.

### 4.4.3 Higher order corrections.

Since the next-to-leading order corrections to heavy quark production have recently been calculated it might be argue that we should not be satisfied with the use of the lowest order matrix-elements. However so-far, the explicit expressions for the differential distributions to next-to-leading order have not been published, though a plot of d\( \sigma \)/dp\(_T\), for a few different rapidities is presented in figure 4.14 as a function of p\(_T\) (Nason 89).
Figure 4.14 p_T distribution for charm production to next-to-leading order compared to the lowest order fusion model calculations (from Nason 89).

The difference in the shape of the p_T distributions, from lowest order and next-to-lowest order calculations, is relatively small in the region of p_T below 2 GeV/c, which is of relevance to our experiment. (As discussed above, larger relative difference at higher p_T's can be expected.) The correction due to the shape of the cross-section in next to leading order would not amount to more than 5-10% when extrapolating to a total cross-section from a limited p_T range below 2 GeV/c.
Figure 4.15 $x_F$ distributions at $\sqrt{s} = 63$ GeV a) and 630 GeV/c b) for D meson production predicted by the Monte Carlo program Twister. See text for explanations of the fitted curves.

4.4.4 Comparison with measured differential cross-sections.

Charmed particle distributions from Twister or the related program Charis and their predecessor Pythia 3.4 (Bengtsson, Ingelman 85), have already been compared with data in a few different papers both at the ISR and at fixed-target energies. The NA27 and the E649 collaboration have
made comparisons to their $x_F$ and $p_T$ distributions at $\sqrt{s} = 27$ GeV and $\sqrt{s} = 39$ GeV and found a reasonable agreement, (Aguilar-Benitez et al 88, Ammar et al 88). Chauvat et al 87 found that their data on $\Lambda_c$ production as a function of $x_F$ had a similar shape to the prediction from Twister, though with a different absolute level.

An example of $x_F$ and $p_T$ distributions from Twister is shown in figure 4.15a for D mesons at $\sqrt{s} = 63$ GeV. The fitted curves correspond to the distributions given in formula 4.2. The fit parameters give $b = 2.15$, and $n_2 = 6.9$ ($n_1 \sim 2$, the function 4.1 gave a less good fit). The predicted mean $p_T$ was 1.0 GeV/c which is in reasonable agreement with the ISR measurements (see section 4.2).

4.4.5 Differential cross-sections at 630 GeV.

At the CERN $p\bar{p}$ collider two things are different as compared to the charm searches at the ISR. First, $\sqrt{s}$ is ten times higher. Second, we have collisions between $p$ and $\bar{p}$ instead of $p$ and $p$. The increase in energy means that we are sampling a new region of smaller parton momentum fractions $x_1$ and $x_2$. This, in turn, implies that the gluon fusion sub-process can be expected to dominate even more, due to the abundance of gluons with small $x$ values, consequently, there should be no difference between $pp$ and $p\bar{p}$ at $\sqrt{s} = 630$ GeV/c. This is true, in the central region, were our experiment is sensitive as can be deduced from figure 4.16 where the $x_F$ distributions, predicted by Twister for D and $D_s$ mesons and $\Lambda_c$, are compared to the acceptance of the UA2-RICH experiment. It might be interesting to note that the presence of a valence quark from the initial $p$ or $\bar{p}$, is expected to result in an excess forward (or backward) production, particularly of $\Lambda_c$ also at 630 GeV. However, now we have a charge asymmetry at large $|x_F|$, but equal total production. This $x_F$ region was outside the acceptance of the UA2-RICH experiment.
Figure 4.16  $x_F$ distribution predictions by Twister at 630 GeV for $D$ and $D_s$ mesons and $\Lambda_c$ production plots a, b, and c, together with the acceptance of the UA2-RICH experiment. The charge asymmetry at large $x_F$ is displayed by plotting the respective particle and antiparticle states with rings and crosses.
A comparison between figure 4.15a and 4.15b shows that the $x_F$ distribution of the D mesons now has a more peaked appearance than at 63 GeV. In fact, this distribution is not well fitted by a function of the type $(1 + |x_F|)^n$, instead the "invariant" form $\frac{1}{x_F} (1-|x_F|)^n$ gives a very good fit in the central region with $n = 5.1$, see figure 4.15b. This is, most likely, an effect of the factor $\frac{1}{x}$ in the assumed gluon distribution, EHLQ (Eichten et al 84), which starts to show when the small $x$ gluons becomes important (The average $x$ of the initial partons that contributed to the $c\bar{c}$ production was $\bar{x} \sim 5 \cdot 10^{-2}$.

The predicted $p_T$ distributions for D mesons are shown in figure 4.17, together with our acceptance in the two electron $p_T$ bins, 0.9–1.5 and 1.5-2.0 GeV/c. The mean $p_T$ has increased from the ISR prediction, to $<p_T> = 1.3$ GeV/c, and the distribution now falls off slower giving $b = 1.7$, when fitted with the function 4.2. The distributions for the other charmed particles are very similar and the percentage of the $p_T$ distribution that can be observed with electrons between $0.9 < p_T < 2.0$ 10%, 8% is 9% for the D, the $D_s$, and the $\Lambda_c$ respectively, disregarding the different semileptonic branching fractions.

Figure 4.17 The $p_T$ distribution of D mesons at 630 GeV as predicted by Twister. The acceptance of the UA2-RICH experiment using electrons with $p_T$ between 0.9 and 2.0 GeV/c is indicated with open circles.
A property that can affect the behaviour of the cross-section at small $p_T$ is the assumed distribution of the primordial transverse momentum ($k_T$) of the quarks within the colliding hadrons, i.e. the transverse motion not created by the hard scattering. In Twister this is taken to be gaussian with $<k_T^2> = 0.19$ while, e.g., Aguilar-Benitez et al 88 used $<k_T^2> = 0.64$. This increases the predicted acceptance in the kinematic region of the UA2-RICH experiment by a factor 1.1.

4.4.6. Particle ratios and decay properties.

The differential distributions for the charged and neutral D mesons are predicted to be very similar, however, we still need to know their relative frequency if we want to estimate the total charm cross-section, since they have very different semileptonic branching ratios, see table 4.1. The assumptions in Jetset 6.3, result in 25% $D^\pm$ and 56% $D^0/\bar{D}^0$ of all produced charmed particles. The direct D meson production is expected to give equal amounts of the neutral and charged states, however 75% of the D mesons are created via the decay of the vector states $D^*$, with different branchings to charged and neutral pseudoscalars, see table 4.2. The ratio, $3:1$, comes from counting the number of available spin states. This prediction of the pseudoscalar to vector mesons ratio is not confirmed by data on light particles (see e.g. Collins and Martin 82), but it is expected to work better with increasing mass. The data from LEBC-EHS, as discussed in paragraph 4.2.1, are about 2 standard deviations away from the D meson ratios given above. Using the LEBC-EHS cross-sections, (Aguilar-Benitez et al 88, we find

$$\frac{\sigma(D^0/\bar{D}^0)}{\sigma(D^+/\bar{D})} = 1.54 \pm 0.29$$

to compare with the 2.2 expected from the $3:1$ assumption and the branching ratios in table 4.2.

The production of $s$ quarks is suppressed, relative to $u$ and $d$, by a factor of 0.3 in Jetset, explain the probability of 11% to produce a $D_s$ meson. This factor is derived from the tunneling formula given in section 4.3.

Finally, diquarks are suppressed with a factor of 0.09, determined from data, as compared to ordinary quarks, (Sjöstrand 86), resulting in a suppressed baryon production. Of the total amount of charmed particles, about 8% are predicted to be $\Lambda_c$ or $\bar{\Lambda}_c$. 
With the acceptances for the different charmed particles mentioned above and the branching ratios from table 4.1, the average branching ratio predicted by Twister (Jetset) will be 11.2%, while if we instead use the ratio of charged to neutral D's measured by NA27 we get an average semileptonic branching ratio of 12.2%.

A further point to consider in the semileptonic decay of the D mesons, is the resulting electron spectrum. The decay can proceed either as \( D \to K^\pm e^\pm \nu_e \) or \( D \to K^* e^\nu_e \). (A small (Cabibbo suppressed) fraction is also expected to decay through \( D \to \pi^\pm e^\pm \nu_e \).) Due to the difference in mass between the pseudo-scalar and vector states of the kaon, \( \sim 0.5 \text{ GeV} \) as compared to \( \sim 0.9 \text{ GeV} \), the \( p_T \) spectrum of the resulting electrons will depend on the relative probability of the two decays. In Jetset the kaons are created from the hadronisation of the s-quark from the c-quark decay with a probability of creating a \( K^* \) of 60%, as assumed for particle production by hadrons. Data on the semileptonic decay of D mesons indicate that this ratio might be an over estimate. It is in good agreement with the measurement by the DASP collaboration (Brandelik et al 77) who found 35±12% K, while the MARK III collaboration (Pacino et al 79) found 55±14% K also in reasonable agreement. More recently the E691 experiment (see e.g. Purohit 88) has measured the decay ratio \( B(D^+ \to K^{*0} e^+ \nu_e)/B(D^+ \to K^\pi^\pi^+) = 0.49 \pm 0.04 \pm 0.05 \), this corresponds to about 80% K in the semileptonic decays. The WA75 (Aoki et al 88) experiment has measured the semimuonic mode and found 76±6% K. The situation does not seem to be completely clear. We have chosen a ratio of \( K^*/K = 0.4 \) corresponding approximately to the choice in the EURODEC Monte Carlo (Bos and Van Eijk 89).
4.4.7 Predicted electron to hadron ratio.

Figure 4.18 displays the predicted \( e/h \) ratio from the semileptonic decays of the D and \( D_s \) mesons and the \( \Lambda_c \) baryons for those electrons detected by both planes of the scintillator hodoscope in front of the RICH.

![Graph](image)

**Figure 4.18** Electron to hadron ratio from the D, \( D_s \) and the \( \Lambda_c \) semileptonic decays at 630 GeV. The normalization uses the charged particle spectrum measured by UA2.

Figure 4.18 has been computed using a \( K^*/K = 0.4 \) and \( D^0/D = 1.54 \). This prediction confirms the assumption in chapter 3 of a constant \( e/h \) ratio also at \( \sqrt{s} = 630 \) GeV.

4.5 Charm cross-section estimate at 630 GeV.

In this section we will discuss how to convert the measured \( e/h \) ratio into a charm cross-section. We will then calculate an upper limit on \( \sigma(c\bar{c}) \) by assuming that all observed prompt electrons originate from semileptonic decays of charmed particles.

We will then attempt to calculate by Monte Carlo the contributions to the \( e/h \) ratio from vector mesons and semileptonic decays of beauty particles, so as to obtain the best estimate of \( \sigma(c\bar{c}) \).
4.5.1 Conversion of the e/h ratio into $\sigma(c\bar{c})$.

With the result presented in figure 4.18 we can calculate a preliminary $\sigma(c\bar{c})$ according to:

$$
\sigma(c\bar{c}) = \left(\frac{e}{h}\right)_{\text{measured}} \cdot \left(\frac{e_{\text{MC, accepted}}}{h_{\text{UA2}}}\right)^{-1} \cdot \sigma(c\bar{c})_{\text{MC}}
$$

(4.8)

$\sigma(c\bar{c})_{\text{MC}}$ is the total cross-section predicted by Twister and $e_{\text{MC, accepted}}$ is the number of electrons predicted to fall in the acceptance of the RICH. The normalization of the spectrum of accepted electrons in the Monte Carlo was obtained from the charged particle distribution, equation 3.4 in section 3.13.3, measured by UA2. The constant $A$ is

$$A = (7.73\pm0.28) \cdot 10^{-25} \: \text{cm}^2 \: \text{GeV}^{-2} \: \text{c}^3,$$

(Banner et al 85).

It is important to notice that the $\sigma(c\bar{c})$ calculated in equation 4.8 does not depend explicitly on the predicted total cross-section but only on the ratio $\sigma(c\bar{c} \rightarrow e + X)_{\text{accepted}} / \sigma(c\bar{c})_{\text{total}}$ found in the Monte Carlo. To be more explicit 4.8 can be rewritten as

$$
\sigma(c\bar{c}) = \left(\frac{e}{h}\right)_{\text{measured}} \cdot \left(\frac{d\sigma_{h+h^-}}{dp_T}\right)_{\text{UA2}} \cdot \left(\frac{N_{\text{electron}}}{N_{c\bar{c}}}\right)_{\text{Monte-Carlo}}^{-1}
$$

(4.9)

where $N_{\text{electron}}$ is the number of electrons observed in the RICH sector for a certain $p_T$ range, $N_{c\bar{c}}$ is the total number of $c\bar{c}$ events generated and $\sigma_{h+h^-}$ is the charged hadron cross-section within the same solid angle integrated over the $p_T$ bin.

Application of 4.9 to the e/h values in table 3.8 gives

$$
\sigma(c\bar{c}) = 0.69\pm0.47\pm0.22 \: \text{mb} \quad \text{for} \quad 0.9 < p_T < 1.5 \: \text{GeV/c}
$$

$$
\sigma(c\bar{c}) = 2.0\pm1.6\pm0.4 \: \text{mb} \quad \text{for} \quad 1.5 < p_T < 2.0 \: \text{GeV/c}.
$$

Where the second error correspond to the systematic error from the e/h measurement.
4.5.2 Acceptance of the prompt electrons from charmed particle decays.

Now we have to consider the fact that we normalized our prompt electron rate with the accepted charged hadrons from our minimum bias sample, thus, assuming implicitly that the electron events due to charmed particle decays have the same structure the as the MB sample, with respect to the cuts applied in the prompt electron analysis.

To investigate this assumption, the requirement from the UA2-RICH analysis of a single isolated electron in the RICH sector with no accompanying charged particle, or gamma above threshold in the calorimeter, was implemented in the Monte Carlo. A sub sample was also run through the complete detector simulation. The results of the cuts were studied in the case where the accompanying particles considered were allowed to be

1) any particle,
2) a particle created in the hadronisation of the c or c̄ quark,
3) a particle from the primary charmed-hadron decay-chain.

In the case of string fragmentation the 2'nd class can not be unambiguously defined, as for instance in the case of a fragmenting string between the c quark and a beam-jet particle. Therefore the effect of these cuts were also investigated using independent fragmentation. In fact the difference between the two fragmentation schemes was found to be small which is explained by the observation that most of the inefficiency is caused by particles from the decay cascade. Thus the correction calculated in this way should be fairly reliable.

The corrections to the two $p_T$ bins together with the resulting cross-section is given in table 4.6.

<table>
<thead>
<tr>
<th>$p_T$ (GeV/c)</th>
<th>Acceptance (%)</th>
<th>$\sigma(c\bar{c})$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9 - 1.5</td>
<td>86</td>
<td>0.80±0.55±0.25</td>
</tr>
<tr>
<td>1.5 - 2.0</td>
<td>81</td>
<td>2.5±2.0±0.49</td>
</tr>
</tbody>
</table>

*Table 4.6 The acceptance for the charm event topology and the resulting $\sigma(c\bar{c})$ calculated using equation 4.8.*
4.5.3 An upper limit on the charm cross-section.

Under the assumption that all prompt electrons are the result of semileptonic decays of charm we can use the values calculated in table 4.6 to compute an upper limit on $\sigma (c\bar{c})$. Before we do this we should consider the systematic errors in the Monte Carlo evaluation. These were obtained by varying the Monte Carlo parameters and assumptions within reasonable limits (Ingelman 89). The major contributions are given in table 4.7.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Systematic error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fragmentation scheme</td>
<td>12</td>
</tr>
<tr>
<td>Primordial $K_t$</td>
<td>10</td>
</tr>
<tr>
<td>Average branching fraction</td>
<td>10</td>
</tr>
<tr>
<td>Inefficiency from associated particles</td>
<td>8</td>
</tr>
<tr>
<td>$K^*/K$ ratio</td>
<td>12</td>
</tr>
<tr>
<td>Higher order corrections to the $p_T$ distribution</td>
<td>10</td>
</tr>
<tr>
<td>Other small effects</td>
<td>5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>26</strong></td>
</tr>
</tbody>
</table>

Many uncertain parameters like e.g. the mass of the charm quark has a large effect on the total cross-section predicted by Twister, while the effect on the acceptance factor $N_{\text{electron}}/N_{c\bar{c}}$ of equation 4.8 is small. Other parameters that was investigated but did not effect the ratio substantially is $\Lambda_{QCD}$, the definition of the $Q^2$ scale, and the parametrization of the parton densities.

To obtain an upper limit we resort to the (questionable) procedure of adding the statistical and systematic error in quadrature. At 95% confidence level (1.64 $\sigma$ in the one-sided case) we find

$$\sigma (c\bar{c}) < 1.9 \text{ mb} \quad 0.9 < p_T < 1.5 \text{ GeV/c}$$

$$\sigma (c\bar{c}) < 6.1 \text{ mb} \quad 1.5 < p_T < 2.0 \text{ GeV/c}.$$  

(If we weight the two bins together the first dominates and we get a limit of 1.95 mb.)
4.6 Subtraction of beauty and vector meson contributions.

So-far we have considered as prompt electron sources, decays of charmed particles and electron positron pairs from Dalitz decays of $\pi^0$ and $\eta$ mesons. The latter were discarded in the analysis, when possible, and the residual contributions were calculated by Monte Carlo and subtracted from the data. This approach follows that adopted in the ISR measurements of the $e/h$ ratio. As indicated in figure 1.1 there are, however, other prompt electron sources which, though they might be interesting in a different context, constitute backgrounds, if we want to interpret the $e/h$ ratio in terms of a charm cross-section.

The most important competing sources, in the $p_T$ interval in question are the decays, of vector mesons and of mesons with open beauty.

4.6.1 Vector mesons.

The neutral $J^P = 1^-$ mesons are listed in table 4.8. The vector mesons containing the 3 light quark flavours, the $\rho$, $\omega$ and $\phi$, have small, but important, branching ratios to $e^+ e^-$, since these mesons are copiously produced in hadron collisions. In fact it is believed that about 50% of the produced pions at the ISR, result from decays of $\rho$ and $\omega$.

<table>
<thead>
<tr>
<th>Vector meson</th>
<th>Mass (MeV)</th>
<th>Branching ratio to $e^+ e^-$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho^0$</td>
<td>770±3</td>
<td>0.0044±0.0002</td>
</tr>
<tr>
<td>$\omega$</td>
<td>782.0±0.1</td>
<td>0.0071±0.0003</td>
</tr>
<tr>
<td>$\phi$</td>
<td>1019.4±0.01</td>
<td>0.031±0.001</td>
</tr>
<tr>
<td>$J/\psi$</td>
<td>3096.9±0.1</td>
<td>6.9±0.9</td>
</tr>
</tbody>
</table>

Due to the relatively large masses in these two body decays, the opening angle of the $e^+ e^-$ pair will almost always sufficiently large for the partner of a detected $e^+$ or $e^-$ to escape the acceptance of the RICH, or even the magnetic spectrometer. Since there are no measurements of $\rho$, $\omega$ and $\phi$ production at $\sqrt{s} = 630$ GeV we again have to resort to a model calculation.
For this purpose we choose the Monte Carlo program Pythia 4.8 (Bengtsson and Sjöstrand 87). This program has a lot in common with the previously described Monte Carlo Twister since both programs are developments of Pythia 3.4. However Pythia 4.8 is better adapted to the simulation of minimum bias-type events with the inclusion of initial state parton cascades, multiple interactions and additional low \( p_T \) reactions. It does not, however, include the matrix elements with explicit heavy-quark masses available in Twister.

The hadron spectra generated by Pythia are in good agreement with the available data at \( \sqrt{s} = 630 \) GeV. The ratio of the generated vector mesons to the pions are constant as a function of transverse mass \( m_T = \sqrt{m^2 + p_T^2} \), in agreement with ISR data (see e.g. Bourquin, Gaillard 76). The observed ratios are given in table 4.9.

Table 4.9. The cross-section ratio of vector mesons to \( \pi^0 \) evaluated at a common value of the transverse mass as generated by Pythia 4.8.

<table>
<thead>
<tr>
<th>Vector meson</th>
<th>( \frac{\nu}{\pi^0} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho^0 )</td>
<td>1.2</td>
</tr>
<tr>
<td>( \omega )</td>
<td>1.2</td>
</tr>
<tr>
<td>( \phi )</td>
<td>0.09</td>
</tr>
</tbody>
</table>

In the Monte Carlo calculation minimum bias events were generated and the produced vector mesons were required to decay in the \( e^+e^- \) channel. The electron spectrum in the solid angle corresponding to the RICH scintillator was recorded and weighted with the relevant branching ratios. If both the \( e^+ \) and the \( e^- \) from the same meson were detected they were both excluded. (This was very unlikely.) The electron spectrum was normalized to the charged hadron spectrum according to 3.1. The resulting \( e/h \) ratio for the 3 different mesons and the sum of their contributions are shown in figure 4.19.
Figure 4.19 e/h ratio expected for the three vector mesons ρ, ω and φ according to Pythia 4.8.

The integrated contributions corrected for the shape of the UA2-RICH trigger acceptance in the same fashion as described in section 3.13.9 for the residual background, amount to

\[
\left( \frac{e}{h} \right)_{\omega, \phi} = (2.1 \pm 1.0) \cdot 10^{-5} \quad 0.9 < p_T < 1.5 \text{ GeV/c}
\]

\[
\left( \frac{e}{h} \right)_{\omega, \phi} = (1.2 \pm 0.7) \cdot 10^{-5} \quad 1.5 < p_T < 2.0 \text{ GeV/c}.
\]

This is about 10% of the measured e/h ratio in the first p_T bin and about 2% in the second. We have allowed for a systematic error of ~50% due to the lack of experimental data on vector-meson production.

The contribution from J/ψ decay was not estimated in this work since the cross-section close to p_T = 0, the only part that would contribute, is very uncertain. The contribution to the electron p_T spectrum below 1.5 GeV/c should be small due to the large mass of the J/ψ implying an electron momentum of 1.55 GeV/c already in the J/ψ rest system.
4.6.2 Prompt electrons from semileptonic decays of beauty particles.

In the case of particles with open beauty there exists an estimate of the total cross-section by UA1 of $\sigma(b\bar{b}) = 10.1\pm3.3 \, \mu b$ (Albajar et al 88b). To study the contribution of the beauty particles to the prompt $e^\pm$ spectrum, $b\bar{b}$ pairs were generated using the Monte Carlo program Twister and the final result was weighted so that the total cross-section would agree with the UA1 estimate. An average semileptonic branching fraction of $(12.3\pm0.8)\%$ (Review of particle properties 88) was assumed.

The dependence of the result on the generated $p_T$ distribution of the beauty particles should be smaller than in the case of charm due to the large mass of the beauty mesons. Thus the decay will dominate the kinematic distribution of the electrons from beauty, in the $p_T$ range of the UA2-RICH experiment.

The resulting $e/h$ ratio as a function of $p_T$ seen by the RICH hodoscope is plotted in figure 4.20.

![Figure 4.20](image-url)

**Figure 4.20** Electron to hadron ratio from the semileptonic decay of beauty particles.
The integrated contribution corrected for the shape of the UA2-RICH trigger acceptance, amounts to

\[ \left( \frac{e}{p_T} \right)_{b\bar{b}} = (1.0 \pm 0.3) \cdot 10^{-5} \quad 0.9 < p_T < 1.5 \text{ GeV}/c \]

\[ \quad = (3.5 \pm 1.1) \cdot 10^{-5} \quad 1.5 < p_T < 2.0 \text{ GeV}/c \]

with a systematic error from the UA1 measurement of about 30%.

### 4.6.3 Estimate of \( \sigma (c\bar{c}) \).

In table 4.10 we summarize the information on \( \sigma (c\bar{c}) \).

<table>
<thead>
<tr>
<th>( p_T ) (GeV/c)</th>
<th>V-meson + b\bar{b} contribution (%)</th>
<th>( \sigma (c\bar{c}) ) (mb)</th>
<th>stat</th>
<th>sys, exp</th>
<th>Errors sys, acc</th>
<th>sys, v+b</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9 - 1.5</td>
<td>15.2</td>
<td>0.68</td>
<td>0.55</td>
<td>0.25</td>
<td>0.18</td>
<td>0.04</td>
</tr>
<tr>
<td>1.5 - 2.0</td>
<td>8.8</td>
<td>2.3</td>
<td>2.0</td>
<td>0.5</td>
<td>0.6</td>
<td>0.06</td>
</tr>
</tbody>
</table>

### 4.7 Discussion of the results on \( \sigma (c\bar{c}) \).

In this section we will try to comment on the overall degree of certainty that can be attached to the above determination of \( \sigma (c\bar{c}) \), and compare with recent QCD estimates.

The first point that might create some worry is the small fraction of all charmed particle decays that was actually observed in the UA2-RICH experiment. In fact this fraction was only about \( 10^{-4} \). Fortunately this number contains several factors that need not concern us. The average semileptonic branching fraction could not be measured in this experiment but the results can easily be rescaled in the event of a future measurement. The \( \sim 7\% \) azimuthal coverage should not introduce any kinematic bias. In
figure 4.21 the predicted rapidity dependence (using Twister) of the electrons from charmed particle decays is displayed and the location of the RICH detector has been indicated. The variation is relatively slow over the region including the RICH sector.

![Graph showing pseudo-rapidity distribution](image)

**Figure 4.21** Pseudo-rapidity distribution of electrons from charmed particle decays as predicted by Twister. The location of the RICH has been indicated by the arrows.

The remaining factor comes from the $p_T$ distribution. Again trusting the Monte Carlo, about 10% of the electrons from $c\bar{c}$ decays will be detected in the range $0.9 < p_T < 1.5$ GeV/c and about 1% in the bin $1.5 < p_T < 2.0$ GeV/c. The bin $0.5 < p_T < 0.9$ GeV/c that we choose not to consider due to the dominant background and the large systematic error can be expected to be sensitive to an additional part of the spectrum corresponding to about 25%. The fact that the measured e/h value is consistent with that of the central bin gives at least some indication that nothing dramatic happens when the $p_T$ of the charmed particles approaches zero.

Obviously the statistical error is uncomfortably large. However, the total systematic error is of the same order. A source of worry particularly in next to leading order (see discussion in section 4.3) is the behaviour of the gluon structure function for small $x$ and $Q^2$ values. This is not well known, also it is not clear that the procedure of evolving the parton distributions
downwards to a $Q^2$ scale of the order of $m_c^2$, is really valid. The parton distribution used here have been fitted at a scale $Q^2_0 = 10 \text{ (GeV)}^2$ (DFLM) and $Q_0 = 4 \text{ (GeV)}^2$ (EHLQ). It has been suggested (Schuler 89) that using parton distributions fitted at a scale of $Q^2_0 \sim (1 \text{ GeV})^2$ results in a dramatically different (a rapid increase) behaviour of the $p_T$ distribution close to zero in next to leading order.

This might suggest that we should refrain from extrapolating the total cross-section below a lower cutoff of e.g. $p_T > 0.5 \text{ GeV/c}$. If we apply such a cutoff in the generation of the $c\bar{c}$ pairs at the hard scattering level we instead get $\sigma(c\bar{c}, p_T > 0.5 \text{ GeV/c}) = 0.64\pm0.52\pm0.29 \text{ mb}.

In figure 4.22 our estimate of $\sigma(c\bar{c})$ from section 4.5 is compared to the recent next to leading order QCD calculations by Nason et al. The curves correspond to those presented in figure 4.13 now extended to 630 GeV (Nason and Martinelli 89). The reason for plotting $pp$ instead of $p\bar{p}$ is that this gives a better agreement with the points at small $\sqrt{s}$ while there is no difference at all at 630 GeV as discussed in section 4.4.

![Graph showing the comparison of $\sigma(c\bar{c})$ with QCD calculations by Nason et al.](image)

Figure 4.22  Next to leading order calculation of $\sigma(c\bar{c})$ from Nason and Martinelli 89, compared with data from ISR and fixed target experiments, and with our estimate at 630 GeV/c. At 630 GeV we have only included the experimental systematic errors.
The agreement is reasonable, however, the calculation was performed using $Q^2 = (3 \text{ GeV})^2$ and it was not possible to investigate the behaviour at smaller scales.
Chapter 5

SUMMARY AND CONCLUSIONS

5.1 Detector aspects.

In this thesis a few of the early steps in the development of a Ring Imaging CHerenkov detector have been described.

The properties of drift chambers for photon detection were discussed, with particular emphasis on the use of TMAE as photo-sensitive vapour. A complete ring imaging detector system, suitable for installation in a collider experiment, was designed and built. Presently large detector systems using the same basic ideas are being installed in the DELPHI-detector at LEP and under construction for the SLD-detector at SLC.

The purpose of these RICH detectors is to separate pions kaons and protons with a confidence corresponding to a few $\sigma$. The UA2-RICH experiment had to separate electrons from hadrons with a probability of mistaking a pion for an electron that had to be less than $\sim 10^{-4}$. This is a difficult enough problem already below the pion Cherenkov-threshold but it was indeed shown that such a high level of confidence could be reached with the $\sim 70$ cm $C_2F_6$-RICH built for this purpose.

The relatively low efficiency obtained with this detector was not critical in the UA2-RICH experiment and the specific detector response of $N_0 = 47$ cm$^{-1}$ was better than achieved by other RICH detectors used in actual physics experiments at the time. For the separation of kaons and protons from pions, a better efficiency is desirable. This should be possible with a better quality of the optical components in the RICH system, i.e. mirrors and windows.
The UA2-RICH experiment demonstrated that it is possible to operate a RICH detector in the environment of a hadron-collider.

5.2 Physics aspects.

This experiment has provided the first measurement of inclusive prompt electron production in hadron collisions one order of magnitude above the ISR energy range. At $\sqrt{s} = 630$ GeV the measured values of the electron to hadron ratios

$$
e/h = \left\{ 2.0 \pm 1.4 \text{(stat)} \pm 0.6 \text{(sys)} \right\} \cdot 10^{-4} \quad 0.9 < p_T < 1.5 \text{ GeV/c}$$
$$e/h = \left\{ 6.4 \pm 4.3 \text{(stat)} \pm 1.0 \text{(sys)} \right\} \cdot 10^{-4} \quad 1.5 < p_T < 2.0 \text{ GeV/c}$$

are consistent with the values of $1 - 2 \cdot 10^{-4}$ observed at the ISR in spite of the order of magnitude increase in the centre of mass energy.

Assuming that the main sources of prompt electrons are the same as at the ISR, we have estimated the total charm cross-section to be

$$\sigma (c\bar{c}) = 0.68 \pm 0.55 \text{(stat)} \pm 0.25 \text{(sys,exp)} \pm 0.21 \text{(sys,MC)} \text{ mb}$$

were the first systematic error comes from the $e/\pi$ measurement and the second from the Monte Carlo corrections. The limit corresponding to the assumption that all electrons emanate from charm is

$$\sigma (c\bar{c}) < 1.9 \text{ mb}$$

at the 95% confidence level.

This limit is an important constraint on the fast rise with energy, suggested by some experiments at the ISR and theories devised to explain them. After some re-measurements and with better known branching ratios most data at the ISR now seem to favour cross-sections of the order of $0.1 - 0.3$ mb for centrally produced charm. Our data point at $\sqrt{s} = 630$ GeV is perfectly consistent with a charm cross-section of the same order. It is more difficult to reconcile our limit with the large cross sections of order $3 - 5$ mb deduced from the Tien Shan cosmic ray measurements at $\sqrt{s}$ above $200$ GeV. Of course we can not exclude the presence of a very large forward component as suggested by the ISR $\Lambda_c$ data since the acceptance of the UA2-RICH experiment did not include the very forward region.
Looking at figure 4.22 it seems that perturbative QCD, after the recent inclusion of the $\alpha_s^3$ contributions, has no problem in explaining the data either at 630 GeV nor at 63 GeV and below (perhaps with the exception of $\Lambda_c$ at the ISR). However, one has to remember that the theoretical calculations suffer from considerable uncertainties mainly connected with the "small" mass of the charm quark and the large size of the ratio $\sqrt{s}/m_c$ at a centre-of-mass energy of 630 GeV/c. Thus it appears at present difficult to make any high precision tests of perturbative QCD using the charm quark even with improved quality of the data.

In conclusion the present experiment has been the first attempt to estimate a total cross-section for open charm production at $\sqrt{s} \geq 630$ GeV and in the event of a future measurement, using a different experimental technique, this result should continue to be an important constraint.
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