High 4-Momentum Elastic Electroproduction of Vector Mesons at HERA.

Vijaya Kumar Nadendla
Louisiana State University and Agricultural & Mechanical College

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_disstheses

Recommended Citation
https://digitalcommons.lsu.edu/gradschool_disstheses/6267

This Dissertation is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Historical Dissertations and Theses by an authorized administrator of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.
INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6” x 9” black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI
A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA
313/761-4700 800/521-0600

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
HIGH $Q^2$
ELASTIC ELECTROPRODUCTION OF VECTOR MESONS AT HERA

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Physics and Astronomy

by
Vijaya Kumar Nadendla
B. Sc., S.V.University, India, 1989
M. Sc., University of Hyderabad, 1991
August 1996
To My Parents
Acknowledgments

My thanks to the LSU High Energy Physics group - Profs. Richard Imlay, William Metcalf and Roger McNeil, Research Assistant Prof. Hong Joo Kim and Research Associate Suramanian Kartik - for introducing to me and patiently teaching me this wonderful field. Hong Joo and Kartik spent a lot of time with me at DESY in Germany. High $Q^2$ elastic vector meson electroproduction at HERA is Hong Joo's brain child. The analysis in this thesis has been developed with the help of these people.

This dissertation has been read a countless number of times by Profs. Richard Imlay and William Metcalf. Their experience taught me how to write a scientific document. My thanks are also due to my dissertation committee members - Profs. Ravi Rau, Michael Cherry and Guillermo Ferreyra - for their comments which made this dissertation a more complete document.

I would like to thank the HERA machine group and ZEUS collaboration - their work was essential for making this study possible. This study included the work of other people, primarily, the Deep Inelastic Scattering group, the SRTD analysis group and the Elastic Vector Meson analysis subgroup.
My thanks also to all my teachers from my childhood, including my parents, for all the time they spent on me teaching me how to read, write and comprehend.

My thanks are due to my parents for their love and affection and their faith in me and to my brother for his companionship. Finally, I wish to thank my wife Aparna for her support, patience and love in the hard times of a finishing graduate student immediately after our marriage.

This work was supported by the United States Department of Energy under contract DE-FG05-91-ER40617.
Contents

Acknowledgments ................................................................. iii

Abstract ..................................................................................... viii

1 Introduction .............................................................................. 1
  1.1 The particles of nature ....................................................... 1
  1.2 The Standard model .......................................................... 3
  1.3 The place of this thesis in this scheme ............................... 4
  1.4 Organization of the thesis .................................................. 5

2 Deep Inelastic Scattering and Diffraction ............................ 7
  2.1 Deep inelastic scattering ..................................................... 7
  2.2 Cross-sections .................................................................... 8
  2.3 Parton model ....................................................................... 11
  2.4 QCD improved parton model .............................................. 13
  2.5 Diffraction .......................................................................... 14

3 Models of Elastic Vector Meson Electroroduction .......... 20
  3.1 General kinematic variables ............................................... 21
  3.2 Review of data on elastic vector meson electroproduction .... 23
  3.3 Models for electroproduction of vector mesons .................. 25

4 HERA, a Positron - Proton Collider .................................. 30
  4.1 The positron and proton beams ........................................ 30
  4.2 Data taking ......................................................................... 34
  4.3 Bunch structure of the beams ............................................. 35
  4.4 Expected luminosity ............................................................. 35
  4.5 Satellite bunches ............................................................... 36
  4.6 Backgrounds at HERA ....................................................... 37
  4.7 Performance of HERA ........................................................ 37

5 ZEUS - the Detector ............................................................. 39
  5.1 The veto wall and C5 counter ............................................. 41
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2 Luminosity monitor</td>
<td>42</td>
</tr>
<tr>
<td>5.3 Calorimeter</td>
<td>44</td>
</tr>
<tr>
<td>5.4 Charged particle tracking</td>
<td>51</td>
</tr>
<tr>
<td>5.5 Small-angle rear track detector</td>
<td>55</td>
</tr>
<tr>
<td>6 Data Reconstruction and Trigger</td>
<td>57</td>
</tr>
<tr>
<td>6.1 Data reconstruction</td>
<td>59</td>
</tr>
<tr>
<td>6.2 First-level trigger</td>
<td>61</td>
</tr>
<tr>
<td>6.3 Second-level trigger</td>
<td>64</td>
</tr>
<tr>
<td>6.4 Third-level trigger</td>
<td>66</td>
</tr>
<tr>
<td>7 Detector and Trigger Simulation</td>
<td>71</td>
</tr>
<tr>
<td>7.1 ZEUS detector and trigger simulation</td>
<td>72</td>
</tr>
<tr>
<td>7.2 Event simulation for the present analysis</td>
<td>74</td>
</tr>
<tr>
<td>8 Overview of the Data</td>
<td>78</td>
</tr>
<tr>
<td>8.1 Stability of the detector</td>
<td>79</td>
</tr>
<tr>
<td>8.2 Data pre-selection</td>
<td>80</td>
</tr>
<tr>
<td>9 Positron Identification</td>
<td>85</td>
</tr>
<tr>
<td>9.1 Positron identification</td>
<td>86</td>
</tr>
<tr>
<td>9.2 Position reconstruction</td>
<td>88</td>
</tr>
<tr>
<td>9.3 Energy reconstruction</td>
<td>89</td>
</tr>
<tr>
<td>10 Elastic $\phi$ Electroproduction</td>
<td>100</td>
</tr>
<tr>
<td>10.1 Cuts for the $\phi$ analysis</td>
<td>101</td>
</tr>
<tr>
<td>10.2 Comparison of Monte Carlo and data</td>
<td>107</td>
</tr>
<tr>
<td>10.3 Acceptance studies</td>
<td>108</td>
</tr>
<tr>
<td>10.4 Background study</td>
<td>114</td>
</tr>
<tr>
<td>10.5 The $ep$ cross-section</td>
<td>121</td>
</tr>
<tr>
<td>10.6 The $\gamma^*p$ cross-sections</td>
<td>122</td>
</tr>
<tr>
<td>10.7 Systematic studies</td>
<td>125</td>
</tr>
<tr>
<td>10.8 Helicity of the $\phi$</td>
<td>127</td>
</tr>
<tr>
<td>10.9 Comparison with theoretical predictions</td>
<td>129</td>
</tr>
<tr>
<td>11 Ratio of $\rho^0$ to $\phi$ Production</td>
<td>133</td>
</tr>
<tr>
<td>11.1 Data selection and analysis</td>
<td>133</td>
</tr>
<tr>
<td>11.2 The $\rho^0$ production cross-section</td>
<td>142</td>
</tr>
<tr>
<td>11.3 Ratio of $\phi$ to $\rho^0$ production</td>
<td>150</td>
</tr>
<tr>
<td>11.4 Result</td>
<td>153</td>
</tr>
</tbody>
</table>
Abstract

The production of \( \phi \) mesons in the reaction \( e^+ p \rightarrow e^+ \phi p \ (\phi \rightarrow K^+ K^-) \), for \( 7 < Q^2 < 25 \text{ GeV}^2 \) and for virtual photon-proton center of mass energies (\( W \)) in the range 42-134 GeV, has been studied with the ZEUS detector at HERA. When compared to lower energy data at similar \( Q^2 \), the results show that the \( \gamma^* p \rightarrow \phi p \) cross-section rises strongly with \( W \). This behavior is similar to that previously found for the \( \gamma^* p \rightarrow \rho^0 p \) cross-section. This strong dependence cannot be explained by production through soft pomeron exchange. The ratio of \( \sigma(\phi)/\sigma(\rho^0) \), which has previously been determined by ZEUS to be 0.065 ± 0.013 (stat.) in photoproduction at a mean \( W \) of 70 GeV, is measured to be 0.24 ± 0.05 (stat.) ± 0.03 (syst.) at a mean \( Q^2 \) of 11.9 GeV^2 and mean \( W \) of 98 GeV and is thus approaching at large \( Q^2 \) the value of 2/9 predicted from the quark charges of the vector mesons and a flavor independent production mechanism.
Chapter 1

Introduction

Particle physics is the study of the constituents of matter and their interactions. From the five element theory of ancients, to the modern standard model, it has been a quest of man to understand what the world is made of.

1.1 The particles of nature

Experimental evidence suggests that matter is constituted of two kinds of particles:

- **Fermions with half-integer spin:**
  The fermions come as two types, quarks with fractional electric charge and leptons with integral charge. Quarks and leptons are point-like and structureless to a scale of $10^{-17}$m. There are 6 quarks (up, down, strange, charm, top and bottom) and 6 leptons (electron, muon, tau and their neutrinos) with corresponding antiparticles. These can be arranged in pairs as shown below. The fact that the three generations
(each with a pair of quarks and leptons) are reproductions of each other could indicate the existence of a substructure.

\[
\begin{pmatrix}
\nu_e \\
e \\
\nu_\mu \\
\mu \\
\nu_\tau \\
\tau
\end{pmatrix},
\begin{pmatrix}
u_\mu \\
\mu \\
\nu_\tau \\
\tau
\end{pmatrix},
\begin{pmatrix}
u_e \\
e \\
\nu_\mu \\
\mu \\
\nu_\tau \\
\tau
\end{pmatrix},
\begin{pmatrix}
u_e \\
e \\
\nu_\mu \\
\mu \\
\nu_\tau \\
\tau
\end{pmatrix}
\]

- **Bosons with integral spin:**

These are the field quanta of the interactions between the fermions. There are four kinds of interactions between fermions - gravitational, electromagnetic, weak and strong. Each type of interaction has a characteristic constant signifying the coupling between the fermion and the boson that mediates the interaction. There is also a source - a specific property of the fermion that causes the interaction. For example, electric charge is the source for the electro-magnetic interactions among fermions. There are four spin one bosons to mediate the full electroweak force

\[
\gamma, \ W^+, \ W^-, \ Z
\]

where the photon is massless and the \( W^\pm \), \( Z \) have masses. Color charge carried by the quarks is the 'source' of strong interactions. Gluons are the gauge bosons which mediate the color interaction.
1.2 The Standard model

In this model, electro-weak interactions between the leptons and the quarks are described by a gauge field theory with broken SU(2)xU(1) symmetry where the photon, W and Z are the associated gauge bosons. The strong interactions of quarks are described by Quantum-ChromoDynamics (QCD) with the gluon as the gauge boson. QCD is a gauge field theory defined by its Lagrange density. The QCD Lagrangian is invariant under SU(3) gauge transformations. The non-abelian nature of QCD is reflected in the fact that gluons carry color charge and hence interact with each other along with colored quarks. These gauge field self-interactions make QCD markedly different from QED where they are absent. Unlike QED where electric charge increases as one penetrates the virtual photon cloud of the electron, in QCD the observed color coupling becomes smaller, leading to asymptotic freedom: the interaction becomes weaker at shorter distances. Extensive searches for the existence of free quarks have failed leading to the hypothesis of confinement: the interaction between quarks is such that the quarks cannot be separated once they are inside a hadron.

\[ \alpha_s \] is the strong coupling constant of QCD similar to the coupling constant \[ \alpha = e^2/(4\pi) = 1/137 \] of QED. \[ \alpha_s \] is not a true constant but is dependent on the masses or momentum transfers involved in a process. The dominant

\[ \text{In this thesis units with } h, c = 1 \text{ are used.} \]
mass or momentum transfer \( (Q^2) \) is said to set a scale in the process. \( \alpha_s \) decreases as the scale in the process increases. For \( Q^2 \to \infty \), \( \alpha_s \) vanishes. Unfortunately, QCD is not an exactly soluble theory so one must resort to approximation schemes to make calculations and predictions. pQCD is a perturbative expansion in powers of \( \alpha_s(Q^2) \). This requires that the scale \( Q^2 \) is large so that \( \alpha_s \) is small. In this scheme each observable (e.g., the gluon structure function) can be written in the form

\[
xG(x, Q^2) = \sum_{n=0} C_n(\alpha_s)^n(L^n + a_{n-1}L^{n-1} + \ldots + a_0),
\]

where \( L \) stands for \( \log(Q^2) \) and \( C_i \) and \( a_i \) are calculated using Feynman diagrams and are dependent on kinematic quantities. \( x \) is defined in chapter 2. This expression doesn't converge per se. Nor are individual terms easy to calculate. Partial sums are evaluated that are approximate to the whole sum in various parts of phase space. When only terms to leading order in \( \log(Q^2) \) are summed, one refers to the leading \( \log(Q^2) \) approximation.

### 1.3 The place of this thesis in this scheme

QCD provides the theoretical framework for formulating the structure of hadrons from quarks and gluons. However, due to approximation schemes that must be used to calculate even something as basic as the structure of the proton, experiments are essential in providing input to understand this structure. The proton can be probed by real and virtual photons of high energy. This thesis studies a particular exclusive reaction in such a process.
This reaction is currently one of the few easily measurable and calculable exclusive reactions in QCD.

Because perturbative QCD (pQCD) requires a large scale for the method to be valid, processes without a large scale must be understood using non-perturbative models based on QCD. The reaction studied in this thesis has been measured before and understood using non-perturbative models. This thesis measures the reaction in a different region in phase-space and the results cannot be explained by non-perturbative models. The results are of wide interest because of disagreements over the extent to which they are consistent with current pQCD models. The results of this discourse will be an improvement in our understanding of QCD in the perturbative regime. It is an epsilon of progress in our understanding of proton structure and of using QCD to understand the structure of hadrons.

1.4 Organization of the thesis

The next chapter describes deep inelastic scattering and diffraction. Models of elastic vector meson production are presented next along with a review of data on the process. The lepton-proton collider at HERA follows in chapter 4. Next, those parts of the ZEUS detector used in this analysis are described. The trigger and data reconstruction follow along with a discussion of the detector and trigger simulation. An overview of data used and pre-selection
is given in chapter 8. The procedures used to identify the scattered positron are discussed in chapter 9. The measurement of the $ep \rightarrow e\phi p$ cross-sections is described in chapter 10 and the ratio of $\phi/\rho^0$ production cross-sections in chapter 11. The results are summarised at the end.
Chapter 2
Deep Inelastic Scattering and Diffraction

The principle behind scattering experiments is simple - scatter a point-like projectile from a target and measure the energy and angular distribution of the scattered particle. Information on the structure of the target can be deduced from the measured distributions. For example, the existence of a hard nuclear core in the atom was inferred from the occasional scatterings of $\alpha$ particles at large angles when a beam of $\alpha$ particles impinges on a gold foil. Later, instead of $\alpha$ particles, electrons or positrons were accelerated to several GeV and used as projectiles on proton or nuclear targets. At HERA, 30 GeV electron or positron beams are scattered on 820 GeV protons. This is equivalent to a lepton beam of 52 TeV impinging on a fixed proton target.

2.1 Deep inelastic scattering

Figure 2.1 shows a schematic picture of electron-proton scattering. A lepton of momentum $e$ scatters off a nucleon of momentum $p$ with the exchange of a photon or $Z^0$. The relevant kinematic variables are given in table 2.1. The effective probe of structure is the exchanged virtual photon or $Z^0$ with
Figure 2.1: A schematic picture of electron-proton scattering.

The differential cross-section for deep inelastic scattering of unpolarized electrons from an unpolarized nucleon target in the single photon approximation is small at present $Q^2$ and is neglected.

---

2.2 Cross-sections

The differential cross-section for deep inelastic scattering of unpolarized electrons from an unpolarized nucleon target in the single photon approximation is small at present $Q^2$ and is neglected.
Table 2.1: Some Kinematic variables at HERA.

<table>
<thead>
<tr>
<th>Notation</th>
<th>formula</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_e, E_p$</td>
<td>$(0,0,-E_e, E_e)$</td>
<td>Electron, proton beam energies</td>
</tr>
<tr>
<td>$e$</td>
<td>$(0,0,0,0)$</td>
<td>Four momentum of incoming electron</td>
</tr>
<tr>
<td>$p$</td>
<td>$(0,0,E_p, E_p)$</td>
<td>Four momentum of incoming proton</td>
</tr>
<tr>
<td>$e'$</td>
<td>$(E_e' \sin \theta_e', 0, E_e' \cos \theta_e', E_e')$</td>
<td>Four momentum of scattered electron</td>
</tr>
<tr>
<td>$s$</td>
<td>$(e + p)^2$</td>
<td>Square of total center of mass energy</td>
</tr>
<tr>
<td>$q^2 = -Q^2$</td>
<td>$(e - e')^2$</td>
<td>Square of four momentum transfer</td>
</tr>
<tr>
<td>$\nu$</td>
<td>$q \cdot p / m_p$</td>
<td>Energy loss of electron in p rest system</td>
</tr>
<tr>
<td>$y$</td>
<td>$q \cdot p / e \cdot p$</td>
<td>Fraction of energy transfer</td>
</tr>
<tr>
<td>$x$</td>
<td>$Q^2 / 2q \cdot p$</td>
<td>Bjorken scaling variable</td>
</tr>
<tr>
<td>$W^2$</td>
<td>$(p + q)^2$</td>
<td>Mass squared of final hadronic system</td>
</tr>
<tr>
<td>$\delta$</td>
<td>$h / Q$</td>
<td>Resolving power</td>
</tr>
</tbody>
</table>
Table 2.2: Some Kinematic variables accessible at HERA and Pre-HERA.

<table>
<thead>
<tr>
<th>Variable</th>
<th>HERA</th>
<th>Pre-HERA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s$ (GeV$^2$)</td>
<td>$10^5$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>Practical $Q^2_{\max}$</td>
<td>$40,000$</td>
<td>$400$</td>
</tr>
<tr>
<td>$\alpha$ cm$^{-1}$</td>
<td>$10^{-16}$</td>
<td>$10^{-15}$</td>
</tr>
<tr>
<td>$\nu_{\max}$ (GeV)</td>
<td>$52,000$</td>
<td>$500$</td>
</tr>
<tr>
<td>$x_{\min}$ at $Q^2 = 10$</td>
<td>$10^{-4}$</td>
<td>$10^{-2}$</td>
</tr>
</tbody>
</table>

is related to two structure functions $W_1$ and $W_2$ by

$$\frac{d^2\sigma}{dQ^2d\nu} = 4\pi\alpha^2 \frac{E_e'}{Q^4} \left[ W_2(\nu, Q^2)(\cos\theta_e/2)^2 + 2W_1(\nu, Q^2)(\sin\theta_e/2)^2 \right]. \quad (2.1)$$

This expression can be rewritten with the help of the Mott scattering cross-section $\sigma_{Mott}$ for the elastic scattering of an electron from a spinless unpolarized object. The structure functions measure the departure from point-like proton structure and contain all the information that can be obtained about the proton in this process.

$$\frac{d^2\sigma}{dQ^2d\nu} = \sigma_{Mott}[W_2(\nu, Q^2) + 2W_1(\nu, Q^2)(\tan\theta_e/2)^2]. \quad (2.2)$$

The differential cross-section can also be expressed in terms of the absorption of transversely ($\sigma_T$) and longitudinally polarized ($\sigma_L$) virtual photons as

$$\frac{d^2\sigma}{dQ^2d\nu} = \Gamma(\epsilon\sigma_L + \sigma_T). \quad (2.3)$$
The flux of transverse virtual photons is given by $\Gamma$, and $\epsilon$ measures longitudinal polarization\(^6\). The absorption cross-sections are related to the structure functions by

\[
\sigma_L = \frac{4\pi\alpha^2}{\sqrt{\nu^2 - Q^2}} [W_2(1 + \nu^2/Q^2) - W_1],
\]

(2.4)

\[
\sigma_T = \frac{4\pi\alpha^2}{\sqrt{\nu^2 - Q^2}} W_1.
\]

(2.5)

The quantity $R$ is defined by

\[
R = \frac{\sigma_L}{\sigma_T} = \frac{W_2}{W_1} (1 + \nu^2/Q^2) - 1.
\]

(2.6)

### 2.3 Parton model

The first results from SLAC inelastic measurements showed two prominent and unexpected features. The measured inelastic cross-section decreased more slowly with $Q^2$ than elastic scattering at constant $W$ and the data appeared to scale, i.e. in the limit of large $\nu$ and $Q^2$, the quantities $2M_p W_1$ and $\nu W_2$ depended only on the ratio $x$ and not separately on $Q^2$ and $\nu$;

\[
2MW_1(\nu, Q^2) = F_1(x)
\]

(2.7)

\[
\nu W_2(\nu, Q^2) = F_2(x).
\]

(2.8)

J.D. Bjorken suggested that deep inelastic electron proton scattering might give an indication of point-like constituents inside the proton. Feynman formulated the parton model to explain these results. He assumed that protons

\(^6\) $\Gamma$ and $\epsilon$ are further discussed in chapter 10.
are made up of point-like constituents called partons. The struck parton is assumed to be quasi-free during its interaction with the electron. The structure function \( F_2 \) is interpreted as the momentum distribution\(^c\) of the partons \( q_i(x) \) weighted by the squares of their charges \( e_i^2 \)

\[
F_2(x) = x \sum_i e_i^2 q_i(x). \tag{2.9}
\]

Later, partons were interpreted as quarks\(^2\) which Gell-Mann had already suggested as constituents of nucleons. In 1968 C. Callan and D. Gross\(^3\) showed that \( R \) defined in equation 2.6 is related to the spin of the parton constituents and that the structure functions are related by

\[
2xF_1(x) = F_2(x), \tag{2.10}
\]

if the spin of the constituents is 1/2. In the quark-parton model the proton is composed of three valence quarks in a sea of low \( x \) \( q\bar{q} \) pairs and gluons which are responsible for binding the valence quarks inside the proton. The \( u \) and \( d \) quark distributions can be written as

\[
u(x) = u_v(x) + u_s(x) \tag{2.11}
\]

\[
d(x) = d_v(x) + d_s(x), \tag{2.12}
\]

where subscript \( v \) or \( s \) indicates the contribution of valence or sea quarks and \( u(x) = u_v(x) \) and \( d(x) = d_v(x) \). The proton structure function can then be

\(^c\)The momentum distribution \( q_i(x) \) of a parton is the probability of finding a parton of type \( i \) carrying a fraction \( x \) of the nucleon's momentum.
written as

\[ F_2^p(x) = x\left[ \varepsilon_u^2 (u(x) + u(x)) + \varepsilon_d^2 (d(x) + d(x)) \right], \quad (2.13) \]

and similarly for the neutron structure function. Consider

\[ \frac{1}{2} \int_0^1 [F_2^p(x) + F_2^n(x)] = \frac{\varepsilon_u^2 + \varepsilon_d^2}{2} \int_0^1 x[u(x) + u(x) + d(x) + d(x)]. \quad (2.14) \]

The integral on the right-hand side is the total momentum fraction carried by quarks and antiquarks, and should be equal to 1 assuming that they carry all the nucleon’s momentum. However, from SLAC proton and neutron inelastic experiments this sum was found to be approximately 0.5. Later, the missing momentum was attributed to the gluons which hold the quarks together.

## 2.4 QCD improved parton model

In the naive quark model, processes where gluons are radiated from quarks are neglected. The contribution from \( g \to q\bar{q} \) is also ignored. In the QCD improved parton model, parton distributions acquire a \( Q^2 \) dependence \( q_i(x) \to q_i(x, Q^2) \) due to these processes. This implies that the structure functions no longer scale. This scale breaking was observed in subsequent lepton scattering experiments which revealed a slight variation of the structure functions with increasing \( Q^2 \) at constant \( x \). Gluon emission is also observed experimentally.
The DGLAP\textsuperscript{4} equations describe how the quark and gluon number densities change with $Q^2$ due to the QCD processes. The equations are

$$\frac{dq_i(x, Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int x z \left[ p_{qq}(x/z) q_i(z, Q^2) + p_{qg}(x/z) g(z, Q^2) \right], \quad (2.15)$$

$$\frac{dg(x, Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int x z \left[ \sum_j p_{gq}(x/z) q_j(z, Q^2) + p_{gg}(x/z) g(z, Q^2) \right], \quad (2.16)$$

where $q_i(x, Q^2)$ and $g(x, Q^2)$ are quark and gluon distribution functions. The splitting function $p_{ab}(x/z)$ describes the probability for a parton ‘b’ carrying momentum fraction $z$ to emit another parton ‘a’ with a fraction $x/z$ of the parent parton momentum. Recalling that the transverse coordinate resolution of the virtual photon varies as $Q^{-1}$, the DGLAP equations can be interpreted as the change in quark and gluon densities of the nucleon as one changes the spatial resolution of the probe. A quark which is point-like at a scale $1/Q$ may be seen as a quark and a gluon at a finer momentum scale. At very small values of $x$, these number densities grow rapidly with $Q^2$.

### 2.5 Diffraction

Diffraction is a peripheral collision of particles where the quantum numbers of the initial and the final states for each particle are the same. Diffraction includes the elastic process where the target (the proton in the case of e-p scattering) is in the identical state after the reaction, and inelastic processes where the proton could fragment or go into an unstable excited state with the same quantum numbers. Diffraction is said to occur through the exchange
of a pomeron, a particle with vacuum quantum numbers. The pomeron can be viewed as a 'Reggion' as explained below.

When one considers the angular momentum of composite states (i.e. resonances) with the same number of nodes in their radial wave function, for example: \( ^3S_1(770) \), \( ^3P_2(1320) \), \( ^3D_3(1690) \), etc as a function of mass it is found that they lie on a straight line. The radial equation can in fact be solved for non-integer angular momentum \( J \) considered as a continuous function of mass. The function \( J(M^2) \) is called the Regge trajectory of this set of resonances. For example, Fig. 2.2 shows the angular momentum of the \( \rho \) and \( \omega \) families of resonances versus their mass squared, \( t \). They lie on a straight line of equation

\[
\alpha(t) = 0.55 + 0.86t. \tag{2.17}
\]

This straight line can be extrapolated to negative values of \( t \) where \( t \) is then interpreted as the momentum transfer in virtual particle exchange. The contribution of the exchange of the particles of a family to elastic scattering amplitudes is then

\[
T(s, t) \approx \beta(t)s^{\alpha(t)}\xi_{\alpha(t)}, \tag{2.18}
\]

where \( \sqrt{s} \) is the center of mass energy, \( \beta(t) \) is an unknown real function and \( \xi_{\alpha(t)} \) is a phase dependent upon the slope of the 'Regge trajectory'. The optical theorem in turn relates the total cross-section to \( s^{-1} \) times the imaginary part of the forward scattering amplitude which includes contributions from all exchanged particle families.
Figure 2.2: The Regge trajectories for the $\rho$ and $\omega$ families as well as soft and hard pomerons are shown. The glueball candidate from WA91 is also shown in the figure.
The $\rho, \omega, a_2, f_2$ families have $\alpha(0) = 1/2$ which means that Regge theory predicts a falling total cross-section as a function of center of mass energy. But experiment finds a rising cross-section. The concept of the pomeron was introduced to explain this. Figure 2.3 shows $pp$ and $p\bar{p}$ total cross-sections with fits using contributions from both the pomeron and other particle families. The pomeron contribution is found to be $\alpha(t) \approx 1.08\alpha(0) + 0.25t$. This pomeron cannot be described by simple perturbation theory and is interpreted as arising from soft gluon exchange. This is supported by the fact that the glueball candidate from WA91$^5$ lies on the soft pomeron trajectory.

Such a soft pomeron trajectory, however, fails to describe the recently measured energy dependences of the cross-sections at HERA for elastic $J/\psi$ photoproduction$^8$ and the elastic electroproduction of $\rho^0$ mesons$^9,10$ at large values of $Q^2$. It also fails to describe the inclusive DIS diffractive cross-section.$^{11}$ Indeed, recent results at HERA on the small-x behavior of $F_2$ and elastic $\rho^0$ electroproduction indicate the existence of a 'hard' pomeron contribution. Estimates of $\alpha(0)$ for the hard pomeron vary from 1.3 to 1.5. The hard pomeron is purely perturbative and its trajectory can be obtained by solving the BFKL equation.$^{12}$ However, Cudell et al$^{13}$ have argued that experimentally there is no significant BFKL pomeron contribution for the soft processes, hence its magnitude in a hard process is constrained and perhaps undetectable. They further assert that while the power of W predicted by the BFKL equation can fit the observed behavior in recent HERA data, the magnitude of the constant that multiplies it is too small. A further
Figure 2.3: A fit of $pp$ and $p\bar{p}$ total cross-sections using contributions from both the pomeron and other particle families. The pomeron contribution is found to be $\alpha(t) \approx 1.08\alpha(0) + 0.25t$. This figure is from [6].
A discussion is given in chapter 10 where a similar behavior is found for elastic $\phi$ electroproduction.
Chapter 3
Models of Elastic Vector Meson Electrorroduction

The elastic vector meson electroproduction reaction is
\[ e \ (\text{or } \mu) + p \rightarrow e' \ (\text{or } \mu') + V + p, \] (3.1)
where \( V \) represents any possible neutral vector meson (\( \rho^0, \omega, \phi, J/\psi, \Upsilon \) etc).
The occurrence of this reaction can be explained using an electroweak propagator but the calculated cross-section for such a process is far less than is observed experimentally. Exchange of a quark or a gluon is ruled out by confinement and the lack of color string fragmentation, respectively. The latter implies the exchanged object is a color singlet. It could be a neutral meson or the previously mentioned pomeron. The slow rise in the \( \rho^0 \) photoproduction cross-section with \( W \), the \( \gamma p \) centre of mass energy, indicates that the pomeron exchange dominates. Thus one expects reaction 3.1 to proceed as shown in Fig. 3.1. This chapter describes the general kinematic variables and presents a review of data on elastic vector meson electroproduction and the \( \phi/\rho^0 \) electroproduction ratio. It also summarizes the models of this reaction.
Figure 3.1: Schematic diagram of exclusive $\phi$ production in deep inelastic $e^+p$ interactions.

### 3.1 General kinematic variables

Fig 3.1 shows the Feynman diagram of elastic vector meson electroproduction via pomeron exchange for the case of $\phi$:

$$e^+(k) + p(P) \rightarrow e^+(k') + \phi(V) + p(P'). \quad (3.2)$$

The $\phi$ decay into $K^+K^-$ is also shown. The general kinematic variables, some of which have already been discussed, are the following: the negative of the squared four-momentum transfer carried by the virtual photon$^a$

$$Q^2 = -q^2 = -(k - k')^2, \quad (3.3)$$

$^a$In the $Q^2$ range covered by this data sample, $ep$ interactions are described to sufficient accuracy for this analysis by the exchange of a single virtual photon.
where \( k \) (\( k' \)) is the four-momentum of the incident (scattered) electron; the Bjorken variable

\[
x = \frac{Q^2}{2P \cdot q},
\]

(3.4)

where \( P \) is the four-momentum of the incident proton; the variable which describes the energy transfer to the hadronic final state

\[
y = \frac{q \cdot P}{k \cdot P},
\]

(3.5)

\( W \), the center of mass energy of the \( \gamma^* p \) system,

\[
W^2 = (q + P)^2 = \frac{Q^2 (1 - x)}{x} + M_p^2,
\]

(3.6)

where \( M_p \) is the proton mass; and \( \sqrt{s} \), the center of mass energy of the \( ep \) system,

\[
s = (k + P)^2 \approx yW^2.
\]

(3.7)

An extra variable is also needed:

\[
t' = |t - t_{\text{min}}|
\]

(3.8)

where \( t \) is the four-momentum transfer squared, \( t = -(q - v)^2 = -(P - P')^2 \), to the vector meson (with four-momentum \( v \)) from the photon (with four-momentum \( q \)) and \( t_{\text{min}} \) is the minimum kinematically allowed value of \( t \). The squared transverse momentum \( p_T^2 \) of the \( \phi \) with respect to the photon direction is a good approximation to \( t' \) since it is, in general, small (\( \leq 1 \text{ GeV}^2 \)).

For the analysis presented here \( t_{\text{min}} \) ranges from \(-0.0006 \) to \(-0.08 \text{ GeV}^2 \).
The vector meson helicity decay angular distribution \( H(\cos \theta_h, \phi, \Phi) \) can be used to identify the vector meson spin state. \(^{14}\) Here \( \theta_h \) and \( \phi \) are the polar and azimuthal angles of the \( \pi^+ \) in the vector meson center of mass system and \( \Phi \) is the azimuthal angle of the vector meson production plane with respect to the electron scattering plane. The quantization axis is defined as the vector meson direction in the \( \gamma^* p \) center of mass system. Only the \( \cos \theta_h \) dependence is presented here. After integrating over \( \phi \) and \( \Phi \), the decay angular distribution can be written as

\[
\frac{d\sigma}{d(\cos \theta_h)} = \frac{3}{4} [1 - r_{00}^{04} + (3r_{00}^{04} - 1) \cos^2 \theta_h],
\] (3.9)

where \( r_{00}^{04} \) is one of the vector meson density matrix elements and represents the probability to produce a longitudinally polarized vector meson by either transversely or longitudinally polarized photons.

### 3.2 Review of data on elastic vector meson electroproduction

The elastic photoproduction of \( \phi \) mesons, \( \gamma p \rightarrow \phi p \), has been studied in fixed target experiments \(^{15} - ^{17}\) and at HERA \(^{18}\) for photon-proton centre of mass energies \( (W) \) up to 70 GeV. For \( W > 10 \) GeV, the reaction \( \gamma p \rightarrow \phi p \) displays the characteristics of a soft diffractive process: \( s \)-channel helicity conservation, a cross-section rising weakly with \( W \) and an exponential \( t \) dependence. \(^{4}\) Elastic electroproduction of \( \rho^0 \) mesons shows similar characteristics. For a review see [9] and references therein.
(where \( t \) is the four-momentum transfer squared at the proton vertex) with a slope \( b(W) \) which is also increasing slowly with \( W \). Soft diffraction can be described by the exchange of a 'soft' pomeron Regge trajectory \( \alpha(t) = \alpha(0) + \alpha' t \) with an intercept \( \alpha(0) = 1.08 \) and slope \( \alpha' = 0.25 \text{ GeV}^{-2} \). The intercept is determined from fits\(^{19} \) to hadron-hadron total cross-sections. The same intercept also describes the energy dependence of the photon-proton total cross-section\(^{20} \). In addition, soft diffraction and the Vector Dominance Model\(^{15} \) can describe the energy dependence of both \( \phi \)\(^{18} \) and \( \rho^0 \)\(^{21} \) elastic photoproduction at HERA energies.

In contrast, the soft pomeron fails to describe the recently measured energy dependences of the cross-sections at HERA for elastic \( J/\psi \) photoproduction\(^8 \) and elastic \( \rho^0 \) electroproduction\(^9,10 \) at large values of \( Q^2 \). It also fails to describe the inclusive DIS diffractive cross-section\(^{11} \). The rapid rise with energy of the cross-sections for exclusive vector meson production is consistent with recent perturbative QCD (pQCD) calculations\(^{22 -- 24} \) in which the pomeron is treated as a perturbative two-gluon exchange. In such calculations, the large scale needed to justify the use of perturbation theory may be the mass of the vector meson for \( J/\psi \) photoproduction,\(^{22} \) the \( Q^2 \) for elastic \( \rho^0 \) or \( \phi \) electroproduction,\(^{23} \) or a large value of \( t. \)\(^{24} \)

From the quark charges of the vector mesons and a flavor independent production mechanism, the ratio \( \sigma(\phi)/\sigma(\rho^0) \) of exclusive production cross-sections is expected to be \( 2/9. \)\(^{52} \) The pQCD prediction increases from
2/9 to 2.4/9.0 at asymptotically large $Q^2$. Experimentally, for photoproduction the ratio is found to be $0.076 \pm 0.010$ at $W = 17 \text{ GeV}$ and $0.065 \pm 0.013$ at 70 GeV. At larger $Q^2$, NMC has determined that $\sigma(\phi)/\sigma(\rho^0)$ is $\approx 0.1$ for $2 < Q^2 < 10 \text{ GeV}^2$. The NMC measurements are for $W \approx 15 \text{ GeV}$. Thus for the regime of $Q^2$ and $W$ of these experiments, the ratio is not consistent with a flavor independent production mechanism. It is of interest to determine this ratio at both large $Q^2$ and large $W$.

This thesis is a measurement of the exclusive cross-section for $\phi$ mesons produced at large $Q^2$ (7-25 GeV$^2$) by the process $\gamma^* p \rightarrow \phi p$ at HERA. This $Q^2$ corresponds to a lower region in Bjorken $x$ ($4 \cdot 10^{-4} < x < 1 \cdot 10^{-2}$) or, equivalently, a higher $W$ region (42-134 GeV) than any previous measurement of this process. This thesis also measures the $\phi/\rho^0$ production ratio in the same region of phase space.

### 3.3 Models for electroproduction of vector mesons

This process is the only fully calculable exclusive process in QCD. All models describing diffractive vector meson production assume pomeron exchange with the pomeron treated as a pair of gluons. (A color singlet single gluon is unphysical). The models range from perturbative gluon exchange to non-perturbative approaches. They also differ in the description of the
intermediate $q\bar{q}$ pair and the vector meson wave function. The various models are briefly described here.

**Donnachie and Landshoff model:** The Donnachie and Landshoff soft pomeron model is a consequence of non-perturbative gluon exchange applied to $\rho^0$ or $\phi$ electroproduction. The relevant diagrams are those of Fig. 3.2, applicable for $0 \leq t \leq 1$ GeV$^2$. The two diagrams tend to cancel at large $Q^2$ and together give a factor of $1/Q^2$ in the amplitude. The energy dependence, $(W^2)$, has to be put in by hand. A more refined model, shown symbolically in Fig. 3.3, is to introduce the complete $ggqq$ amplitude which results in the lower amplitude being approximately the gluon structure function. This is done in the model we discuss next.

**Brodsky, et al model:** This model calculates the forward cross-section for diffractive leptoproduction of vector mesons in terms of the light-cone $q\bar{q}$ wavefunction of the vector meson and the gluon distribution of the target.

---

**Figure 3.2:** Simple model for $\gamma^* p \rightarrow V_0 p$
using perturbative QCD. The calculations are in the leading \( \ln (1/x) \) and leading \( \ln (Q^2/\Lambda_{QCD}^2) \) limit. The model assumes \( s/m_V^2 \gg 1, \ s/Q^2 \gg 1, \ -t \ll Q^2, \ Q^2/\Lambda_{QCD}^2, \) and \( Q^2/m_V^2 \gg 1. \) (See table 2.1 for definitions of kinematic quantities).

The differential cross-section for vector meson production is

\[
\frac{d\sigma_{\gamma^* N \rightarrow V N}}{dt} \bigg|_{t=0} = \frac{12 \pi^2 \Gamma_{ee} m_V \alpha_s^2(Q) \eta_V^2 \ I_V(Q^2)^2 \ xG(x, Q^2) + i \frac{\pi}{\sqrt{\alpha}} \frac{\partial}{\partial \ln x} xG(x, Q)^2}{\alpha Q^6 N_c^2}.
\]  

(3.10)

The parameter \( \eta_V \) is defined as

\[
\eta_V = \frac{1}{2} \int dz \Phi_V(z),
\]

(3.11)

where \( \Phi_V \) is the light-cone wave function of the vector meson. \( I_V(Q^2) \) arises from the transverse momentum overlap intergral between the light-cone wave function of the \( \gamma^*_L \) and that of the vector meson. 

In Eq. 3.10, \( \Gamma_{ee} \) is the decay width of the vector meson into \( e^+e^- \), \( \alpha \) is the fine structure constant, \( N_c \) is the number of colors, \( xg(x, Q^2) \) is the momentum density of the gluon in the proton, and \( m_V \) is the mass of the vector meson.
This result is for a longitudinally polarized photon to produce a longitudinally polarized vector meson. It is not spin averaged over initial photon states. The $Q^{-6}$ dependence of the cross-section is a prediction of the model for longitudinally polarized photons. For $Q^2 \gg m_V^2$, the above equation predicts the cross-section ratio of vector mesons:

$$R(V_1, V_2) \equiv \left. \frac{\frac{d\sigma(\gamma p \rightarrow V_1 + N)}{dt}}{\frac{d\sigma(\gamma p \rightarrow V_2 + N)}{dt}} \right|_{t=0} = \frac{\Gamma_{V_1} m_{V_1} \eta_{V_1}^2}{\Gamma_{V_2} m_{V_2} \eta_{V_2}^2}. \quad (3.12)$$

It can be seen from Eq. 3.12 that $R(\phi, \rho) \sim 1.0 \times e_\phi^2(\phi)/e_\rho^2(\rho)$ for $\eta_\phi/\eta_\rho \sim 0.9^{31}$ and $R(J/\psi, \rho) \sim 1.2 \times e_\psi^2(J/\psi)/e_\rho^2(\rho)$ for $\eta_{J/\psi}/\eta_\rho = 2$. The effective charge squared for standard SU(3) wave functions might naively be expected to determine the $R$'s ($e_\phi^2(\phi) = 1/2, 1/18, 1/9, 4/9$ for the $\rho, \omega, \phi, \Psi$ respectively). This gives $R(\phi, \rho) \sim 2/9$.

Another prediction is that the $t$ dependence of the process is universal. The upper part of the amplitude corresponding to $\gamma^* \rightarrow V$ is effectively dipole-like at large $Q^2$ and depends only weakly on $t$ for $-t \ll Q^2$. The $t$-dependence is due to the two-gluon coupling to the scattered proton and is determined by a universal two-gluon form factor, independent of the vector meson type.

**Ryskin model:** The model by Ryskin$^{22}$ also describes diffractive vector meson production in terms of exchange of a colorless two-gluon system. The Feynman diagram for the process is shown in Fig. 3.2 with the two gluon system replaced by a gluon ladder. The cross-section is calculated in the
leading-log approximation and the result is

$$
\frac{d\sigma(\gamma^* N \rightarrow V N)}{dt} = \left[ F_{NN}^{2G}(t) \right]^2 \frac{G_1^2}{3\alpha_{em} m_V^3} \pi^3 \left[ \bar{x} G(\bar{x}, \bar{q}^2) \frac{2q^2 - p_{tV}^2}{(2q^2)^3} \right]^2 (1 + \frac{Q^2}{m_V^2}),
$$

(3.13)

where

$$
\bar{x} = \frac{m_V^2 + Q^2 + p_{tV}^2}{W^2},
$$

and

$$
\bar{q}^2 = \frac{m_V^2 + Q^2 + p_{tV}^2}{4},
$$

and $p_{tV}$ is the transverse momentum of the $V$ with respect to the $\gamma$. In this model, $2\bar{x}$ is the fraction of the proton’s momentum carried by the two gluons and $-4\bar{q}^2$ their momentum. The function $F_{NN}^{2G}$ is a form factor characterizing the correlation between two gluons in the proton. This is a new function to be measured experimentally. For a rough estimate, the electro-magnetic form factor $F_{NN}^{em}(t) = (1 - t/\cdot71)^{-2}$ can be used. This model also predicts that longitudinally polarized photons producing longitudinal vector mesons is the dominant part of the cross-section.
Chapter 4

HERA, a Positron - Proton Collider

HERA is the only electron (positron) - proton collider in the world. It is built in a 6.336 km tunnel, 10-25 meters under a city park in Hamburg, Germany. The layout of the HERA collider ring is shown in Fig. 4.1. There are four possible collision points, located in halls East, West, North and South in the picture. The data for this analysis was taken by the ZEUS detector at one of the collision points (South) during the year 1994 using a positron beam. A competing general purpose experiment H1, a spin experiment HERMES, and a fixed target experiment HERA-B are situated in the other halls.

4.1 The positron and proton beams

The HERA injection scheme is shown in Fig 4.1. Linac II accelerates positrons (or electrons) to 500 MeV. The positrons are then transferred into a small storage ring PIA until the current per bunch is 60 mA. After DESY II accelerates them to 7 GeV, the bunches are transferred into PETRA which
Figure 4.1: The HERA collider layout and injection scheme.
stores them until 70 bunches are obtained. They are then accelerated to
14 GeV and injected into HERA.

To obtain the proton beam, $H^-$ ions are accelerated to 50 MeV in a linac. They are stripped of the electrons and the protons collected into bunches in DESY III, accelerated to 7.5 GeV and transferred to PETRA. After PETRA collects 70 bunches they are accelerated to 40 GeV and injected into HERA. Protons and positrons in HERA are contained in separate magnetic systems. The proton beam energy is determined by the magnetic field provided by the superconducting magnets (4.5 T) which must contain the protons in an orbit within the tunnel. The maximum positron energy is determined by the capacity of the radio frequency cavities to replenish the energy lost due to the synchrotron radiation. The design values for the proton and positron beam energies are 820 GeV and 30 GeV respectively. The 1994 values are 820 GeV and 27.52 GeV, respectively, giving a center of mass energy, $\sqrt{s}$, of 300 GeV. The design parameters of HERA are shown in table 2.1.

Close to the interaction region, the protons are deflected using guiding magnets into the same orbit as the positrons. After passing the interaction point they are brought back into the proton ring. The collision region is about 40 cm long mainly determined by the proton beam length in the beam direction.
Table 4.1: Some HERA design parameters

<table>
<thead>
<tr>
<th>General Parameters of HERA</th>
<th>Positron</th>
<th>Proton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal energy</td>
<td>30 GeV</td>
<td>820 GeV</td>
</tr>
<tr>
<td>Center of mass energy</td>
<td>314 GeV</td>
<td></td>
</tr>
<tr>
<td>Injection energy</td>
<td>14 GeV</td>
<td>40 GeV</td>
</tr>
<tr>
<td>Bunch current</td>
<td>60 mA</td>
<td>160 mA</td>
</tr>
<tr>
<td>Number of bunch buckets</td>
<td>220</td>
<td>220</td>
</tr>
<tr>
<td>Maximum number of bunches</td>
<td>210</td>
<td>210</td>
</tr>
<tr>
<td>Beam crossing angle</td>
<td>head on</td>
<td></td>
</tr>
<tr>
<td>Bunch distance</td>
<td>28.8 m (96 ns)</td>
<td></td>
</tr>
<tr>
<td>Bunch length at maximum energy</td>
<td>7.8 mm</td>
<td>110-150 mm</td>
</tr>
<tr>
<td>Beam width at interaction points</td>
<td>.3 mm</td>
<td>.32 mm</td>
</tr>
<tr>
<td>Beam height at interaction points</td>
<td>.04 mm</td>
<td>.1 mm</td>
</tr>
<tr>
<td>Filling time</td>
<td>15 min</td>
<td>20 min</td>
</tr>
</tbody>
</table>

A large number of bunches and a short bunch crossing interval are required to achieve high luminosity. This presents a unique challenge for data acquisition systems.
4.2 Data taking

The proton beam is filled first because proton filling takes a longer time and the proton beam has a longer lifetime. Then the positrons are filled. Each proton fill can have one or more positron fills. When the proton and positron beams are focussed and brought into collision it is called the luminosity period and the experiments can take data. The point of collision is called the interaction point. When the positron beam has decayed substantially so that the luminosity delivered is low, the positron beam is dumped and a new positron beam is filled. When the proton beam has decayed, then both positron and proton beams are dumped and filled again.

A ZEUS run is a period of uninterrupted data taking. A run can last one positron fill. However, problems with data acquisition or the detector can result in two or more runs being taken in a single fill. The beam conditions during a given luminosity period are usually stable. However, they may vary from fill to fill and this is taken into account in this analysis. The nominal interaction point is taken to be \((0,0,0)\) in the ZEUS coordinate system. There is a spread around this point due to the finite size of the beams. The size in the beam direction has a Gaussian shape with a sigma of a few tens of cm. The transverse spread of the beams is around 200 microns.
4.3 Bunch structure of the beams

The positron and proton beams are not continuous but are pulsed. Each pulse is called a bunch and the position of the bunch is called a bucket. There are 220 buckets at HERA separated by 96 ns or 28.8 m giving a bunch crossing rate of 10.4 MHz. In 1994 HERA filled 170 proton and 168 positron bunches. Of these 153 are paired, i.e. positron and proton bunches collide. The others are called pilot bunches and are used to estimate beam related backgrounds. There are 15 positron pilot bunches and 17 proton pilot bunches. The proton bunch length varied between 12-18 ns. The beam currents are typically 45 – 50 mA and 20 – 30 mA respectively for protons and positrons.

4.4 Expected luminosity

In the approximation that all bunches have the same transverse size, the expected luminosity is given by

\[
L_{\text{expected}} = \frac{f \sum_{\text{all bunches}} N^i_e N^i_p}{2\pi \sqrt{\sigma_{zp}^2 + \sigma_{ze}^2 \sqrt{\sigma_{yp}^2 + \sigma_{ye}^2}}},
\]

where \( f \) is the revolution frequency of HERA and is 47.317 kHz, \( N^i_e \) and \( N^i_p \) are the number of positrons and protons in bunch \( i \) and \( \sigma_{jb} \) is the rms transverse size in coordinate \( j \) for beam \( b \). Assuming the number of particles

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
in each bunch is the same, and using the currents of the beams, we obtain

\[ L_{\text{expected}} = \frac{I_e I_p}{2 \pi f e^2 \sqrt{\sigma_{zp}^2 + \sigma_{zp}^2 \sqrt{\sigma_{yp}^2 + \sigma_{yp}^2}}}. \]  

(4.2)

\(I_e\) and \(I_p\) are functions of time even within a fill because the beam currents decay with time. Different fills can also have different currents. The peak specific luminosity at HERA is designed to be \(10^{-29}\) cm s\(^{-1}\). The 1994 value was \(10^{-30}\) cm s\(^{-1}\).

### 4.5 Satellite bunches

The satellite bunches come from harmonics of the main RF frequency in the proton machine. The normal operation of the machine is at an RF frequency of 52 MHz. But if this frequency were to be used at ramp time, the bunch length would be very long. Therefore, in order to "squeeze" the bunch, a harmonic of the main frequency (208 MHz) is used. The control is not perfect, so some protons actually get filled in the buckets for this frequency, \(ie\) 5 ns away from the main bunch. So we have several residual bunches at 5 ns intervals from the main bunch at run time. The collision of the satellite bunch with the positron bunch occurs at a distance of about 75 cm from the nominal interaction point. The satellite bunches contribute to the experimental measurement of the luminosity.
4.6 Backgrounds at HERA

There is a constant cosmic ray background to the experiments at HERA. In addition there are beam related backgrounds due to collisions of the proton and electron beams with the few remaining gas molecules in the beam-pipe (beam - gas event). Finally particles in the tails of the beams can collide with the beam pipe, magnets, collimators or other elements of the beamline (beam scraping background). Beam scraping far from the collision point can produce muons that accompany the proton beam. These are halo muons and can be several meters from the beam axis.

4.7 Performance of HERA

In 1994 HERA started operation with electrons. Because of problems with backgrounds, HERA switched to positrons. Positrons can repel the heavy ions that accumulate near the entrance and exit ports of dipole magnets and cause bad background conditions. In 1994 HERA delivered 6.186 nb⁻¹ of data in 474 runs including 5.106 nb⁻¹ in 346 runs with positrons. Fig. 4.2 shows the integrated luminosity collected by ZEUS as a function of time.
Figure 4.2: The luminosity delivered by HERA as a function of time.
Chapter 5

ZEUS - the Detector

The analysis of particle reactions requires a knowledge of the four momenta and identity of the particles produced. Particle detectors are instruments that measure these quantities. A particle going through a device can be detected only if it interacts with the device in some way. For example, a particle going through superheated liquid produces bubbles along its path. At higher energies and multiplicities it is contrived to get electrical signals from the detector which are then automatically read out and stored electronically. Modern experiments are multipurpose and hence are a hybrid of various parts which use different principles for detection of particles and which may measure different quantities such as position, time, energy and momentum.

ZEUS is a detector for studying positron-proton collisions at HERA. Unlike existing $e^+e^-$ or $p^+p^-$ colliders the $e^+p$ collider at HERA has a moving center of mass frame. As a result, large energy flow takes place in the proton direction. The geometry of the detector reflects the energy asymmetry in the
Figure 5.1: The longitudinal and the transverse views of the ZEUS detector.
lab frame. It is thicker in the proton direction. The detector is designed to handle a wide range of energies. Fig. 5.1 shows longitudinal and transverse views of the ZEUS detector. The detector is made as hermetic as possible to detect all the particles produced. However, the proton remnant or the proton (in the case that it doesn't break-up), low angle positrons and occasionally other particles can escape down the beampipe. The various parts of the detector used in the current analysis are described next.

5.1 The veto wall and C5 counter

The veto wall is situated 7.5 m upstream of the interaction point. It consists of an iron wall and two scintillator hodoscopes on both sides of the wall with a hole for the beam. It absorbs some background particles and vetos events produced by particles passing through the wall. The veto wall helps to reduce beam-gas events, beam scraping events and halo muons that accompany the beam.

The C5 detector, made of four scintillation counters, surrounds the beampipe in the area of the collimating magnet (called C5) at the rear side of the RCAL detector at a distance of roughly 315 cm from the interaction point.

---

*The ZEUS Coordinate System has its origin at the nominal interaction point, the z-axis along the nominal proton beam direction (this is anticlockwise around HERA when viewed from above), the x-axis horizontal and directed towards the center of HERA and the y-axis normal to the z-x plane (pointing to the sky).*
point. The signals from this detector can be used to veto background events arising from beam halo particles traveling close to the beam line. Measurements of the time distributions of particles that orbit along with the proton and positron bunches but outside the ring allow the determination of bunch structure and timing.

5.2 Luminosity monitor

Luminosity is measured through detection of hard photon bremsstrahlung, $ep \rightarrow e' \gamma$. The final state positron and photon are emitted at very small angles with respect to the initial positron direction and are detected in coincidence. The cross-section for the bremsstrahlung process integrated over angles is given by the Bethe-Heitler formula\textsuperscript{32}:

$$\frac{d\sigma}{dk} = 4\alpha r_e^2 \frac{E'}{kE} \left( \frac{E}{E'} + \frac{E'}{E} - \frac{2}{3} \right) \left( \ln \frac{4E_pEE'}{Mmk} - \frac{1}{2} \right),$$

where $k$ is photon energy, $E$ and $E'$ are the primary and secondary positron energies respectively, $E_p$ is the proton energy, $M$ (m) is the mass of proton (positron) and $r_e$ is the classical radius of the electron.

The rate for this process at full HERA luminosity is approximately 50 kHz. The radiative corrections are small, approximately 0.3%.

The luminosity monitor (LUMI) consists of a $\gamma$ detector close to the proton beam pipe at a distance of 106 m from the interaction point and a
Figure 5.2: The layout of the luminosity detector

positron detector near the positron beam at a distance of 34.7 m. The energy resolution of the $\gamma$ detector is $\sigma(E_\gamma) = 0.18/\sqrt{E_\gamma}$ with $E_\gamma$ measured in GeV and the position is measured to better than 3 mm. The acceptance for the $\gamma$ detector is 98 \% for photons with $E_\gamma > 5$ GeV and emitted collinearly with the positrons. The positron detector is a lead-scintillator calorimeter. The acceptance is approximately 70\% for positrons in the energy range $0.35E_e$ to $0.65E_e$. 

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
5.3 Calorimeter

The calorimeter measures the energies of particles by total absorption. The incident particle interacts in the detector generating secondary particles that interact to produce tertiary particles and so on until most of incident energy appears as ionization or excitation energy in the medium. This is called a shower. In ZEUS only a part of the shower is sampled and the calorimeter is calibrated using test beams of known energy. Calorimeters can give information quickly about the energy deposited and at ZEUS this information is used in the online event selection (trigger).

Construction of ZEUS calorimeter: The calorimeter consists of interleaved plates of depleted uranium as absorber and plastic scintillator as active material. The scintillator is read out on two sides by wavelength shifter bars, light guides and photomultipliers. The uranium radioactivity provides a stable calibration signal which is used to transport the absolute energy scale from tests to the experiment and provide long term calibration and monitoring. The choice of scintillator and photomultipliers for readout results in pulses much shorter than the bunch crossing time of 96 ns and thus avoids pile-up effects. The timing of the pulses can be determined to the accuracy of a nanosecond. This helps in suppression of the cosmic ray background. The calorimeter is designed to achieve compensation and the best possible energy resolution for hadrons. Compensation means that the calorimeter produces equal signals, on average, for equal energy hadrons and
electrons\((e/h = 1)\). Compensation is achieved through optimum detection of neutrons produced in nuclear breakup. The \(e/h\) can be tuned by varying the ratio of the scintillator thickness to the absorber thickness. A \(e/h\) ratio of 1 helps to minimize the systematic error in the energy and hence in kinematic measurements. This is achieved for absorber plate thicknesses of one radiation length (3.3 mm), at a scintillator thickness of 2.6 mm. The hadronic energy resolution is \(35\%/\sqrt{E}\); while the electro-magnetic energy resolution is \(18\%/\sqrt{E}\).

**Calorimeter geometry:** The calorimeter is divided into three sections: the forward (FCAL), barrel (BCAL) and rear (RCAL) calorimeters. RCAL and FCAL are segmented in the x-y coordinates while the BCAL is segmented approximately in \(z-\phi\). The basic readout unit is a tower. It has a cross-section of 20 x 20 cm. It is divided longitudinally into one electro-magnetic (EMC) and two (one) hadronic (HAC) sections in FCAL and BCAL(RCAL). Each EMC section is subdivided into 4 cells in FCAL and BCAL and 2 in RCAL. HAC sections are not subdivided. The depth of EMC cells is 25 radiation lengths corresponding to one interaction length \((\lambda \approx 22\,\text{cm})\). Each HAC section has a depth of 3\(\lambda\) for FCAL and RCAL and 2\(\lambda\) for BCAL.

The scintillators of each cell are read out on each side through a wave length shifter coupled by a light guide to a photomultiplier tube (PMT). The total number of PMTs is 11,896. The calorimeter provides almost a
4π solid angle coverage (99.7%) except for the 20 cm by 20 cm holes at the beampipe.

**Electromagnetic showers:** At energies \( E \geq 100\,MeV \) the principal mechanism of energy loss is bremsstrahlung for electrons and positrons and pair production for photons. The characteristic dimension is the radiation length and is defined by the equation \( \delta E(\text{radiation}) = -E(\delta X/X_0) \) for bremsstrahlung by high energy electrons.

**Hadronic showers:** The bremsstrahlung process of energy loss in matter is suppressed for particles other than electrons due to their larger masses. The dominant energy loss process for hadrons is by inelastic collisions. The incident hadron collides inelastically with the nuclei of the absorber material resulting in the production of secondary hadrons which undergo the same process. Neutral pions are also produced which decay into two photons and this part of the shower proceeds electromagnetically. Hadrons shower with a different length scale than electrons, positrons or photons.

**Calorimeter Readout method:** A schematic overview of the calorimeter read out system is shown in Fig. 5.3. Each cell of the calorimeter is read out by two PMTs. The electronic signal from the PMTs is shaped and stretched in analogue cards mounted on the endbeam of each module. The signal is split into two and each part amplified by a different factor (gain). This provides a larger dynamic range than can be obtained with a single 12 bit ADC. The
higher gain channel is used for lower energies ($\leq 20$ GeV) and the low gain for higher energies. A large dynamic range is necessary because the energy in a cell could range from 10 MeV (uranium radioactivity used to monitor stability) to 400 GeV in FCAL. The shaped pulse is measured at intervals of 96 ns a maximum of 8 times and stored in an analogue pipeline. At least 3 readings are necessary to reconstruct the energy and time for the cell and the additional ones are used to detect possible pile-up effects\(^6\). When the event is accepted by the first level trigger these samples are digitized. The energy and arrival time are reconstructed from the pulse heights.

**Calorimeter Calibration:** The following methods are used to calibrate the signals from the calorimeter:

- **Electronic calibration:** Programmable precision DC voltage and charge injection built into the analogue cards are used to measure gains and linearities, the absolute energy scale, and the low/high gain ratio of the read out electronics. Charge injection is also used to calibrate the trigger electronics.

---

\(^6\)Hadronic showers develop slowly compared to electron showers and there is considerable energy in the shower tail. The measured energy hence depends on the gate time. Compensation depends on the gate time and the ratio of absorber to scintillator thickness. At ZEUS the gate time is fixed by HERA bunch crossings, and the thickness ratio is then optimized.
Figure 5.3: Schematic overview of calorimeter readout system. The pipeline is 58 cells long giving a trigger decision window of 4.3 µs. There are two gain scales giving a dynamic range of 1:40,000. $I_{\text{uno}}$ is used for calibration. Insert is the profile of a pulse from a PMT and sampling times $h_0, h_1$ etc. The charge and time reconstruction methods are also shown. $s_1/s_2$ is the ratio of slopes on either side of the peak and is almost jitter independent.
• **Laser light:** Laser light is injected in front of the PMTs and the resulting signal is read out at the end of the chain. The laser is able to produce a large range of intensity. This is used to test the linearity of the PMT and read out electronics to energies not measurable through test beams. This is also used in the calibration of the time measurement, and in determination of individual time offsets for each channel.

• **Uranium Radioactivity:** The natural radioactivity of uranium induces a very stable, small read out signal (UNO). A single reading of the integral of this signal for 20 ms has a statistical uncertainty less than 1%. This current \( I_{\text{uno}} \) is proportional to the gain of the channel being measured up to and including the PMT. The gains for all PMTs are set such that the UNO signal is within 1% of some nominal value \( I_{\text{uno}}^{\text{nominal}} \) which depends on the size of the cell. The reconstructed charge of each cell is then corrected by the factor \( \frac{I_{\text{uno}}^{\text{nominal}}}{I_{\text{uno}}^{\text{measured}}} \). A large number of systematic uncertainties (eg cell and wave-length shifter imperfections) cancel in the ratio of the shower signal to the UNO signal. The UNO signal is also used to correct for long term (few days) gain variations (\( \approx 2\% \)). Very long term effects like radiation damage are also monitored with it.

• **\( ^{60}\text{Co} \) source scan:** Before installation, each of the modules of the calorimeter was scanned with a movable \( ^{60}\text{Co} \) source. This exercise is
repeated every year. This can detect ageing effects in the wavelength shifter and check mechanical stability.

**Beam and cosmic ray tests:** Studies have been conducted at CERN\textsuperscript{33} (FCAL and RCAL) and FNAL\textsuperscript{34} (BCAL) on the response of the calorimeter modules to known energy beams. The electron energy resolution was found to be $18\% / \sqrt{E}$ (19\% / $\sqrt{E}$ for BCAL) and hadronic energy resolution 35\% / $\sqrt{E}$ where E is in GeV. The e/h ratio is found to be 1 within 1\% for FCAL EMC's and BCAL. RCAL and FCAL HAC's which use a different type of PMTs show a deviation of 2\%. Tests using cosmic rays have been conducted\textsuperscript{35} which indicate that tower to tower and module to module uniformity at the 1\% level has been reached using the UNO signal.

**Absolute energy scale:** The absolute energy scale is the conversion between the pulse heights and the corresponding energy deposited by the particles\textsuperscript{c}. This has been obtained for a subset of FCAL, RCAL and BCAL modules using beams of known energy at CERN\textsuperscript{33} and FNAL.\textsuperscript{34} The $I_{\text{uno}}$ stability and uniformity over modules allows the transport of this calibration from the test beam to the experiment, provided the modules are mechanically stable. Comparison between the momentum of electrons measured in the CTD and their energy deposited in the calorimeter and studies of

\textsuperscript{c}At the beam tests it was found that when the UNO current was set at 100 nA in EMC sections of FCAL modules, the absolute scale is 9.51 pC/GeV.\textsuperscript{36}
Compton events have verified the results above. Verification of the energy scale using halo muons is found to agree with that from cosmic ray tests to within 1%. The energy calibration is also found to be stable to 1% over a period of months.

5.4 Charged particle tracking

For many measurements it is crucial to know the momentum and identity of the charged particles emerging from the interaction point. It is necessary to determine precisely a set of position coordinates to determine the particle trajectory. From the deflection of the trajectory in a magnetic field, the three momentum of the particle is determined. The detectors used to measure the interaction point (vertex) and the trajectories of particles are drift chambers.

Consider a gas-filled cylindrical metal or glass tube at negative potential with a fine central anode wire at positive potential. An electron liberated by ionization when a charged particle passes through will, as it drifts towards the anode, gain energy and ionize more gas atoms. This process continues, leading to an avalanche of electrons and positive ions. If the gas amplification factor per initial ion pair is independent of the number of primary electrons, the device is called a proportional counter. In a multiwire

\[\text{\footnotesize{However, the electron energy spectrum of the ZEUS DIS sample agrees poorly with that from the Monte Carlo. This is still under study but the energy scale is not the probable cause. It is discussed further in chapter 9.}}\]
proportional counter many anode wires are stretched in a plane between two cathode plates. The electrons drift towards the anode with a fast rise time (.1 ns) while the less mobile positive ions induce pulses of duration 30 ns. Drift chambers on the other hand use a low-field region to drift electrons. Then the collection time of the avalanche gives a measure of the spatial position.

Central Tracking Detector: The Central Tracking Detector is a 2 m long cylindrical drift chamber designed to fulfill the following requirements:

- Charge and momentum measurement of the tracks up to $P_t \approx 150$ GeV over a wide angular range, $15 < \theta < 164^0$, where $P_t$ is the transverse momentum of the track.
- A short maximum drift time (the HERA bunch crossing interval is 96 ns) and a fast read out (to be used in triggering).
- High position and direction resolution of the tracks to enable good momentum resolution and matching to other detectors (calorimeter and VXD).

Construction: The Central Tracking Detector has 72 sense wire layers arranged in nine superlayers (4608 sense wires in all). One octant of the CTD is shown in Fig. 5.4. Five of the superlayers have wires parallel to the beam axis and four have small angle tilt (stereo-wires). These stereo
wires provide good polar angle accuracy. The wires within a super layer are divided azimuthally into cells each containing eight sense wires. The maximum drift length within the cell is 2.5 cm and the inter-bunch time requires a fast ($\approx 50 \, \mu\text{m/ns}$) drift gas. A mixture of argon, carbon-dioxide and ethane is used as the drift gas. The CTD wires are read out by a 100 MHz Flash Analogue to Digital Converter system. The digitizations are processed at the frontend providing a drift time and pulse height for each wire. Data is stored in a pipeline until the first level trigger (FLT) makes a decision. If it decides to accept the event, the data is transferred to an event buffer. The data is operated on by digital signal processors which perform zero suppression, extraction of drift time and pulse height information. From

Figure 5.4: An octant of the CTD.
these the position coordinates along the track are extracted to a precision of \( \sigma \approx 250 \, \mu m \). Separate timing modules operate on the signals from three of the nine superlayers and feed information to FLT modules. These modules use the arrival times of signals at both ends of the chamber to get the \( z \) coordinate of the vertex with a precision of \( \sigma(z) \approx 3 \, cm \). This is used to discriminate against beam gas events in the trigger.

**Vertex detector:** The vertex detector (VXD) is a drift chamber next to the beampipe with wires parallel to the beam axis. It has a 3.6 cm active radius between 10.65 and 14.24 cm from beam axis and extends from +90 to -50 cm in \( z \). The polar angle acceptance is \( 8.6 < \theta < 165^\circ \). It has 12 sense wire layers with 120 cells (1440 wires in all). The cells are oriented nearly radially (\( 5^\circ \) Lorentz angle). A slow gas (di methyl ether, 5 \( \mu m/ns \)) results in a spatial resolution of 35 \( \mu m \). It is used along with the CTD to measure the vertex of events. It also provides more coordinates (hits) on the trajectory of the particle. A pattern recognition algorithm is then used to find tracks from the hits in the CTD and the VXD. The track candidates are fit to a 5 parameter helix model.\(^3\)\(^8\) Five independent parameters completely describe a track in a known magnetic field.

**Solenoid:** The momentum of charged particles is measured using the curvature of the tracks in an axial magnetic field of 1.4 Tesla in the tracking region. A thin, superconducting solenoid located between the central tracking detector and the barrel calorimeter produces the magnetic field. The
effect of this magnetic field on the HERA beams is compensated by a high field superconducting solenoid, called the compensator, located in the rear end-cap of the iron yoke. The location of these magnets is shown in Fig. 5.1.

5.5 Small-angle rear track detector

The Small-angle Rear Track Detector (SRTD) is a scintillator hodoscope close to the beampipe at the face of the RCAL 146 cm from the interaction point. The layout of the SRTD is shown in Fig. 5.5. It consists of two planes of scintillator strips in 4 sectors each 24 cm by 44 cm. The strips are placed parallel to each other in planes in the x or y direction. A couple of strips are
removed in Fig. 5.5 to show the back plane. Each strip is 1 cm wide, either 24 or 44 cm long and 0.5 cm thick. There is a support plane made of low Z material to reduce backscatter between the strip planes. The SRTD covers an area of 68 cm by 68 cm with a hole 10 cm by 10 cm for the beampipe. The strips are read out via light fibers and PMTs with sufficient photo-electrons to achieve sub-nanosecond timing. The SRTD improves the position resolution for the scattered positron. It is also used to reject events during data taking that are from beam-gas interactions and have a large energy deposit in the SRTD. It is also used to correct the energy loss in the dead material. This is further discussed in chapter 10. The author was involved in the construction of this detector and in reconstruction of the data from it.
Chapter 6

Data Reconstruction and Trigger

At HERA, positron and proton bunches cross every 96 ns, most of the time without interacting. The positron-proton interaction rate is much smaller than the rate of proton interactions with the residual gas or the rate of the cosmic rays that go through the detector. The time between the bunch crossings is extremely short - 96 ns. In addition, the number of channels to be read out (250,000) per event is large. Thus the ZEUS data acquisition (DAQ) system must handle short time intervals, large amounts of data and huge backgrounds. It must examine each event in real time and decide whether it is an interesting ep interaction or background and decide whether to record the event. This problem is tackled using a three-level trigger system with data buffered on all levels to select events on line. The three level trigger successfully reduces the rate to 1 kHz, 100 Hz and 5 Hz respectively, mostly cutting out background. The trigger system activates the DAQ whenever an interesting interaction is found. A simplified flow diagram of the DAQ is shown in Fig. 6.1. The ZEUS trigger uses some of the reconstructed quantities. Hence the ZEUS reconstruction is described next.
Figure 6.1: The Overview of the ZEUS data acquisition system.
6.1 Data reconstruction

The data reconstruction is done with the ZEus PHYSics Reconstruction program (ZEPHYR). It organises raw data into ADAMO\textsuperscript{37} data structures. It then reconstructs the calibrated energies and directions of tracks. The ultimate aim is to find the four-vectors of all of the produced particles.

**Energy reconstruction:** During the data taking period, the UNO signals are measured frequently. These are used to correct for variations in PMT gain. The corrected pulse heights of the two PMTs are added for each calorimeter cell and converted into a calibrated cell energy using the absolute energy scale. The energy of each PMT is recorded along with its time. For each cell an energy imbalance is defined as the difference between the calibrated energies of the two PMTs. Occasionally, calorimeter PMTs suffer a sudden discharge between the increasing static charge on the PMT and the PMT shielding. The discharge produces a large signal in one PMT that is identified as an energy deposit. Energy imbalance is used to identify such cells since only one of the two PMTs on a cell experiences a discharge.

**Time reconstruction in the calorimeter:** The time a particle enters a calorimeter cell is extracted from the PMT pulses. The resolution is about one nano-second for a few GeV energy deposit. Times for the individual
PMTs are adjusted by offsets so that particles originating from the nominal interaction point at the bunch crossing time have calorimeter time zero. An energy weighted average time of the PMTs of each section of the calorimeter is taken as that section’s global time.

**Track Reconstruction in CTD:** For each CTD wire that registers a signal in an event, the hit time is defined to be time at which the pulse reaches a preset fraction of its total height. From a knowledge of the time of the pulse, and drift velocity, the position can be determined. A pattern recognition algorithm is then used to find tracks from the hits in the CTD. The track candidates are fit to a 5 parameter helix model. Five independent parameters completely describe a track in a known magnetic field.

**Vertex reconstruction:** A non-linear iteration process is used to fit for the vertex position while simultaneously refitting the direction and curvature of each track originating from the vertex. Trajectories that are incompatible with a source near the beam-line are removed. Tracks that contribute too much to $\chi^2$ are also discarded one by one. A diffuse pseudo-proton centered near the beam spot in the x-y plane, with $\sigma_x = \sigma_y = 0.7$ cm, participates in the vertex reconstruction. This procedure discriminates against secondary vertices or off-axis vertices. It introduces no bias in the z coordinate of the vertex.
For matching to energy deposits in the calorimeter and other parts of the detector, the trajectory is traced in the inhomogenous magnetic field beyond the CTD. This extrapolation is stopped if the track starts to return.

### 6.2 First-level trigger

The data from each bunch crossing (96 ns) is stored in a pipeline 56 bunch crossings deep, while the first-level trigger calculations are being performed and the first-level trigger signal is propagating back to the components. For some components, such as the calorimeter, this pipeline is a switched capacitor array, which is an analog device that stores charge. For other components, such as the tracking detectors, the information is already digital and is stored in a digital pipeline. The first-level trigger operates on a subset of the full data. Each component completes its internal trigger calculations and passes information for a particular crossing to the global first-level trigger (GFLT). The GFLT calculations take a minimum of 20 crossings (1.9 µ sec) after receiving information from the individual components. The GFLT decision is issued exactly 46 crossings, or 4.4 µ sec after the crossing that produced it. If a global first-level trigger is not issued for a crossing, the component data are discarded. The disposition of every event and some basic information about it are retained for analysis of trigger performance. There is additional processing of calorimeter trigger data by the fast clear between arrivals of global first-level triggers. The fast clear rejects some additional events
before processing by the second-level trigger. The design goal of the first-level trigger, including the fast clear, is to reduce the event rate to below 1 kHz.

The calorimeter first-level trigger uses three approaches to identify interesting events while rejecting beam gas background:

- Detection of isolated electrons and muons using pattern analysis logic
- Identification of patterns of energy deposit obtained from local energy sums
- Recognition of characteristic deposits of total transverse and missing transverse energy.

The particular first-level trigger patterns for the data used for this analysis are discussed next.

**Isolated electron trigger:** There is a high background rate from low energy hadrons that are misidentified as electrons. To reduce this, the pattern logic finds an electromagnetic signal and checks that the towers around it are quiet. This is done in real time while taking data. Figure 6.2 shows the efficiency of the trigger as a function of the electron energy.

**REM C threshold trigger:** The REMC threshold trigger is a non-isolated electron trigger. It is a coarse sum of EMC energies in 8 towers around the rear beampipe. This trigger in effect requires one of the following:
Figure 6.2: The Efficiency of the isolated electron trigger as a function of energy.
• at least 3 towers each with EMC energy greater than 1.25 GeV

• at least one tower above 1.25 GeV and one above 2.5 GeV

• at least one tower above 5 GeV.

6.3 Second-level trigger

The issuing of a first-level trigger causes component data to be transferred to buffers for processing by the second-level trigger. The second-level trigger processor functions as an asynchronous pipeline, i.e. a series of parallel processors. The second-level trigger decisions are made in the order events are received. The second-level trigger has access to a large fraction of the full data for the event. For example, in the case of the calorimeter, while the first-level trigger would examine groups of cells with a reduced digitization accuracy, the second-level trigger performs calculations on the individual cells with the full dynamic range. The second-level trigger is able to perform iterative calculations that are not possible in the pipelined structure of the first-level trigger. The data passing the second-level trigger is then sent to third-level trigger.

Most of the events seen by the second-level trigger (SLT) are triggered by upstream proton beam gas interactions. By definition, the calorimeter time for an event originating from the interaction point is zero. Proton beam gas events can be vetoed by their large deposit of energy in the RCAL.
and their early time in RCAL. Another class of events seen by the SLT are noise events due to sparks in photomultiplier tubes. Each cell in the calorimeter is read out by two photomultiplier tubes. There will be a large energy imbalance \((E_{pmt1} - E_{pmt2})/(E_{pmt1} + E_{pmt2})\) between the two PMTs of the cell for such events in contrast to normal events. Cosmic ray muon events can be removed by considering the difference between the time of energy deposits in upper and lower halves of the BCAL. Another fact used in removing various backgrounds is that from simple kinematics it can be deduced that the quantity \(E - p_z = \sum_i E_i (1 - \cos \theta_i) = 2E_e = 55.4 \) GeV when all the final state particles are detected. Here the sum \(i\) runs over all calorimeter cells. Particles travelling down the beampipe in the proton direction have \(E_i - p_{zi} \approx 0\) while those down the beampipe in the positron direction have \(E_i - p_{zi} \approx 2E_i\). Hence a cut on the minimum value of \(E - p_z\) is sensitive to particles lost down the beampipe in the positron direction even though the proton or its remnant is not detected. As a result, this cut removes photoproduction events and decreases radiative corrections. This cut also removes events where significant part of the positron shower is lost down the beampipe or those that have an unphysically large beam energy.

The data stream used for the present analysis is the nominal neutral current trigger at SLT. It requires energy in the rear or barrel calorimeter EMC section > 2.5 GeV or energy either in the HAC or EMC sections in the
calorimeter > 10 GeV. It also requires $E - p_z + 2E_\gamma > 18$ GeV where $E_\gamma$ is the energy of any photon in the luminosity monitor.

When a positive SLT decision is taken, each component sends the data from digital buffers to the event builder. The event builder collects data from all the components into one event.

### 6.4 Third-level trigger

The goal of the Third-Level Trigger (TLT) is to reduce the event rate to no more than 5 Hz. It is implemented on a farm of SGI computers. A small fraction of the input events are kept regardless of the trigger decision (passthrough) for diagnostic purposes. A flow chart of the TLT decision making process is shown in Fig. 6.3.

The calorimeter reconstruction is performed as explained above but with calibration constants that change less frequently than the offline reconstruction. The energy is zero-suppressed \(^1\) and a calorimeter cell is defined to be a 'spark' if there is large energy imbalance between its two PMTs:

\[
E_L + E_R > 1.5 GeV 
\]

\[
|(E_L - E_R)/(E_L + E_R)| > 0.9, 
\]

\(^1\)Noisy electronics and Uranium radioactivity cause false 'energy deposits'. This is taken care of with a cut of 60 MeV on EMC cells and 110 MeV on HAC cells.
where $E_L$ and $E_R$ are left and right PMT energies. Events are rejected if they contain a single spark cell and energy in the calorimeter is less than 2 GeV. The energy weighted average time is calculated for three calorimeter regions, RCAL, FCAL, and the entire CAL, using PMTs above 200 MeV for which the energy asymmetry between the two PMTs of a cell is less than 0.2. This average time of arrival of particles in the calorimeter is used to reject beam gas events and cosmic and halo muon events.

The data then undergoes track and vertex reconstruction similar to the offline reconstruction described earlier. The calorimeter quantities are then recalculated with the new vertex information.

Cosmic and halo muons are rejected using an algorithm called MUTRIG\textsuperscript{39} based on the correlation between the time and position of energy deposits in the calorimeter and muon detector information. Next, two electron finders\textsuperscript{2} ELEC5 and LOCAL\textsuperscript{40} are used to reconstruct positrons and electrons in the calorimeter. The event is then passed on to various physics filters. The data from the other parts of the detector are reconstructed depending on the filters. These are routines that perform analysis similar to offline analysis.

\textsuperscript{2}Particles passing through matter create an avalanche of particles (called a shower) along the direction of propagation. For positrons (electrons) and photons, only the electromagnetic interactions are important, whereas hadrons are usually absorbed by strong interactions. Shower characteristics can be used to distinguish between electromagnetic and hadronic showers.
with loose cuts. The TLT cuts for the data stream in the current analysis are:

- A positron is found

- \( E - p_z + 2E_\gamma > 24 \text{ GeV}. \)

Figure 6.3: A flowchart of the Third-Level Trigger.

The trigger rate for the 1994 data taking at all the three levels is shown in Fig. 6.4. After an event has been accepted by the third-level trigger, it is
Figure 6.4: The Trigger rate for the ZEUS in 1994. The specific luminosity is $10^{-30}$ cm s$^{-1}$. 
stored for offline reconstruction. The third-level trigger farm is connected to the main DESY IBM via an optical link, over which data can be written to tape at the rate of approximately 1 Mbyte/s.
Chapter 7

Detector and Trigger Simulation

To determine cross-sections, the various factors which could effect the true kinematic distributions, such as the response of the detector to all possible event topologies, have to be considered. An efficient way is by simulating the detector and modelling the reaction. Events are generated according to assumed distributions in kinematic variables and the events are passed through a simulated detector and trigger. An event being generated means, in the case of HERA, that a positron and proton are made to collide as they do in the real collider and final state particles are generated according to a model of the reaction being studied. For example, in the reaction of the present analysis, a positron and proton collision produces a positron, a proton and a vector meson in the final state. Further the vector meson decays into lighter mesons. The detector measures energy and time of arrival in different points in space resulting from the reaction. From this the four vectors of the particles produced at the interaction point are deduced. Fig. 7.1 shows a schematic overview of the data and simulation chain at ZEUS.
7.1 ZEUS detector and trigger simulation

The simulation of the ZEUS detector is based on the GEANT\textsuperscript{41} and GHEISA\textsuperscript{42} Monte Carlo packages. The outgoing stable particles are traced through the detector. The response of the detector to physical processes such as energy loss, electromagnetic and strong interactions and multiple scattering are built into the simulation.

Two tunable shower terminators\textsuperscript{43} were developed to adjust the GEANT based simulation to agree with test beam results. An electro-magnetic shower terminator is used to correct shower profiles and a neutron shower terminator to reproduce $e/h = 1$ and the energy resolution of the calorimeter. Figure 7.2 shows the $e/h$ ratio as a function of kinetic energy for pions and protons. Test beam data are shown with open symbols and MC points are connected by solid lines. Calorimeter beam test measurements were used to tune the shower terminators and to include geometrical effects such as inefficiency near the boundaries. The simulation gives reasonable agreement with test beam data for $e/h$, energy resolution of both electromagnetic and hadronic
showers, and for shower profiles in the momentum range 0.5 - 100 GeV. The effect of dead material in front of the calorimeter is also reproduced except near the beam pipe in the positron direction\textsuperscript{a}.

![Figure 7.2: $e/h$ ratio as a function of kinetic energy for pions and protons. Testbeam data are shown with open symbols and MC points are connected by solid lines.](image)

The ZEUS trigger logic is simulated by a FORTRAN program that can run either on data or on generated events that were passed through the detector simulation. The three levels of the trigger system treat data in nearly the same way as the offline reconstruction. So one can simulate the effects of the trigger as well as check for trigger effects or inefficiencies (using passthrough events) in the real data. Also the effects of resolution smearing,

\textsuperscript{a}This is further discussed in chapter 10.
random noise, signal propagation delay and inefficiencies in the frontend electronics can be simulated. This was used in the design of trigger criteria, in evaluation of the actual trigger performance, and in calculating the trigger efficiencies.

7.2 Event simulation for the present analysis

The reaction $e p \rightarrow e V p$ where $V = \phi$ or $\rho^0$ is modeled using an event generator based on the work of Ryskin. It describes diffractive vector meson production in terms of exchange of a colorless two-gluon system. An overview of the events generated is given in tables 7.1 and 7.2. Events were generated with flatter distributions than expected from theory and the results of previous experiments, to ensure good statistics in large regions of phase space. Events were then given weights to produce expected distributions. The weight is defined such that

$$\text{weight} = \frac{d\sigma}{d\xi} \cdot \frac{d\xi}{dN},$$

(7.1)

where $\frac{d\sigma}{d\xi}$ is the Ryskins model's cross-section for the event, $\xi$ is the set of variables used to describe the process and $\frac{d\xi}{dN}$ are the generated distributions.

Elastic vector meson electroproduction is defined by 3 independent variables. One set of such variables is $Q^2$, $x$, $p_t^2$, $\cos(\theta_h)$ and $\Psi$ defined in chapter 3. The weighted distributions have been fit in order to recover the Ryskin model parameters. The $Q^2$, $x$ and $y$ distributions have been fit to a power law ($\alpha^q$).
and the $p_T^2$ distribution to an exponential. The fit values are presented in table 7.3.

Table 7.1: Some parameters for the simulated events. The decay modes, fractions, mass and width are from the Particle Data Book[45].

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Events generated</th>
<th>Decay mode</th>
<th>Decay Fraction</th>
<th>$m_\nu$ GeV</th>
<th>$\Gamma_0$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+p \rightarrow e^0p$</td>
<td>119,530</td>
<td>$\rho^0 \rightarrow \pi^+\pi^-$</td>
<td>100%</td>
<td>.77</td>
<td>.151</td>
</tr>
<tr>
<td>$e^+p \rightarrow e\phi p$</td>
<td>44,339</td>
<td>$\phi \rightarrow K^+K^-$</td>
<td>49.1%</td>
<td>1.02</td>
<td>.0044</td>
</tr>
</tbody>
</table>

A similar reaction to the one studied in the present analysis is $e^+p \rightarrow eVX$ where $V = \phi$ or $\rho^0$. In this reaction, the proton dissociates into a state $X$ but it still has the same quantum numbers as the elastic reaction. This forms a background to the elastic reaction when the proton remnant is not detected. Another event generator (RHODI), based on the the work of Forshaw and Ryskin,\textsuperscript{24} was used to model this process with a $d\sigma(\gamma^*p)/dM_X \propto 1/M_X^{2.5}$ dependence where $M_X$ is the mass of the proton remnant. Different $M_X$ dependences were obtained by weighting the events. Events were generated for $M_X^2$ values between 1.2 and 4000 GeV$^2$.

In all cases, the generated events pass through a simulation of the ZEUS detector and trigger and undergo the same reconstruction as the data.
Table 7.2: Generated kinematic distributions and ranges. Where no range is indicated the events are generated from threshold to the maximum allowed value.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Generated distributions</th>
<th>Generated Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e p \to e \phi p$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>Breit-Wigner</td>
<td></td>
</tr>
<tr>
<td>$Q^2$</td>
<td>$Q^{-2}$</td>
<td>4-100 GeV</td>
</tr>
<tr>
<td>$y$</td>
<td>$y^{-1}$</td>
<td>.008-0.7</td>
</tr>
<tr>
<td>$p_t^2$</td>
<td>$e^{-3t}$</td>
<td>-</td>
</tr>
<tr>
<td>$e p \to e p^0 p$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>Flat</td>
<td>0.3-2 GeV</td>
</tr>
<tr>
<td>$Q^2$</td>
<td>$Q^{-2}$</td>
<td>2-100 GeV$^2$</td>
</tr>
<tr>
<td>$y$</td>
<td>$y^{-1}$</td>
<td>.08-0.7</td>
</tr>
<tr>
<td>$p_t^2$</td>
<td>$e^{-2t}$</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 7.3: Input weights for the Monte Carlo compared with the values obtained for a similar reaction is $ep \rightarrow e\rho^0p$ by ZEUS.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Fit form</th>
<th>Ryskin weights</th>
<th>ZEUS $^9$ Measured value $ep \rightarrow e\rho^0p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q^2$</td>
<td>$Q^{-a}$</td>
<td>$\alpha = 6.22 \pm .016$</td>
<td>$6.2 \pm .08^{+1.4}_{-0.5}$</td>
</tr>
<tr>
<td>$y$</td>
<td>$y^{-a}$</td>
<td>$\beta = 1.1 \pm .007$</td>
<td>Unpublished</td>
</tr>
<tr>
<td>$x$</td>
<td>$x^{-\gamma}$</td>
<td>$\gamma = 0.92 \pm .21$</td>
<td>Unpublished</td>
</tr>
<tr>
<td>$p_t^2$</td>
<td>$e^{-\delta p_t^2}$</td>
<td>$\delta = 5.6 \pm .5$</td>
<td>$5.1^{+1.2}_{-0.5} \pm 1.0$</td>
</tr>
</tbody>
</table>

When using the Monte Carlo to correct the data for detector effects, the bin sizes are selected to be larger than the resolution in each of the kinematic variables being studied. This resolution is taken from the gaussian fit to $(A_{gen} - A_{recon})/A_{gen}$. Events that are generated in a particular bin may be reconstructed in a different bin. This is defined as migration. Acceptance is defined to be the ratio of events reconstructed in a bin to the number of events that are generated in that bin. This includes migration and the detector efficiency, i.e., the fraction of events generated in a bin that are successfully reconstructed by the detector. The kinematic region of study is chosen such that the acceptance does not vary steeply among bins.
Chapter 8

Overview of the Data

An overview of the data collected by ZEUS in 1994 is presented in table 8.1. The luminosity was 0.42 pb$^{-1}$ for data taken with $e^-$ and 3.3 pb$^{-1}$ for that with $e^+$ beams. A total of 615,316,772 events passed the First Level Trigger and 14,516,046 events are recorded of which 67.7 % are from lepton-proton collisions:

- Runs 8,498 — 9,163 were taken with electrons, and correspond to an integrated luminosity of 0.42 pb$^{-1}$.

- Runs 9,251 — 10,156 and 10,188 — 10,263 were taken with positrons and had a nominal interaction vertex at $z = 5 \text{ cm}$. This sample corresponds to a luminosity of 3.3 pb$^{-1}$.

- Runs 10,157 — 10,187 were taken with a positron beam, but with the interaction vertex shifted to +67 cm, as a way of reaching $Q^2$ values...
not attainable with the normal setup. These runs are also not used in this analysis.

Table 8.1: Overview of data.

<table>
<thead>
<tr>
<th>Beam Lepton</th>
<th>HERA delivered Luminosity pb⁻¹</th>
<th>Run range</th>
<th>Data taken pb⁻¹</th>
<th>Good runs pb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrons</td>
<td>1.080</td>
<td>8498 - 9163</td>
<td>0.42</td>
<td>0.29</td>
</tr>
<tr>
<td>Positrons</td>
<td>5.106</td>
<td>9251-10263</td>
<td>3.3</td>
<td>2.95</td>
</tr>
<tr>
<td>Total</td>
<td>6.186</td>
<td>8498 - 10263</td>
<td>3.72</td>
<td>3.24</td>
</tr>
</tbody>
</table>

Good quality runs and event ranges have been selected, where various parts of the detector are working satisfactorily. The criteria include the exclusion of events with a large number of dead channels in the calorimeter, problems with the electronics or no hits in the CTD. The corresponding luminosity is shown in table 8.1. Further, the runs in the range 10157-10263 have been dropped from this analysis because of noisy FCAL modules. The runs used in the present analysis are in range 9251-10156 and have an integrated luminosity of 2.62 pb⁻¹.

8.1 Stability of the detector

Each event has a set of bits which signify if the event satisfies certain cuts. For this analysis the event is required to have bit 13 set which corresponds
to the following cuts:

- \( E - p_z = \sum_i E_i(1 - \cos \theta_i) + 2E_\gamma \cos(\theta_\gamma) > 25 \text{ GeV} \)

- Number of tracks < 5.

The data were taken over a period of several months in 1994. In order to monitor the quality of the data and the stability of the detector, the rates for certain key quantities were studied as a function of run number. Figure 8.1 shows the bit 13 event rate per unit luminosity (henceforth called rate) vs. the run number for the entire sample. The error bars represent the statistical error in the rate. Figure 8.1 also shows the rate of events with a good positron, as defined by \( E - p_z > 35 \text{ GeV} \) and \( E_\gamma > 5 \text{ GeV} \) and with a box cut\(^2\) on positron position. Figure 8.2 shows (a) the rate of events with only two charged tracks found from the vertex and (b) a positron track in addition. Various other quantities like vertex position, energy in various parts of the detector, energy unmatched to the tracks, etc. were studied. The data are found to be reliable and the detector stable.

### 8.2 Data pre-selection

For ease of analysis, the events were pre-selected before they were analysed in detail. It is expected that \( ep \rightarrow e\phi p \) events have 2 tracks other than those

---

\(^1\)This cut is discussed in chapter 6.

\(^2\)This cut is described in the next chapter.
caused by the positron\textsuperscript{3} whereas inclusive reactions are expected to have events with more than two tracks. However, there could also be stray tracks that are not from the vertex. Hence for pre-selection it is required that there should be only two non-positron tracks from the vertex but allow for any number of tracks not associated with the vertex. The systematic error due to rejection of events with a badly reconstructed track or track ill-matched to the positron is estimated to be 5\%. A flowchart of the event pre-selection is shown in Fig. 8.3. An outline of the analysis program is also shown. This program writes out variables important for the analysis in the form of ntuples that can be rapidly processed by a CERN package called PAW.\textsuperscript{45}

\textsuperscript{3}Some positrons may shower due to dead material in front of the CTD which can lead to more than one track being associated with the positron.
Figure 8.1: (a) The event rate as a function of run for bit 13. (b) The event rate for bit 13 with a good positron found. A good positron is defined as an event with $E - p_z > 35$ GeV and satisfying the box cut as described in the text.
Figure 8.2: (a) The rate of two track events with a good positron found in the calorimeter. (b) The rate for events in which the positron leaves a track in the CTD.
Sparks & Cosmics rejected

Event rejected if running conditions not good

Preselection cuts
2 tracks from vertex excluding tracks matched to positron

Analysis
Positron & $\rho/\phi$ finding
Kinematic variables calculated
Conversions tagged

Event variables written out for further analysis

Tracks from the vertex are matched to positron if $<10$ cm from the positron energy deposit. There should be 2 unmatched tracks from vertex (assumed vector meson decay tracks)

Charge and momentum of each track is measured from the curvature in the magnetic field of 1.4 T. The invariant mass of two tracks is found assuming they are kaons, pions, electrons or muons

Positron energy recalculated by kinematic constraints. Corrected four momenta used for calculating $Q^2$, $x$, $y$ etc.

Tracks are extrapolated back to point of tangency and tagged if consistent with being from a conversion.

Figure 8.3: A flow chart of the event selection
Chapter 9

Positron Identification

The current analysis studies the process \( ep \rightarrow eVp \) (where \( V \) is a vector meson) at non-zero \( Q^2 \). The final state positron and the decay products of the vector meson are detected while the proton escapes down the beam pipe. The Uranium calorimeter is the main component in the positron identification and energy measurement. The positron position measured by the SRTD, if available, is used in preference to that measured by the calorimeter. This chapter describes the algorithms for positron identification and the positron energy measurement. Kinematic constraints and energy deposited in SRTD are two methods used to correct the energy loss in the dead material. A map of dead material is made and compared with the Monte Carlo. Studies presented in this chapter use the \( \rho^0 \) instead of the \( \phi \) Monte Carlo and data samples\(^1\) because of the higher statistics for the \( \rho^0 \). Studies using the \( \phi \) samples give consistent results to those shown here.

\( ^1 \)After all the analysis cuts except those on the positron. The analysis cuts are discussed in chapter 11.
9.1 Positron identification

Positrons (electrons) and hadrons passing through matter create an avalanche of particles (called a shower) in a cone along the direction of propagation. For positrons (electrons) and photons only electro-magnetic interactions are important, whereas hadrons are usually absorbed by strong interactions. The resulting differences in shower characteristics can be used to distinguish between electromagnetic and hadronic showers. A new kind of positron finder has been developed at ZEUS based on a neural net algorithm. Whenever positron is used in the following discussion it is understood that it applies equally well to electrons.

Neural net positron finder - SINISTRA: Positron showers in the calorimeter typically result in energy deposits above noise level in three or four cells. Hadronic showers are much deeper longitudinally and broader transversely. A 10 GeV pion typically will leave energy in 7 EMC cells and 6 HAC cells.

A cluster algorithm is used to merge cells that are likely to be from a single particle. A single electromagnetic showering particle is expected to be well contained transversely in a window of 3 X 3 towers centered on the highest energy deposit tower. The total number of EMC and HAC cells in this region is 54. The pattern of energy deposits depends on the angle of incidence of the particle. A neural network with 55 parameters (54 cells + angle
of incidence) is trained using a sample of simulated deep inelastic neutral current events. The neural network assigns a probability that a cluster is due to a positron. The results are also cross checked using a conventional positron finder, LOCAL.

**Conventional Positron finder - LOCAL:** Conventional positron finders reduce the 54 cells to be examined to a manageable number of variables. Local defines two variables

$$\epsilon = \frac{E_{EMC}^W}{E_{tot}^W}$$

and

$$r = \sqrt{\frac{\sum_{i=1}^{2} \sum_{\text{cells}} E_{cell,i,cell}^W}{E_{tot}^W} - \left( \frac{\sum_{\text{cells}} E_{cell,i,cell}^W}{E_{tot}^W} \right)^2},$$

where $E_{cell}^W$ denotes the energy deposited in a cell located at position $(r_1, r_2)$ in the transverse plane. Only cells in a window of 3 X 3 towers around the highest energy tower are considered. $E^W$ denotes the energy in the window. $\epsilon$ is the fraction of energy deposited in the electromagnetic part of the calorimeter compared to the total energy of the cluster and it characterizes the longitudinal energy profile. The variable $r$ denotes an energy weighted radius of the shower describing its transverse spread. Each cluster described by $\epsilon$ and $r$ has a probability to be an electromagnetic cluster. The efficiencies of the positron finders SINISTRA and LOCAL as a function of positron

\footnote{The neural network can also be analysed to find how many variables are independent. It is found that in ZEUS there are three variables instead of the two used in the local finder.}
energy are shown in the Fig. 9.1. For both finders the efficiency is greater than 95% for energies above 15 GeV. SINISTRA performs better than LOCAL at lower energies where the efficiency drops.

![Efficiency curve](image)

Figure 9.1: The efficiencies of the positron finders as a function of positron energy are shown. The dotted line is for the neural net finder SINISTRA and the solid line is for the conventional finder LOCAL.

### 9.2 Position reconstruction

The determination of the positron position in the calorimeter is based on a parameterisation of the energy imbalance in two neighboring cells as the position of the positron sweeps across the faces of cells. The parameterisation was developed using CERN beam test data. However, it is found that this
algorithm biases the position toward the cracks between cells. The energy imbalance as the position of the positron sweeps across the faces of cells is shown in Fig. 9.2.

The positron position determined from the calorimeter is used as input to a more accurate SRTD position algorithm. A search is made for a cluster of energy in the SRTD within 5 cm of the input position in each direction. The center of gravity of the energy in three strips around the shower maximum is then taken to be the positron position. Although the average resolution of the calorimeter is worse than that of the SRTD, for a few events near the crack between two EMC cells the calorimeter resolution (0.5 mm) is more accurate. From a study of such events the resolution for the SRTD is found to be 3 mm as shown in Fig. 9.2. However, the position as reconstructed in the SRTD is used, if available, in preference to that measured by the calorimeter even for occasional events for which the calorimeter position is more accurate.

9.3 Energy reconstruction

The spectrum of positron (electron) energies measured with the ZEUS calorimeter is inconsistent with the reconstructed energy spectrum obtained from the Monte Carlo simulations. The cause of this discrepancy is still not well understood. The various possibilities are:
Figure 9.2: a) Positron position in the calorimeter measured from the crack between two EMC cells as a function of energy imbalance for the data. The parameterisation of position as a function of energy imbalance is plotted. b) The position resolution of the SRTD in y and x using positrons near the crack as shown by fiducial cuts in a. This figure is from [47].
• A scale problem in the calorimeter calibration. The energy calibration of the calorimeter for electromagnetic showers could be inaccurate. However, this has been studied using the ratio of the energy in the calorimeter matched to a track with the energy measured by the CTD and no firm indication of a problem has been found.

• Incomplete description of the inactive material. The thickness in radiation lengths of material between the calorimeter and the nominal interaction point as implemented in the detector simulation is shown in Fig. 9.3. The large amount of dead material in the rear direction is due to cables and CTD flanges. This inactive material between the interaction point and the calorimeter (especially the rear end near the beam pipe) could be inadequately described or some piece missing in the detector simulation.

Two methods have been used to correct the reconstructed energies in both the data and Monte Carlo thereby reducing the discrepancy between them.

• Kinematic calculation of positron energy

The angle and momentum of the vector meson and the scattered positron angle have been used to correct the positron energy using the constraint of four-momentum conservation. In this method, the
Figure 9.3: The number of radiation lengths as a function of polar angle from the nominal interaction point to the calorimeter as implemented in the detector simulation.
scattered positron energy is determined by

\[ E'_e \approx \frac{(s + m_V^2 - M_X^2)/2 - (E_e + E_p)(E_V - \beta_c p_V \cos \theta_V)}{(E_e + E_p)(1 - \beta_c \cos \theta'_e) - (E_V - |p_V| \cos \theta'_{eV})}, \]  

(9.1)

where \( \theta_V \) and \( \theta'_e \) are the angles of the \( V \) and scattered positron, respectively, \( \theta_{eV} \) is their angular separation, \( E_V \) and \( p_V \) are the energy and momentum of the vector meson, \( M_X \) is the invariant mass of the proton (or its remnant) and \( \beta_c \equiv (E_p - E_e)/(E_p + E_e) \) is the velocity of the center of mass.

- Energy correction using the shower multiplicity measured in the SRTD.

A particle going through matter showers and part of its energy is absorbed by the material. The SRTD can be used to correct for the energy lost in the inactive material. The energy loss of the particle is related to the number of interactions the particles in the shower undergo in the dead material. This is related to the multiplicity of the shower. The amount of energy deposited in each strip when a particle passes through has been measured before installation of the SRTD. Hence the multiplicity of the shower can be determined from the energy measured. However due to the small size of the SRTD and the presence of the beam hole a part of the shower could be lost and the shower multiplicity measured by the SRTD is not always accurate.
Figure 9.4: The generated (solid line) and reconstructed (dashed line) positron energy distributions obtained from the $\rho^0$ Monte Carlo. The reconstructed Monte Carlo energies are also corrected using two methods, the solid dots by Eq. 9.1 and open squares by the shower multiplicity measured in the SRTD.
Fig. 9.4 shows the generated energy distribution and reconstructed energy distribution in the Monte Carlo after the cuts. This is also compared with the positron energy after recalculation using the above two methods. In the data the positron energy corrected by Eq. 9.1 provides a reference energy against which the energy correction by measurement of the shower multiplicity in SRTD can be compared. The good agreement in Fig. 9.4 gives confidence in this method when the positron energy cannot be recalculated. The positron energy corrected by Eq. 9.1 also gives an opportunity to investigate the dead material in ZEUS by studying the energy loss as a function of distance from the beam axis. Fig. 9.5 and 9.6 show the average positron energy loss fraction as a function of distance from the beam on the face of the RCAL for data and Monte Carlo. The dotted line is the width of the distribution. The Monte Carlo distribution has a different shape from the data. This indicates that the inactive material is inadequately simulated in the Monte Carlo. There could also be a small energy scale problem.

**Box cut and energy containment:** Part of the positron shower can be lost down the beampipe. Fig. 9.7 shows the fraction of energy lost as a function of the position at the RCAL for the data. Here the reference energy is the positron energy corrected by Eq. 9.1. All four quadrants are added together. The corrections are large near the edge of the beam hole indicating that some of positron shower is lost. A similar effect is seen in the Monte Carlo. When the energy loss down the beampipe is large, the positron energy
Figure 9.5: The positron energy loss fraction plotted as a function of the distance from the beam axis for the elastic $\rho^0$ data sample. The energy is lost in the inactive material or down the beam pipe. The dotted line is the width of the distribution.
Figure 9.6: The positron energy loss fraction plotted as a function of the distance from the beam axis for the $\rho^0$ Monte Carlo. The energy is lost in the inactive material or down the beam pipe. The dotted line is the width of the distribution. The average energy loss fraction distribution has a different shape than that of the data.
and position are poorly determined. Hence the positron position is required to be greater than 2 cm from the edge of the SRTD and 6 cm from the edge of the calorimeter. This will be one of the cuts invoked in the next chapter.
Figure 9.7: The average positron energy loss in dead material in the elastic $\rho^0$ final sample as a percentage of corrected positron energy is shown on the face of the RCAL. The energy is lost in the inactive material or down the beam pipe. The large energy loss near the edge of the beampipe necessitates the box cut.
Chapter 10

Elastic $\phi$ Electroproduction

In this chapter the cross-section for $\phi$ production is measured in the kinematic region $7 < Q^2 < 25 \text{ GeV}^2$, $0.02 < y < 0.2$ and $|t| \approx p_t^2 < 0.6 \text{ GeV}^2$. The helicity of the $\phi$s produced and the $W$ dependence of the cross-section are investigated. The starting point for this analysis is the pre-selection data sample discussed in chapter 8. Events in this sample had to satisfy the criteria $E_e > 5 \text{ GeV}$, $E - p_z = \sum_i E_i(1 - \cos \theta_i) > 25 \text{ GeV}$ and number of tracks $\leq 5$ with exactly two non-positron tracks from the vertex. The acceptance correction is obtained for these events using about 45,000 simulated events from the generator DIPSI as discussed in chapter 6. Only $\phi \rightarrow K^+K^-$ decay mode of $\phi$ is simulated in the generator since only this decay fraction is studied. However, the cross-section is corrected using the branching fraction of $\phi \rightarrow K^+K^-$ from Particle Data Book.
10.1 Cuts for the $\phi$ analysis

The following cuts are used to select $\phi$ events. A schematic view of the geometric cuts is shown in Fig. 10.1.

Figure 10.1: A schematic view of the geometric cuts used for this analysis.

Positron identification cuts:

- To ensure accurate measurement of the positron position, an event must have a scattered positron in the SRTD in the region defined by $|x + 1| > 12$ or $|y| > 12$ cm or in the calorimeter in the region defined by $|x + 1| > 16$ or $|y| > 16$ cm where $x$ and $y$ are the positron impact coordinates.
position. These two requirements on the positron position are together referred to as the box cut. The reason for this cut was discussed in chapter 9.

- $E_e > 5$ GeV. This is the energy region in which the positron finders are reliable. This also removes background events that have a $\gamma$ from $\pi^0 \rightarrow 2\gamma$ identified as a positron.

- $E - p_z = \sum_i E_i (1 - \cos \theta_i) > 35$ GeV. This cut is discussed in chapter 6. It removes photoproduction events and decreases radiative corrections. This cut also removes events where significant part of the positron shower is lost down the beampipe.

**Tracking and vertex cuts:**

- The $z$ coordinate of the vertex ($V_2$) as reconstructed from the CTD and the VXD is required satisfy $|V_2 + 5| < 45$ cm.

- Only two tracks are allowed from the vertex other than the positron track(s). Some positrons may shower due to dead material in front of the CTD. A study of the Compton scattering sample revealed that 5% of positrons with tracks have more than 1 track matched to the positron.
• $|\eta_{\text{track}}| < 1.75$ and $p_{t}^{\text{track}} > 150$ MeV is required to keep tracks from the vector meson decay in the region where the performance of the tracking detectors is well understood and simulated reliably in the Monte Carlo. 

$\eta_{\text{track}}$ is the pseudorapidity of the track, defined as $-\log(\tan(\theta/2))$ where $\theta$ is the polar angle of the track. $p_{t}^{\text{track}}$ is the transverse component of the momentum of the track with respect to the beam direction.

• The two non-positron tracks have to have opposite charge as determined from the curvature of the tracks.

**Removal of non-exclusive events:**

• $E_{\text{CAL}}/E_{KK} < 1.5$ where $E_{\text{CAL}}$ is the calorimeter energy excluding that of the scattered positron and $E_{KK}$ is the sum of the absolute values of the momenta of the two oppositely charged tracks. This cut suppresses background events with additional calorimeter energy unmatched to the tracks. Fig. 10.2 compares this quantity for the data with the Monte Carlo expectation for all the cuts listed until now. The excess at higher values of $E_{\text{CAL}}/E_{KK}$ comes from background exclusive processes such as $\omega \rightarrow \pi^{+}\pi^{-}\pi^{0}$ or $\phi \rightarrow K_{S}K_{L}$ and from non-exclusive events neither of which are included in the Monte Carlo simulation.
Figure 10.2: The $E_{CAL}/E_{KK}$ distribution is shown for the data (points) and Monte Carlo (solid line), with none of the kinematic cuts applied. The excess at large values of $E_{CAL}/E_{KK}$ comes from background not included in the Monte Carlo simulation.
Removal of conversions:

- Single photons converting in the material of the detector are topologically similar to \( \phi \) production and decay. To remove such events the conversion radius is required to be less than 5 cm. The tracks are extrapolated back to the point of closest approach in the \( x - y \) plane. The distance between this point and the reconstructed vertex is the conversion radius.

Mass range of \( \phi \) considered:

- In order to enhance the signal to background ratio events are limited to the \( K^+K^- \) invariant mass range \( 1.01 < M_{K^+K^-} < 1.03 \text{ GeV} \). The cross-section is corrected for the full range of \( \phi \) mass assuming a Breit-Wigner shape.

Kinematic cuts: In anticipation of the acceptance studies discussed below the phase space region studied is limited to the following region:

- \( 7 < Q^2 < 25 \text{ GeV}^2 \)
- \( 0.02 < y < 0.2 \)
- \( p_t^2 < 0.6 \text{ GeV}^2 \).
After the application of these cuts, 39 events survive which are referred to henceforth as the \( \phi \) sample. The selection criteria and the selected numbers of events after each cut are summarized in Table 10.1.

Table 10.1: Summary of cuts and selected numbers of events after each cut.

<table>
<thead>
<tr>
<th>Cut</th>
<th># of events left</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preselection</td>
<td>78,663</td>
</tr>
<tr>
<td>Trigger</td>
<td>69,607</td>
</tr>
<tr>
<td>Positron energy &gt; 5 GeV</td>
<td>47,168</td>
</tr>
<tr>
<td>Box cut</td>
<td>35,577</td>
</tr>
<tr>
<td>( E - p_z &gt; 35 \text{ GeV} )</td>
<td>32,347</td>
</tr>
<tr>
<td>(-50 &lt; V_z &lt; 40 \text{ cm} )</td>
<td>28,051</td>
</tr>
<tr>
<td>(</td>
<td>\eta_{\text{track}}</td>
</tr>
<tr>
<td>Oppositely charged tracks</td>
<td>10,528</td>
</tr>
<tr>
<td>( E_{\text{CAL}}/E_{\text{KK}} &lt; 1.5 )</td>
<td>2,656</td>
</tr>
<tr>
<td>(1.01 &lt; M_{K^+K^-} &lt; 1.03 \text{ GeV} )</td>
<td>156</td>
</tr>
<tr>
<td>Conversions rejected</td>
<td>140</td>
</tr>
<tr>
<td>( p_t^2 &lt; 0.6 \text{ GeV}^2 )</td>
<td>89</td>
</tr>
<tr>
<td>(7 &lt; Q^2 &lt; 25 \text{ GeV}^2 )</td>
<td>47</td>
</tr>
<tr>
<td>(0.02 &lt; y &lt; 0.2 )</td>
<td>39</td>
</tr>
</tbody>
</table>
10.2 Comparison of Monte Carlo and data

Figure 10.3 shows the $E_{\text{cal}}/E_{\text{kk}}$ distribution for the data and Monte Carlo after all the cuts. The agreement indicates that the backgrounds have been reduced to a reasonable level. The level of non-exclusive background can be tested by plotting the most energetic deposit unmatched to either of the kaon tracks. This is indicative of the presence of an extra particle in the detector other than the positron and the kaons. Figure 10.4 compares the most energetic unmatched deposit for Monte Carlo and data samples after all the cuts. Again the background is seen to be low. The subtraction of the remaining background will be discussed later.

The physical quantities measured directly are the tracks of the kaons (and hence the angle and energy of the phi) and the angle and energy of the positron. It is important that the Monte Carlo and the data agree to a reasonable level for these quantities because the acceptance corrections are obtained from the Monte Carlo. As an example, Fig. 10.5 shows the angle of the phi in the lab system after all the cuts. The Monte Carlo is normalized to the same number of events as the data. Various other kinematic quantities including the momentum and the $p_T^2$ of the tracks and of the $\phi$, the opening...
angle of the decay tracks of the $\phi$ and the electron angle are also found to be in reasonable agreement with the Monte Carlo.

![Graph](image)

Figure 10.3: The ratio of the energy deposited in the calorimeter to the kinetic energy of the tracks in the CTD assuming they are kaons. The solid line is the Monte Carlo expectation for this process.

### 10.3 Acceptance studies

For the primary acceptance calculation the Ryskin model weights are used. The average acceptance for the cuts given above is found to be $0.56 \pm 0.03$ including the correction for the tails outside the mass range selected.

Figure 10.6 shows the resolution of the detector as function of various...
Figure 10.4: The energy of the most energetic condensate not matched to either of the kaon tracks and not part of the positron. The solid line is the Monte Carlo expectation for this process.
Figure 10.5: The lab angle of the phi. The points are data and the solid line is the Monte Carlo normalised to same number of events as the data.

kinematic quantities. The resolution is around 6% in $Q^2$ and $x$ and 1% in $y$. Figure 10.7 shows the acceptance for various kinematic quantities with events weighted according to the Ryskin model. The vertical lines show the phase space used for this analysis. Note that the shape of the acceptance in one variable is dependent on cuts in the other variables. Each of the acceptance plots is now discussed in detail.

The plot of $Q^2$ acceptance is restricted to a $y$ range of $0.02 < y < 0.2$ motivated by the study of $y$ acceptance that follows. The fall in acceptance at low $Q^2$ is geometrical in origin due to the box cut on the positron position.
The range of $Q^2$ chosen for further analysis is $7 < Q^2 < 25$ with the low end chosen somewhat below the point where the acceptance begins to drop in order to increase statistics and the high end chosen because there are few events above this value. Like the $Q^2$ acceptance, the acceptance as a function of $y$ is also partly limited by the geometrical cuts. Low $y$ events correspond to a low energy virtual photon that is knocked in the direction of the proton by the pomeron in contrast to high $y$ events when a very energetic photon collides with the pomeron. Furthermore, the CTD has a reliable region defined by cuts on the pseudorapidity of tracks. Because of the correlation between the angles of the tracks and $y$, this cut on the angle of tracks results in good acceptance being limited to a narrow range of $y$. Figure 10.7(c) shows the acceptance as a function of $y$ integrated over $Q^2$ in a range $7 < Q^2 < 25$ and over $p_t^2 < 0.6$ GeV$^2$ and over all values of other independent variables.

The $p_t^2$ acceptance is flat up to 0.6 GeV$^2$. At larger values of $p_t^2$, the acceptance increases due to migration of events from low $p_t^2$ bins. The $\cos(\theta_h)$ acceptance is relatively flat as shown in Fig. 10.7(e). Hence the distribution of events in $\cos(\theta_h)$ is not corrected for acceptance.
Figure 10.6: The resolutions for various kinematic quantities as functions of the generated variables. The distributions have all the cuts described in the text except on the variable being plotted. The horizontal lines on the two plots with resolutions instead of fractional resolutions indicate the size of the bins.
Figure 10.7: The acceptances for various kinematic quantities as functions of the generated variables. The distributions have all the cuts described in the text except on the variable being plotted. The x acceptance is over all generated y and hence the fall in acceptance at x=.004 corresponds to the $Q^2 = 7 \text{ GeV}^2$ and $y = .02$ cuts.
**Phase space considered for this analysis:** Motivated by the above considerations the phase-space selected for this analysis is:

- $7 < Q^2 < 25 \text{ GeV}^2$
- $0.02 < y < 0.2$
- $t \approx p_t^2 < 0.6 \text{ GeV}^2$.

The phase space chosen is shown in the $x - Q^2$ plane along with the $\phi$ data sample in Fig. 10.8. There are 89 events after the cuts of which 39 are in the chosen kinematic region. The acceptance, purity, and migration in the $x - Q^2$ plane are shown in Figs. 10.9, 10.10 and 10.11 integrated over $p_t^2 < 0.6 \text{ GeV}^2$. The purity is high, migrations small and the acceptance doesn’t vary sharply in the chosen kinematic region. These conditions are necessary for an accurate cross-section measurement.

### 10.4 Background study

The important sources of background for the reaction $ep \rightarrow e\phi p$ are:

- Diffractive $\rho$ and $\omega$ production. The tracks in the CTD are assumed to be from kaons. They are not specifically identified. The pion tracks from $\rho^0 \rightarrow \pi^+\pi^-$ or $\omega \rightarrow \pi^+\pi^-\pi^0$ decays when assumed to be kaons

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 10.8: $x - Q^2$ scatter plot of $\phi$ events. The region bounded by the dashed and solid lines is the phase space considered for this analysis.
Figure 10.9: The $x - Q^2$ acceptance for the DIPS1 MC. The region bounded by dashed and solid lines is the phase space considered for this analysis.
Figure 10.10: Purity in \( x - Q^2 \) phase space. Purity is defined as the percentage of events that are generated in the bin in which they are accepted out of all the events that are accepted in that bin. The region bounded by dashed and solid lines is the phase space considered for this analysis.
Figure 10.11: Migration in $x - Q^2$ phase space. Migration is defined as the probability that events generated in a bin will be accepted in a bin along the direction shown. The size of the arrow represents the probability of migration to a bin multiplied by the distance of the center of the bin where the event is accepted from that where it is generated. The region bounded by dashed and solid lines is the phase space considered for this analysis. It can be seen that the migrations are small in the phase space region used for this analysis.
can have a reconstructed mass consistent with the $\phi$. In this analysis no attempt was made to identify the $\pi^0$. However, this background is reduced by the cut on the $p_t^2$ imbalance between the tracks and the positron. The $\omega$ background is estimated to be $< 1\%$ from a Monte Carlo study.

- Non-resonant $K^+K^-$ production and other inclusive processes. Any reaction that loses part of the event in the beampipe and has two tracks in the CTD, and a real or fake positron in the calorimeter is a background source. The amount of such background is reduced by the requirements that the vector sum of the transverse momenta of the $\phi$ and the positron should balance (by the $p_t^2 < 0.6$ GeV cut) and that there should be no energy in the calorimeter other than that of positron and the kaon tracks. The residual background is evaluated from a fit to the data and from Monte Carlo study.

The $\phi$, being a narrow resonance, can be described by a non-relativistic Breit-Wigner line shape. Fits of the mass distribution of the final sample without any mass cut to a Breit-Wigner distribution plus various background parameterizations are used to estimate the background from the above sources. Mass fits were done with and without $Q^2$ and $y$ cuts. Both
give similar results but the fits with no $Q^2$ and $y$ cuts have larger statistics and are more stable. Monte Carlo background studies show that a significant portion of the background is from $ep \rightarrow e\rho^0 p$ with the pions from the $\rho^0 \rightarrow \pi^+\pi^-$ incorrectly assumed to be kaons and this is expected to have a similar $Q^2$ dependence to $\phi$ production. Hence the fraction of background with and without the $Q^2$ cuts are assumed to be same. The results are shown in Fig. 10.12. The fit values of $M_\phi = 1.02 \pm 0.0005$ GeV and $\Gamma_0 = 0.0035 \pm 0.00067$ GeV are in good agreement with the Particle Data Book values. The background estimate is $6\% +/- 5\%(\text{stat}) +/- 7\%(\text{systematic})$. The systematic error is calculated by using different cuts (including $x$ and $Q^2$ cuts), fitting methods and different mass ranges.

**Proton dissociative events:** Since the proton was not detected, the contribution from proton dissociation had to be subtracted to find the cross-section for the elastic reaction. Due to the limited statistics this cannot be estimated from the $\phi$ data. Hence it is assumed that proton dissociative contribution is the same as for $\rho^0$ production. This is estimated to be $(22 \pm 8 \pm 15)\%$ as discussed in section 12.3.
Figure 10.12: The mass distribution with all the cuts except the kinematic
cuts. The fit is described in section 10.4.

10.5 The ep cross-section

The cross-section, measured in the kinematic region defined above, is ob­tained from $\sigma(ep \rightarrow e\phi p) = N(1 - \Delta)/(C_1 \cdot A \cdot L_{int})$, where $N (= 39)$ is the
observed number of events after all cuts, $\Delta$ is the estimated background frac­tion, $A$ is the acceptance as discussed above, $L_{int}$ is the integrated luminosity
of 2.62 pb$^{-1}$ and $C_1$ is the correction for QED radiative effects. These ra­diative corrections were calculated for the exclusive reaction using the $x$ and
$Q^2$ dependences found in this experiment for a similar reaction $ep \rightarrow epp$
and vary between 1.10 (at low $Q^2$ and low $y$) and 1.14 (at high $Q^2$ and
high $y$). Uncertainties in the dependence on $x$ and $Q^2$ input into radiative corrections cause a systematic uncertainty of $\pm 10\%$ in $C_1$ and hence on the cross-section. The corrected $ep$ cross-section for elastic $\phi$ electroproduction at $\sqrt{s} = 300$ GeV is

$$\sigma(ep \rightarrow e\phi) = 0.037 \pm 0.007(stat.) \pm 0.011(syst.) \text{ nb},$$

integrated over the ranges $7 < Q^2 < 25$ GeV$^2$, $0.02 < y < 0.20$ and $p_t^2 < 0.6$ GeV$^2$. The acceptance corrected mean values of $Q^2$ and $W$ are 10.8 GeV$^2$ and 80.8 GeV, respectively. The error in the acceptance calculation is included in statistical error. The systematic error determination is discussed in section 10.7.

10.6 The $\gamma^* p$ cross-sections

The $ep$ cross-section was converted to a $\gamma^* p$ cross-section as follows. The differential $ep$ cross-section for one photon exchange can be expressed in terms of the transverse and longitudinal virtual photoproduction cross-sections as:

$$\frac{d^2\sigma(ep)}{dxdQ^2} = \frac{\alpha}{2\pi x Q^2} \left[ (1 + (1 - y)^2) \cdot \sigma_T^{\gamma^* p}(y, Q^2) + 2(1 - y) \cdot \sigma_L^{\gamma^* p}(y, Q^2) \right].$$

(10.1)
The virtual photon-proton cross-section can then be written in terms of the positron-proton differential cross-section:

\[
\sigma(\gamma^*p \rightarrow \phi p) = (\sigma_T^\gamma p + \epsilon \sigma_L^\gamma p) = \frac{1}{\Gamma_T} \frac{d^2\sigma(ep \rightarrow e\phi^0 p)}{dx dQ^2},
\]  
(10.2)

where \( \Gamma_T \), the flux of transverse virtual photons, and \( \epsilon \), the ratio of the longitudinal to transverse virtual photon flux, are given by

\[
\Gamma_T = \frac{\alpha (1 + (1 - y)^2)}{2\pi xQ^2} \quad \text{and} \quad \epsilon = \frac{2(1 - y)}{(1 + (1 - y)^2)}.
\]

Throughout the kinematic range studied here, \( \epsilon \) is in the range \( 0.97 < \epsilon < 1.0 \).

Using Eq. 10.2, \( \sigma(\gamma^*p \rightarrow \phi p) \) was determined in two bins in \( W \) and one in \( Q^2 \) with the photon flux calculated from the \( Q^2 \), \( x \) and \( y \) values on an event-by-event basis. It is also found in two bins in \( Q^2 \) but one in \( W \). The 31% overall systematic uncertainty on \( \sigma(ep) \) applies to \( \sigma(\gamma^*p \rightarrow \phi p) \) and thus becomes an overall normalization uncertainty. The results are tabulated in table 10.2.

\(^b\)These two results are not independent.
Table 10.2: The number of events is given in the first column. The $Q^2$ and $y$ ranges are given in the next two columns. The fourth column gives the average acceptance in this kinematic region. The next two columns give the mean values of $Q^2$ and $W$ for the corresponding events (after correcting for acceptance). The last column gives the $\gamma^*p$ cross-section for the previously listed range. The errors given in the table for the $\gamma^*p$ cross-sections are first the statistical error, and then the systematic error. The radiative correction for the bins from 7-10 and 7-25 in $Q^2$ are 10% while that for the bin from 10-25 is 15%.

<table>
<thead>
<tr>
<th>Events</th>
<th>$Q^2$ range</th>
<th>$y$ range</th>
<th>Acceptance</th>
<th>$&lt; Q^2 &gt;$ GeV$^2$</th>
<th>$&lt; W &gt;$ GeV</th>
<th>$\sigma_{\phi}(\gamma^*p)$ nb</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>7-25</td>
<td>0.02-0.2</td>
<td>0.56 ± 0.03</td>
<td>11.9</td>
<td>98.3</td>
<td>4.3 ± 0.8 ± 1.3</td>
</tr>
<tr>
<td>18</td>
<td>7-10</td>
<td>0.02-0.2</td>
<td>0.53 ± 0.03</td>
<td>8.6</td>
<td>98.0</td>
<td>9.4 ± 2.5 ± 2.8</td>
</tr>
<tr>
<td>21</td>
<td>10-25</td>
<td>0.02-0.2</td>
<td>0.60 ± 0.03</td>
<td>13.6</td>
<td>99.7</td>
<td>3.1 ± 0.7 ± 0.9</td>
</tr>
<tr>
<td>20</td>
<td>7-25</td>
<td>0.02-0.06</td>
<td>0.58 ± 0.03</td>
<td>11.8</td>
<td>59.9</td>
<td>4.3 ± 1.1 ± 1.3</td>
</tr>
<tr>
<td>19</td>
<td>7-25</td>
<td>0.06-0.2</td>
<td>0.54 ± 0.03</td>
<td>11.9</td>
<td>107.0</td>
<td>3.9 ± 1.0 ± 1.2</td>
</tr>
</tbody>
</table>
10.7 Systematic studies

Table 10.3 tabulates the systematic errors from various sources, and gives the total systematic error by adding them in quadrature. They are estimated by varying the cuts on key variables and the parameters in the Monte Carlo modelling of the reaction. Some have already been discussed. A few important systematic errors are described below.

- Due to the low Q-value, the decay of $\phi \rightarrow K^+K^-$ has a small opening angle and the CTD may not be able to resolve the tracks. When a minimum 4° opening angle cut was placed on both the data and Monte Carlo, it changed the cross-section by 5%.

- The $E/p < 1.5$ cut is used in this analysis to reject non-exclusive events. Changing the $E/p$ cut by 0.2 units from the nominal value changes the cross-section by 1%. In addition, a check was performed by considering the matching of tracks to clusters in the calorimeter, and placing a cut on unmatched cluster energy $< 0.8$ GeV instead of the $E_{CAL}/E_{KK} < 1.5$ cut. This decreased the cross-section by 3%. Since they are independent, the systematic error due to cut on exclusiveness of the sample is 4%.
Table 10.3: Systematic errors for the DIS $\phi$ cross-section calculation. Errors are presented as percentage variation of the $e-p$ cross-section.

<table>
<thead>
<tr>
<th>Source of systematic error</th>
<th>Error in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRTD/CAL relative position</td>
<td>3</td>
</tr>
<tr>
<td>Trigger</td>
<td>2</td>
</tr>
<tr>
<td>$E - p_z &gt; 35$ GeV</td>
<td>13</td>
</tr>
<tr>
<td>$E_e &gt; 5$ GeV</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Box Cut</td>
<td>8</td>
</tr>
<tr>
<td>Pre-selection</td>
<td>5</td>
</tr>
<tr>
<td>$</td>
<td>\eta^{track}</td>
</tr>
<tr>
<td>$p_T^{track} &gt; 150$ MeV</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>$</td>
<td>V_z + 5</td>
</tr>
<tr>
<td>Vertex x-y determination</td>
<td>8</td>
</tr>
<tr>
<td>$K^+K^-$ opening angle</td>
<td>5</td>
</tr>
<tr>
<td>$E_{CAL}/E_{KK}$</td>
<td>4</td>
</tr>
<tr>
<td>Conversion cut</td>
<td>3</td>
</tr>
<tr>
<td>Non-exclusive background fits</td>
<td>7</td>
</tr>
<tr>
<td>Monte Carlo weights</td>
<td>3</td>
</tr>
<tr>
<td>Radiative Corrections</td>
<td>10</td>
</tr>
<tr>
<td>Proton Dissociative background</td>
<td>15</td>
</tr>
<tr>
<td>Mass range for $\phi$</td>
<td>7</td>
</tr>
<tr>
<td>$p_t^2 &lt; 0.6$ GeV$^2$</td>
<td>5</td>
</tr>
<tr>
<td>Total systematic error</td>
<td>31</td>
</tr>
</tbody>
</table>
• The $p_t^2$ imbalance between the $\phi$ and the positron is found to be sensitive to the vertex x-y determination. The beam transverse size is 200 $\mu$m. Using the average beam position for each run as the vertex x-y position changes the cross-section by 8%.

10.8 Helicity of the $\phi$

The helicity angle distribution as defined in chapter 3 is shown in Fig. 10.13. The acceptance as shown in Fig. 10.7 is flat. The residual background is found to be largest near $|\cos(\theta)| \approx 1$. Thus, to estimate the parameter $r_{00}^{04}$ as defined in Eq. 3.12, the region $|\cos \theta_H| \geq 0.8$ is excluded. An unbinned maximum likelihood fit was performed on the 24 events that remain. No acceptance correction was made, as the acceptance is essentially flat. We find $r_{00}^{04} = 0.80^{+0.11}_{-0.16}(\text{stat.}) \pm 0.05(\text{sys})$. The systematic errors are obtained by performing $\chi^2$ fits, binned likelihood fits, fits with acceptance corrections, and fits extending the range to $|\cos \theta_H| < 0.9$, as well as unbinned likelihood fits in this extended region.

The data indicate a significant fraction of longitudinally polarised $\phi$s are produced in this reaction in the kinematic range of this experiment. If
Figure 10.13: The distribution in the helicity angle, $\cos \theta_h$. The data are not corrected for acceptance. The $\cos^2 \theta_h$ dependence indicates that a significant fraction of longitudinally polarised $\phi$s are produced in this reaction in the kinematic range of this experiment.

S-channel helicity conservation (SCHC) $^{49}$ is assumed, an estimate of $R$, the ratio of longitudinal to transverse cross-sections, for $\phi$ production is obtained $^{50}$:

$$ R = \frac{\sigma_L}{\sigma_T} = \frac{1}{1-r_{00}^{04}} \frac{r_{00}^{04}}{1} = 4.0^{+7.5}_{-2.75} $$

where the statistical and systematic uncertainties in $r_{00}^{04}$ have been added in quadrature.
10.9 Comparison with theoretical predictions

The measured $\gamma^* p$ cross-sections can be compared with the predictions of models by Brodsky, et al. and Ryskin$^{23,22}$ described in chapter 3. The theoretical predictions have large uncertainties because the arguments of $xG(x, Q^2)$, $x$ and $Q$ are each uncertain to a factor of two because the $x$ of the event is not the $x$ of each of the gluons. The following values are used in the calculation: $\alpha_s = 0.16$ at $Q^2 = 11.9$ GeV$^2$, $x = .0012$, $\eta_\phi = 3.1$, $N_c = 3$ and $xG(x, Q^2) = 10$. The last value is from the CTEQ3$^{51}$ parameterization.

$\sigma_{\gamma^* p \rightarrow \phi p}$ is assumed to have the form $e^{-bt}$ and the value of $b (=5.1)$ measured for a similar process at ZEUS$^9$ is used. The calculated cross-section from Eqs. 3.10 and 3.13 are multiplied by $(1+R)/R$ using the value of $R$ measured in the previous section because the equations are for production of longitudinal photons only whereas in the experiment transverse photons also contribute. For the Ryskin model it is assumed $xG(\bar{x}, \bar{q}^2) \approx xG(x, Q^2)$ so that the two models can be compared and because there is a theoretical uncertainty of a factor of two in $Q$ anyway and $\bar{q}^2 \approx Q^2/4$. The electromagnetic form factor $F_{p}^{em} = 1$ is used as an approximation for $F_{p}^{2G}$. The values obtained are tabulated in table 10.4 and are in good agreement with the
measurements. However, both these models are silent about the interaction of the two gluons with the proton. In the calculations above parameterizations of $xG(x, Q^2)$ from experimental data are used.\textsuperscript{51}

Table 10.4: The measured value of $\sigma(\gamma^*p \rightarrow \phi p)$ at $<Q^2> = 11.9$ GeV$^2$ and $<x> = .0012$ at ZEUS compared with the predictions of the Brodsky model and Ryskin model. The calculation of the cross-section using the Brodsky and Ryskin models is described in the text.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>$\sigma(\gamma^*p \rightarrow \phi p)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZEUS Measurement</td>
<td>$4.3 \pm 0.8 \pm 1.3$ nb</td>
</tr>
<tr>
<td>Brodsky model</td>
<td>3.5</td>
</tr>
<tr>
<td>Ryskin model</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Since $x \approx Q^2/W^2$, the data can be analysed as a function of $Q^2$ and $W$, the $\gamma^*p$ center of mass energy, instead of $Q^2$ and $x$. The cross-sections $\sigma(\gamma^*p \rightarrow \phi p)$ from table 10.2 are plotted as a function of $W$ for two $Q^2$ values in Fig. 10.14. Also shown in the figure are the measurements from several experiments at lower $\gamma^*p$ center of mass energy and for photoproduction of $\phi$s. For comparision with the NMC results, the two points for this analysis (at $Q^2$ of 8.6 and 13.6 GeV$^2$) have been scaled to $Q^2$ values of 8.3 and 14.6 GeV$^2$. 

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
by assuming a $Q^2$ dependence of $Q^{-1.2}$, as measured by ZEUS. The high $Q^2$ data exhibit a strong rise with $W$.

This result is to be viewed in connection with other experimental data (see chapters 2 and 3) summarised here. Total cross-sections for hadron-hadron and photon-hadron collisions all increase at high energy by the same slowly varying power of energy $(W^2)^{0.08}$ which can be interpreted as arising from soft pomeron exchange. Elastic electroproduction of vector mesons at high $Q^2$ but low $W$ also shows the same behavior. Elastic electroproduction at large $Q^2$ which indicate steeper variation with energy than expected from the soft pomeron contribution. Elastic $\phi$ electroproduction as shown in Fig. 10.14 also has the same steep variation with $W$. One explanation is that the perturbative BFKL pomeron is responsible and that its contribution is small at NMC energies but increases more rapidly than the soft pomeron term such that it becomes important in the ZEUS data. Cudell et. al consider this to be unlikely. The small value of the BFKL term in the soft processes constrains its magnitude in the hard processes. There is still

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 10.14: The cross-section measured in this experiment is shown, compared to other measurements. The two points for this analysis (the lower two open squares) have been scaled to $Q^2$'s of 8.6 and 14.2 GeV$^2$ by assuming a $Q^2$ dependence of $Q^{-4.2}$ as measured by ZEUS [9] for $\gamma^* p \rightarrow \rho^0 p$. The errors shown are statistical only. Each data point also has an associated systematic error of 31%, a large fraction of which is an overall normalization error. The rise of the cross-section compared to the lower energy measurements at the same $Q^2$ (from NMC), is inconsistent with the slow rise predicted by the soft-pomeron picture of Donnachie and Landshoff.

no success in understanding the steep rise in cross-sections for elastic vector meson electroproduction (and $F_2$ and $J/\psi$ photoproduction) at small x.
Chapter 11

Ratio of $\rho^0$ to $\phi$ Production

From the quark charges of the vector mesons and a flavor independent production mechanism, the ratio $\sigma(\phi)/\sigma(\rho^0)$ of exclusive production cross-sections is expected to be $2/9$.\textsuperscript{52} Experimentally, the elastic photoproduction of mesons containing charm and strange quarks is suppressed. For photoproduction the ratio is found to be $0.076 \pm 0.010$ at $W = 17$ GeV\textsuperscript{17} and $0.065 \pm 0.013$ at 70 GeV.\textsuperscript{18} At larger $Q^2$, NMC has determined that $\sigma(\phi)/\sigma(\rho^0)$ is $\approx 0.1$ for $2 < Q^2 < 10$ GeV\textsuperscript{2} and $W \approx 15$ GeV\textsuperscript{27} while ZEUS has found the ratio to be $0.18 \pm 0.05 \pm 0.03$ at $< Q^2 > = 12.3$ GeV\textsuperscript{2} and $< W > = 98$ GeV. At asymptotically large $Q^2$ perturbative QCD predicts\textsuperscript{23,25,26} a dramatic increase to 0.27. Therefore it is of interest to determine this ratio at both large $Q^2$ and large $W$.

11.1 Data selection and analysis

The ratio is extracted in this chapter using the $\phi$ signal described earlier in this thesis and the $\rho^0$ signal from the same data sample. The $\rho^0$ pre-
selection is the same and the selection cuts similar to those for the \( \phi \). The main difference is that the tracks are assumed to be pions and kaons for the \( \rho^0 \) and \( \phi \) analyses, respectively. Hence the exclusiveness cut is applied to the quantity \( E_{\text{cal}}/E_{\pi^\pm} \) for the \( \rho^0 \), corresponding to \( E_{\text{cal}}/E_{KK} \) for the \( \phi \). The selection criteria and the selected numbers of events after each cut are summarized in table 11.1. There are 328 events after all cuts which are used for further analysis.

The acceptance correction is obtained using simulated events from the generator DIPSI\(^\text{48} \) as discussed in chapter 6. The \( \rho^0 \) mass peak unlike the \( \phi \) is broad and the acceptance could vary with mass. Events were generated with a flat distribution to ensure good statistics in all mass bins. In addition to the event weights discussed in section 6.3 the mass distribution is weighted to a relativistic Breit-Wigner shape. Figure 11.1 and Fig. 11.2 show the efficiency\(^1 \) after all the cuts as a function of mass in two bins each of \( y \) (0.02-0.06 and 0.06-0.2) and \( Q^2 \) (7-10 and 10-25 GeV\(^2 \)). The acceptance as a function of mass first decreases and then increases for high \( y \), while it decreases and then flattens out for low \( y \).

The angle between the decay tracks of the \( \rho^0 \rightarrow \pi^+\pi^- \) (opening angle) increases as a function of mass as shown in Fig. 11.3 and there is a greater probability that one of the decay tracks could miss the cut on the pesudo-

\(^1\)Efficiency is defined as the ratio of events reconstructed in a bin to the events generated in that bin.
Table 11.1: Summary of cuts and selected numbers of events after each cut.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>69,607</td>
</tr>
<tr>
<td>Positron energy &gt; 5 GeV</td>
<td>47,168</td>
</tr>
<tr>
<td>Box cut</td>
<td>35,577</td>
</tr>
<tr>
<td>$E - p_z &gt; 35$ GeV</td>
<td>32,347</td>
</tr>
<tr>
<td>$-50 &lt; V_z &lt; 40$ cm</td>
<td>28,051</td>
</tr>
<tr>
<td>$</td>
<td>\eta_{\text{track}}</td>
</tr>
<tr>
<td>Oppositely charged tracks</td>
<td>13,366</td>
</tr>
<tr>
<td>$E_{\text{CAL}}/E_{\pi\pi}$</td>
<td>2,530</td>
</tr>
<tr>
<td>$M_{K^+K^-} &gt; 1.05$ GeV</td>
<td>2,336</td>
</tr>
<tr>
<td>$0.6 &lt; M_{\pi\pi} &lt; 1.0$ GeV</td>
<td>1,314</td>
</tr>
<tr>
<td>Conversions rejected</td>
<td>1,312</td>
</tr>
<tr>
<td>$p_t^2 &lt; 0.6$ GeV</td>
<td>865</td>
</tr>
<tr>
<td>$7 &lt; Q^2 &lt; 25$ GeV</td>
<td>407</td>
</tr>
<tr>
<td>$0.02 &lt; y &lt; 0.2$</td>
<td>328</td>
</tr>
</tbody>
</table>
Figure 11.1: Efficiency and acceptance as a function of mass in two bins of $Q^2 (7, 10)$ (upper) and $(10, 25)$ (lower) for $0.02 < y < 0.06$. The fit for efficiency is overlaid on acceptance. Since migrations are low the efficiency is used to find the acceptance curve.
Figure 11.2: Efficiency and acceptance as a function of mass in two bins of $Q^2(7,10)$ (upper) and $(10,25)$ (lower) for $0.06 < y < 0.2$. The fit for efficiency is overlaid on acceptance plot. Since migrations are low the efficiency is used to find the acceptance curve.
rapidity of the tracks. This accounts for the decrease of efficiency with mass. However, as mass increases, the positron is found to make a bigger angle with its initial direction (at fixed $Q^2$) as shown in Fig. 11.4. Hence there is less probability of being rejected by the box cut. At large mass this overcomes the opening angle effect especially at high $y$.

Figure 11.3: Opening angle of the $\rho^0$ as a function of the mass for simulated events. The bars indicate the spread.

Figure 11.5 shows the scatter plot of generated and reconstructed mass of the $\rho^0$ demonstrating excellent correlation. Figure 11.6 shows the purity in each bin of mass. Migration between the bins is found to be of order 5%. Figure 11.1 and Fig. 11.2 also show the acceptance as a function of
Figure 11.4: The scattered positron angle in the ZEUS coordinate system for two mass ranges (0.6-0.9 GeV) and (1.2-1.6 GeV) showing that on average the scattered positron makes a bigger angle with the beam axis with increasing mass.
mass with the efficiency function overlaid on them demonstrating that these curves have the same shape. Because the flat mass distribution is weighted to a resonance peak, a few events from the peak migrating into the tail can cause large fluctuations in the individual bins in the tail due to the limited Monte Carlo statistics. So efficiency curves can be better determined. Hence the migrations are ignored and the efficiency curve is used as the acceptance curve for mass in this analysis.

![Figure 11.5: The scatter plot of the reconstructed mass of the $\rho^0$ vs the generated mass for simulated events. They show excellent correlation with little migration.](image)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Figure 11.6: The reconstructed events in a bin as a fraction of the generated events after all the cuts. The solid lines are 5% migration lines.
11.2 The $\rho^0$ production cross-section

For each event a weight (=1/acceptance) is chosen depending on $Q^2, y$ and $M$ with two bins in both $Q^2$ and $y$. The contributions to the signal come from three sources:

- the reaction under study $ep \rightarrow e\rho^0 p$.

- A similar reaction where the proton breaks up, $ep \rightarrow e\rho^0 X$. If the proton remnant escapes totally down the beampipe this reaction has the same topology and the $\rho^0$ mass has the same lineshape as the elastic reaction.

- other backgrounds without the resonance lineshape in mass distribution.

The first two form the resonant part and the third the non-resonant background to the $\rho^0$ signal. First the latter background is subtracted to get the resonant part. Then the elastic and proton dissociative parts are differentiated to get elastic $\rho^0$ production cross-section. The main non-resonant backgrounds to the $\rho^0$ signal are:

- $\phi$ and $\omega$ production. The contamination from $\phi \rightarrow K_L K_S$ and $\omega \rightarrow \pi^+\pi^-\pi^0$ is estimated to be less than 1% each. They are included in the background estimate from fits. $\omega \rightarrow \pi^+\pi^-$ is $< 0.3\%$ and is ignored. $\phi \rightarrow K^+K^-$ is excluded by a cut on $M_{K^+K^-}$. 

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
• Conversions. These are $\gamma \rightarrow e^+e^-$ events. They are found to be near threshold when reconstructed incorrectly assuming that the tracks are pions. Their contribution is calculated to be negligible.

• Non-exclusive background. These are contributions from processes in which part of the event is lost down the beam pipe, and non-resonant $\pi\pi$ production in diffractive events. The contribution from interference between the resonant $\pi^+\pi^-$ production and a non-resonant Drell-type background as discussed by Söding is expected to be small at high $Q^2$. The size of the term is calculated in this analysis.

• There are no events with an electron energy in the range $5 < E'_e < 14 \text{ GeV}$. So the photoproduction background is negligible.

• No events were found from the unpaired bunches demonstrating that the beam-gas background is also negligible.

In order to extract the contribution of the resonant part to the differential cross-section $d\sigma/dM_{\pi\pi}$, the function

$$
\frac{d\sigma}{dM_{\pi\pi}} = f_\rho \cdot BW_\rho(M_{\pi\pi}) + f_I \cdot I(M_{\pi\pi}) + f_B
$$

was fit to the measured mass distribution. The term

$$
BW_\rho(M_{\pi\pi}) = \frac{M_{\pi\pi} M_\rho^0 \Gamma_\rho^0(M_{\pi\pi})}{(M_{\pi\pi}^2 - M_{\rho_0}^2)^2 + M_{\rho_0}^2 \Gamma_{\rho_0}^2(M_{\pi\pi})}
$$

was fit to the measured mass distribution. The term
is a relativistic $p$-wave Breit-Wigner function, with a momentum dependent width

$$\Gamma_{\rho^0}(M_{\pi\pi}) = \Gamma_0 \left(\frac{p^*}{p_0^*}\right)^3 \frac{M_{\rho^0}}{M_{\pi\pi}},$$

(11.3)

where $\Gamma_0$ is the width of the $\rho^0$, $p^*$ is the $\pi$ momentum in the $\pi\pi$ rest frame and $p_0^*$ is the value of $p^*$ at the $\rho^0$ nominal mass $M_{\rho^0}$. The function

$$I(M_{\pi\pi}) = \frac{M_{\rho^0}^2 - M_{\pi\pi}^2}{(M_{\pi\pi}^2 - M_{\rho^0}^2)^2 + M_{\rho^0}^2 \Gamma_{\rho^0}(M_{\pi\pi})^2}$$

(11.4)

is a parametrization of the interference term. The background $f_B$ is assumed to be a constant for this initial fit. All the following fits are done in the mass range $0.6 < M_{\pi\pi} < 1$. The free parameters in the fit were $M_{\rho^0}$, $\Gamma_0$ and the coefficients $f_{\rho^0}$, $f_l$ and $f_B$.

As noted in Fig. 11.7 the contribution from the interference term $f_l$ is found to be consistent with zero as expected and this term is ignored in the rest of this study. Next various types of background shapes are tried. It is expected that the background must have two zeros, one at threshold and the other at $\sqrt{s} = 300$ GeV. Hence the following form is tried,

$$f_B = N(m_{\pi\pi} - 2m_\pi) c_1 e^{-c_2 (m_{\pi\pi} - 2m_\pi)},$$

(11.5)

where $N$ is a constant and $2m_\pi$ is the mass threshold. However, it is found that this fit is unstable as there are too many parameters for it to converge. Therefore, in the region of the fit it is approximated by a first order polynomial. The fit is shown in Fig. 11.8. The fit values of the $\rho^0$ mass and width
Figure 11.7: The acceptance corrected number of events after all the cuts. The points represent the ZEUS data and the curves indicate the results of the fit to the data using expressions (11.1-11.4). The dotted line shows the contribution of the Breit-Wigner term, the dash-dotted line that of the interference term, and the dashed line that of the background term. The solid curve is the sum of these three terms. Only statistical errors are shown. The horizontal bars indicate the size of the bins. The strength of the interference term is consistent with zero (2 ± 3%).
Table 11.2: Results of the fit to the mass spectrum. Only statistical errors are given.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>stat. error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\rho^0}$</td>
<td>0.759 GeV</td>
<td>0.006 GeV</td>
</tr>
<tr>
<td>$\Gamma_0$</td>
<td>0.142 GeV</td>
<td>0.026 GeV</td>
</tr>
<tr>
<td>$f_{\rho^0}$</td>
<td>140.3 pb</td>
<td>12.7 pb</td>
</tr>
</tbody>
</table>

are in good agreement with the accepted ones. This fit is also found to agree with the mass spectrum outside the fit range as shown in Fig. 11.9.

The results of the fit are listed in table 11.2. The resonant part of the total $\pi^+\pi^-$ signal is given by the parameter $f_{\rho^0}$ multiplied by the integral of the relativistic Breit-Wigner curve, that is the area under the dotted curve in Fig. 11.9. There is some arbitrariness in the choice of the integration limits of the Breit-Wigner curve. The integral was carried out in the range $2m_\pi < M_{\pi\pi} < M_{\rho^0} + 5\Gamma_0$, where the $\rho^0$ mass and width values were taken from the fit and the quantity $m_\pi$ is the pion mass. This requires an extrapolation beyond the measured region. The upper limit for the integration range approximately corresponds to the mass of the nearest resonance, the $\rho^0(1450)$, with the same quantum numbers and quark content as the $\rho^0$. If the integral is computed up to $M_{\rho^0} + 4\Gamma_0$, the cross-section decreases by 3%; if instead it is extended to $M_{\rho^0} + 6\Gamma_0$, the cross-section increases by 2%.
Figure 11.8: The acceptance corrected number of events after all the cuts. The points represent the ZEUS data and the curves indicate the results of a fit to the data. The dotted line shows the contribution of the background term which is assumed to be a first order polynomial as an approximation to the shape given by Eq. 11.5. The dashed line is the relativistic p-wave Breit-Wigner. The solid curve is the sum of these two terms. Only statistical errors are shown. The horizontal bars indicate the size of the bins.
Figure 11.9: The acceptance corrected number of events after all the cuts. The fits are the same as Fig. 11.8 and the fit agrees with the mass-spectrum outside the fit range. The dotted line shows the contribution of the background term which is assumed to be a first order polynomial as an approximation to Eq. 11.5. The dashed line is the relativistic p-wave Breit-Wigner. The solid curve is the sum of these two terms. For $M_{\pi\pi} < 0.5$ the acceptance falls steeply, an effect which is not taken into account in the parametrization of acceptance. Only statistical errors are shown. The horizontal bars indicate the size of the bins.
Since the proton was not detected, the contribution from proton dissociation had to be subtracted to find the cross-section for the elastic reaction. A Monte Carlo generator (RHODI), based on the model of Forshaw and Ryskin, was used to model the proton dissociative process with a \( \frac{d\sigma(\gamma^*p)}{dM_X^2} \propto \frac{1}{M_X^{2.5}} \) dependence. Different \( M_X \) dependences were obtained by weighting the events. Events were generated for \( M_X^2 \) values between 1.2 and 4000 GeV\(^2\). The events were passed through the detector and trigger simulation and data reconstruction chain. The events are characterized by the same topology as elastic \( \rho^0 \) production except for the dissociated proton sometimes depositing energy in the FCAL. The normalization was obtained by requiring that the Monte Carlo generated sample have the same number of events with energy between 1 and 20 GeV in the FCAL as for the data when the constraint that \( E_{\text{CAL}}/E_{\pi^+\pi^-} < 1.5 \) was relaxed to \( (E_{\text{CAL}} - E_{\text{FCAL}})/E_{\pi^+\pi^-} < 1.5 \) and the additional constraint \( \theta_{\pi^\pm} > 50^\circ \) was imposed where \( \theta_{\pi^\pm} \) is the angle of the track in ZEUS coordinate system. These changes allow a study of events where the dissociated proton deposits energy in the FCAL. Assuming an \( M_X \) dependence of the form \( 1/M_X^{2.25} \), as measured by the CDF experiment for \( \bar{p}p \to \bar{p} + X \), yielded a contribution of \((22 \pm 8 \pm 15)\%\) where the systematic error was obtained from varying the exponent of \( 1/M_X \) between 2 and 3.

---

\(^2\)This is a study done for 1993 data by the author and others. More precise measurements are underway for the 1994 data.
The radiative corrections were calculated to be (10-15)\%\(^3\) for the selection cuts used in the current analysis and for the \(Q^2\) and \(W\) dependences found in the data. They are taken into account in the cross-section given below. The sources of systematic error are similar to those of \(\phi\) production (see Table 10.3). The error in the acceptance determination (3\%) and the error due to background subtraction is included in the statistical error. The systematic errors which are different from the \(\phi\) are discussed in section 11.3. The total systematic error is found to be 26\%. The corrected \(ep\) cross-section for exclusive \(\rho^0\) production at \(\sqrt{s} = 300\) GeV is

\[
\sigma(ep \rightarrow e\rho^0 p) = 0.15 \pm 0.03(\text{stat.}) \pm 0.04(\text{syst.})\; \text{nb},
\]

integrated over the ranges \(7 < Q^2 < 25\) \(\text{GeV}^2\), \(0.02 < y < 0.20\) and \(p_T^2 < 0.6\) \(\text{GeV}^2\), with acceptance corrected \(< Q^2 >\) and \(< W >\) of 11.0 \(\text{GeV}^2\) and 78.9 \(\text{GeV}\), respectively. This compares well with the measurement by ZEUS in 1993.\(^9\)

11.3 Ratio of \(\phi\) to \(\rho^0\) production.

The ratio of the production cross-sections for \(\phi\) and \(\rho^0\) can be written as

\[
\frac{\sigma(\phi)}{\sigma(\rho^0)} = R = \frac{N_{\phi}^{\text{corr}}}{N_{\rho^0}^{\text{corr}}} \frac{1}{BR(\phi \rightarrow K^+K^-)}.
\]  

\(^3\)These were calculated for 1993 data for the author and others. The cuts are the same for 1994 data. The corrections are currently being verified using a DIPSI Monte Carlo with initial state radiation incorporated in it.
Here $N_\phi^{corr}$ and $N_{\rho}^{corr}$ are the acceptance corrected number of $\rho^0$ and $\phi$ events, respectively and $BR(\phi \rightarrow K^+K^-)$ is the branching ratio of $\phi$ to charged kaons. Using the 1994 $\phi$ and $\rho^0$ samples described above, this ratio is found to be $\sigma(\phi)/\sigma(\rho^0) = 0.24 \pm 0.05$ (stat.) at $<Q^2> = 11.9$ GeV$^2$ and $<W> = 98$ GeV.

Many systematic errors cancel in the direct determination of the ratio. The main systematic errors in the determination of the $\phi$ and $\rho^0$ cross-sections are listed in table 11.3 along with a comment about the extent to which they cancel in the ratio of cross-sections.

The systematic errors that do not cancel are evaluated as follows:

- The shape of the non-exclusive background under the $\rho^0$ is unknown. Fits with different background shapes yielded a systematic uncertainty of 4%.
- The error on the background subtraction for the $\phi$ is 7%.
- The arbitrariness in the limits of integration of the $\rho^0$ Breit-Wigner curve and in the shape of the mass resonance is found to give an error of 5%.
- $\phi \rightarrow K^+K^-$ makes a smaller opening angle compared to $\rho^0 \rightarrow \pi^-\pi^-$. The ability of the CTD to resolve tracks with small opening angle may
Table 11.3: A study of the systematic errors in the vector meson analysis. Some of the systematic errors cancel in the ratio of the production cross-sections of $\phi$ and $\rho^0$ and others are assumed to cancel.

<table>
<thead>
<tr>
<th>Source of systematic error</th>
<th>Error %</th>
<th>Error cancels in ratio?</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRTD/CAL relative position</td>
<td>3</td>
<td>yes</td>
</tr>
<tr>
<td>Trigger</td>
<td>2</td>
<td>yes</td>
</tr>
<tr>
<td>$E - p_z &gt; 35$ GeV</td>
<td>13</td>
<td>yes</td>
</tr>
<tr>
<td>$E_e &gt; 5$ GeV</td>
<td>&lt; 1</td>
<td>yes</td>
</tr>
<tr>
<td>Box cut</td>
<td>8</td>
<td>yes</td>
</tr>
<tr>
<td>Pre-selection</td>
<td>5</td>
<td>yes</td>
</tr>
<tr>
<td>$</td>
<td>\eta^{\text{track}}</td>
<td>&lt; 1.75$</td>
</tr>
<tr>
<td>$p_{\text{track}}^T &gt; 150$ MeV</td>
<td>&lt; 1</td>
<td>yes</td>
</tr>
<tr>
<td>$</td>
<td>V_z + 5</td>
<td>&lt; 45$ cm</td>
</tr>
<tr>
<td>Vertex x-y determination</td>
<td>8</td>
<td>yes</td>
</tr>
<tr>
<td>Decay tracks opening angle</td>
<td>5</td>
<td>no</td>
</tr>
<tr>
<td>$E_{\text{CAL}} / E_{\text{tracks}} &lt; 1.5$</td>
<td>4</td>
<td>yes</td>
</tr>
<tr>
<td>Conversion cuts</td>
<td>3</td>
<td>yes</td>
</tr>
<tr>
<td>Non-exclusive background fits</td>
<td>7</td>
<td>no</td>
</tr>
<tr>
<td>Monte Carlo weights</td>
<td>3</td>
<td>yes</td>
</tr>
<tr>
<td>Radiative Corrections</td>
<td>10</td>
<td>assumed yes</td>
</tr>
<tr>
<td>Proton Dissociative background</td>
<td>15</td>
<td>assumed yes</td>
</tr>
<tr>
<td>$p_t^2 &lt; 0.6$ GeV$^2$</td>
<td>5</td>
<td>assumed yes</td>
</tr>
<tr>
<td>Total systematic error</td>
<td>31</td>
<td></td>
</tr>
</tbody>
</table>
not be simulated well in the Monte Carlo. The systematic error due to this is estimated to be 6%.

Table 11.4: Individual contributions to the systematic error on the ratio.

<table>
<thead>
<tr>
<th>Contribution from</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-resonant background subtraction for $\rho^0$</td>
<td>4%</td>
</tr>
<tr>
<td>Non-resonant background subtraction for $\phi$</td>
<td>7%</td>
</tr>
<tr>
<td>$\rho^0$ line shape</td>
<td>5%</td>
</tr>
<tr>
<td>Opening angle</td>
<td>6%</td>
</tr>
<tr>
<td>Total</td>
<td>11.2%</td>
</tr>
</tbody>
</table>

11.4 Result

With the assumption that the proton dissociation background and the radiative corrections are identical, a value of $\sigma(\phi)/\sigma(\rho^0) = 0.24 \pm 0.05$ (stat.) $\pm 0.03$ (syst.) is obtained at $<Q^2> = 11.9 \text{ GeV}^2$ and $<W> = 98 \text{ GeV}$. The error in the determination of the $\phi$ and $\rho^0$ acceptances, 5% and 3% respectively, have been included in the statistical error. The systematic errors are summarized in table 11.4. This result is shown in Fig. 11.10 along with ZEUS measurement of the ratio at $Q^2 = 0 \text{ GeV}^2$ and NMC measurements. The measurement from ZEUS at $<Q^2> = 11.9 \text{ GeV}^2$ is consistent with the value of $2/9$ expected from the quark charges and a flavor independent production
mechanism unlike the NMC measurements at similar $Q^2$ but different $W$ and the ZEUS photoproduction measurements.

![Graph](image)

Figure 11.10: The ratio of the $\phi$ to $\rho$ cross-sections as a function of $Q^2$. The black triangles are ZEUS data.
Chapter 12

Conclusions

The results of this thesis can be summarised as follows:

- The $ep$ cross-section for elastic $\phi$ electroproduction at $\sqrt{s} = 300$ GeV is

  $$\sigma(ep \rightarrow e\phi p) = 0.037 \pm 0.007(stat.) \pm 0.011(syst.) \text{ nb}, \quad (12.1)$$

  integrated over the ranges $7 < Q^2 < 25$ GeV$^2$, $0.02 < y < 0.20$ and $p_t^2 < 0.6$ GeV$^2$. The acceptance corrected mean values of $Q^2$ and $W$ are 10.8 GeV$^2$ and 80.8 GeV, respectively.

- The cross-section $\sigma(\gamma^*p \rightarrow \phi p)$ at different values of $Q^2$ and $W$ is summarized in table 10.2. The results are plotted as a function of the $\gamma^*p$ center of mass energy $W$ for two mean $Q^2$ values in Fig. 10.14 along with the measurements from several experiments at lower $\gamma^*p$ center of mass energies as well as for photoproduction of $\phi$s. The high $Q^2$ data exhibit a strong rise in $W$ when compared to the measurements from NMC,$^{27}$ which is markedly different from the slow rise seen for
the low $Q^2$ data. This strong rise supports the hypothesis that the mechanism for $\phi$ production at high $Q^2$ is different from that proposed by the soft-pomeron picture.

- The $ep$ cross-section for exclusive $\rho^0$ production at $\sqrt{s} = 300$ GeV is

$$\sigma(ep \rightarrow e\rho^0p) = 0.15 \pm 0.03(stat.) \pm 0.04(syst.) \text{ nb}, \quad (12.2)$$

integrated over the ranges $7 < Q^2 < 25$ GeV$^2$, $0.02 < y < 0.20$ and $p_T^2 < 0.6$ GeV$^2$, with acceptance corrected $<Q^2>$ and $<W>$ of 11.0 GeV$^2$ and 78.9 GeV, respectively.

- With the assumption that the proton dissociative background and the radiative corrections are identical for $\rho^0$ and $\phi$ production, a value of $\sigma(\phi)/\sigma(\rho^0) = 0.24 \pm 0.05 \text{ (stat.)} \pm 0.03 \text{ (syst.)}$ is obtained at $<Q^2> = 11.9$ GeV$^2$ and $<W> = 98$ GeV. This result is shown in Fig. 11.10 along with the ZEUS measurement of the ratio at $Q^2 = 0$ GeV$^2$ and NMC measurements. The measurement from ZEUS at $<Q^2> = 11.9$ GeV$^2$ is consistent with the value of $2/9$ expected from the quark charges and a flavor independent production mechanism unlike the NMC measurements, at similar $Q^2$ but different $W$, and the ZEUS photoproduction measurement.

In 1995, two and half times more useful data has been collected by ZEUS. When it is analysed it will give a more precise measurement of $\sigma(ep \rightarrow e\phi p)$. Also $\sigma(\phi)/\sigma(\rho^0)$ can be measured without the assumptions made in
this thesis about the universality of the t slope, the same fraction of proton
dissociative events and equal radiative corrections. Therefore, the work on
the exclusive electro-production of vector mesons will continue to play a
key role in elucidating the nature of the pomeron and its role in diffractive
scattering at large $Q^2$. 

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Bibliography


aThese refer to high energy physics preprints available on WWW at http://xxx.lanl.gov/


35. ZEUS internal notes, 90-102 and 92-068.
36. ZEUS internal note, 90-111.
38. G.F. Hartner et al., ZEUS internal note, 96-013.
40. H. Abramowicz et al., ZEUS internal note, 93-078.
42. H.C. Fesefeldt, Simulation of hadronic showers, PITHIA 85-02, RWTH Aachen (1985).
45. CERN Program Library, Long Writeup Q121.
46. A. Caldwell and G. Briskin, ZEUS internal note, 95-035.
47. J. Ng et al., ZEUS internal note, 95-037.
51. CTEQ Collab., R. Brock et al., FERMILAB-PUB-93/094.
Vita

Vijaya Kumar Nadendla was born in the temple town of Tirupathi in India to school teachers - Nadendla Dattatreyulu and Kuppa Andhra Bharathi on March 17, 1969. He completed his Master of Science at the University of Hyderabad in 1991. He joined Louisiana State University in the fall of 1991 as a graduate student in physics. He spent two years during 1993-1995 at DESY, Germany participating in the ZEUS experiment. He returned to United states in the fall of 1995. He completed his doctorial studies in the summer of 1996.
Candidate:
Vijaya Kumar Nadendla

Major Field:
Physics

Title of Dissertation:
High Q^2 Elastic Electroproduction of Vector Mesons at HERA

Approved:

[Signatures]

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

[Signatures]

Co-Chair

Date of Examination:
June 4, 1996