

Strange particle production at the ZEUS detector

Andrew C. Cottrell
Lincoln College, Oxford

Thesis submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy at the University of Oxford

Michaelmas Term, 2005



Abstract

The production of the neutral strange particles Λ , $\bar{\Lambda}$ and K_s^0 at HERA has been studied with the ZEUS detector, using an integrated luminosity of 121pb^{-1} . Differential cross-sections are measured in a High Q^2 DIS sample ($Q^2 \geq 25\text{GeV}^2$), a Low Q^2 DIS sample ($5 \leq Q^2 \leq 25\text{GeV}^2$) and a photoproduction sample. The photoproduction sample has $Q^2 < 1\text{GeV}^2$ and at least two jets that satisfy $E_T^{jet} > 5\text{GeV}$ and $|\eta^{jet}| < 2.4$. Cross-sections are measured as a function of the particle P_T and η , and additionally as a function of the event Q^2 and x in the DIS samples, and as a function of x_γ in the photoproduction sample. The DIS cross-sections are compared to the ARIADNE Monte Carlo, which broadly describes the data. The photoproduction cross-sections are compared to PYTHIA, where the agreement is less good, particularly at low x_γ . The baryon-antibaryon asymmetry, defined as $\frac{(\Lambda - \bar{\Lambda})}{(\Lambda + \bar{\Lambda})}$, is measured and always found to be consistent with zero, indicating little transfer of the Baryon Number from the beam proton to the Λ system in the detector region. The polarization of Λ and $\bar{\Lambda}$ is measured and also found to be always consistent with zero, indicating that there is no preferred frame in Λ production. The baryon-meson ratio $(\Lambda + \bar{\Lambda})/K_s^0$ is studied, and is found to generally agree with ARIADNE in DIS, but give an excess over PYTHIA in photoproduction. The excess is particularly prominent at low x_γ in events with no clear jet structure. This is interpreted as hadron production in this region depending on a more-than-one-dimensional overlap of quark wavefunctions. An excess of strangeness in this region at low x_γ with no high E_T jets would be significant. It is investigated by taking the ratio of strange particles to charged tracks but no excess is seen.

To my Parents

Acknowledgements

Working on the ZEUS experiment is to work with a collaboration of hundreds of physicists, technicians and engineers, all of whom it should be the duty of those writing a thesis to thank. So thank you.

Special thanks must primarily go to Roman Walczak, for being a constant source of direction, enthusiasm, and insight. Others in the Oxford ZEUS group have also managed to impart something of their knowledge and skills. Many thanks to Mark Sutton and Grzegorz Grzelak, for their immense understanding of all things pertaining to ZEUS and a willingness to divulge as much as possible of it to a new graduate student. Thanks also to Claire and Bruce for their advice later in the analysis. For making the Oxford ZEUS group such a convivial environment to work in, thanks must go to Robin, for his relaxed but efficient leadership, and, of course, to the other students it was my good fortune to share an office with at some point - James, Sunil, Mark, Philip and Katherine.

Beyond the confines of the Oxford group, the time in Hamburg was more enjoyable and useful for the presence of John, Joanna, Tim, Catherine, Billy, Umer, Alex, Richard, Matt, Jo, Eileen and the remainder of the UK group, and was particularly constructive in terms of the analysis on account of the hard work and advice of Sergei, Chuanlei, Amita, and the remainder of the particle production group. Thanks also to PPARC, for providing the funding to study physics for three years, and to Susan Ketels, whose administrative gifts made the frequent journeyings between Hamburg and Oxford as easy as they were.

Finally, many thanks to Heidi, who from proof-reading the manuscript to being uniformly delightful has so improved the last three years.

Contents

1	Introduction	1
1.1	On the nature of things	1
1.1.1	QCD	2
1.2	Electron Proton Scattering	2
1.3	DIS Kinematics	3
1.4	DIS Cross Sections	4
1.5	Quark Parton Model	4
1.6	Improved Quark Parton Model	6
1.6.1	Evolution of PDFs	7
1.7	Photoproduction	8
2	Strange Particle Production	11
2.1	Hadronisation	11
2.2	Strange Particles	11
2.2.1	Λ Polarization	13
2.2.2	Baryon Number Asymmetry	15
2.2.3	Baryon to Meson Ratio	16
2.2.4	The Fireball Region	18
3	HERA and ZEUS	20
3.1	HERA	20
3.1.1	Lepton Beam	21
3.1.2	Proton Beam	22
3.2	The ZEUS Detector	23
3.2.1	Inner Tracking	24
3.2.2	Calorimetry	27

3.2.3	Muon Chambers	29
3.2.4	Background Rejection	29
3.2.5	Luminosity Monitor	30
3.2.6	Trigger and Data Acquisition	30
4	Reconstructing Events	32
4.1	Event Kinematics	32
4.1.1	Electron Method	32
4.1.2	Jacquet-Blondel Method	32
4.1.3	Double Angle Method	33
4.2	Electron Finding	33
4.3	Jet Reconstruction	34
4.3.1	Cone Algorithms	34
4.3.2	The $K_{\perp}$ Cluster Algorithm	35
4.4	The Hadronic Final State	36
4.5	Track and Vertex Reconstruction	36
5	Monte Carlo	38
5.1	PYTHIA	39
5.1.1	Strangeness Suppression	39
5.1.2	Baryon Production	40
5.1.3	Multi-parton Interactions	40
5.2	HERWIG	41
5.2.1	Hadronisation	41
5.2.2	Multi-parton Interactions	42
5.3	DJANGO / ARIADNE	42
6	Event Selection	43
6.1	High Q^2 DIS	43
6.1.1	Online Selection	44
6.1.2	Offline Selection	45
6.1.3	Monte Carlo	46
6.2	Low Q^2 DIS	48

6.2.1	Online Selection	48
6.2.2	Offline Selection	48
6.2.3	Monte Carlo	49
6.3	Photoproduction	49
6.3.1	Online Selection	49
6.3.2	Offline Selection	52
6.3.3	Monte Carlo	53
7	Reconstructing Strange Particles	56
7.1	Reconstructing Λ and K_s^0	56
7.1.1	Agreement with Monte Carlo	59
7.2	Obtaining the Cross-section	60
7.3	Obtaining the Polarization	65
7.4	Correction Procedure	66
7.4.1	Preliminary $P_T - \eta$ Correction	66
7.4.2	Further Corrections	68
7.4.3	Statistical Errors	70
7.5	Tracks	71
7.6	Further Variables	74
7.6.1	Fraction of E_T in highest E_T jet	74
7.6.2	$E_T - P_T$	76
8	Results	78
8.1	Differential Cross-Sections	78
8.1.1	$5 \leq Q^2 \leq 25\text{GeV}^2$	78
8.1.2	$Q^2 \geq 25\text{GeV}^2$	84
8.1.3	Photoproduction	88
8.2	Polarization	93
8.2.1	$5 \leq Q^2 \leq 25\text{GeV}^2$	93
8.2.2	$Q^2 \geq 25\text{GeV}^2$	96
8.2.3	Photoproduction	99
8.3	Baryon - Antibaryon Asymmetry	102
8.3.1	$5 \leq Q^2 \leq 25\text{GeV}^2$	102

8.3.2	$Q^2 \geq 25\text{GeV}^2$	104
8.3.3	Photoproduction	106
8.4	Baryon - Meson Ratio	109
8.4.1	$5 \leq Q^2 \leq 25\text{GeV}^2$	109
8.4.2	$Q^2 \geq 25\text{GeV}^2$	112
8.4.3	Baryon-meson ratio across the $x - Q^2$ plane	120
8.4.4	Photoproduction	120
8.5	Ratio of Strange Particles to Tracks	124
8.5.1	$5 \leq Q^2 \leq 25\text{GeV}^2$	124
8.5.2	$Q^2 \geq 25\text{GeV}^2$	128
8.5.3	Photoproduction	130
9	Conclusions	132
9.1	Cross-sections	132
9.2	Polarization	133
9.2.1	Transverse Polarization	133
9.2.2	Longitudinal Polarization	134
9.3	Baryon - Antibaryon Asymmetry	135
9.4	Baryon - Meson Ratio	137
9.4.1	The Insufficiency of Multiple Interactions	139
9.5	Strange Particle to Track Ratio	140
9.6	Final Conclusions	140
A	Systematic Errors	142
	Bibliography	154

List of Figures

1.1	Lowest order Feynman diagrams for Neutral Current and Charged Current deep inelastic scattering	3
1.2	The kinematics of electron proton interactions	5
1.3	Summary of ZEUS and fixed target F_2 data	7
1.4	The parton densities inside the proton, extracted from fitting next-to-leading order evolution equations to DIS data	8
1.5	Some examples of direct photoproduction	9
1.6	Some examples of resolved photoproduction	9
1.7	The x_γ^{obs} distribution for data compared with various Monte Carlo predictions	10
2.1	Boson-gluon fusion producing a quark-antiquark pair	12
2.2	Typical hard interaction, leading to a high energy quark and gluon, which then fragment	12
2.3	Transverse Λ and $\bar{\Lambda}$ polarization, as observed by the HERMES collaboration in inclusive eN scattering	14
2.4	Transverse Λ and $\bar{\Lambda}$ polarization, as observed in proton beryllium scattering	14
2.5	The baryon to meson ratios observed by STAR and PHENIX at RHIC .	17
2.6	Comparison of the fragmentation and recombination models to Au + Au collision data, collected by the PHENIX collaboration	18
3.1	Location of HERA	20
3.2	HERA injection system	21
3.3	The luminosity provided by HERA for each year of running	23
3.4	Cross-section of the ZEUS detector in the zy plane	24
3.5	The arrangement of wires, cells and superlayers in the CTD	25
3.6	The arrangement of wires in a CTD cell	26

6.1	Comparison of data and MC detector level event distributions for the High Q^2 sample	47
6.2	Comparison of data and MC detector level event distributions for the Low Q^2 sample	50
6.3	The best fit x_γ distribution	54
6.4	Comparison of data and MC detector level event distributions for the Photoproduction sample	55
7.1	K_s^0 detection efficiency at ZEUS, as measured in [61]	57
7.2	Plot showing Λ and K_s^0 invariant mass of each candidate	59
7.3	Detector level Λ and K_s^0 mass peaks	60
7.4	Detector level comparison between data and MC of strange particle quantities in the Low Q^2 sample	61
7.5	Detector level comparison between data and MC of event variables for events containing a Λ or $\bar{\Lambda}$ candidate in the Low Q^2 sample	61
7.6	Detector level comparison between data and MC of event variables for events containing a K_s^0 candidate in the Low Q^2 sample	62
7.7	Detector level comparison between data and MC of strange particle quantities in the High Q^2 sample	62
7.8	Detector level comparison between data and MC of event variables for events containing a Λ or $\bar{\Lambda}$ candidate in the High Q^2 sample	63
7.9	Detector level comparison between data and MC of event variables for events containing a K_s^0 candidate in the High Q^2 sample	63
7.10	Detector level comparison between data and MC of strange particle quantities in the photoproduction sample	64
7.11	Detector level comparison between data and MC of event variables for events containing a Λ or $\bar{\Lambda}$ candidate in the photoproduction sample	64
7.12	Detector level comparison between data and MC of event variables for events containing a K_s^0 candidate in the photoproduction sample	65
7.13	Strange particle correction factors as a function of P_T and η	67
7.14	Λ , $\bar{\Lambda}$ and K_s^0 mass peaks for one bin of $P_T - \eta$ fit to a Gaussian + 1st Order Polynomial	69

7.15	Detector level comparison between data and MC track variables in the High Q^2 sample	72
7.16	Detector level comparison between data and MC track variables in the Low Q^2 sample	73
7.17	Detector level comparison between data and MC track variables in the photoproduction sample	73
7.18	Track correction factors as a function of P_T and η	74
7.19	The distribution of the total E_T compared to the E_T of the highest E_T jet for photoproduction events	75
7.20	(a) The $E_T - P_T$ distribution for DIS events with $Q^2 \geq 25\text{GeV}^2$. (b) A slice through (a)	77
8.1	Differential cross-sections for $\Lambda + \bar{\Lambda}$ production in events with $5 \leq Q^2 \leq 25\text{GeV}^2$	79
8.2	Differential cross-sections for Λ production in events with $5 \leq Q^2 \leq 25\text{GeV}^2$	80
8.3	Differential cross-sections for $\bar{\Lambda}$ production in events with $5 \leq Q^2 \leq 25\text{GeV}^2$	81
8.4	Differential cross-sections for K_s^0 production in events with $5 \leq Q^2 \leq 25\text{GeV}^2$	82
8.5	Differential cross-sections for $\Lambda + \bar{\Lambda}$ production in events with $Q^2 \geq 25\text{GeV}^2$	84
8.6	Differential cross-sections for Λ production in events with $Q^2 \geq 25\text{GeV}^2$.	85
8.7	Differential cross-sections for $\bar{\Lambda}$ production in events with $Q^2 \geq 25\text{GeV}^2$.	86
8.8	Differential cross-sections for K_s^0 production in events with $Q^2 \geq 25\text{GeV}^2$	87
8.9	Differential cross-sections for $(\Lambda + \bar{\Lambda})$ production in photoproduction . .	89
8.10	Differential cross-sections for Λ production in photoproduction	90
8.11	Differential cross-sections for $\bar{\Lambda}$ production in photoproduction	91
8.12	Differential cross-sections for K_s^0 production in photoproduction	92
8.13	Angular distributions to obtain the transverse polarization in the Low Q^2 sample	94
8.14	Angular distributions to obtain the longitudinal polarization in the Low Q^2 sample	95
8.15	Angular distributions to obtain the transverse polarization in the High Q^2 sample	97

8.16	Angular distributions to obtain the longitudinal polarization in the High Q^2 sample	98
8.17	Angular distributions to obtain the transverse polarization in the photoproduction sample	99
8.18	Angular distributions to obtain the longitudinal polarization in the photoproduction sample	100
8.19	$(\Lambda - \bar{\Lambda})/(\Lambda + \bar{\Lambda})$ asymmetry in the Low Q^2 sample	103
8.20	$(\Lambda - \bar{\Lambda})/(\Lambda + \bar{\Lambda})$ asymmetry in the Low Q^2 sample divided into High and Low fractions of the total E_T carried by the highest E_T jet	104
8.21	$(\Lambda - \bar{\Lambda})/(\Lambda + \bar{\Lambda})$ asymmetry in the High Q^2 sample	105
8.22	$(\Lambda - \bar{\Lambda})/(\Lambda + \bar{\Lambda})$ asymmetry in the High Q^2 sample divided into High and Low fractions of the total E_T carried by the highest E_T jet	107
8.23	$(\Lambda - \bar{\Lambda})/(\Lambda + \bar{\Lambda})$ asymmetry in the photoproduction sample	108
8.24	$(\Lambda - \bar{\Lambda})/(\Lambda + \bar{\Lambda})$ asymmetry in the photoproduction sample divided into High and Low fractions of the total E_T carried by the highest E_T jet	110
8.25	$(\Lambda + \bar{\Lambda})/K_s^0$ ratio for the Low Q^2 sample	111
8.26	$(\Lambda + \bar{\Lambda})/K_s^0$ ratio for the Low Q^2 sample divided into High and Low fractions of the total E_T carried by the highest E_T jet	113
8.27	$(\Lambda + \bar{\Lambda})/K_s^0$ ratio for the High Q^2 sample	114
8.28	$(\Lambda + \bar{\Lambda})/K_s^0$ ratio for the High Q^2 sample divided into High and Low fractions of the total E_T carried by the highest E_T jet	115
8.29	$(\Lambda + \bar{\Lambda})/K_s^0$ ratio for the High Q^2 data sample divided into events with High and Low E_T/P_T	116
8.30	$(\Lambda + \bar{\Lambda})/K_s^0$ ratio for the High Q^2 MC sample divided into events with High and Low E_T/P_T	117
8.31	$(\Lambda + \bar{\Lambda})/K_s^0$ ratio in the region $25 \leq Q^2 \leq 120\text{GeV}^2$ and $x \leq 0.002$ divided into events with High and Low E_T/P_T	118
8.32	Detector level η^{max} distributions	119
8.33	$(\Lambda + \bar{\Lambda})/K_s^0$ ratio as a function of x in four bins of Q^2	121
8.34	$(\Lambda + \bar{\Lambda})/K_s^0$ ratio as a function of Q^2 in four bins of x	122
8.35	$(\Lambda + \bar{\Lambda})/K_s^0$ ratio for the photoproduction sample	123

8.36	$(\Lambda + \bar{\Lambda})/K_s^0$ ratio for the photoproduction sample divided into High and Low fractions of the total E_T carried by the highest E_T jet	125
8.37	Ratios of strange particles to total number of tracks as a function of P_T and η in the Low Q^2 sample	126
8.38	Ratios of strange particles to total number of tracks as a function of P_T and η in the Low Q^2 sample divided into High and Low fractions of the total E_T carried by the highest E_T jet	127
8.39	Ratios of strange particles to total number of tracks as a function of P_T and η in the High Q^2 sample	128
8.40	Ratios of strange particles to total number of tracks as a function of P_T and η in the High Q^2 sample divided into High and Low fractions of the total E_T carried by the highest E_T jet	129
8.41	Ratios of strange particles to total number of tracks as a function of P_T and η in the photoproduction Q^2 sample	130
8.42	Ratios of strange particles to total number of tracks as a function of P_T and η in the photoproduction sample divided into High and Low fractions of the total E_T carried by the highest E_T jet	131
9.1	Proton-antiproton asymmetry, $2\frac{(p-\bar{p})}{(p+\bar{p})}$ in photoproduction at HERA measured by H1, shown as a function of momentum and azimuthal angle . .	136
A.1	Systematic errors for $\frac{d\sigma(\Lambda+\bar{\Lambda})}{dP_T}$ in the Low Q^2 sample	143
A.2	Systematic errors for $\frac{d\sigma(K_s^0)}{dP_T}$ in the Low Q^2 sample	144
A.3	Systematic errors for $\frac{d\sigma(\Lambda+\bar{\Lambda})}{d\eta}$ in the Low Q^2 sample	144
A.4	Systematic errors for $\frac{d\sigma(K_s^0)}{d\eta}$ in the Low Q^2 sample	145
A.5	Systematic errors for $\frac{d\sigma(\Lambda+\bar{\Lambda})}{dx}$ in the Low Q^2 sample	145
A.6	Systematic errors for $\frac{d\sigma(K_s^0)}{dx}$ in the Low Q^2 sample	146
A.7	Systematic errors for $\frac{d\sigma(\Lambda+\bar{\Lambda})}{dQ^2}$ in the Low Q^2 sample	146
A.8	Systematic errors for $\frac{d\sigma(K_s^0)}{dQ^2}$ in the Low Q^2 sample	147
A.9	Systematic errors for $\frac{d\sigma(\Lambda+\bar{\Lambda})}{dP_T}$ in the High Q^2 sample	148
A.10	Systematic errors for $\frac{d\sigma(K_s^0)}{dP_T}$ in the High Q^2 sample	148
A.11	Systematic errors for $\frac{d\sigma(\Lambda+\bar{\Lambda})}{d\eta}$ in the High Q^2 sample	149
A.12	Systematic errors for $\frac{d\sigma(K_s^0)}{d\eta}$ in the High Q^2 sample	149

A.13 Systematic errors for $\frac{d\sigma(\Lambda+\bar{\Lambda})}{dx}$ in the High Q^2 sample	150
A.14 Systematic errors for $\frac{d\sigma(K_s^0)}{dx}$ in the High Q^2 sample	150
A.15 Systematic errors for $\frac{d\sigma(\Lambda+\bar{\Lambda})}{dQ^2}$ in the High Q^2 sample	151
A.16 Systematic errors for $\frac{d\sigma(K_s^0)}{dQ^2}$ in the High Q^2 sample	151
A.17 Comparing correction factors from the full sample of High Q^2 MC with a sample with the same ratio of events with $E_P = 820\text{GeV}$ to events with $E_P = 920\text{GeV}$ as the data	152
A.18 The ratio of correction factors obtained from the full High Q^2 MC sample to the correction factors obtained from the MC sample with the same ratio of events with $E_P = 820\text{GeV}$ to events with $E_P = 920\text{GeV}$ as the data	153

List of Tables

2.1	Baryon to meson ratios measured in e^+e^- collisions	17
3.1	Luminosity provided by HERA between 1992 and 2000	22
3.2	Angular acceptance of the three UCAL sections	28
6.1	Luminosity recorded by ZEUS as good for physics	45
6.2	Monte Carlo samples used in the High Q^2 analysis	46
6.3	Luminosity recorded by ZEUS as good for physics after the prescale applied by DIS01 trigger	48
6.4	Monte Carlo samples used in the Low Q^2 analysis	49
6.5	Available Monte Carlo samples used in the photoproduction analysis . .	53
7.1	Definition of the $P_T - \eta$ grid	66
7.2	Definition of the $\cos \theta$ bins used to obtain the polarization	70
7.3	Definition of the x and Q^2 bins for the High Q^2 event sample	70
7.4	Definition of the x and Q^2 bins for the Low Q^2 event sample	70
7.5	Definition of the x_γ bins	70
8.1	Variations in the selection criteria in order to estimate the systematic error of Λ and K_s^0 production in the High Q^2 and Low Q^2 samples	83
8.2	Polarization values in the Low Q^2 sample, including both statistical and systematic errors	96
8.3	Polarization values in the High Q^2 sample, including both statistical and systematic errors	97
8.4	Polarization values in the photoproduction sample	101
8.5	Bin boundaries to obtain x dependence in bins of Q^2	120
8.6	Bin boundaries to obtain Q^2 dependence in bins of x	120

Chapter 1

Introduction

1.1 On the nature of things

High Energy Physics is the attempt to understand the nature of the universe at its most fundamental level. What are the fundamental particles? How do they interact? Why do they behave as they do? These are the questions it seeks to answer. A good theory is one that describes as much of the universe as possible using as few ideas as possible, and necessitating as few as possible parameters to be input to the theory to make it describe the universe as it is observed.

One of the best ever theories in these terms is the Standard Model. In this model the electromagnetic and weak forces are unified into an $SU(2)\otimes U(1)$ gauge group with a single coupling constant, and the strong force is an $SU(3)$ group. Electrons, muons and taus with their respective neutrinos (and antiparticles) make up the fundamental particles in the electroweak sector. The three pairs of quarks, ud , cs and tb are the fundamental particles acted upon by the strong force. The electroweak force is mediated by γ , Z^0 and $W^\pm$ which observe the quantum numbers charge and isospin. The strong force is mediated by gluons, which observe the colour quantum number. The theory of the strong force is known as Quantum Chromodynamics (QCD). The mass of such particles as the Z^0 and $W^\pm$ is generated by hypothesizing a field (the Higgs field) with a non-zero vacuum expectation value. The existence of this field is crucial to the success of the Standard Model, and will be testable in the experiments at the Large Hadron Collider (LHC), as its existence also requires the existence of a Higgs particle, which may be directly observed at the energies which the LHC will reach.

The HERA accelerator, colliding electrons with protons, is a good tool with which to study various physics processes, particularly in this thesis, aspects of QCD.

1.1.1 QCD

QCD is analogous to Quantum Electrodynamics (QED) in that the electric charge of QED corresponds to colour in QCD. However, there are significant differences between the two. Firstly, in QED the charge may be only either $+$ or $-$, whereas in QCD there are three different possible colours, by convention red, blue, green, each with their anticolours. Secondly, the mediating boson in QED, γ , carries no charge (an abelian group), whereas the gluons in QCD do carry colour, allowing for self-interactions (hence a non-abelian group). Thirdly, while the coupling of QED, α_e , is always $\ll 1$, the equivalent in QCD, α_s is not.

The value of α_s is not constant but varies as a function of scale. At very high values of 4-momentum transfer (or small distances) α_s is small, and so can be treated perturbatively. However, at lower 4-momentum (large distances) α_s increases such that perturbative expansions are no longer possible. This increasing value of α_s gives some explanation of the confinement problem - why quarks, or any particles with overall colour are never observed. Coloured particles are always produced with their corresponding anti-coloured particles, by symmetry. If these particles move away from each other it becomes energetically favourable to produce new quark-antiquark pairs which then combine to form the colourless observables known as hadrons.

1.2 Electron Proton Scattering

The lowest order process in electron-proton interactions involves one particle transferred between the electron and proton. This can be either a γ or a Z^0 , or a $W^\pm$, as in Fig. 1.1. The nature of the transferred particle divides the interactions into Neutral Current (NC) and Charged Current (CC). The interactions are generally of the form shown in Eqn. 1.1. Here, X is generally a high multiplicity hadronic system.

$$e + P \rightarrow e' X \quad (\text{NC}); \quad e^+(e^-) + P \rightarrow \bar{\nu}(\nu) X \quad (\text{CC}) \quad (1.1)$$

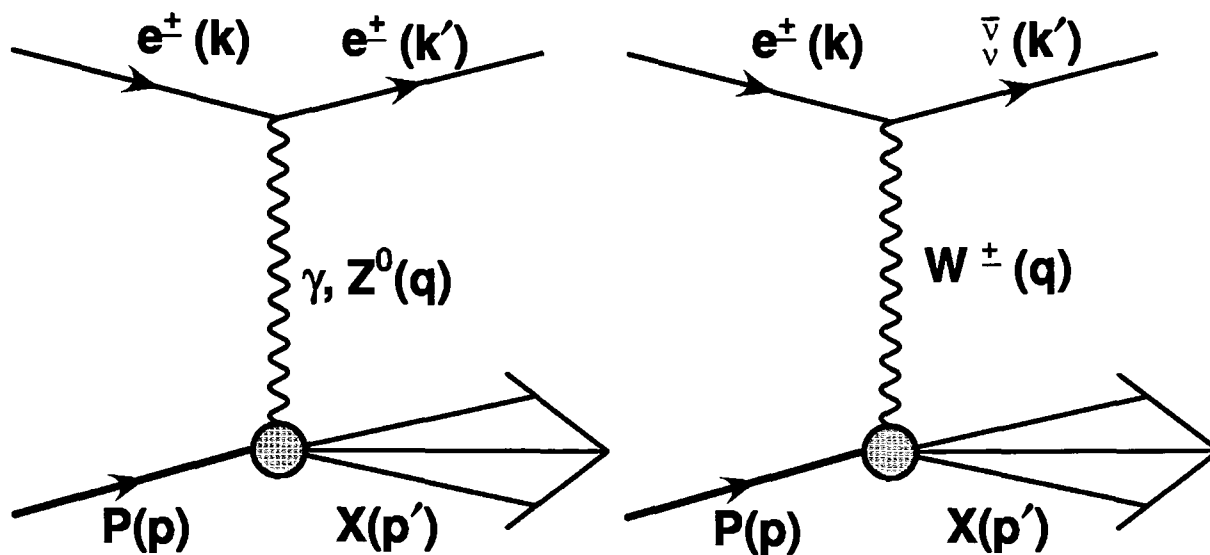


Figure 1.1: Lowest order Feynman diagrams for Neutral Current and Charged Current deep inelastic scattering.

Such interactions, where a lepton interacts with a proton with a high momentum transfer, are known as Deep Inelastic Scattering (DIS).

1.3 DIS Kinematics

The kinematics of deep inelastic scattering are defined using various 4-momenta, as shown in Fig. 1.1. $k = (E, \mathbf{k})$ and $k' = (E', \mathbf{k}')$ are the 4-momenta of the incoming and outgoing lepton. $p = (E_p, \mathbf{p})$ and $q = (E_q, \mathbf{q})$ are the 4-momenta of the incoming proton and transferred boson respectively. From these, three Lorentz-invariant quantities can be made:

$$Q^2 = -q^2 = -(k - k')^2 \quad (1.2)$$

$$y = \frac{p \cdot q}{p \cdot k} \quad (1.3)$$

$$x = \frac{Q^2}{p \cdot q} \quad (1.4)$$

The centre-of-mass energy squared of the electron proton system is:

$$s = (k + p)^2 \simeq 2k \cdot p = \frac{Q^2}{xy} \quad (1.5)$$

where the approximation is that the particle masses are small compared to the centre-of-mass energy. This approximation is very good for the HERA machine. Hence, for a given centre of mass energy, any two of x , y , and Q^2 fully define the eP scattering kinematics.

The centre-of-mass energy, W , of the hadronic system is:

$$W^2 = (q + p)^2 \simeq 2p \cdot q + q^2 \quad (1.6)$$

1.4 DIS Cross Sections

The general form of the DIS cross section can be expressed in terms of the leptonic ($L_{\mu\nu}$) and hadronic ($W_{\mu\nu}$) tensors:

$$d\sigma^{eP} \sim L_{\mu\nu} \cdot W^{\mu\nu} \quad (1.7)$$

$L_{\mu\nu}$ is calculable from QED, and has the form:

$$2[k'_\mu k'_\nu + k'_\nu k'_\mu - k' \cdot k' g_{\mu\nu}] \quad (1.8)$$

where $g_{\mu\nu}$ is the metric tensor.

$W_{\mu\nu}$ parameterizes the hadronic vertex, and may be written as:

$$W_{\mu\nu} = W_1(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}) + \frac{W_2}{m^2}(p_\mu - \frac{p \cdot q}{q^2} q_\mu)(p_\nu - \frac{p \cdot q}{q^2} q_\nu) \quad (1.9)$$

where m is the proton mass, and $W_{1,2}$ are structure functions that may be expressed in terms of any two of Q^2, x and y .

It is convenient to re-write $W_{1,2}$ as follows:

$$F_1 = W_1; \quad F_2 = W_2 \frac{p \cdot q}{m^2} \quad (1.10)$$

The cross section may then be written

$$\frac{d\sigma^{eP}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[\left(1 + (1-y)^2\right) F_2(x, Q^2) - y^2 F_L(x, Q^2) \right] \quad (1.11)$$

where $F_L = F_2 - 2xF_1$.

For more details see, for example, [1].

1.5 Quark Parton Model

In the naive quark parton model, the proton is considered in the infinite momentum frame. In this frame it is made up of non-interacting point-like particles (partons) that

have negligible transverse momentum. These are identified as quarks. Inelastic electron proton collisions then become elastic electron parton collisions. Each quark carries a fraction ξ of the total proton momentum, as in Fig. 1.2. Considering an elastic scatter

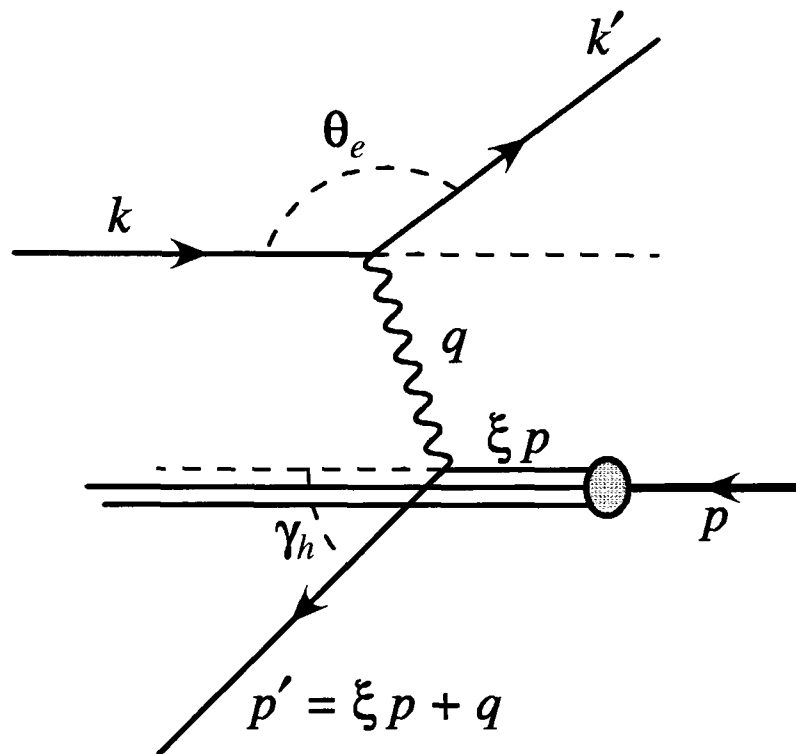


Figure 1.2: The kinematics of electron proton interactions.

between the transferred boson and the parton gives:

$$p'^2 = (\xi p + q)^2 \simeq 2\xi p \cdot q + q^2 \simeq 0 \quad (1.12)$$

where the approximations are that the mass of the parton is negligible.

From this it can be seen that:

$$\xi = \frac{-q^2}{2p \cdot q} = \frac{Q^2}{2p \cdot q} = x \quad (1.13)$$

The DIS cross section (Eqn. 1.11) must depend on the cross section of an electron interacting with a parton of a certain momentum multiplied by the probability of finding the parton with the correct fraction of the proton momentum. A new variable, $f_i(x)$ is introduced as the probability of finding a parton i with momentum x in the proton, and is called the parton distribution function (PDF). In the quark parton model, the structure function F_2 may now be written

$$F_2(x) = \sum_i e_i^2 x f_i(x) \quad (1.14)$$

where e_i is the charge on the parton in units such that the charge on the electron = -1.

The Callan-Gross relation

$$F_1(x) = \frac{1}{2x} F_2(x) \quad (1.15)$$

comes about from assuming only point-like, charged partons with spin = $\frac{1}{2}$ (i.e. quarks) in the proton [2].

With these structure functions, the cross section becomes

$$\frac{d\sigma^{eP}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \left[\left(1 + (1-y)^2 \right) F_2(x) \right] \quad (1.16)$$

where the Q^2 dependence now comes solely from the photon propagator. The lack of a Q^2 dependence in the structure functions is known as scaling, and historically, its observation at SLAC was a convincing piece of evidence that the proton was indeed partonic [3].

1.6 Improved Quark Parton Model

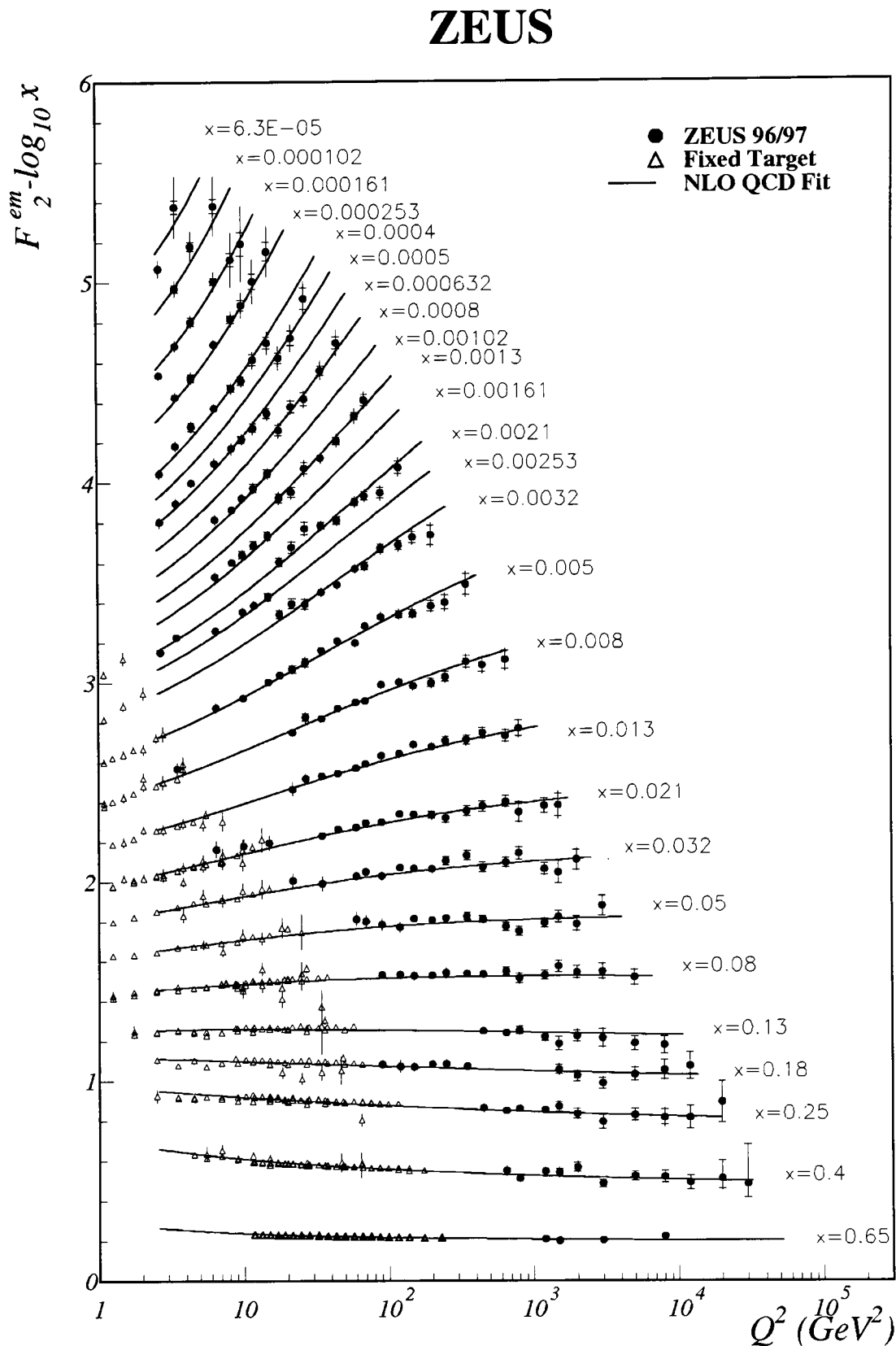
If the quark parton model was correct, and the only partons in the proton were quarks, then the sum of all the partonic momenta should equal the proton momentum:

$$\sum_i \int_0^1 x f_i(x) dx = 1 \quad (1.17)$$

However, a low Q^2 ($0.5 \lesssim Q^2 \lesssim 2.5 \text{ GeV}^2$) neutrino scattering experiment measured this to be ~ 0.5 [4] which indicates the presence additionally of neutral partons in the proton. These are identified as gluons, the gauge bosons of QCD. The existence of such particles was experimentally confirmed at DESY by the observation of 3-jet events in e^+e^- collisions [5].

QCD allows quarks to radiate gluons, and this leads to the assumption of zero transverse momentum becoming invalid. This allows longitudinally polarized photons to have a non-zero interaction probability, so F_L is no longer non-zero.

Additionally, scaling, the dependence of the structure functions only on x , is no longer valid due to the gluon radiation. As Q^2 increases then more partons may be resolved, so the total momentum is distributed more thinly - more particles will have lower x . A summary of F_2 measurements may be seen in Fig. 1.3 [6].

Figure 1.3: Summary of ZEUS and fixed target F_2 data.

1.6.1 Evolution of PDFs

Gluon radiation causes Eqn. 1.14 to need some adjustment. The conventional approach is to define a factorization scale, μ , below which soft and collinear gluon emission is absorbed into the bare parton densities. Perturbative QCD is used to evolve these initial parton densities at the factorization scale up to higher values of Q^2 . For details of the evolution see, for example, [7]. The evolution is perturbative, so the final result is dependent on how many orders of perturbation theory are used.

The evolution equations can be fitted to the various measurements of DIS cross sections to give the parton densities at any value of Q^2 . Typical PDFs can be seen in Fig. 1.4 [8]. It is conventional to split the quark densities into sea quarks (those that come from gluon splitting) and valence quarks (the original quarks).

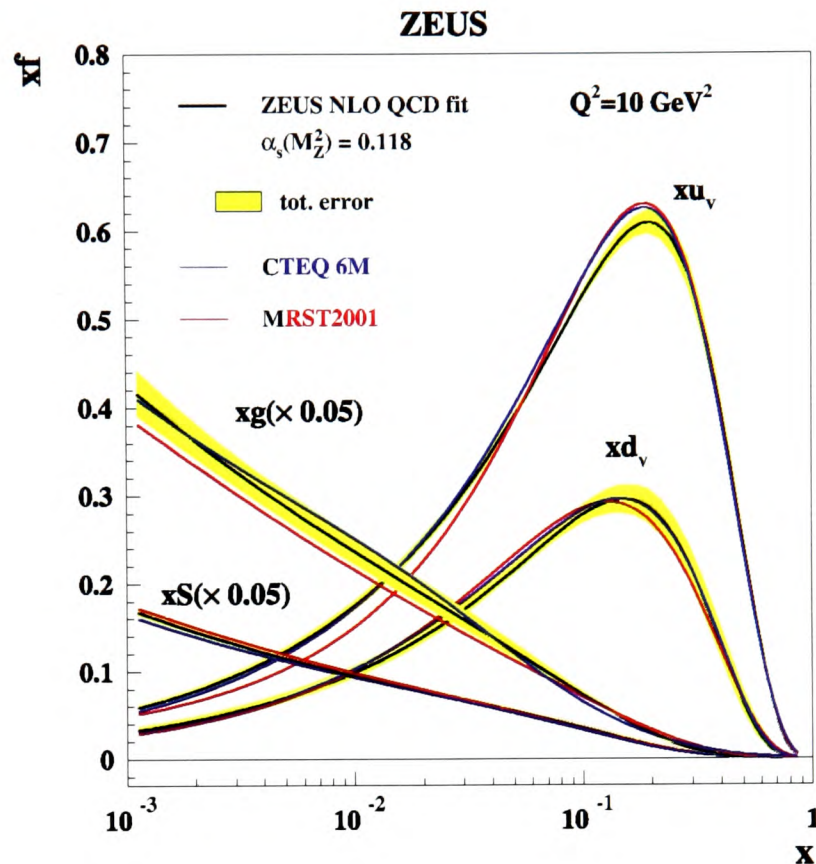


Figure 1.4: The parton densities inside the proton, extracted from fitting next-to-leading order evolution equations to DIS data.

1.7 Photoproduction

As can be seen from the form of Eqn. 1.11 the cross section increases extremely rapidly as Q^2 decreases. This, incidentally, is exactly the region where perturbative calculations are no longer possible, due to the rise in α_s (unless another momentum scale is found). Processes with a very low Q^2 ($Q^2 < 1$) are termed photoproduction, as an almost real photon is transferred.

In order to maintain the validity of perturbative QCD calculations, another momentum scale is required. This is typically obtained by looking at final states containing

jets, the transverse energy of the jets setting the scale.

Jet production in photoproduction can be divided into two classes in leading-order QCD. Direct photoproduction occurs when the photon acts as a point-like particle. Resolved photoproduction occurs when the photon itself acts as a source of partons. The photon may split into a quark-antiquark pair, after which these may radiate gluons analogously to the evolution of the proton parton densities. One of these partons, carrying a fraction x_γ of the total photon momentum, interacts with a parton from the proton. Examples of direct and resolved photoproduction can be seen in Fig. 1.5 and Fig. 1.6 respectively.

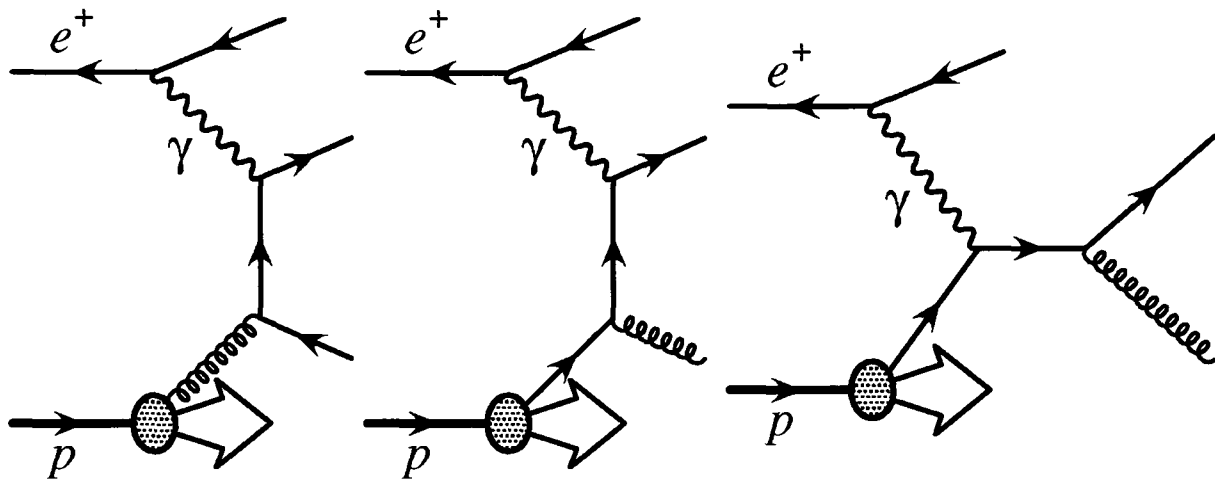


Figure 1.5: Some examples of direct photoproduction.

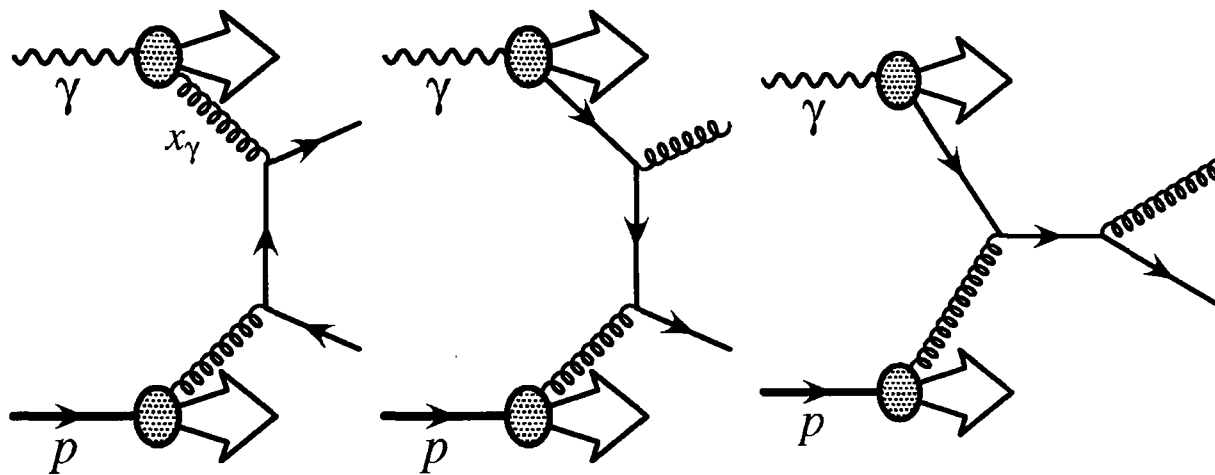


Figure 1.6: Some examples of resolved photoproduction.

The fraction of the photon momentum carried by the interacting parton is given, at leading order, by

$$x_\gamma^{LO} = \frac{\sum_{partons} E_T^{partons} e^{-\eta^{partons}}}{2yE_e} \quad (1.18)$$

Here yE_e is the photon momentum, and η is the pseudorapidity¹. For direct photopro-

¹ $\eta = -\ln(\tan(\theta/2))$

duction $x_\gamma^{LO} = 1$, whereas for resolved photoproduction $x_\gamma^{LO} < 1$

The ZEUS detector measures jets rather than partons, so a new variable is defined as follows:

$$x_\gamma^{obs} = \frac{\sum_{jets} E_T^{jets} e^{-\eta^{jets}}}{2yE_e} \quad (1.19)$$

Due to higher order and/or hadronisation effects x_γ^{obs} is generally slightly smaller than one for direct events. A typical x_γ^{obs} distribution for dijet production in ZEUS can be seen in Fig. 1.7 [9]. Here the sum in 1.19 runs over the two highest E_T jets.

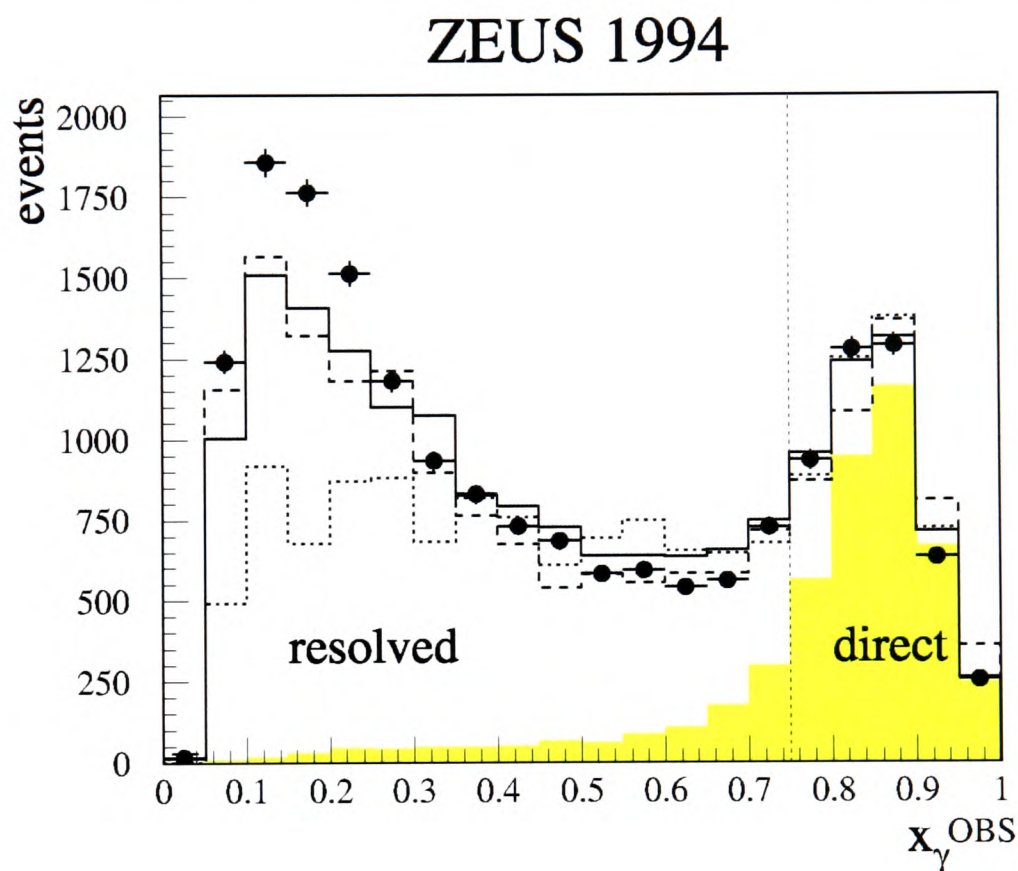


Figure 1.7: The x_γ^{obs} distribution for dijet events with $E_T^{jet} > 6\text{GeV}$, $-1.375 < \eta^{jet} < 1.875$. Data (black dots) is compared with various Monte Carlo predictions: HERWIG with Multiple Interactions (MI), solid line; HERWIG without MI, dotted line; PYTHIA with MI, dashed line. The resolved components of the MC samples are scaled by a factor 1.2 relative to the direct components. The shaded area represents the direct HERWIG events.

By convention, ZEUS photoproduction data is classified as direct-dominated if $x_\gamma^{obs} > 0.75$ and resolved-dominated if $x_\gamma^{obs} < 0.75$.

Chapter 2

Strange Particle Production

2.1 Hadronisation

Perturbative QCD is very successful in describing the hard scatter of eP collisions, when the parton inside the proton is asymptotically free and α_s is small, given the large momentum transferred. However, recalling that α_s becomes ~ 1 at lower momentum transfer (large distances) leads to the conclusion that perturbative QCD is no longer appropriate to describe the process that turns the struck parton into the observed hadron. This process of hadronisation may be measured and modelled in an attempt to understand it more fully. The measurements presented in this thesis form part of such an attempt.

2.2 Strange Particles

The strange quark is certainly not heavy enough for its mass to define a new hard scale, as may be done with production of the heavier quarks. Owing to its low mass ($\sim 100\text{MeV}$ [10]) it is produced in abundance, in a variety of ways in the eP collisions at HERA.

As was observed in Fig. 1.4 the proton itself contains significant amounts of sea quarks, from the splitting of gluons to quark-antiquark pairs. Of these, some fraction will be strange quarks. The splitting of the transferred photon into a strange-antistrange quark pair is another possible source of strange quarks. Strange quarks may also be produced in the hard interaction. For example, boson-gluon fusion (Fig. 2.1) leads to a quark-antiquark pair of any flavour being produced. Finally, strange quarks may be produced after the hard interaction, in the fragmentation that follows. Owing to

the increasing value of α_s with increasing distance, coloured objects, such as quarks or gluons, are not observed, but rather pull quark-antiquark pairs (predominantly u, d, s) out of the vacuum until the final observable jet of hadrons is reached. More details of this development are discussed later in this thesis; for now it is merely noted that strange quarks may come from this process.

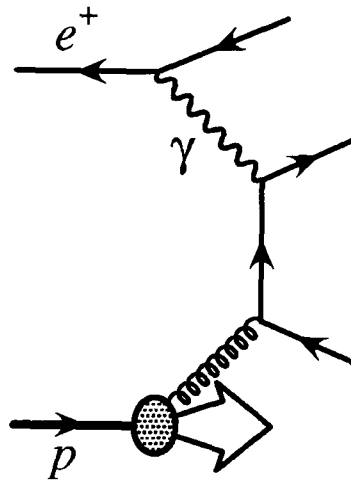


Figure 2.1: Boson-gluon fusion producing a quark-antiquark pair.

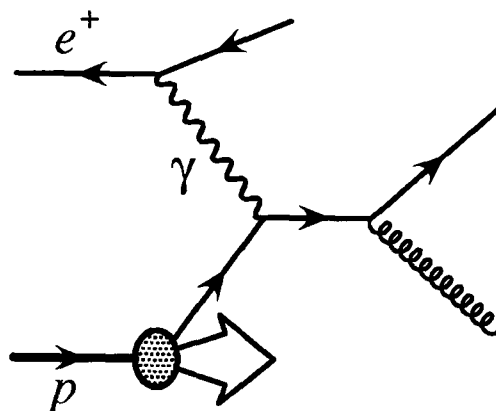


Figure 2.2: Typical hard interaction, leading to a high energy quark and gluon, which then fragment.

For reasons of ease of detection, as will be discussed later, the particular strange particles that are investigated are K_s^0 , Λ and $\bar{\Lambda}$.

The K_s^0 is a meson containing a mixture of $K^0(d\bar{s})$ and $\bar{K}^0(\bar{d}s)$. It decays predominantly to two pions with a lifetime of $0.8958 \pm 0.0006 \times 10^{-10}$ s. Its mass is 497.648 ± 0.022 MeV.

The Λ and its antiparticle $\bar{\Lambda}^1$ are baryon and antibaryon respectively, containing uds (or $\bar{u}\bar{d}\bar{s}$) quarks. The lifetime is $2.632 \pm 0.020 \times 10^{-10}$ s, and the mass is $1115.683 \pm$

¹Hereafter, both Λ and $\bar{\Lambda}$ are referred to as Λ , unless explicit comparison is made

0.006 MeV (all particle data from [10]).

ZEUS has recently made use of observations of neutral strange particles in the search for pentaquarks [11] and glueballs [12]. However, the last publications to focus on the production of K_s^0 and Λ themselves were based on photoproduction data taken in 1994 [13], and DIS data taken in 1993 [14]. These papers observe the production of K_s^0 and Λ from the fragmentation of a fast-moving parton, and make observations on the likelihood of obtaining s quarks, rather than u or d quarks. The much greater statistics available in this analysis opens up further areas of study.

2.2.1 Λ Polarization

The first observation of polarized Λ s being produced from an unpolarized beam [15] was unexpected. Since then, many experiments have observed the phenomenon; a review of the subject, by Panagiotou, may be found in [16].

For this analysis, the model of DeGrand and Miettinen [17] is particularly relevant. In their study, the observation is made that ‘*slow partons preferentially recombine with their spins down in the scattering plane while fast partons recombine with their spins up*’. Here, the scattering plane is the plane containing both the Λ and beam directions, that is the plane perpendicular to $P_\Lambda \times P_{beam}$. Polarization perpendicular to this plane is known as transverse polarization. The model of DeGrand and Miettinen is a simple quark model, assuming SU(6) symmetry of the u , d and s quarks and $\bar{u}$, $\bar{d}$ and $\bar{s}$ antiquarks. The spin of the Λ (or $\bar{\Lambda}$) is then carried solely by the s (or $\bar{s}$) quark, as the non-strange quarks form a singlet state. In this model, Λ polarization is dynamically generated by Thomas precession, which is due to acceleration of the s quark. Assuming the model of DeGrand and Miettinen to be correct, the sign of the polarization therefore gives an indication of the origin of the s quark.

Some results from the HERMES collaboration, where an electron beam is incident on a nuclear target, can be seen in Fig. 2.3 [18]. The positive Λ and negative $\bar{\Lambda}$ polarizations are interpreted using the model of DeGrand and Miettinen. The hypothesis presented is that the s quarks in the Λ and $\bar{\Lambda}$ originate predominantly from $\gamma \rightarrow s\bar{s}$. Hence, the fast s quarks are decelerated when they combine to form the hadron, leading to opposite

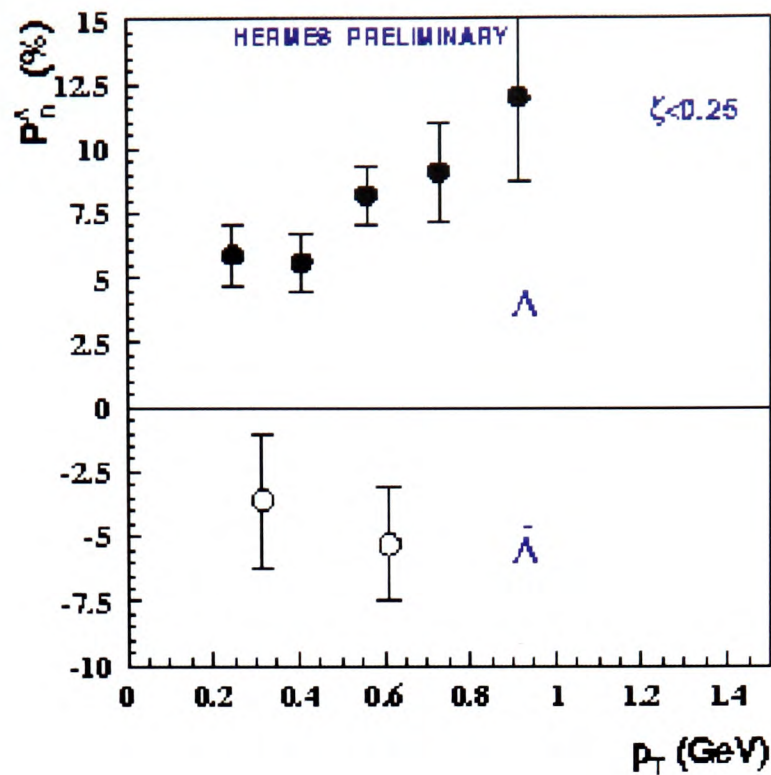


Figure 2.3: Transverse Λ (filled circles) and $\bar{\Lambda}$ (open circles) polarization, as observed by the HERMES collaboration in inclusive eN scattering. $\zeta = (E_\Lambda + P_z)/(E_{Beam} + P_{Beam})$.

sign polarization for Λ compared with $\bar{\Lambda}$, but of approximately equal magnitude.

The HERMES result can be compared with an observation of Λ polarization in proton beryllium scattering at Fermilab, shown in Fig. 2.4 [19]. Here, Λ acquire polarization

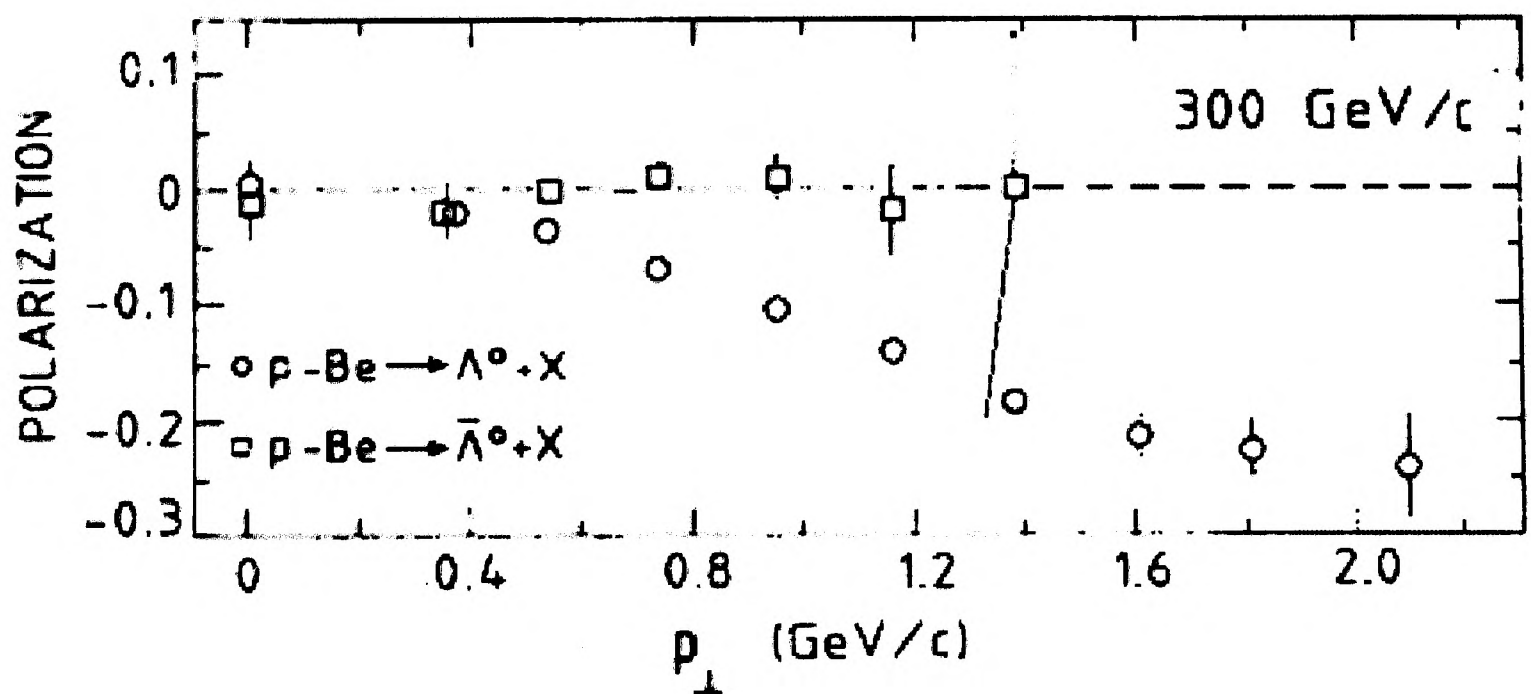


Figure 2.4: Transverse Λ and $\bar{\Lambda}$ polarization, as observed in proton beryllium scattering.

of an opposite sign to that seen by HERMES, and $\bar{\Lambda}$ remain unpolarized. This may be interpreted in the DeGrand-Miettinen model as the Λ originating from a slow sea

s quark which is accelerated when combined with a fast (ud) diquark from the proton beam. Similar valence anti-diquarks are not present in the proton beam, so the same production mechanism is not possible for $\bar{\Lambda}$.

Longitudinal Polarization

With unpolarized beams, Λ polarization along the direction of the Λ is expected to be zero from parity conservation. However, when using a polarized beam, it is possible for some of the beam polarization to transfer to the Λ , the amount depending on the production mechanism. In the analysis of this thesis, data from the unpolarized beams of HERA-I are used. However, the data currently being taken by ZEUS in the HERA-II run includes a polarized lepton beam, which would allow such polarization transfer to be studied.

2.2.2 Baryon Number Asymmetry

The nature of the Baryon Number (BN) has been explored by various authors [20, 21, 22]. A hadron composed of 3 valence quarks is known as a baryon ($\text{BN} = +1$). If composed of 3 antiquarks, then it is an antibaryon ($\text{BN} = -1$). Mesons, with 1 quark and 1 antiquark have $\text{BN} = 0$. In any closed system, BN is seen to be conserved. With the definitions above it is natural to associate BN with the valence quarks. However, considering the reaction

$$\pi^- + p \rightarrow \Omega^- + K^+ + 2K^0 \quad (2.1)$$

one can see that the BN is not carried by the valence quarks. Here, $\text{BN} = +1$ from the proton initially, and $+1$ from the Ω^- finally, and so is conserved, but none of the valence quarks present in the proton initially are also present in the final state Ω^- . Therefore, BN must be carried by some other parton - the gluon. This is the argument of, for example, Garvey, Kopeliovich and Povh in [20]. That the gluon field might carry BN was proposed in 1977 by Rossi and Veneziano [21]. Their model suggested a gluonic string junction as the carrier of BN.

Exactly what carries BN has consequences on how BN moves, and so where baryons are produced. If BN is carried solely by valence quarks, then in order to find, for example,

a baryon at low Bjorken- x , then at least one of the valence quarks must be at low x too (see [22]). Therefore, the produced baryons would be expected to follow the valence quark distribution of $1/\sqrt{x}$. Letting gluon string junctions carry the baryon number gives a different distribution.

Interest in this subject has been revived by recent data from experiments at the Relativistic Heavy Ion Collider (RHIC). Such heavy ion collisions give rise to a significant baryon over antibaryon excess in the central rapidity region, larger than that predicted by many theoretical models [23]. The models that included gluon string junctions to transport BN proved initially more successful in describing the RHIC data. However, other models also exist which can account for the RHIC data. The Parton Cascade Model (PCM) [24] uses rescattering of partons and fragmentation to increase the mid-rapidity baryon density in Au + Au collisions, and concludes with a good description.

HERA collides electrons with protons, so as in RHIC there is an initial non-zero BN, travelling along the beam pipe that has to travel through several units of rapidity for it to be observed in the detector. Λ and $\bar{\Lambda}$ can be distinguished by the ZEUS detector, so examining any baryon asymmetry in this system can add information to aid understanding of what carries the BN. Particularly distinctive about the HERA system, is that events are observed with very low values of Bjorken- x , where the difference between valence quarks and gluon junctions may be large.

2.2.3 Baryon to Meson Ratio

Another topic that has been reawakened by recent data from RHIC is the production of baryons relative to mesons. The baryon to meson ratio becomes so large in various regions of the heavy ion collision phase space, as in Fig. 2.5 [25], that it cannot be explained by the standard fragmentation approach (where each parton produced is convoluted with its probability of becoming a particular hadron).

An alternative to the fragmentation model is the parton recombination model [26]. This model is suggested to be valid when a dense parton phase is created. If quarks are produced so close together that their wavefunctions overlap significantly, then the quarks can combine to form baryons or mesons without having to pull more quarks out

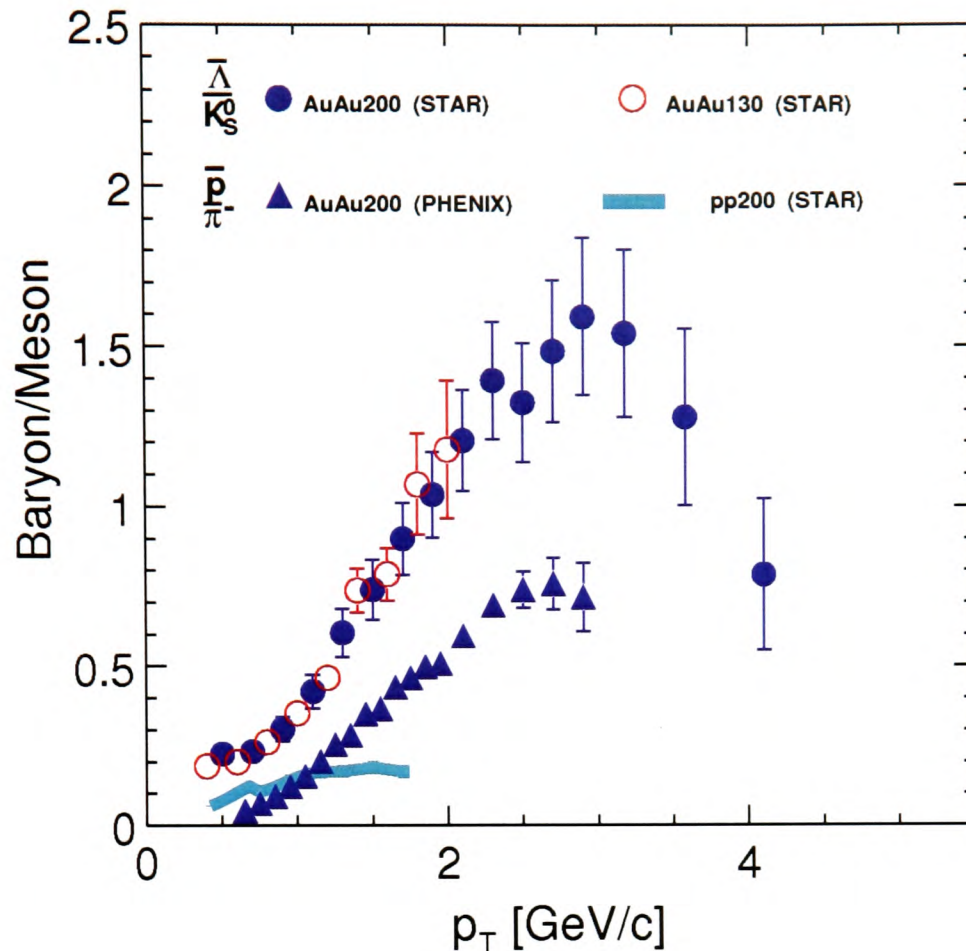


Figure 2.5: The baryon to meson ratios observed by STAR and PHENIX at RHIC.

of the vacuum (as is the case for fragmentation). The work of R.J. Fries et al. expects recombination to dominate over fragmentation at RHIC for $P_T \lesssim 5\text{GeV}$, as can be seen in Fig. 2.6 [27].

Ratios of the baryon to meson production may also be obtained for e^+e^- data, and some values are displayed in Table 2.1. The values here are generally smaller than those observed in RHIC, and the ratio increases as the centre of mass energy increases.

$\sqrt{s}$ (GeV)	≈ 10	29-35	91	130-200
$\frac{(\Lambda + \bar{\Lambda})}{K_s^0}$	0.18 ± 0.02	0.28 ± 0.02	0.38 ± 0.01	0.37 ± 0.04

Table 2.1: Baryon to meson ratios measured in e^+e^- collisions. Data from [10].

The eP collisions provided by HERA are somewhere between the extremely dense heavy ion collisions of RHIC and the lepton-lepton collisions of the e^+e^- machines. Investigation of the $(\Lambda + \bar{\Lambda})$ to K_s^0 ratio across the large phase space that HERA provides should be able to provide useful information on the various mechanisms that lead to baryon and meson formation.

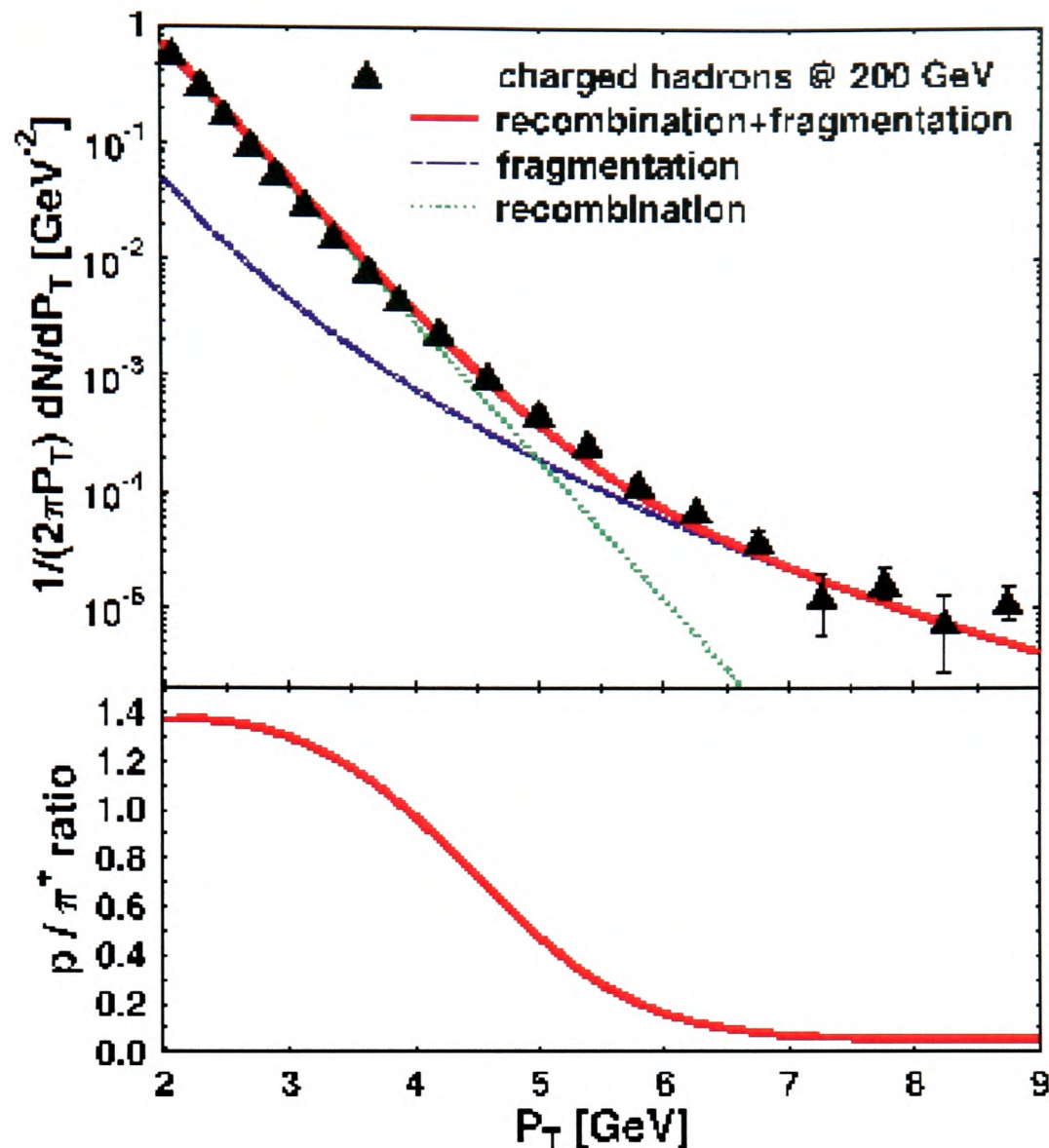


Figure 2.6: Comparison of the fragmentation and recombination models to Au + Au collision data, collected by the PHENIX collaboration.

2.2.4 The Fireball Region

A somewhat neglected region of the HERA phase space is the so-called Fireball Region. Excesses in the HERA jet cross-sections relative to NLO calculations and Monte Carlo predictions have been observed, particularly at low E_T^{jet} and high η^{jet} [28].

This region was investigated particularly for events with a high total E_T [29], [30], to endeavour to keep the validity of perturbative QCD. It was observed that adding Multi-parton Interactions (MI) to the Monte Carlo (allowing more than one parton-parton interaction per photon-proton collision) improved the description of low E_T^{jet} production at high total E_T . However, other event variables (such as y_{jb}) then became less well described. A workshop on HERA phenomenology in 1998 discussed events with such high total E_T : ‘If the events contain a large number of kaons ... then this will point to a highly non-trivial production mechanism’ [29]. The visual similarity between these

fireball events and the hypothesized QCD instanton events [31] was also noted.

A measurement of the amount of strangeness in such events should add further information on their nature.

Chapter 3

HERA and ZEUS

3.1 HERA

The Hadron Elektron Ring Anlage (HERA) collides high energy electrons or positrons¹ with protons. This combination of colliding leptons and hadrons makes it unique among current or previous High Energy Physics experiments. It was constructed at the Deutsches Elektronen-SYNchrotron (DESY) laboratory in the western suburbs of Hamburg, Germany (Fig. 3.1).



Figure 3.1: Location of HERA.

HERA construction began in April 1984, the first electron-proton collisions were obtained in October 1991, and regular data taking for ZEUS and H1 began in May 1992.

¹Hereafter, both electrons and positrons are referred to as electrons, unless explicitly stated otherwise.

This has continued, with various short breaks, until August 2000. At this point a longer break occurred to significantly upgrade the accelerator and detectors, and operation was resumed in the Autumn of 2003.

The electrons and protons are accelerated independently around a ring 6.34km in length. The ring is between 10m and 30m underground, and is composed of four straight sections (in each of which is an experimental hall) and four curved sections, each with radius of curvature 797m. The two beams are brought into collision in the North and South experimental halls, where the H1 and ZEUS detectors respectively observe the products of such collisions. In the East hall, the HERMES experiment studies the collision of the electron beam with a fixed target, and the West hall has been used by the HERA-B experiment to study CP violation in the decay of B-mesons, by using a wire target placed in the proton beam halo.

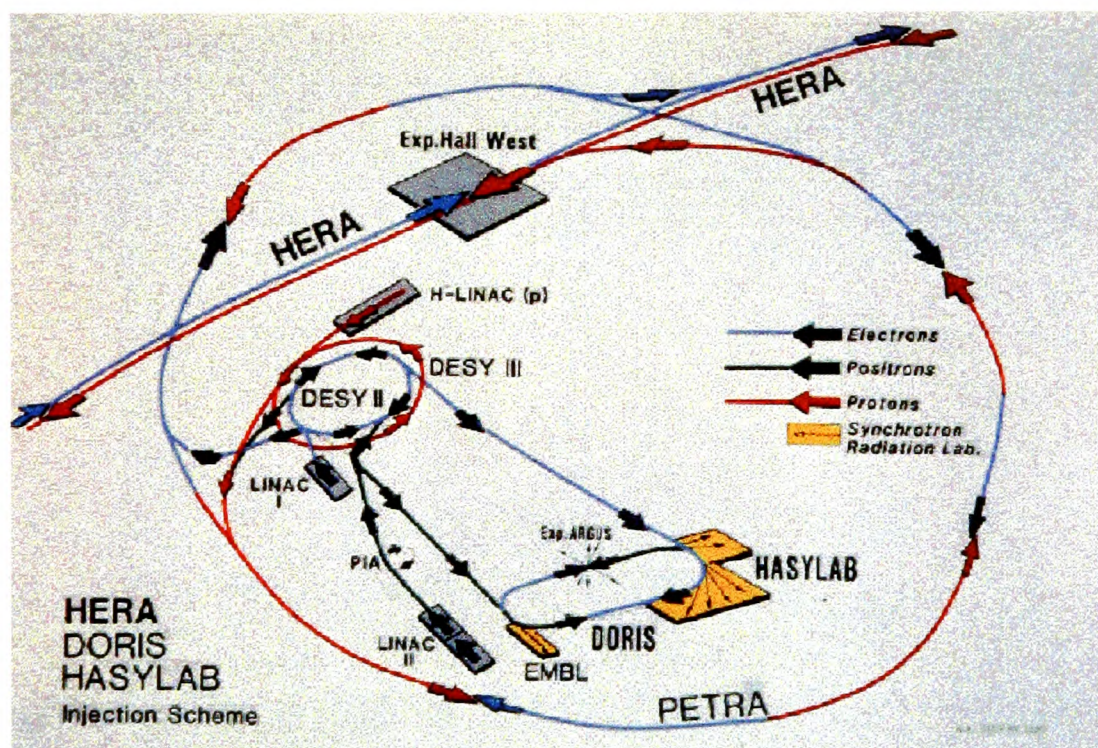


Figure 3.2: HERA injection system.

3.1.1 Lepton Beam

The electrons are first accelerated in a Linear Accelerator to 220MeV (450MeV for positrons). They are then injected into the DESY II synchrotron where they are accelerated to 7.5GeV. From here they are passed to PETRA II, with up to 70 bunches at the HERA bunch spacing of 96ns, and accelerated to the HERA injection energy of 14GeV. Once in HERA, the electrons are accelerated to 27.52GeV (slightly less than the

design energy of 30.0GeV) using both conventional and superconducting magnets. The focusing of the beam is achieved solely with conventional magnets.

HERA can accommodate a maximum of 210 bunches each for electrons and protons. However, it is usually run with significantly fewer - typically, there will be ~ 174 colliding bunches, ~ 15 unpaired electron bunches, ~ 6 unpaired proton bunches and ~ 15 empty bunches. The unpaired (pilot) and empty bunches are used for background calibration purposes.

HERA can accelerate either electrons or positrons, and both have been used since 1992 as described in Table 3.1. Electrons were originally used, but the switch to positrons was made since positron beams have a longer lifetime than electron beams. A beam of electrons attracts the positive ions remaining in the beam-pipe, increasing the interaction rate of electrons, and so shortening the beam lifetime. Positrons repel such positive ions, so can have a longer beam lifetime.

Luminosity (pb^{-1})		
Year	$\mathcal{L}_{e-}$	$\mathcal{L}_{e+}$
1992	0.03	
1993	1.09	
1994	1.08	5.11
1995		12.31
1996		17.16
1997		36.35
1998	8.08	
1999	17.12	28.54
2000		66.41

Table 3.1: Luminosity provided by HERA between 1992 and 2000.

3.1.2 Proton Beam

The proton beam begins as H^- ions. These are accelerated in a Linear Accelerator to 50MeV, before entering the DESY III synchrotron. The electrons are removed by passing the ions through a thin foil, and then the remaining protons are accelerated to 7.5GeV. At this stage there are 11 bunches, with a bunch spacing of 96ns. Protons are then passed to PETRA, which can contain 70 bunches, and accelerated to 40GeV. These are then injected into HERA, which can contain a maximum of 210 bunches, as discussed for the electron beam.

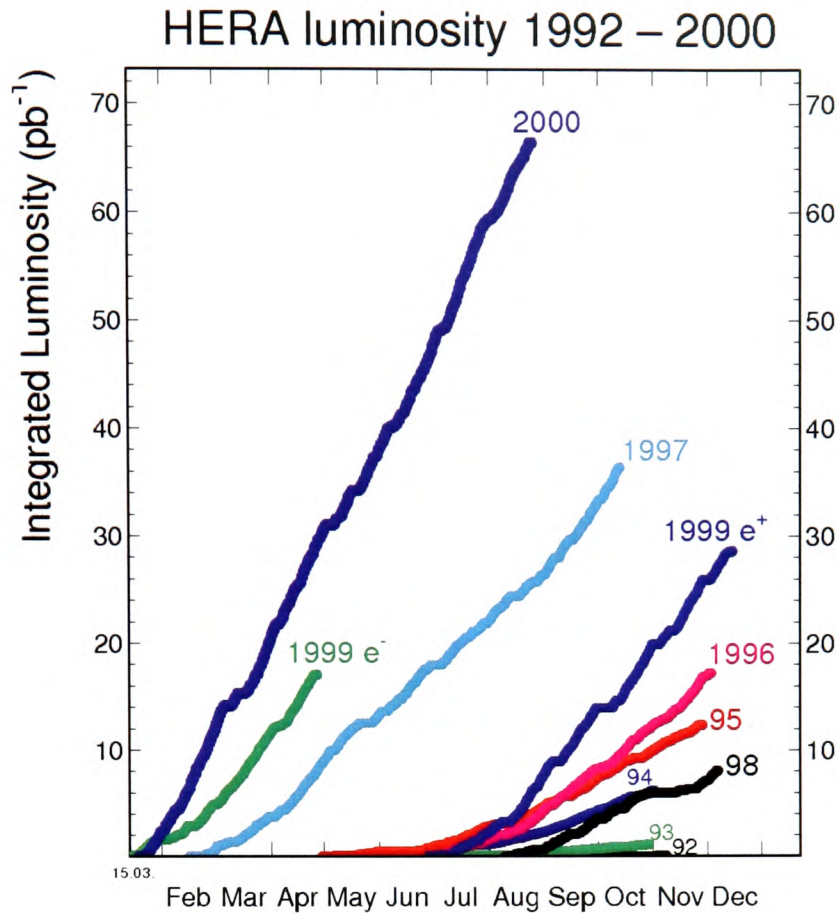


Figure 3.3: The luminosity provided by HERA for each year of running.

Helium-cooled superconducting dipole and quadrupole magnets are used to focus the proton beam in HERA, while the acceleration required is achieved through conventional radio-frequency cavities.

Up until the end of 1997, the HERA proton beam energy was 820 GeV. From 1998 the energy was raised to 920 GeV. Ignoring the masses of the proton (938 MeV) and electron (0.511 MeV) the centre of mass energy is given by $\sqrt{s} \simeq 4E_P E_e$. For 820 GeV protons the centre-of-mass energy $\sqrt{s} \simeq 300$ GeV. For 920 GeV protons, $\sqrt{s} \simeq 318$ GeV.

3.2 The ZEUS Detector

The ZEUS detector is described more fully elsewhere [33], but a brief description of the detector, particularly those components essential to this analysis, is presented now. A schematic diagram showing the layout of the components is shown in Fig. 3.4.

The ZEUS detector is a general purpose detector designed to measure as much information as possible of the particles emerging from the electron proton collisions provided by HERA. Its coordinate system is a right-handed, orthogonal system, and is defined

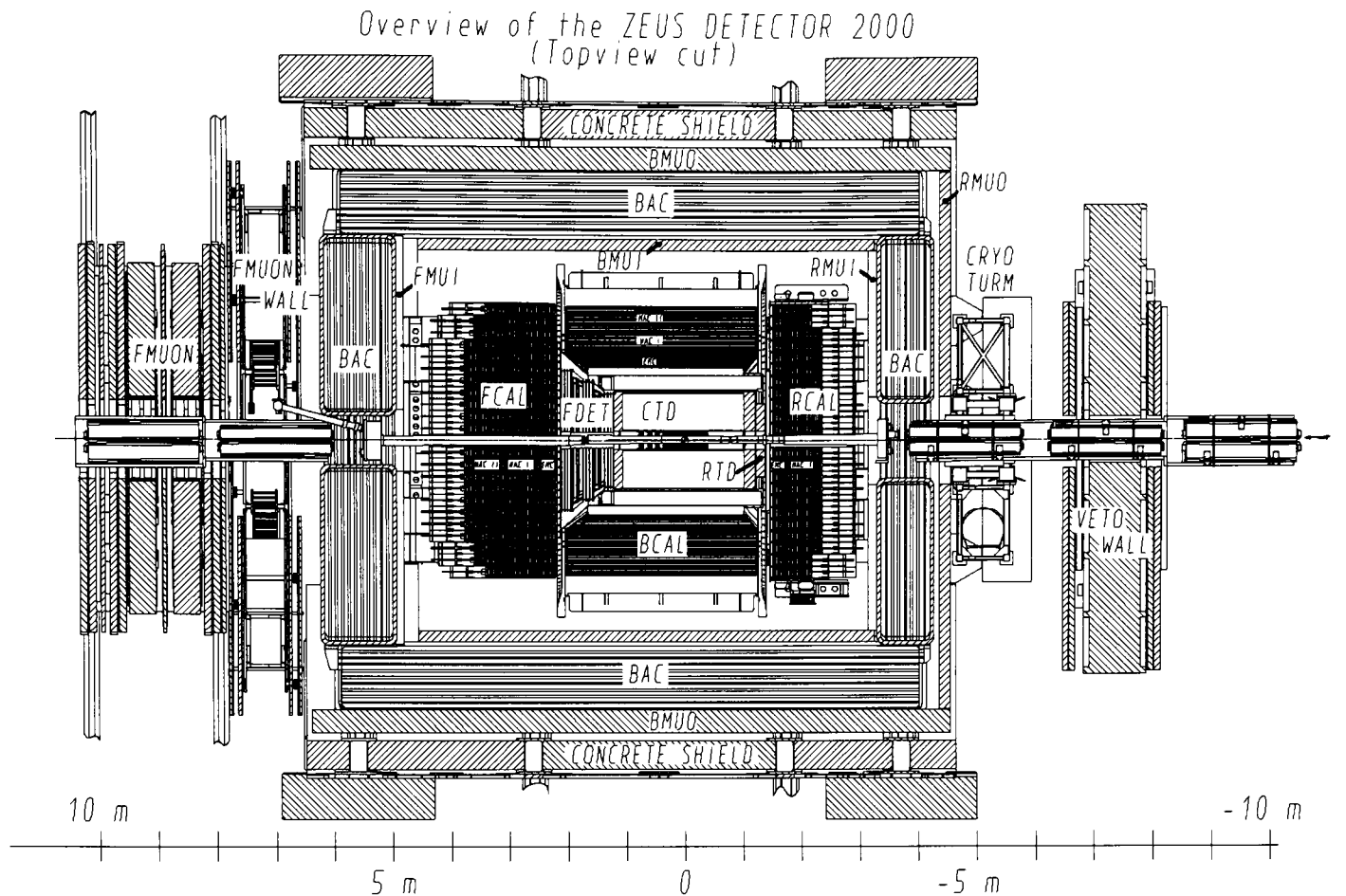


Figure 3.4: Cross-section of the ZEUS detector in the zy plane, showing the layout of the main components. In this view, the electron enters from the left, the proton from the right. The main components are described in the text.

by HERA parameters. The nominal interaction point is defined as the origin, and the nominal proton beam direction is defined as the positive z direction. The x -axis points to the centre of HERA, and so the y -axis points approximately vertically upwards.

When polar coordinates are used, θ is the polar angle, and ϕ is the azimuthal angle from the x -axis. The pseudorapidity, η , is more useful than the polar angle θ , as differences in η are more nearly invariant under boosts in the z direction. Pseudorapidity is defined as $\eta = -\ln(\tan \theta/2)$

ZEUS follows the principles of many detectors around colliding beams: tracking chambers in a magnetic field are closest to the interaction point, followed by calorimeters, followed by muon chambers. The whole detector attempts to be as hermetic as possible.

3.2.1 Inner Tracking

The most crucial component for this analysis is the Central Tracking Detector (CTD). There are Forward and Rear Tracking Detectors as well which can add to the tracking closer to the beam-pipe.

CTD

The CTD [34] is a cylindrical drift chamber. Charged tracks passing through it ionize the contained gas, and the resulting ions and electrons are attracted to wires at high voltage, resulting in an electrical signal. Hence, the track can be reconstructed from observing which wires give a signal. The CTD has a length of 2.05m, and inner and outer radii of 18.2cm and 79.4cm respectively. It consists of 4608 sense wires and 19584 field wires running approximately parallel to the beam line through a gas mixture of Argon(85%), Ethane(10%) and CO₂(5%).

The sense wires are composed of gold-plated Tungsten, and are divided into 9 concentric superlayers, with superlayer 1 closest to the beam. The odd-numbered superlayers run parallel to the beam line (axial superlayers) while the even-numbered superlayers have a small angle ($\sim \pm 5^\circ$) between the sense wires and the beam direction (stereo superlayers). This angle is chosen so as to give approximately similar resolutions in the z direction as in the x and y directions.

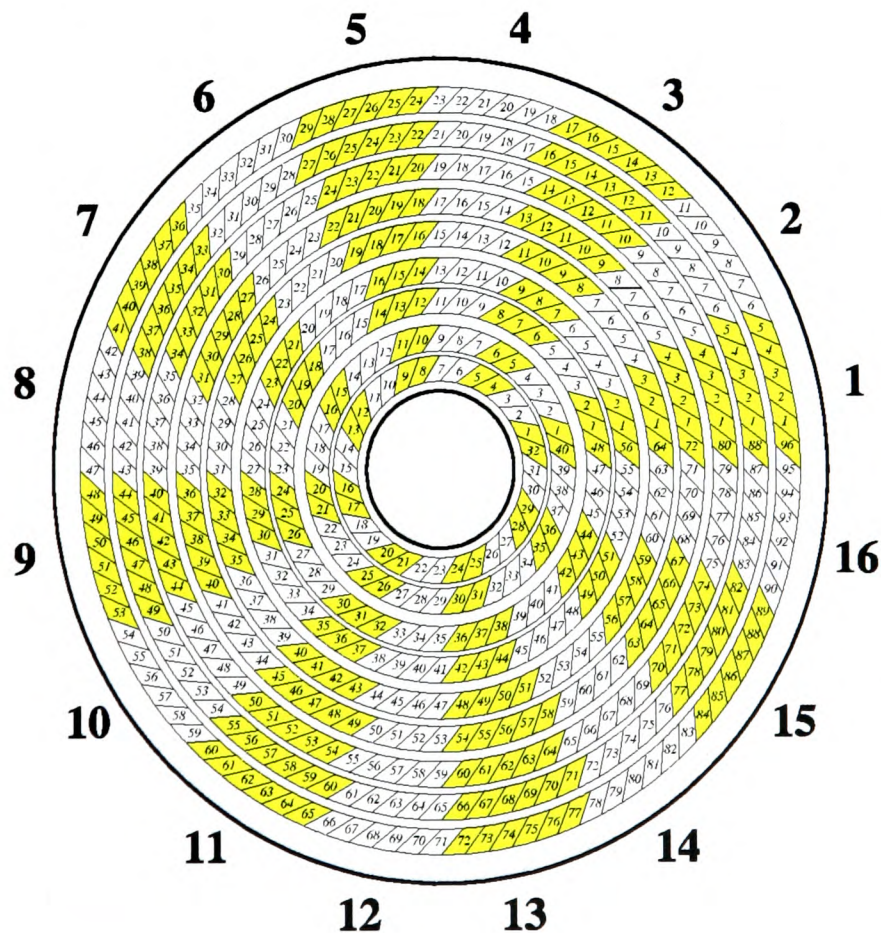


Figure 3.5: The arrangement of wires, cells and superlayers in the CTD.

Within each superlayer the sense wires are arranged into cells. The arrangement of wires, cells and superlayers can be seen in Fig. 3.5. Each cell consists of 8 sense wires.

There are 32 cells in superlayer 1, rising to 96 cells in superlayer 9. The arrangement of wires, and the fields produced in one cell can be seen in Fig. 3.6.

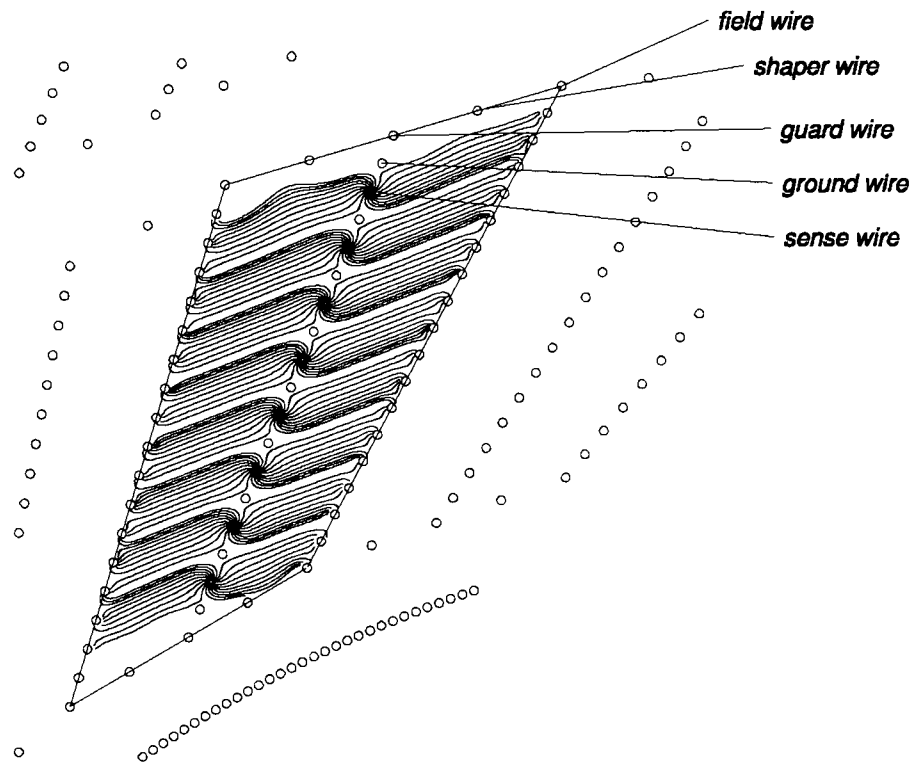


Figure 3.6: The arrangement of wires in a CTD cell.

The sense wires are kept at $\sim 1.2\text{kV}$, and the field wires at between -2.4kV and -3.8kV .

In addition to obtaining the z -position of CTD hits by using the stereo superlayers, the inner three superlayers are also instrumented with a z -by-timing system. This gives an approximate, but much faster, value of the z -position of a hit by comparing the time taken for a pulse to travel through each end of the CTD cylinder.

The resolution of full length tracks through the CTD is $\sigma(P_T)/P_T = 0.0058P_T \oplus 0.0065 \oplus 0.0014/P_T$ [35], obtained by investigating tracks which pass through all 9 superlayers of the CTD (corresponding to approximately $|\eta| \lesssim 1.1$). The first term is due to the resolution of the CTD hits themselves, and the second and third terms are due to multiple scattering.

Forward and Rear Tracking

Additional tracking is provided by the Forward and Rear Tracking Detectors (FTD and RTD). The FTD consists of three drift chambers, extending the tracking angular coverage down to 7° . The gaps between the drift chambers are filled with transition radiation detector modules. The RTD consists of one drift chamber, extending the

angular coverage up to 170° .

Magnets

A thin superconducting solenoid outside the CTD provides a field of strength 1.43 T in the central region. The field is extremely uniform in the region of the CTD, but becomes less uniform outside this region.

3.2.2 Calorimetry

The ZEUS Calorimeter is optimized for the best possible measurements of jets. A basic requirement of the Calorimeter is that it has as large an angular coverage as possible. The ZEUS calorimeter covers 99.7% of 4π . Other requirements are good jet energy resolution, good angular jet resolution, and the ability to separate electrons from hadrons.

Uranium Calorimeter

The Uranium Calorimeter (UCAL) consists of alternating layers of depleted uranium absorber plates and plastic scintillator tiles. The thickness of the uranium and scintillator has been tuned so that the response to electrons and hadrons is the same ($e/h = 1.00 \pm 0.05$). To achieve this response, the thickness of each depleted uranium layer is 3.3mm, and of each scintillator layer is 2.6mm. The response to both electrons and hadrons is a linear function of the energy. The resolution is $\sigma(E)/E = 18\%/\sqrt{E(\text{GeV})}$ for electrons and $\sigma(E)/E = 35\%/\sqrt{E(\text{GeV})}$ for hadrons, as measured by a test beam at CERN.

The UCAL is divided into three mechanically distinct sections in the Forward, Barrel and Rear regions, corresponding to the FCAL, BCAL and RCAL respectively. Each of these sections is divided into Electromagnetic (EMC) and Hadronic (HAC) sections, with the EMC closest to the interaction point, and the HAC furthest from it. For the FCAL and BCAL the HAC is further subdivided into two sections (HAC1 and HAC2). The thickness of the EMC corresponds to one absorption length, which is generally sufficient to contain any purely electromagnetic shower. For the HAC, the FCAL has a thickness of 6.2 absorption lengths (6.2λ), the BCAL a thickness of 4.2λ , and the RCAL a thickness of 3.1λ . The angular acceptances of the UCAL sections are shown in Table 3.2.

	θ range	η range
FCAL	$2.2^\circ \rightarrow 39.9^\circ$	$4.0 \rightarrow 1.0$
FCAL	$36.7^\circ \rightarrow 129.1^\circ$	$1.1 \rightarrow -0.74$
FCAL	$128.1^\circ \rightarrow 176.5^\circ$	$-0.72 \rightarrow -3.5$

Table 3.2: Angular acceptance of the three UCAL sections.

Each FCAL, BCAL or RCAL section is divided into towers of $\sim 20\text{cm} \times 20\text{cm}$. For the EMC these towers are subdivided into four cells ($5 \times 20 \text{ cm}^2$) in the FCAL and BCAL, and two cells ($10 \times 20 \text{ cm}^2$) in the RCAL. The HAC is not so divided, so one HAC cell has the same dimensions as the tower ($20 \times 20 \text{ cm}^2$).

The light produced in the scintillator layers of each calorimeter cell is transported with wavelength shifter bars and light guides to two Photomultiplier Tubes (PMTs) to be read out.

Beam Pipe Calorimeter

The Beam Pipe Calorimeter (BPC) is designed to detect electrons scattered through very small angles, corresponding to events with a very small Q^2 . It is situated very close to the beam pipe at $z \sim -300\text{cm}$, and is a calorimeter composed of alternating layers of tungsten and scintillator. The angular acceptance is $178.1^\circ < 178.9^\circ$, which allows measurements in approximately the range $0.045\text{GeV}^2 < Q^2 < 0.65\text{GeV}^2$.

Presampler

The presampler measures the multiplicity of particles entering the FCAL and RCAL. It consists of 576 scintillator tiles, each of dimension $20 \times 20 \times 0.5 \text{ cm}^3$, read out by PMTs. Particles shower when they interact with dead material between the interaction point and the calorimeter, so the multiplicity is related to the energy lost. Information from the presampler can therefore be used to correct back to the original energy.

Hadron-Electron Separator

The Hadron-Electron Separator (HES) is, obviously, designed to help distinguish between electrons and hadrons. It is placed 3 radiation lengths ($3 X_0$) into the EMC of the FCAL and RCAL, which is where an electromagnetic shower is expected to be at a maximum.

The HES is composed of a plane of silicon diodes, of dimension 3cm x 3cm, significantly smaller than the dimensions of the EMC cells.

Backing Calorimeter

The Backing Calorimeter (BAC) performs two main functions - measuring any energy leakage from the UCAL, and identifying muons that pass through the iron yoke. It is composed of iron plates of thickness 7.3 cm.

Almost all the energy of a jet will be deposited in the UCAL, but there is some leakage, especially for very high energy jets. In order to get the best energy resolution, there is an analogue readout system, which gives little position information, but fairly precise energy information. The resolution of the BAC is $\sigma(E)/E = 100\%/\sqrt{E(\text{GeV})}$.

There is also a digital readout system that gives good two dimensional position information, along with some additional energy data. This allows some muon tracking in the BAC, and also gives some discrimination between leaking hadron showers and muons.

3.2.3 Muon Chambers

Outside the calorimeter components are three muon detectors in the forward (FMUON), barrel (BMUON) and rear (RMUON) directions. These are drift chambers which observe tracks, which are then assumed to be muons, as everything else should have been stopped by the calorimeter. They are sensitive to muons with energy greater than 2GeV.

3.2.4 Background Rejection

There are three main types of background that threaten to swamp the actual eP events:

1. Beam Gas: Interactions of the proton beam with any residual gas in the beam pipe or the walls of the beam pipe can give hadronic energy deposits in the detector.
2. Halo Muons: Any charged pions produced in the interactions of the proton beam decay predominantly to muons, which can then travel with the proton beam halo and also give a signal in the detector.

3. Cosmic Muons: Interactions of cosmic rays with the atmosphere give rise to muons which may pass through the detector giving a signal.

The background is partly reduced by shielding the detector as much as possible - the detector is $\sim 25\text{m}$ underground and surrounded by $\sim 1\text{m}$ of concrete in order to minimize interactions from cosmic muons. The iron VETO wall at $z = -7.5\text{m}$ shields the detector from the proton beam halo. Background is further reduced at the trigger level, particularly using timing information from the VETO wall, the UCAL, the C5 counter and the Small-angle Rear Tracking Detector (SRTD).

3.2.5 Luminosity Monitor

The luminosity is measured using the Bethe-Heitler [36] process, which produces high energy photons at small angles:

$$e + P \rightarrow e' + P + \gamma \quad (3.1)$$

The cross-section of this process is very well known. The luminosity monitor consists of two sampling lead calorimeters to detect the γ and e' .

3.2.6 Trigger and Data Acquisition

ZEUS employs a three level trigger system in order to reduce the $\sim 10\text{MHz}$ interaction rate provided by HERA (mainly from interactions of the proton beam with beam gas) to the much smaller rate of $\sim 1\text{Hz}$ that can be written to tape, but still contains the interesting physics events.

First Level Trigger

HERA provides an eP bunch crossing every 96ns . In order to increase the time available for the First Level Trigger (FLT) to make a decision, data from 46 bunch crossings are stored in a pipeline (allowing a total time of $4.4\mu\text{s}$). Each subcomponent makes a decision, which is passed to the Global FLT Process (GFLT) which makes the decision whether to keep the event or not. The FLT reduces the rate to $\sim 1\text{kHz}$.

Second Level Trigger

The Second Level Trigger (SLT) also requires each component to make a decision, which is then coordinated by a global process. The SLT is software based, and runs on a transputer network. The SLT reduces the rate to a maximum of 60Hz.

Third Level Trigger

Following the SLT, data from the components are combined by the Event Builder to produce the complete event information for the Third Level Trigger (TLT) to act on. The TLT runs a simplified version of the full offline reconstruction code on a dedicated CPU farm. The TLT reduces the rate to $\sim 1\text{Hz}$. Each event, occupying $\sim 0.3\text{MB}$, is then passed along an optical fibre cable to the DESY computing centre for further offline analysis.

Chapter 4

Reconstructing Events

4.1 Event Kinematics

As discussed in Section 1.3 the kinematics of an event are completely defined by any two of Q^2 , x and y . There are various methods of obtaining these variables from the detected quantities, which will now be described. In the formulae below, E_e is the initial energy of the electron, E'_e is the energy of the scattered electron, E_p is the initial energy of the proton, and θ is the polar angle with respect to the proton beam direction.

4.1.1 Electron Method

If the scattered electron is detected, its energy and direction can be used to obtain Q^2 , x and y by the following formulae [37]:

$$Q_e^2 = 2E_e E'_e (1 + \cos \theta) \quad (4.1)$$

$$x_e = \frac{E_e}{E_p} \frac{E'_e (1 + \cos \theta)}{2E_e - E'_e (1 - \cos \theta)} \quad (4.2)$$

$$y_e = 1 - \frac{E'_e}{2E_e} (1 - \cos \theta) \quad (4.3)$$

4.1.2 Jacquet-Blondel Method

The Jacquet-Blondel [38] method allows the reconstruction of the event kinematics purely from the hadronic system. This is particularly useful for photoproduction, when the electron is not detected as it continues down the beam pipe. The variables are estimated

as follows:

$$Q_{jb}^2 = \frac{(\sum_i p_x^i)^2 + (\sum_i p_y^i)^2}{1 - y_{jb}} \quad (4.4)$$

$$x_{jb} = \frac{(\sum_i p_x^i)^2 + (\sum_i p_y^i)^2}{s y_{jb} (1 - y_{jb})} \quad (4.5)$$

$$y_{jb} = \frac{\sum_i (E^i - p_z^i)}{2E_e} \quad (4.6)$$

The sum here ideally runs over final state particles, but in practice runs over calorimeter cells or some other measurement of the final state momenta.

4.1.3 Double Angle Method

An alternative method [37] is to use the scattered electron angle, θ , and the angle of the hadronic system, γ , to obtain the event kinematics. This avoids, to first order, any dependence on the energy scale of the calorimeter.

$$Q_{DA}^2 = 4E_e^2 \frac{\sin \gamma (1 + \cos \theta)}{\sin \gamma + \sin \theta - \sin(\theta + \gamma)} \quad (4.7)$$

$$x_{DA} = \frac{\sin \theta (1 - \cos \gamma)}{\sin \gamma + \sin \theta - \sin(\theta + \gamma)} \quad (4.8)$$

$$y_{DA} = \frac{E_e \sin \gamma + \sin \theta + \sin(\theta + \gamma)}{E_p \sin \gamma + \sin \theta - \sin(\theta + \gamma)} \quad (4.9)$$

where γ is defined by:

$$\cos \gamma = \frac{(\sum_i p_x^i)^2 + (\sum_i p_y^i)^2 - (\sum_i (E^i - p_z^i))^2}{(\sum_i p_x^i)^2 + (\sum_i p_y^i)^2 + (\sum_i (E^i - p_z^i))^2} \quad (4.10)$$

4.2 Electron Finding

Various software routines exist to identify the scattered electron in the ZEUS detector, which is essential for obtaining the event parameters, x , y and Q^2 in DIS events. Sinistra [59] is used as the primary electron finder in this thesis. Sinistra is a neural network that has been trained on low Q^2 data and Monte Carlo events to obtain the best separation between electromagnetic and hadronic shower profiles in the the calorimeter. Alternative electron finders such as Emille are used in addition to Sinistra at the trigger level.

4.3 Jet Reconstruction

The final state of events from eP collisions are often well characterized by the parameters of the jets produced.

ZEUS uses two methods of reconstructing jets - either a cone algorithm, or a cluster algorithm. A brief description of the principles of these algorithms is now presented.

4.3.1 Cone Algorithms

Two cone algorithms are used at ZEUS, PUCELL and EUCELL. Both define the jet properties according to the Snowmass convention [39]:

$$E_T^{jet} = \sum_i E_T^i \quad (4.11)$$

$$\eta^{jet} = \frac{\sum_i \eta^i E_T^i}{E_T^{jet}} \quad (4.12)$$

$$\phi^{jet} = \frac{\sum_i \phi^i E_T^i}{E_T^{jet}} \quad (4.13)$$

The sum here can run over either detector quantities, like calorimeter cells, or hadrons or partons.

Jets in cone algorithms are defined to have a maximum radius, R_{cone} , in $\eta - \phi$ space. An object is combined with the jet if $\Delta R = \sqrt{(\phi_i - \phi_{jet})^2 + (\eta_i - \eta_{jet})^2} < R_{cone}$.

The PUCELL algorithm finds pre-clusters by combining objects within the radius $R_{cone}/2$ with the highest E_T object. This continues until all objects are associated with a pre-cluster. The centre of the pre-cluster is then recalculated, and the procedure repeated iteratively, until a stable state, or a maximum number of iterations, is reached. All pre-clusters above an E_T threshold are called jets. This procedure is based on a CDF jet algorithm.

The EUCELL algorithm also uses pre-clusters. To obtain the EUCELL pre-clusters a grid in $\eta - \phi$ space is used, with cell-size such that $\Delta\eta^{gridcell} \simeq \Delta\phi^{gridcell} \simeq R_{cone}$. Potential pre-clusters are found by sliding a 3×3 cell window over the grid. If the pre-cluster passes a minimum E_T cut then a cone of radius R_{cone} is placed around it, and jets are formed in an iterative process in the same way as the PUCELL algorithm. The

first jet is that with the highest E_T . Successive jets are found with the same procedure from the remaining objects, until there are no more cones above the energy threshold.

4.3.2 The $K_\perp$ Cluster Algorithm

The $K_\perp$ Cluster Algorithm was developed in e^+e^- collisions. A modified form is used in the eP collisions at ZEUS, called KTCLUS [40].

Cluster algorithms work by merging particles together to form jets. An algorithm must therefore define which particles to merge and how to combine them. In this analysis KTCLUS is run in the laboratory frame in the inclusive mode of Ellis and Soper [41]. This is invariant under longitudinal boosts and its recombination scheme, similar to the Snowmass convention, is as follows:

$$E_{T,k} = E_{T,i} + E_{T,j} \quad (4.14)$$

$$\eta_k = \frac{E_{T,i}\eta_i + E_{T,j}\eta_j}{E_{T,k}} \quad (4.15)$$

$$\phi_k = \frac{E_{T,i}\phi_i + E_{T,j}\phi_j}{E_{T,k}} \quad (4.16)$$

To decide which particles to merge the following quantities are made. For each particle:

$$d_i = E_{T,i}^2 \quad (4.17)$$

And for each pair of particles:

$$d_{ij} = \min(E_{T,i}^2, E_{T,j}^2) \left[(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2 \right] / R^2 \quad (4.18)$$

If the smallest of all the d values is a d_{ij} , then particles i and j are combined to form particle k . If the smallest value is a d_i then the i th particle is considered complete, and removed from further clustering. This process is repeated until all particles have been accounted for. R is an additional parameter that is generally set to unity, which although not a physical radius, may be compared to R_{cone} in the cone algorithms.

Cluster algorithms have various advantages over cone algorithms. Ambiguities are present in the cone algorithms regarding their treatment of overlapping jets, and also regarding how the jet pre-clusters are found. Additionally, the cone algorithms as they stand are not infra-red safe at NNLO [42].

4.4 The Hadronic Final State

Although the calorimeter provides the bulk of the information on the hadronic final state, it is sometimes more precise to use information from the tracking detectors. The jet finding algorithms described above run on ZUFOs - ZEUS Unidentified Flow Objects. These are found by software routines that combine the tracking and calorimeter information to give the best possible resolution for each energy deposit.

The energy response of the calorimeter has been obtained by analyzing a sample of high Q^2 DIS events, where the P_T of the scattered electron balances the P_T of the hadronic system. The energy of the electron and hadronic system can be obtained from the calorimeter and compared to the energy of the electron as calculated by the double angle method described above, which is insensitive (at first order) to the energy scale of the calorimeter.

The energy deposited in the calorimeter also needs to be corrected to account for the energy lost in the dead material that particles pass through before reaching the calorimeter. Dead material includes such items as the beam pipe, solenoid, tracking detectors and cables. The correction factors are obtained from requiring conservation of momentum and energy between the scattered electron and the hadronic system in high Q^2 DIS data and MC events.

4.5 Track and Vertex Reconstruction

A full description of the track reconstruction program can be found elsewhere ([43], [44]). However, a brief summary of the method is presented here. The program VCTRAK does the track reconstruction, and may be run in either Regular mode, where all the tracking components are used, or in CTD-only mode, where just the CTD is used. In this analysis, the CTD-only mode is used, as this is better understood over the whole 1996-2000 data taking period.

Tracks begin life as a series of hits in an axial superlayer (1,3,5,7 or 9). This track seed is then extrapolated inwards, guided by a broad virtual hit at the beam spot. As the extrapolation continues, more hits are added to the track, and the track parameters

improved. Each track is parameterized as a 5-parameter helix.

Once the track finding is finished (and the tracks stored in the VCTRHL table) VCTRAK attempts to find vertices. Both the primary vertex (the position of the eP collision) and any secondary vertices (where particles produced in the primary collision decay) are sought.

Only tracks with at least one hit in superlayer-1 are considered in the vertexing. Of these tracks, pairs of tracks are tested for compatibility with originating from a common vertex. From these track pairs, track clusters are formed, which are then the seeds for possible vertices. The vertex fitting procedure then swaps tracks between vertices to minimize the χ^2 of the fit. As part of the vertex finding, the tracks themselves are refitted, such that they are constrained to begin from whichever vertex they are fitted to. The new track parameters of tracks that are refitted to a vertex are stored in tables VCTPAR (primary) and VCPARSEC (secondary).

Chapter 5

Monte Carlo

Detectors in High Energy Physics experiments, such as the ZEUS detector, are extremely complex. So much so, that analytical methods of accounting for detector efficiencies, resolutions and acceptances are not possible. Instead, Monte Carlo (MC) techniques are used. The aim of such techniques is to convert the measured detector quantities back to the original hadronic quantities and hence find the production cross-sections for different classes of events.

The whole process is simulated in three stages:

1. **Physics Process:** The eP scattering is simulated by a Monte Carlo event generator. The hard sub-process is based on leading order perturbative QCD, and parton showers or dipole radiation account for most of the higher order effects. The subsequent hadronisation is simulated by various phenomenological models. Parton Density Functions (see Section 1.5) are inputs to the event generator.
2. **Detector Simulation:** Once events have been generated, they are passed through a full simulation of the ZEUS detector. This program, MOZART, is based on GEANT [45], and includes the best available knowledge of the material and geometry of all the detector components, as well as information on the detector response from physics and test-beam studies.
3. **Trigger Simulation:** The ZEUS trigger response and data acquisition are simulated by the packages ZGANA [46] and ZEPHYR respectively.

Some physics event generators will now be discussed in greater detail.

5.1 PYTHIA

PYTHIA [47] is a general purpose Monte Carlo event generator that can be used to generate ep , e^+e^- and pp events. Version 6.1 is used throughout this thesis to simulate photoproduction events.

The leading order matrix elements are used to simulate the hard sub-process. For this perturbative approach to be valid, a sufficiently hard scale is necessary (above $\sim 1\text{GeV}$). P_T is used as the hard scale, so the matrix elements are only calculated above some value of P_T^{min} . The total cross-section is very dependent on the chosen value of P_T^{min} , increasing to a singularity as P_T^{min} decreases to zero. However, if only events with jets are considered, where $E_T^{jet} \gg P_T^{min}$, then the precise value of P_T^{min} chosen should become unimportant.

The photon spectrum is generated using the Weizsäcker Williams Approximation (WWA) [48], [49]. Corrections for QCD radiation in the final state are made perturbatively (the parton shower). The evolution of the parton shower is ordered in terms of the virtuality of the radiated particles. The parton shower continues until a scale of 1GeV is reached.

The Lund string model [50] is then used to simulate the hadronisation. In this model the partons are considered to be joined by strings. The potential energy stored in the strings increases as the partons move further apart until there is sufficient energy for the string to break, with the creation of a particle-antiparticle pair at the break-point of the string. This continues until there is not sufficient energy for the creation of new particles, whereupon the partons are combined into hadrons.

5.1.1 Strangeness Suppression

PYTHIA assumes that the heavier quarks (c , b , t) will not be produced in the hadronisation phase. However, it does allow u , d and s quarks to be produced, with some arbitrary suppression factor, $\gamma_s = \mathcal{P}(s)/\mathcal{P}(u)$, applied to s quark production to account for this quark's heavier mass. The default value is $\gamma_s = 0.3$.

5.1.2 Baryon Production

Baryon production can be implemented by PYTHIA with various models. The simplest model is the diquark picture. Here, it is assumed that the production of a quark may be replaced by the production of an antiquark. This is controlled by the probability of obtaining a diquark rather than a quark, with the default $\mathcal{P}(\bar{q}\bar{q})/\mathcal{P}(q) = 0.1$. There is an additional suppression of diquarks containing strangeness, with default $\left(\mathcal{P}(us)/\mathcal{P}(ud)\right)/\left(\mathcal{P}(s)/\mathcal{P}(d)\right) = 0.4$.

Alternatively, the Simple Popcorn model may be used. In this model diquarks are not produced. Instead baryons are produced by multiple quark production as follows. Suppose a red-antired quark pair is produced. In the central field between them it is most likely that another red-antired pair will be produced to form two colour neutral mesons. If, however, a green-antigreen fluctuation forms in the field between them, then it becomes favourable for a blue-antiblue pair to be produced to complete the formation of a baryon-antibaryon pair.

$$q_i\bar{q}_i \rightarrow q_iq_1\bar{q}_1\bar{q}_i \rightarrow (q_iq_1q_2)(\bar{q}_2\bar{q}_1\bar{q}_i) \quad (5.1)$$

It is possible for further $q\bar{q}$ pairs to be produced, in which case an additional meson is produced between the baryon-antibaryon pair:

$$q_i\bar{q}_i \rightarrow q_iq_1\bar{q}_1\bar{q}_i \rightarrow q_iq_1q_2\bar{q}_2\bar{q}_1\bar{q}_i \rightarrow (q_iq_1q_2)(\bar{q}_2q_3)(\bar{q}_3\bar{q}_1\bar{q}_i) \quad (5.2)$$

The proportion of baryons coming from the $B\bar{B}$ processes of Eqn. 5.1 compared with the $BM\bar{B}$ processes of Eqn. 5.2 is controlled by another PYTHIA parameter.

The Simple Popcorn model is used for all the PYTHIA MC used in this thesis.

Newer versions of PYTHIA (6.2 and beyond) also allow for a more advanced version of the Popcorn model where more than one meson may be produced amongst baryon-antibaryon pairs.

5.1.3 Multi-parton Interactions

As mentioned in Section 2.2, including Multi-parton Interactions (MI) can lead to a better description of some variables. The principle of there being more than one

parton-parton interaction per electron proton collisions is straight-forward. However, the PYTHIA manual notes that among event generation processes ‘*probably no other area is as poorly understood as this one*’. Nevertheless, MI are included in the PYTHIA MC used in this thesis. With the inclusion of MI, the value of P_T^{min} is again significant, as the average number of hard scatters per event increases as the value of P_T^{min} decreases [30].

Since the value of P_T^{min} affects how well the MC describes the data, a preliminary investigation into the best value of P_T^{min} to use is performed. The χ^2 values obtained from comparing simple event distributions in the data to small PYTHIA samples generated with P_T^{min} values of 2.0, 2.5, 2.7 and 3.0 GeV were examined. The best agreement was obtained with $P_T^{min} = 2.7\text{GeV}$, which is used subsequently.

5.2 HERWIG

HERWIG (Hadron Emission Reactions With Interfering Gluons) [51] is also a general purpose Monte Carlo event generator. As in PYTHIA, it uses the leading order matrix elements to generate the hard sub-process with a suitable hard scale, defined by P_T^{min} . The photon spectrum is generated by the Equivalent Photon Approximation (EPA). The parton shower is similar to PYTHIA, but in HERWIG the emissions are ordered in opening angle, and include the effect of interfering gluons. The parton shower continues down to some hadronisation scale of order a typical meson mass.

5.2.1 Hadronisation

The hadronisation in HERWIG proceeds via the Cluster Model. Any remaining gluons from the parton shower are split into $q\bar{q}$ pairs, and then all the partons are combined into colour-neutral clusters, using the colour connections from the parton shower. Each cluster then either decays into two hadrons or, if it is not sufficiently massive, becomes the lightest hadron consistent with its partonic flavour (in which case its mass may be adjusted by the exchange of momentum with a neighboring cluster). Clusters are split if their mass is above a fission threshold, M_f :

$$M_f^{CLPOW} = CLMAX^{CLPOW} + (RMASS_1 + RMASS_2)^{CLPOW} \quad (5.3)$$

where $RMASS_i$ is the mass of a quark of flavour i . This fission threshold controls both baryon production and strange hadron production. Production of strangeness is also affected by the effective mass of the gluon.

5.2.2 Multi-parton Interactions

HERWIG allows MI in the same way as PYTHIA, with the same dependence on P_T^{min} . Preliminary investigations show that choosing a value of $P_T^{min} = 2.0\text{GeV}$ gives the best agreement with data, which is consistent with the study performed by Nath [30].

5.3 DJANGO / ARIADNE

DJANGO [52] is designed specifically to simulate lepton proton collisions. It includes the program HERACLES [53], which generates Neutral Current DIS events. The hard scale required in order for the perturbative approach to be valid is provided by the momentum transfer, Q^2 .

The DJANGO generator is incorporated into the ARIADNE program [54]. The parton shower is implemented by ARIADNE using the Colour Dipole Model (CDM) [55]. This model views the struck quark and the proton remnant as being connected by a colour dipole. The dipole may radiate gluons, which also form colour dipoles. This process continues until the hadronisation scale is reached.

The hadronisation model used is the Lund String model [50], as in PYTHIA, where partons are considered to be joined by strings, with the potential energy increasing as the partons move apart, until it is energetically favourable for the string to break, with the creation of a new particle antiparticle pair. Regarding the production of strange hadrons, similar strangeness suppression factors and baryon production parameters apply as discussed for the PYTHIA MC in Section 5.1.

ARIADNE has generally been very successful in describing the DIS events observed by ZEUS (see for example [56, 57]).

Chapter 6

Event Selection

This thesis investigates strange particle production across the kinematic range accessible to the ZEUS detector. Detector considerations require that the events are split into three different samples with Q^2 as the physical variable distinguishing them. The samples, which are considered separately until the final results are obtained, are:

1. High Q^2 DIS

- $Q^2 \geq 25\text{GeV}^2$

2. Low Q^2 DIS

- $5 \leq Q^2 \leq 25\text{GeV}^2$

3. Photoproduction

- $Q^2 < 1\text{GeV}^2$

For each sample, events are first selected online by the ZEUS first, second and third level triggers, and then further cuts are applied offline. For each of the data samples a corresponding MC sample is generated, put through the detector simulation and then treated in the same way as the data.

6.1 High Q^2 DIS

Events in the High Q^2 sample are selected according to the standard ZEUS DIS selection, as shown in, for example, [6]. Events are selected such that a well understood, and hence

well described by the MC, sample of DIS events is obtained. The selections outlined below are connected by a logical AND.

6.1.1 Online Selection

Events are required to pass through the 3-level trigger system outlined below:

1. FLT

- The FLT is particularly based around calorimeter information as this is available most quickly. The details of the specific requirements are described elsewhere [6]. Some combinations of calorimeter requirements also require a CTD track candidate to pass the FLT. The CTD FLT reconstructs tracks in a very fast way, and obtains the z-position of hits only by using z-by-timing information [58]. These cuts mainly remove the background from proton beam-gas interactions.

2. SLT

- Timing information from the calorimeter is used to further reduce proton beam-gas background.
- $E - P_Z = \sum_i E_i(1 - \cos \theta_i) > (29 - 2E_\gamma)\text{GeV}$. Here E_γ is the energy deposit in the LUMI calorimeter, and θ_i is the angle with the respect to the nominal interaction point, (0,0,0).

3. TLT - DIS03

- An electron with energy > 4 GeV found by Sinistra or Emille.
- $E - P_Z > (30.0 - 2E_\gamma)$ and $E - P_Z < 100.0\text{GeV}$.
- r_{el} , the electron position when it reaches the CAL, required to be outside a radius of 35 cm around the beam pipe, or outside a radius of 25 cm, or excluding a 28×28 cm box centered on the beam pipe, depending on the running period. The final offline cut is stricter than all of these, so the details of which cuts were applied when are unnecessary.

The total luminosity obtained with this trigger selection can be seen in Table 6.1.

Un-prescaled Luminosity			
Period	e^+/e^-	$E_P(\text{GeV})$	$\mathcal{L}(\text{pb}^{-1})$
96-97	e^+	820	38.62
98-99	e^-	920	16.68
99-00	e^+	920	65.88
Total			121.18

Table 6.1: Luminosity recorded by ZEUS as good for physics.

6.1.2 Offline Selection

The following cuts are applied offline:

- At least one electron found by Sinistra with probability > 0.9 . A scattered electron is the characteristic signature of DIS events.
- An associated track for the electron if $17.2^\circ \leq \theta_e \leq 150^\circ$. This aids the correct electron identification in the region of good tracking acceptance. It removes background from cosmic rays, halo muons, and good physics events where an electromagnetic shower was misidentified as the scattered electron.
- $E_e^{\text{corr}} \geq 10\text{GeV}$. The energy of the electron is corrected for passing through dead material using information from the SRTD, the Pre-sampler and the CAL. The efficiency of finding electrons is high above this energy, and it reduces background from photoproduction.
- $r_{el} \geq 36\text{cm}$. The most stringent trigger selection requires $r_{el} \geq 35\text{cm}$, but $r_{el} \geq 36\text{cm}$ is the lowest cut well simulated by the Monte Carlo.
- $38.0\text{GeV} \leq E - P_Z \leq 65.0\text{GeV}$. If there is no track associated with the electron, the cut is raised to $E - P_Z \geq 44.0\text{GeV}$. This cut reduces the background from photoproduction.
- Energy in a cone of $\eta - \phi$ of radius 0.8 around electron not from electron $\leq 5\text{GeV}$. This reduces the photoproduction background further.
- $|z_{\text{vertex}}| \leq 50.0\text{ cm}$. The beams collide at a nominal value of $z = 0$ with a Gaussian spread $\sigma \sim 12\text{cm}$. This cut therefore reduces beam-gas background events, and events with an incorrectly measured vertex.

- $y_{jb} \geq 0.02$. Below this value a significant fraction of the hadronic system is lost down the forward beam pipe, hence requiring a more detailed simulation of the beam pipe region than currently exists. This cut also defines one boundary of the kinematic region.
- $y_{el} \leq 0.95$. Events with a fake electron found in the FCAL are removed by this cut. This cut also defines one boundary of the kinematic region.
- $Q_{da}^2 \geq 25\text{GeV}^2$. At this relatively low value of Q^2 , the double-angle method gives the most accurate determination of Q^2 . This cut defines one further boundary of the kinematic region.

6.1.3 Monte Carlo

Due to the extremely time-consuming nature of generating MC events and putting them through the detector simulation, it is not possible to generate an independent MC sample for every analysis. MC events from various sources are used, as outlined in Table 6.2. Filters may be applied at the generator level to save putting unnecessary events through the detector simulation. The strange particle filter accepts events that contain a Λ , or K_s^0 , or particles that might decay to these during the detector simulation, that is Σ , Ξ or Ω .

Generator	Minimum $Q^2(\text{GeV}^2)$	$E_P(\text{GeV})$	Filter	Luminosity (pb^{-1})
ARIADNE	2	820	None	19.5
ARIADNE	2	920	None	56.8
ARIADNE	10	920	None	108.7
ARIADNE	12	920	Strange Particle	126.2
Total				311.2

Table 6.2: Monte Carlo samples used in the High Q^2 analysis.

After passing through the detector simulation these MC samples enjoy the same offline selection cuts as the data.

The MC is used to correct the data from the detector level to the hadron level. In order to be confident that no MC model dependence is introduced, it is important for the detector level MC distributions to agree well with the data. Some detector level

distributions demonstrating the good agreement between data and MC are shown in Fig 6.1. The MC is normalized to contain the same number of events in each histogram as the data, in order that the distribution shapes may be compared. After the MC is normalized to the data luminosity an additional multiplicative factor of 1.12 is required to bring it to the same number of events as the data.

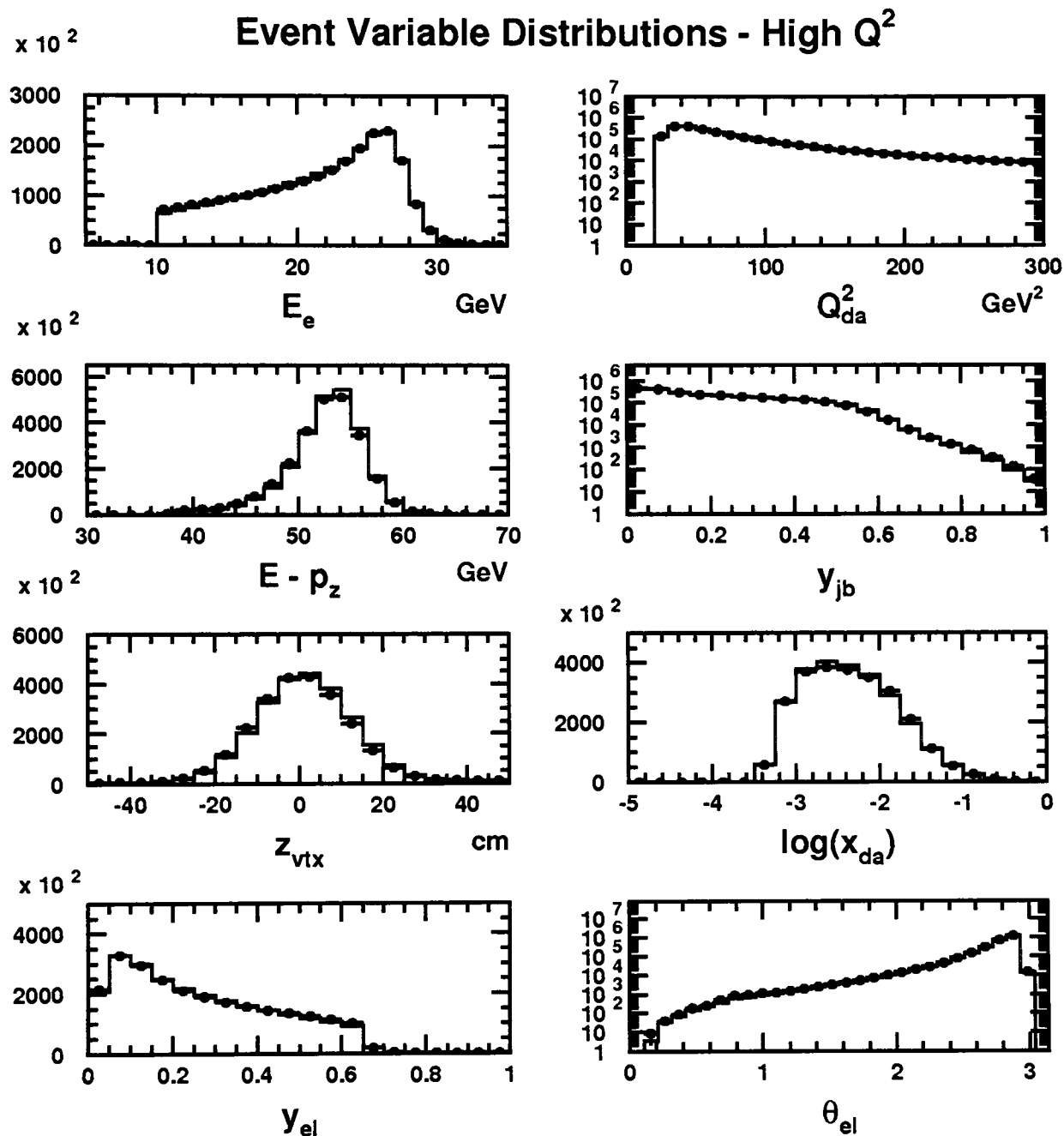


Figure 6.1: Detector level comparison between data (black circles) and ARIADNE (red line). The MC is normalized to the number of events in the data histograms so that the shapes may be compared. The eight variables compared are the corrected energy of the scattered electron, the Q^2 of the event obtained using the double angle method, $E - p_z$, y obtained using the Jacquet-Blondel method, the z-position of the primary vertex, x obtained with the double angle method, y obtained using the electron method, and the polar angle of the scattered electron. The scale on the y-axes is the number of events per bin.

6.2 Low Q^2 DIS

6.2.1 Online Selection

The first and second level trigger selection for the Low Q^2 sample is the same as for the High Q^2 sample. However, at the TLT, DIS01 is required, rather than DIS03. The DIS01 selections are:

- An electron with energy $> 4\text{GeV}$ found by Sinistra or Emille.
- $E - P_Z > (30.0 - 2E_\gamma)$ and $E - P_Z < 100.0\text{GeV}$.
- Electron position when it reaches the CAL required to be outside a box centered on the beam pipe of dimensions $24 \times 12\text{cm}$.

The smaller excluded region about the beam pipe for detecting the scattered electron allows an abundance of Low Q^2 events to pass this trigger. As the cross-section increases so dramatically as Q^2 decreases (Eqn 1.11), this trigger was often prescaled - only a specified fraction of events that passed the trigger selections were actually written to tape. Therefore the effective luminosity for this sample is significantly smaller than for the High Q^2 sample. The total luminosity obtained with this trigger selection can be seen in Table 6.3.

Prescaled Luminosity			
Period	e^+/e^-	$E_P(\text{GeV})$	$\mathcal{L}(pb^{-1})$
96-97	e^+	820	5.273
98-99	e^-	920	4.814
99-00	e^+	920	6.507
Total			16.594

Table 6.3: Luminosity recorded by ZEUS as good for physics after the prescale applied by DIS01 trigger.

6.2.2 Offline Selection

The offline selection is the same as for the High Q^2 sample, except for the Q^2 cut and the electron position cut, which are:

- $5 \leq Q_{da}^2 \leq 25 \text{GeV}^2$.
- Electron position when it reaches the CAL required to be outside a box centered on the beam pipe of dimensions $26 \times 14 \text{cm}$.

6.2.3 Monte Carlo

The MC events generated that simulate the Low Q^2 sample are outlined in Table 6.4.

Generator	Minimum $Q^2(\text{GeV}^2)$	$E_P(\text{GeV})$	Filter	Luminosity (pb^{-1})
ARIADNE	2	820	None	19.5
ARIADNE	2	920	None	43.8
Total				63.3

Table 6.4: Monte Carlo samples used in the Low Q^2 analysis.

After passing through the detector simulation these MC samples have the same offline selection cuts applied as the data. Following such selections the agreement between data and MC can be seen in Fig 6.2, and is generally good. The MC is normalized to contain the same number of events in each histogram as the data, in order that the distribution shapes may be compared. After the MC is normalized to the data luminosity an additional multiplicative factor of 1.18 is required to bring it to the same number of events as the data.

6.3 Photoproduction

The production rate of inclusive photoproduction events would be far too large, as can be seen from Eqn 1.11, to be written to tape. The most inclusive photoproduction sample collected by ZEUS is based on a dijet trigger. The trigger chain and offline cuts are outlined below. Unless explicitly stated otherwise the selections are connected by a logical AND.

6.3.1 Online Selection

1. FLT

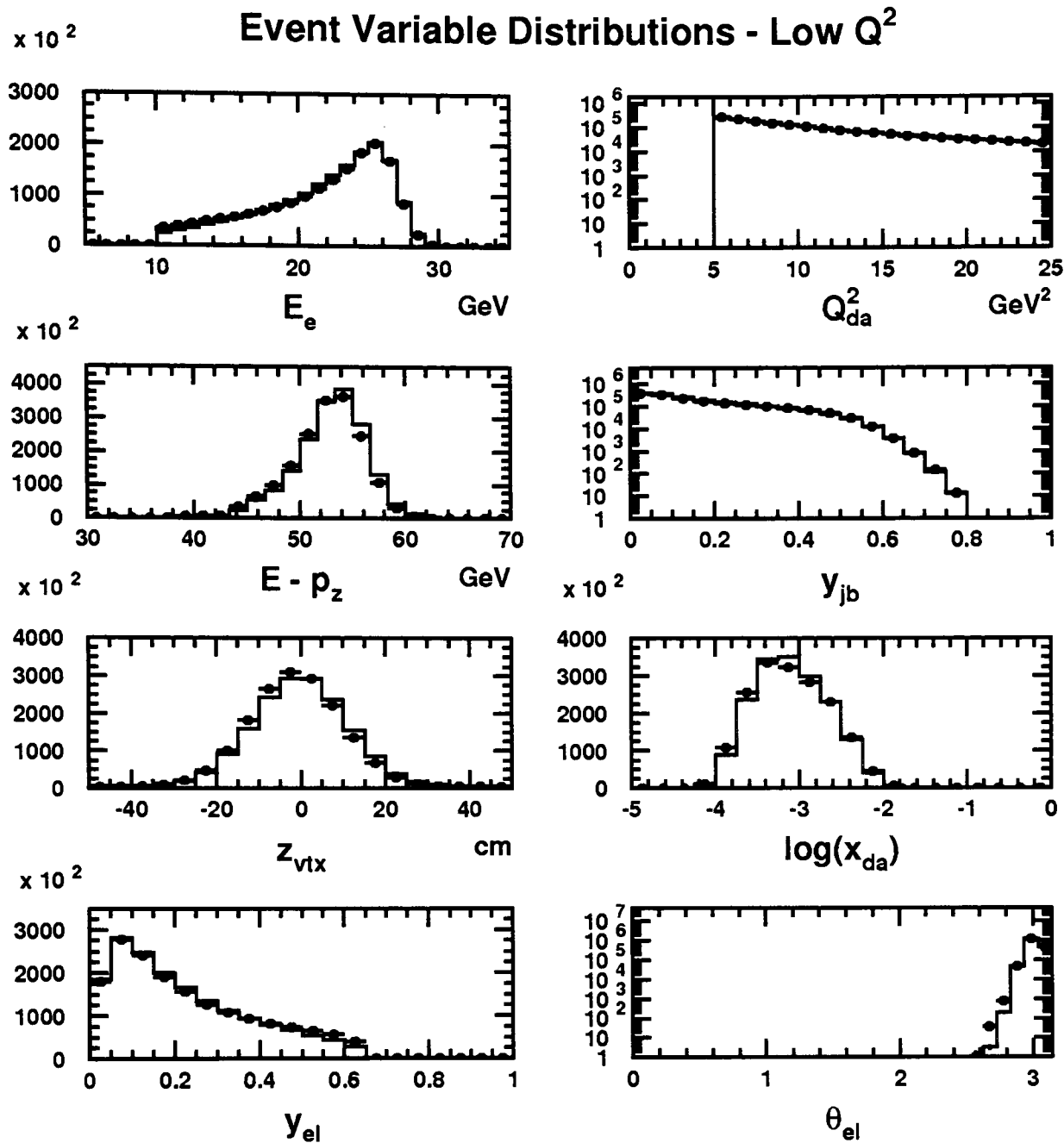


Figure 6.2: Detector level comparison between data (black circles) and ARIADNE (red line). The MC is normalized to the number of events in the data histograms so that the shapes may be compared. The eight variables compared are the corrected energy of the scattered electron, the Q^2 of the event obtained using the double angle method, $E - p_z$, y obtained using the Jacquet-Blondel method, the z-position of the primary vertex, x obtained with the double angle method, y obtained using the electron method, and the polar angle of the scattered electron. The scale on the y-axes is the number of events per bin.

- Calorimeter Requirements

- Total energy in the CAL $> 14.968\text{GeV}$, excluding the ring closest to the beam pipe of the RCAL and three rings closest to the beam pipe for the FCAL.
- OR Total EMC energy $> 10.068\text{GeV}$, with the same regions excluded.
- OR RCAL EMC energy $> 2.032\text{GeV}$, excluding the ring closest to the beam pipe.

- OR BCAL EMC energy $> 3.404\text{GeV}$.
- Vetos
 - Timing information from the C5 counter must be consistent with an eP interaction.
 - Timing information from the VETO wall is used to remove events where the interaction took place outside the detector.
 - SRTD timing information removes further beam gas events.
 - TRKClass > 2 , requires a high proportion of tracks ($\gtrsim 25\% - 30\%$) originating from the nominal vertex.

2. SLT

- At least one track pointing to the nominal vertex.
- $E - P_Z > 8\text{GeV}$.
- $E_T(box) > 8\text{GeV}$, where $E_T(box)$ is the total calorimeter transverse energy excluding the inner ring of the FCAL.
- $E - P_Z > 12\text{GeV}$ or $P_Z/E < 0.95$.

3. TLT - HPP14.

- Two jets found, both satisfying:
 - $E_T^{jet} > 4\text{GeV}$ (up until June 1999).
 - $E_T^{jet} > 4.5\text{GeV}$ (after June 1999).
 - $|\eta^{jet}| < 2.5$.

The jet finding at the TLT is done using the EUCCELL cone algorithm.

- $P_Z/E < 1.0$.
- $|z_{vtx}| < 60.0\text{cm}$.
- $E - P_Z < 75\text{GeV}$.
- Fewer than 6 bad tracks, where a good track satisfies all the following criteria:
 - $P_T \geq 200\text{MeV}$.
 - $0.35 < \eta < 3.13$.

- > 5 hits from axial superlayers used.
- > 5 hits from stereo superlayers used.
- Distance of closest approach to vertex in z is $\leq 75\text{cm}$.

The total luminosity obtained with this trigger selection is the same as for the High Q^2 sample, and can be seen in Table 6.1.

6.3.2 Offline Selection

Offline, the cuts on the jets are made slightly tighter than at the trigger level. Two jets, reconstructed with the KTCLUS algorithm, are required with the following criteria:

- $E_T^{jet} > 5\text{GeV}$
- $|\eta^{jet}| < 2.4$

Additionally, various cuts are made to remove non-photoproduction events. Beam gas events are removed by excluding events where:

- $y_{jb} < 0.2$

Neutral Current DIS events are removed by excluding events where an electron is found by Sinistra with:

- $y_{el} > 0.85$

and also by removing events where:

- $y_{jb} > 0.85$

More details on why these cuts have been chosen can be found in, for example, [60].

Charged Current DIS events are removed by requiring that there is no missing P_T in the event. Events are rejected if:

- $P_T^{missing}/\sqrt{E_T} > 2.0\sqrt{\text{GeV}}$

The missing P_T is scaled by $\sqrt{E_T}$ to account for the resolution of the calorimeter.

6.3.3 Monte Carlo

PYTHIA is chosen as the main generator to correct the photoproduction data. The time-consuming nature of generating large MC samples prevents the use of a large HERWIG sample as a check on the model dependence of the MC corrections. The MC events available that can be used to correct the photoproduction sample are outlined in Table 6.5.

Generator	Resolved / Direct	$E_P(\text{GeV})$	Filter	Luminosity (pb^{-1})
PYTHIA	Resolved	820	Dijet	18.3
PYTHIA	Resolved	820	Dijet + Strange Particle	28.2
PYTHIA	Direct	820	Dijet	40.3
PYTHIA	Resolved	920	Dijet	12.7
PYTHIA	Resolved	920	Dijet + Strange Particle	144.3
PYTHIA	Direct	920	Dijet	147.2
Total Resolved				203.5
Total Direct				187.6

Table 6.5: Available Monte Carlo samples used in the photoproduction analysis.

After passing through the detector simulation these MC samples have the same offline selection cuts applied as the data.

There is, however, one additional ambiguity in photoproduction MC. As the MC events are generated only at leading order, the normalization is generally not adequately described. Therefore, the relative proportion of direct and resolved events is not defined accurately by the generated luminosities. In order to get the best agreement between data and MC the proportions of direct and resolved MC are used such that the best possible fit to the data x_γ distribution is obtained. To do this, data collected during 1996 and 1997 are compared to the dijet-filtered PYTHIA sample with $E_P = 820\text{GeV}$. For each bin, i , of the x_γ distribution the number of MC events is:

$$N_i^{MC} = \alpha N_i^{\text{resolved}} + (1 - \alpha) N_i^{\text{direct}} \quad (6.1)$$

where the resolved and direct samples are normalized to contain the same number of events as the data. The best fit is obtained by minimizing $\chi^2(\alpha)$:

$$\chi^2(\alpha) = \sum_i \frac{(N_i^{\text{data}} - N_i^{MC})^2}{(\sigma_i^{\text{data}})^2 + (\sigma_i^{MC})^2} \quad (6.2)$$

Performing this fit yields a minimum χ^2 value when $\alpha = 0.84$, and the distributions of data, resolved and direct PYTHIA for this value are shown in Fig. 6.3. It is evident that

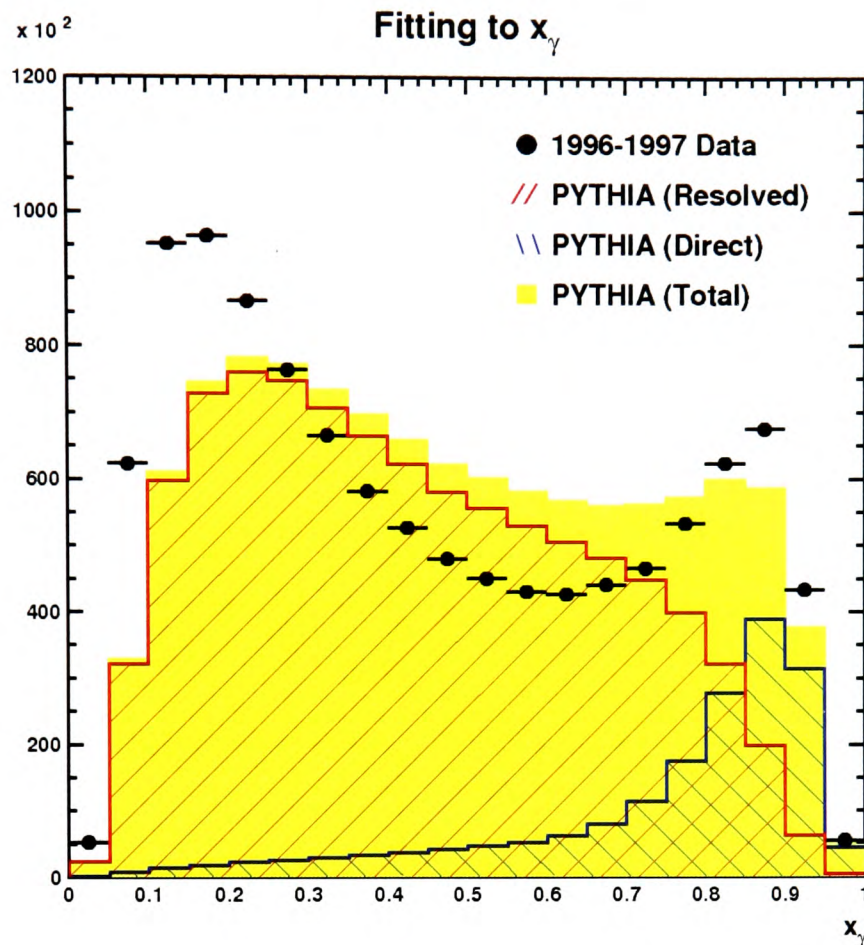


Figure 6.3: The best fit x_γ distribution.

even with the flexibility to mix direct and resolved components as required, the MC is still not sufficient to describe the data very well, particularly at low x_γ . Although this adds excitement in that there might be interesting physics hiding in this region, it also makes it much more hazardous to use this MC to correct the data from detector level to hadron level. Exactly how trustworthy are the corrected data due to this disagreement will be discussed later as part of the discussion on systematic errors.

A comparison of the MC (with the optimal combination of direct and resolved events) with the data for more variables may be seen in Fig. 6.4. Although the MC does relatively well at simulating the E_T of the jets, it is less good at simulating jet η values and y_{jb} and x_γ , as observed above.

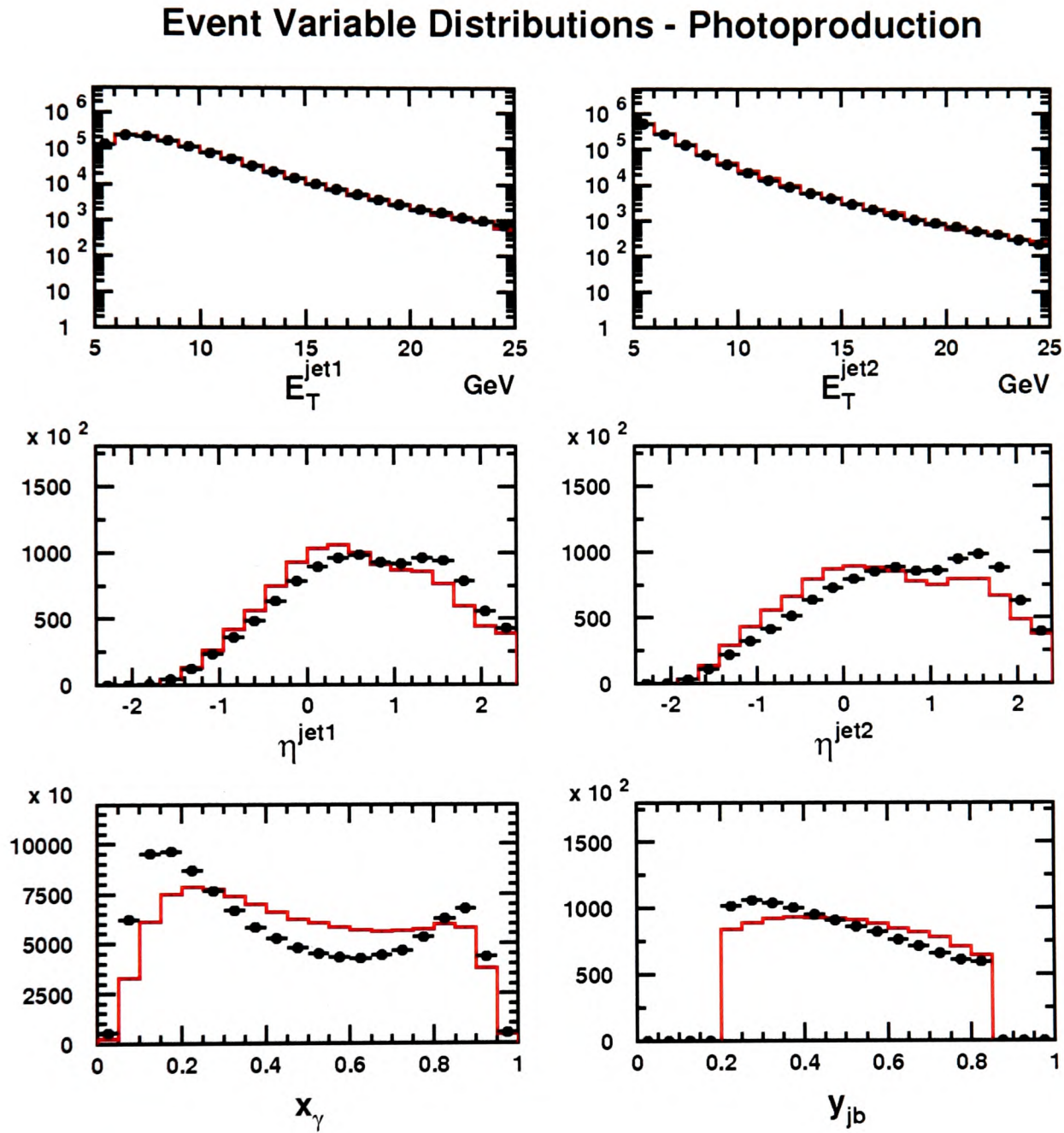


Figure 6.4: Detector level comparison between data (black circles) and PYTHIA (red line). The MC is normalized to the number of events in the data histograms so that the shapes may be compared. The six variables compared are the transverse energy, E_T , of each of the two highest E_T jets, η of the same jets, x_γ , and y_{jb} . The scale on the y-axes is the number of events per bin.

Chapter 7

Reconstructing Strange Particles

7.1 Reconstructing Λ and K_s^0

The following decay modes of Λ and the K_s^0 are observed:

$$\Lambda \rightarrow p\pi^- \quad (7.1)$$

$$\Lambda \rightarrow \bar{p}\pi^+ \quad (7.2)$$

$$K_s^0 \rightarrow \pi^+\pi^- \quad (7.3)$$

The CTD is only sensitive to charged particles, so only the decay products, not the strange particles themselves, are directly observed by ZEUS.

Both the Λ and the K_s^0 decay weakly, so they have relatively long lifetimes ($2.632 \pm 0.020 \times 10^{-10}$ s and $0.8958 \pm 0.0006 \times 10^{-10}$ s, respectively [10]). Therefore, many Λ and K_s^0 travel far enough from the initial interaction point before decaying for a distinct secondary vertex to be resolved.

The charged decay products, p and $\pi^\pm$, are detected in the CTD. The program VC-TRAK reconstructs them as tracks and fits them to a vertex, as described in Section 4.5. Any secondary vertex with exactly two oppositely charged tracks is then considered as a Λ or K_s^0 candidate. Additionally, for any secondary vertex with three secondary tracks, each combination of oppositely charged tracks is considered as a Λ or K_s^0 candidate. This recovers those strange particles where a third track has been placed on the incorrect vertex.

The tracks from secondary vertices are required to satisfy the following constraints,

to reduce combinatorial background and ensure that the secondary vertices are well measured:

- $P_T^{track} \geq 0.15\text{GeV}$
- $|\eta^{track}| \leq 1.5$
- Outer superlayer of CTD passed by track ≥ 5

The momentum of the original decaying particle is then calculated to be the vector sum of the momenta of the two secondary tracks. The momentum at the vertex is then required to satisfy the following criteria:

- $0.6 < P_T^{vertex} < 2.5\text{GeV}$
- $|\eta^{vertex}| < 1.2$

Outside this region, the efficiency of detecting Λ and K_s^0 drops significantly, as can be seen in Fig. 7.1.

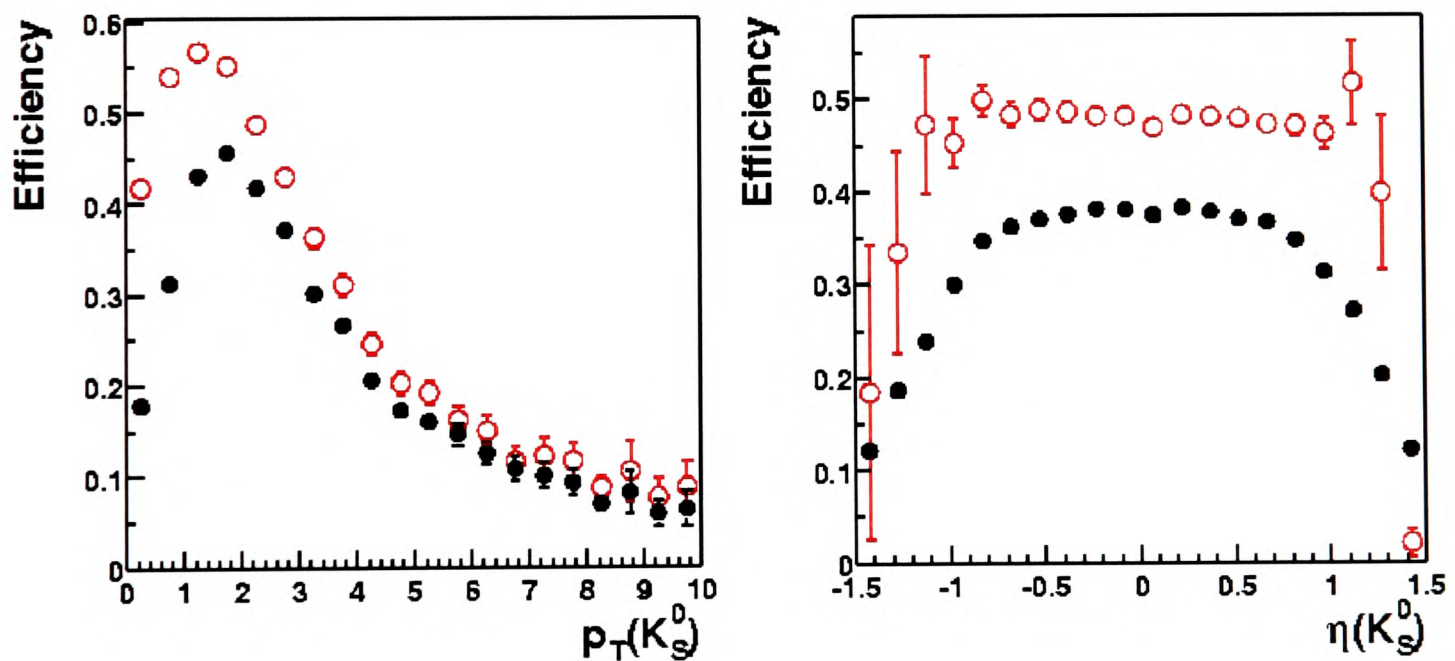


Figure 7.1: K_s^0 detection efficiency at ZEUS, as measured in [61]. Black circles correspond to the efficiency of detecting K_s^0 with $P_T > 0.3\text{GeV}$ and $|\eta| < 1.5$. Open red circles correspond to the efficiency of detecting only those K_s^0 whose decay particles satisfy $P_T^{Daughter} > 0.15\text{GeV}$ and $|\eta^{Daughter}| < 1.0$.

To ensure that the strange particles observed do originate from the electron proton interaction, the following collinearity requirement is made:

$$\theta^{coll} \leq 0.2 \quad (7.4)$$

where θ is the angle between $\mathbf{p}^{\text{vertex}}$ and the vector joining the primary to the secondary vertex.

For each of the remaining Λ or K_s^0 candidates the invariant mass of the mother particle is reconstructed assuming three separate hypotheses:

1. K_s^0 : Both tracks are assumed to have the mass of a π^+ .
2. Λ : The track with the most momentum is assumed to have the proton mass¹. The other track is assumed to have the mass of a π^+ .
3. γ : Both tracks are assumed to have the mass of an electron.

The masses of proton, π^+ and electron are taken from [10].

Photon conversions to e^+e^- are removed by requiring that the invariant mass assuming the third hypothesis is greater than 50MeV (see, for example, [61]).

Finally, Λ and K_s^0 are separated using information from the plot shown in Fig. 7.2. To remove Λ from the K_s^0 signal, candidates below the blue line on the plot are removed (reject if $M(p\pi) < 1.125\text{GeV}$). To remove K_s^0 from the Λ signal, candidates to the right of the red line on the plot are removed (reject if $M(\pi\pi) > 0.475\text{GeV}$).

Λ and $\bar{\Lambda}$ are easily separated: If the track with most momentum is positively charged the decay products are $p\pi^-$, so it is a Λ . If the track with most momentum is negatively charged the decay products are $\bar{p}\pi^+$, so it is a $\bar{\Lambda}$.

Given these selections, particle signals such as those displayed in Fig 7.3 are obtained. The dotted red lines indicate one final selection criteria: In order to qualify as a Λ candidate, the mass must lie within

$$1.11\text{GeV} < M(\Lambda) < 1.122\text{GeV} \quad (7.5)$$

and for the K_s^0 candidates the mass must lie within

$$0.48\text{GeV} < M(K_s^0) < 0.52\text{GeV}. \quad (7.6)$$

¹Given the momentum selections and the mass of the proton being so much greater than the π^+ , the proton will always have greater momentum than the π for real Λ decays.

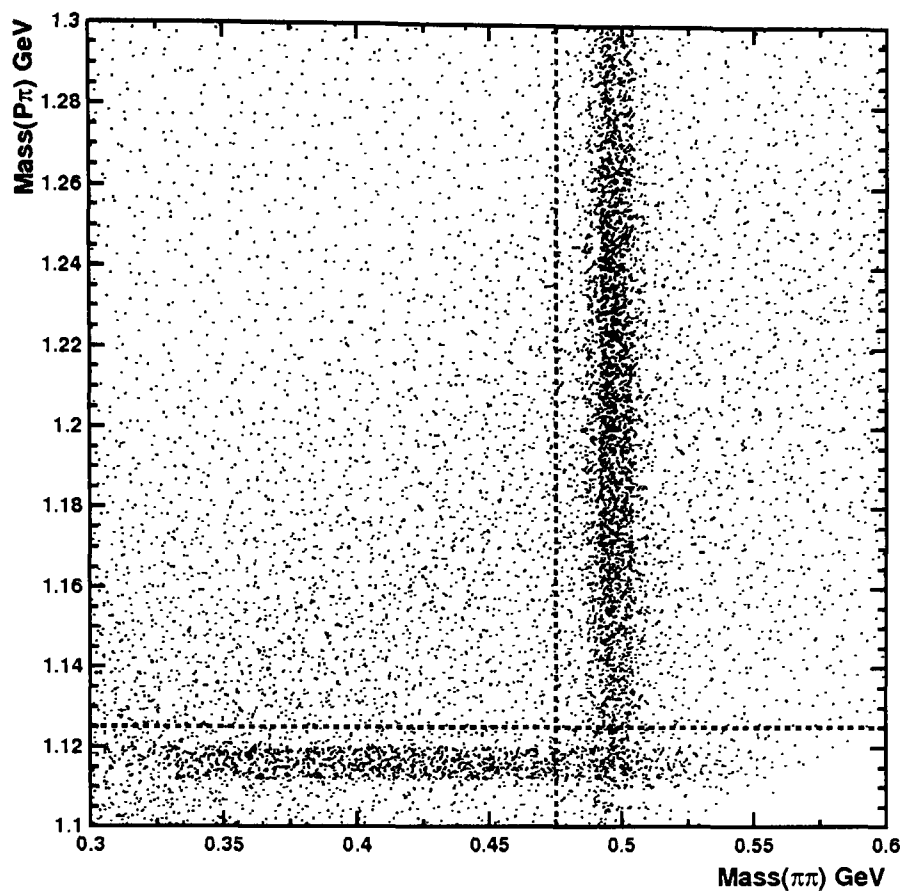


Figure 7.2: The invariant mass of each strange particle candidate assuming the Λ hypothesis is plotted against each candidate assuming the K_s^0 hypothesis. The histogram bins are $6\text{MeV} \times 4\text{MeV}$. The vertical band corresponds to the K_s^0 signal. The horizontal band corresponds to the Λ signal.

7.1.1 Agreement with Monte Carlo

In order to use the MC to correct for detector effects it is important that it adequately describes the data, not only for the event variables of general events shown in Chapter 6, but also for the event variables of those events containing strange particles and for particular variables of the strange particles themselves. The comparison of the Λ , $\bar{\Lambda}$ and K_s^0 quantities between the data and the MC are shown in Fig. 7.4 for the Low Q^2 sample. The comparison of the event variables for those events that contain a Λ or $\bar{\Lambda}$ candidate is shown in Fig 7.5, and for those events that contain a K_s^0 candidate in Fig. 7.6. Similar plots showing data and MC comparisons for the High Q^2 sample are shown in Figures 7.7, 7.8 and 7.9, and for the photoproduction sample in Figures 7.10, 7.11 and 7.12.

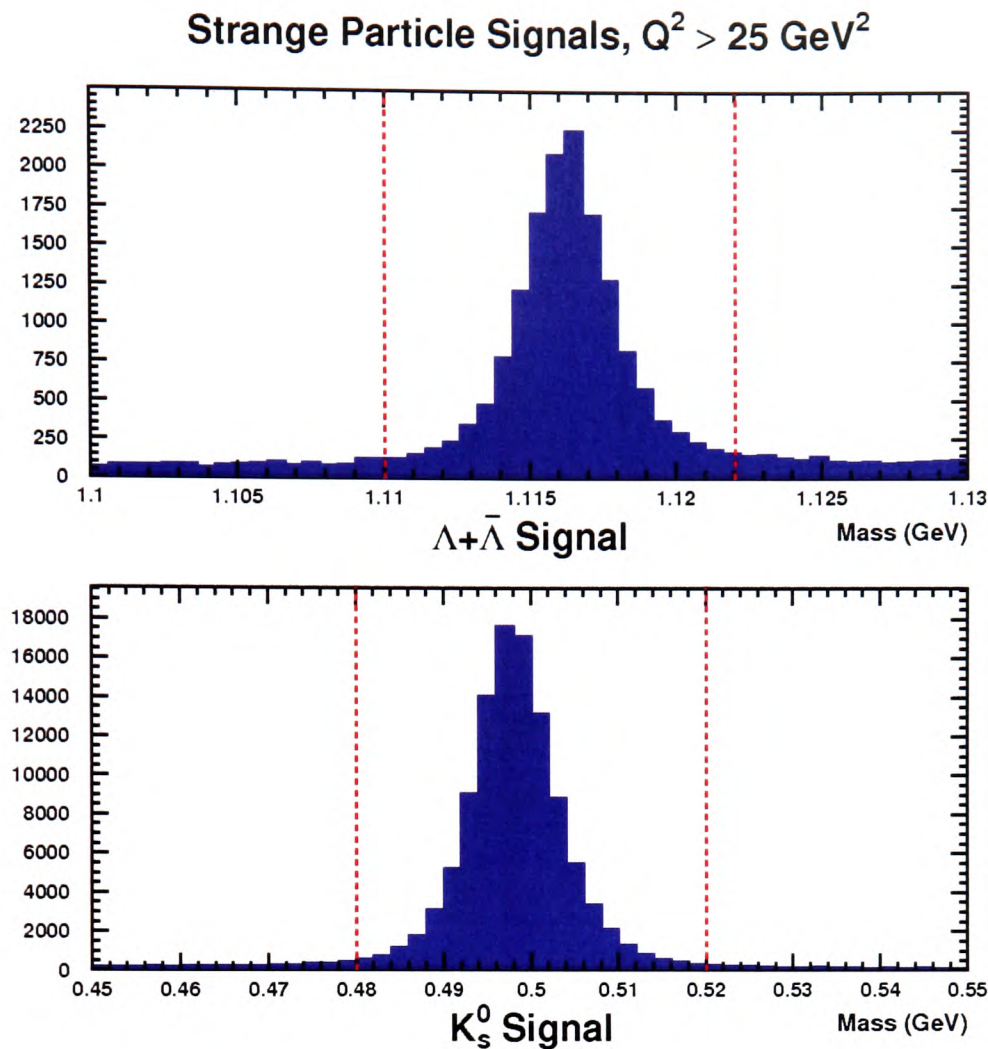


Figure 7.3: Uncorrected mass distribution of Λ and K_s^0 candidates after the selections described in Section 7.1. Data collected by ZEUS according to the High Q^2 selection (Section 6.1).

7.2 Obtaining the Cross-section

The cross-section for Λ and K_s^0 production is measured differentially as a function of x , Q^2 , P_T and η for DIS events, and as a function of x_γ , P_T and η for photoproduction events. The differential cross-section is defined as follows:

$$\frac{d\sigma}{dY} = \frac{N}{A \cdot \mathcal{L} \cdot B \cdot \Delta Y} \quad (7.7)$$

where N is the number of Λ or K_s^0 in a bin of width ΔY , $\mathcal{L}$ is the luminosity, A is the acceptance and B is the branching ratio. The branching ratios used to obtain the cross-sections are taken from [10] and are:

$$K_s^0 \rightarrow \pi^+ \pi^-; \quad B.R. = 68.95 \pm 0.14\% \quad (7.8)$$

$$\Lambda \rightarrow p\pi; \quad B.R. = 63.9 \pm 0.5\% \quad (7.9)$$

The method of correcting for the detector acceptance is described below in Section 7.4.

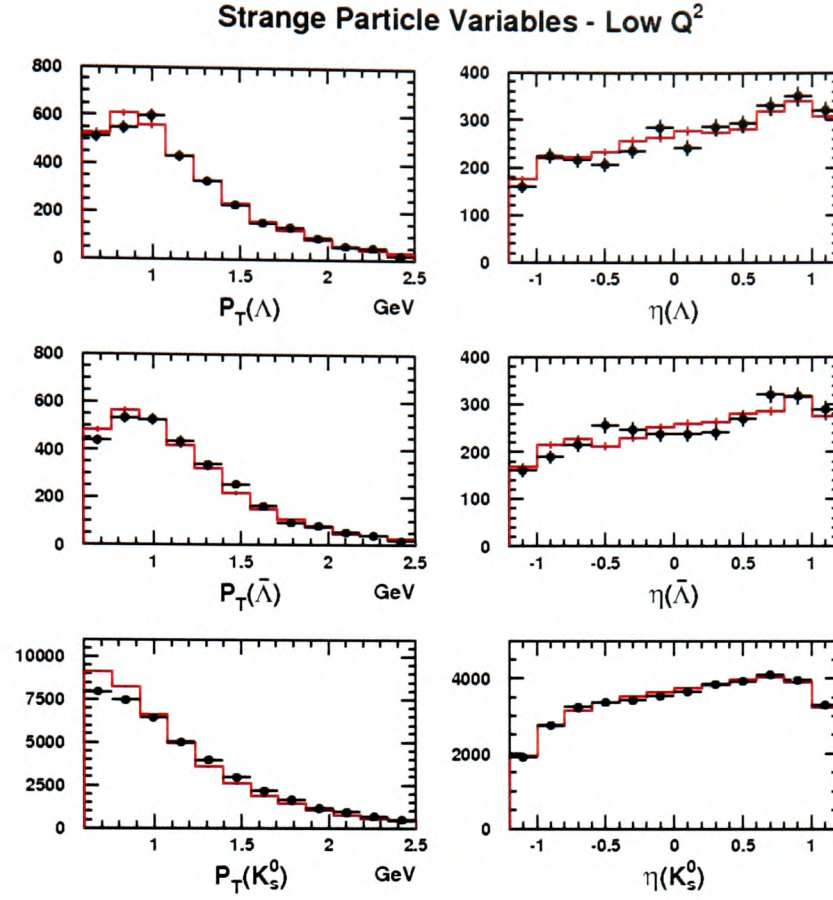


Figure 7.4: Detector level comparison between data strange particle quantities (black circles) and ARIADNE (red line) in the Low Q^2 sample. The MC is normalized to the same number of events as in the data histograms.

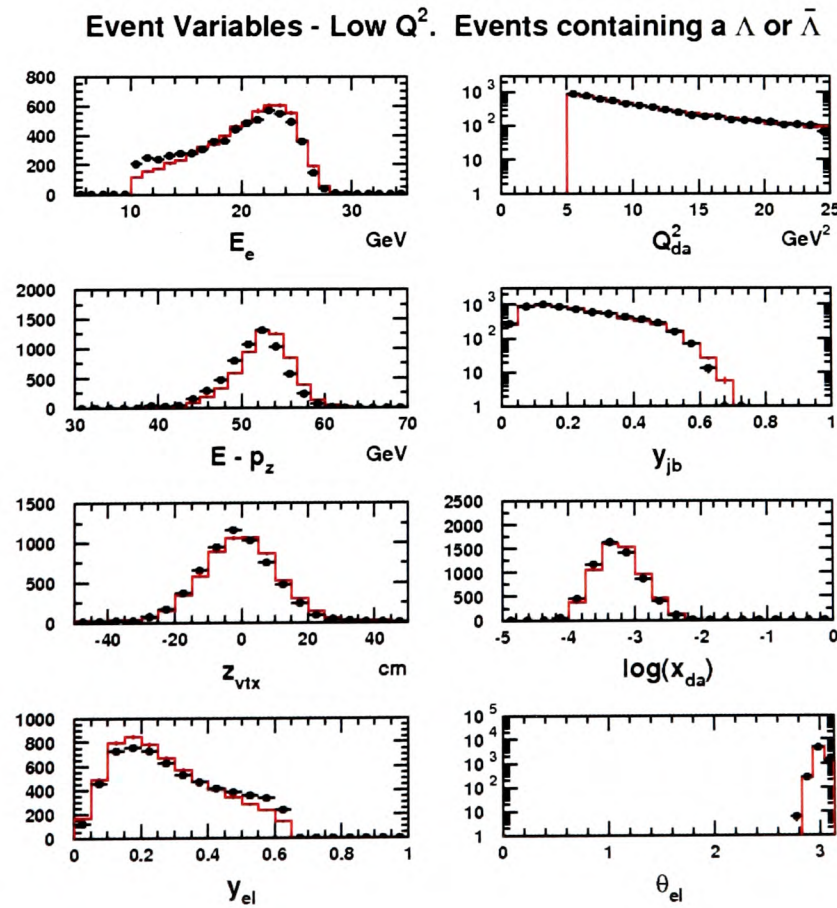


Figure 7.5: Detector level comparison of event variables for events containing a Λ or $\bar{\Lambda}$ candidate between data (black circles) and ARIADNE (red line) in the Low Q^2 sample. The MC is normalized to the same number of events as in the data histograms.

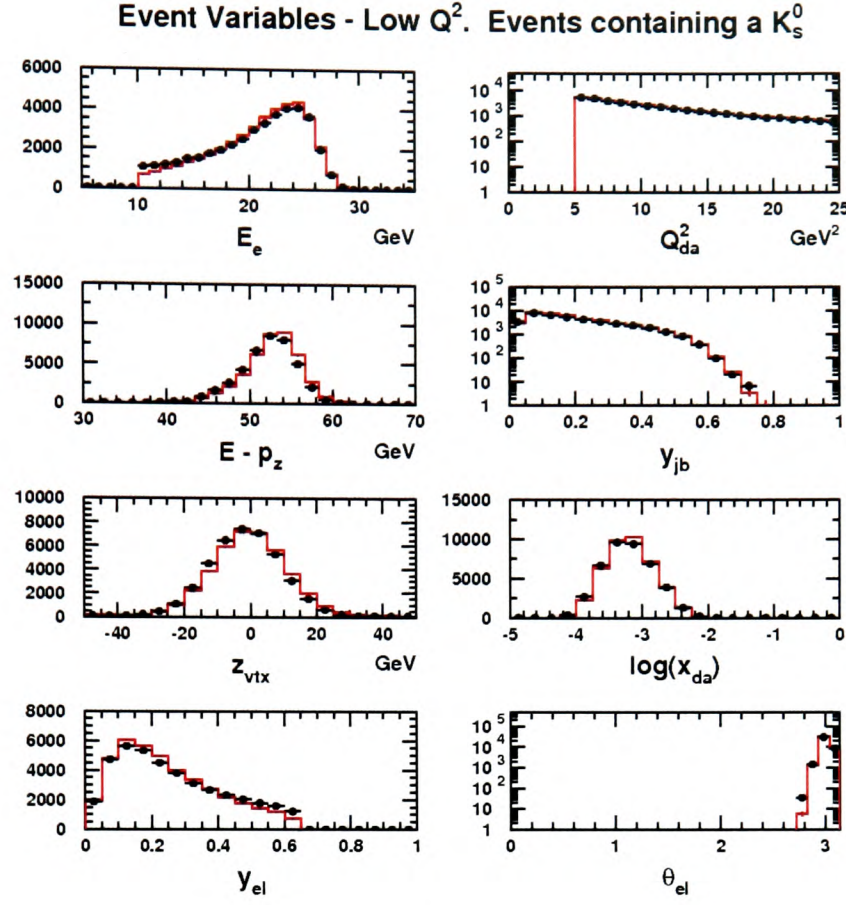


Figure 7.6: Detector level comparison of event variables for events containing a K_s^0 candidate between data (black circles) and ARIADNE (red line) in the Low Q^2 sample. The MC is normalized to the same number of events as in the data histograms.

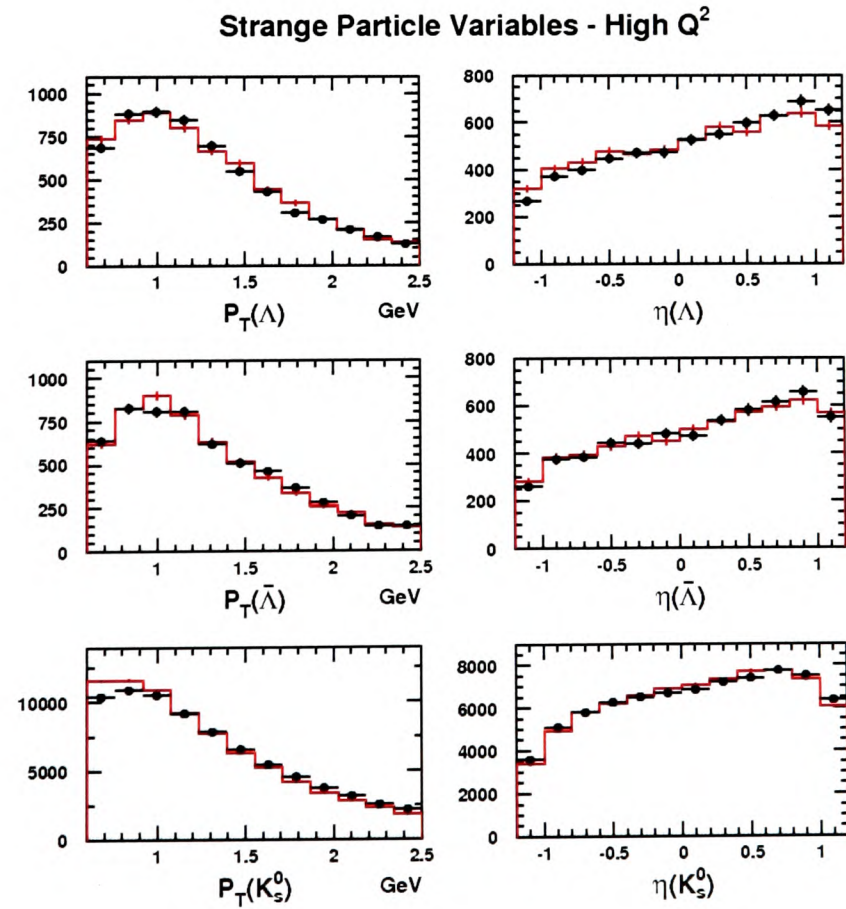


Figure 7.7: Detector level comparison between data strange particle quantities (black circles) and ARIADNE (red line) in the High Q^2 sample. The MC is normalized to the same number of events as in the data histograms.

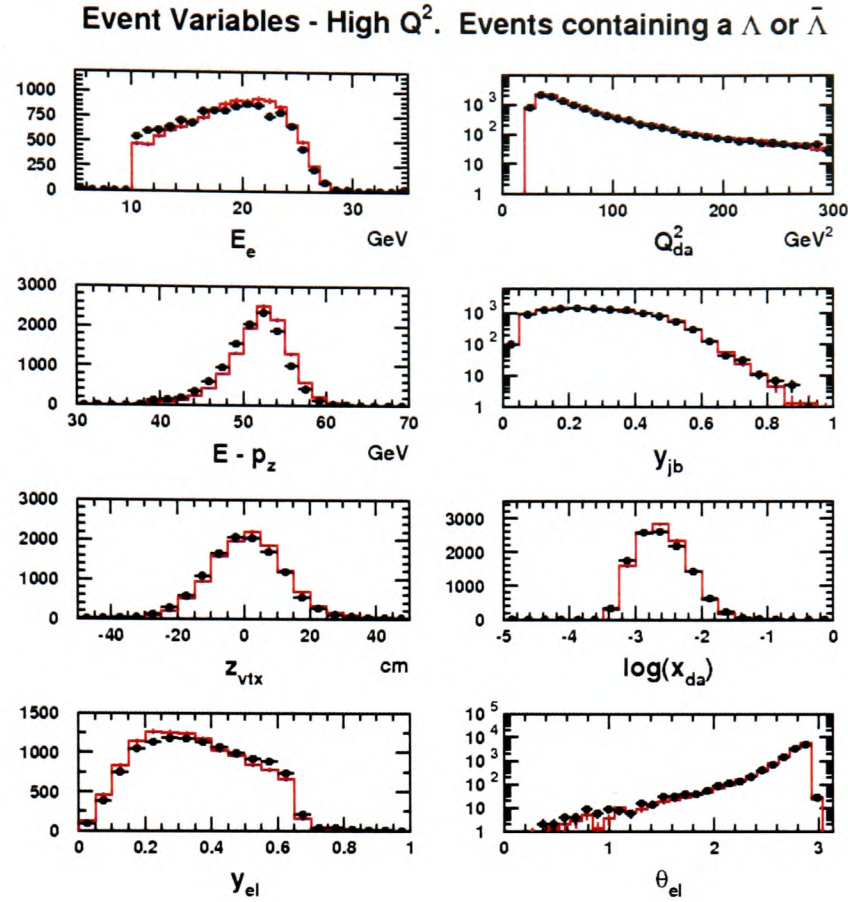


Figure 7.8: Detector level comparison of event variables for events containing a Λ or $\bar{\Lambda}$ candidate between data (black circles) and ARIADNE (red line) in the High Q^2 sample. The MC is normalized to the same number of events as in the data histograms.

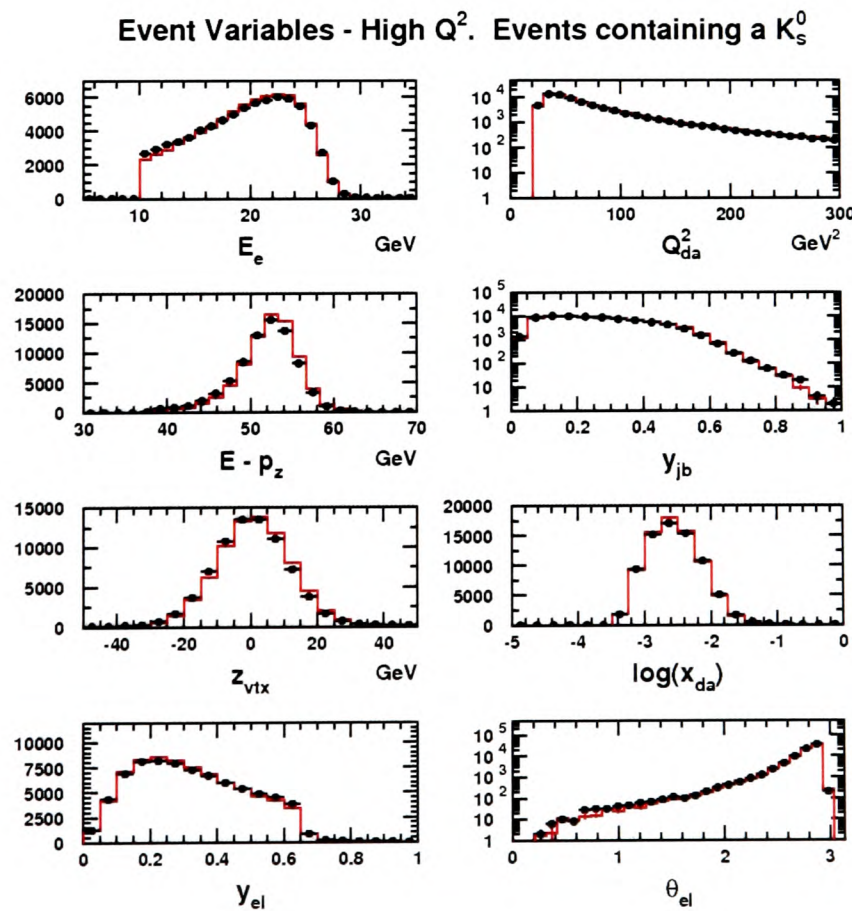


Figure 7.9: Detector level comparison of event variables for events containing a K_s^0 candidate between data (black circles) and ARIADNE (red line) in the High Q^2 sample. The MC is normalized to the same number of events as in the data histograms.

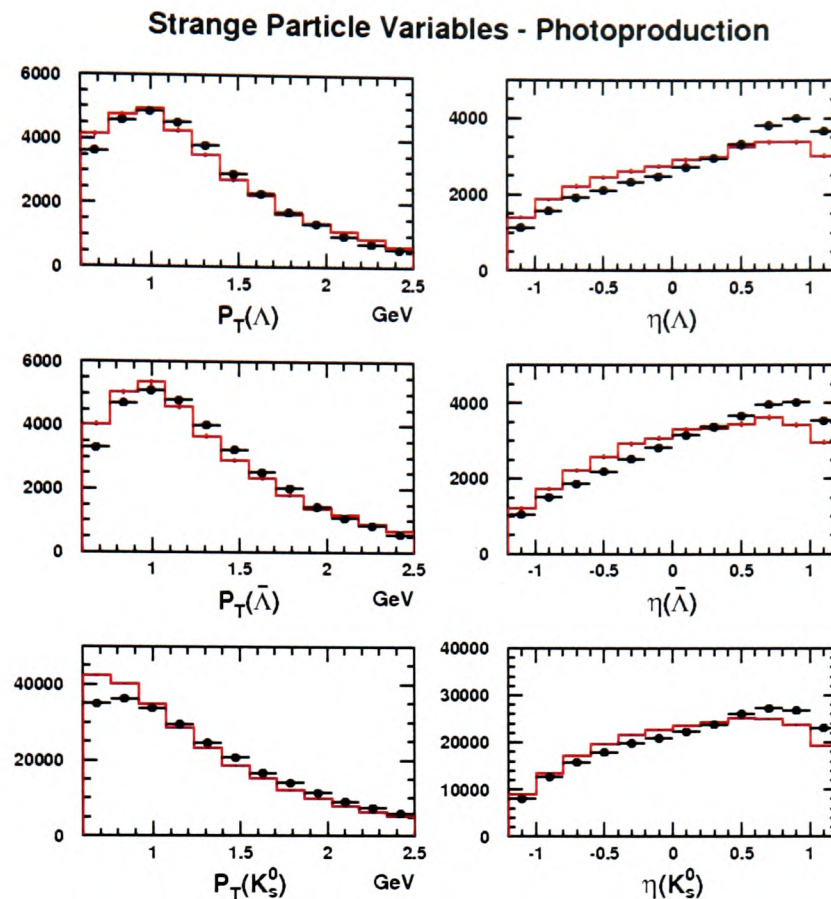


Figure 7.10: Detector level comparison between data strange particle quantities (black circles) and PYTHIA (red line) in the photoproduction sample. The MC is normalized to the same number of events as in the data histograms.

Event Variables - Photoproduction. Events containing a Λ or $\bar{\Lambda}$

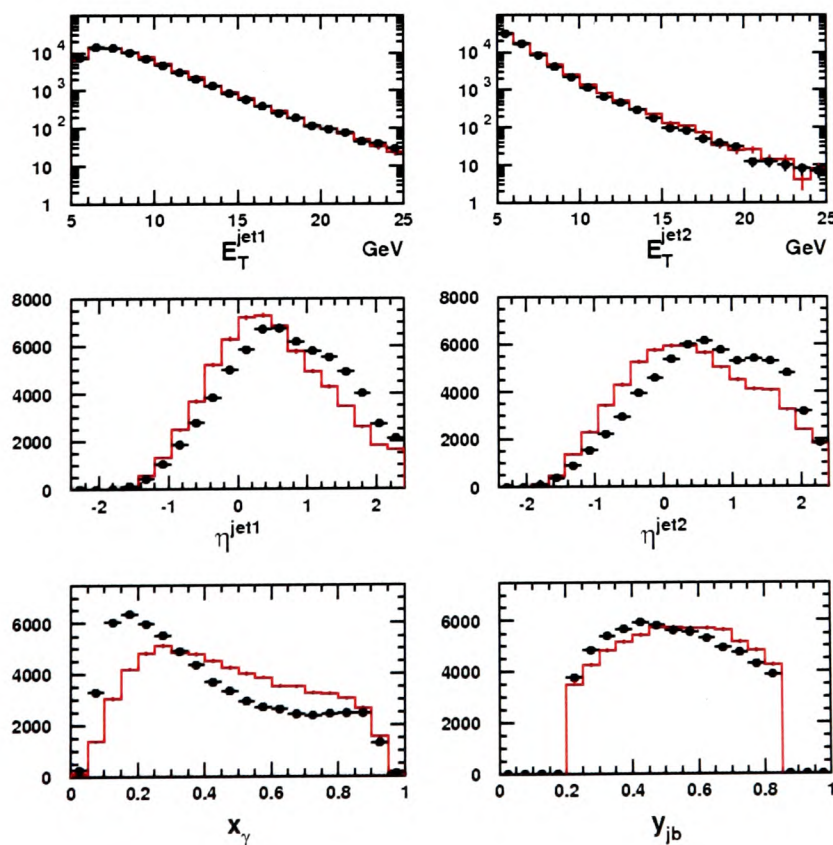


Figure 7.11: Detector level comparison of event variables for events containing a Λ or $\bar{\Lambda}$ candidate between data (black circles) and PYTHIA (red line) in the photoproduction sample. The MC is normalized to the same number of events as in the data histograms.

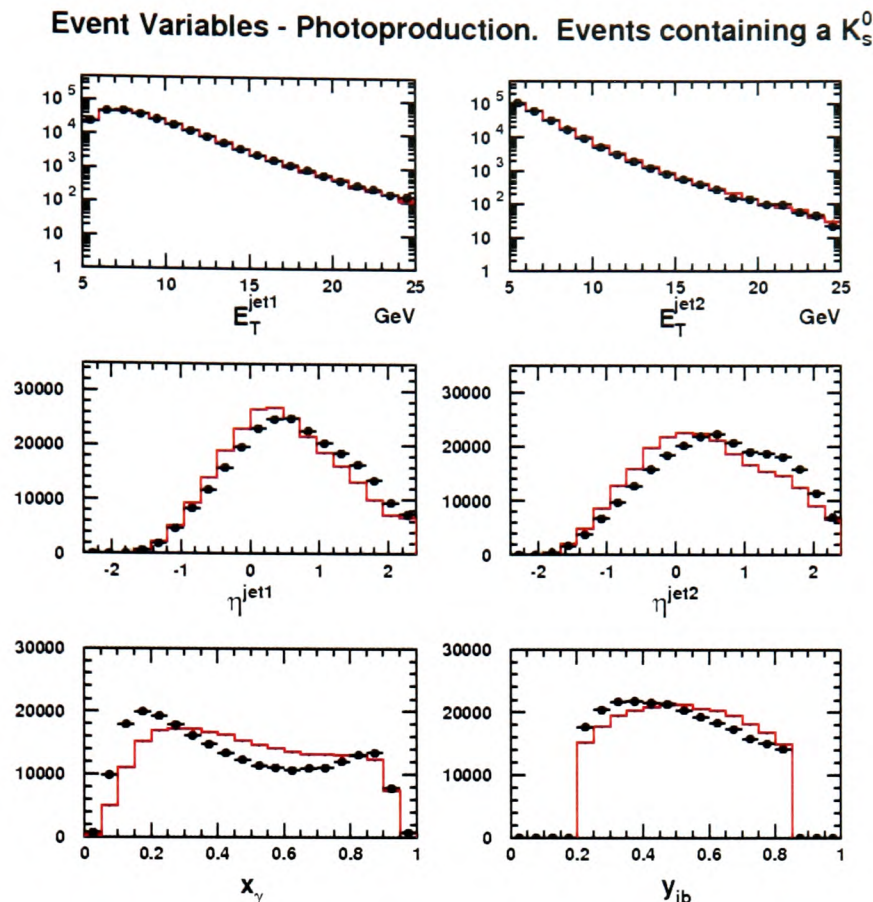


Figure 7.12: Detector level comparison of event variables for events containing a K_s^0 candidate between data (black circles) and PYTHIA (red line) in the photoproduction sample. The MC is normalized to the same number of events as in the data histograms.

7.3 Obtaining the Polarization

The parity violating weak decay of the Λ allows a mixture of S and P waves to be present in the final state - an S wave if the Λ spin is parallel to the decay proton spin, or a P wave if the Λ spin is antiparallel to the decay proton spin. This leads to an asymmetry in the angular distribution of the decay products, as can be seen in, for example, [62]. The proton and antiproton angular distributions for Λ and $\bar{\Lambda}$ decay are of the form:

$$\frac{1}{N} \frac{dN}{d\Omega} = \frac{1}{4\pi} [1 + \alpha P^\Lambda \cos \theta] \quad (7.10)$$

$$\frac{1}{N} \frac{dN}{d\Omega} = \frac{1}{4\pi} [1 - \alpha P^{\bar{\Lambda}} \cos \theta] \quad (7.11)$$

where P^Λ is the polarization, and α is the decay asymmetry parameter, measured to be $\alpha = 0.642 \pm 0.013$ [10]. θ is the angle between the proton direction and the polarization axis. The longitudinal polarization axis is defined as the direction of the momentum of the Λ or $\bar{\Lambda}$. The transverse polarization axis is defined as the vector $\hat{n} = \hat{p}_{beam} \times \hat{p}_\Lambda$, where $\hat{p}_{beam}$ is the direction of the electron beam.

In order to measure the polarization, the angular distribution of the decay proton, corrected for detector acceptance, is plotted, as a function of $\cos \theta$. This is fitted to a straight line of the form

$$\frac{dN}{d\cos\theta} = A + B\cos\theta \quad (7.12)$$

using the default PAW fitting procedure [63]. The gradient then gives the polarization:

$$P^\Lambda = \frac{B}{\alpha A} \quad (7.13)$$

7.4 Correction Procedure

If the MC simulation agrees extremely well with the data in all detector level quantities then the acceptance used in Equation 7.7 can be calculated from the MC as the ratio of the number of reconstructed Λ or K_s^0 divided by the number of generated Λ or K_s^0 for each bin of the differential variable. This will take account of the detection efficiency and any migrations to and from the bin.

7.4.1 Preliminary $P_T - \eta$ Correction

As the MC does not perfectly simulate the data, in order to improve on the above method, a slightly different technique is employed. Whether a produced Λ or K_s^0 is observed or not depends significantly on its position in $P_T - \eta$ space. For each of the three MC event samples (High Q^2 , Low Q^2 and photoproduction) one two-dimensional 6×6 histogram in $P_T - \eta$ is filled containing the generated strange particles (Λ , $\bar{\Lambda}$ and K_s^0 are treated separately, of course) and another is filled containing the $P_T - \eta$ position of the reconstructed candidates. The definition of this $P_T - \eta$ grid may be seen in Table 7.1, with the bins chosen in order to keep the statistics approximately constant for each bin. The correction factors are obtained by taking the ratio of the generated to reconstructed histograms.

Bin boundaries in P_T	0.6	0.8	1.0	1.2	1.4	1.7	2.5
Bin boundaries in η	-1.2	-0.65	-0.2	0.2	0.6	0.9	1.2

Table 7.1: Definition of the $P_T - \eta$ grid.

The correction factors that are obtained from this method are displayed in Fig. 7.13. These correction factors account for both the probability of the strange particle being detected and the probability that the event itself is accepted by the trigger and passes the event selection criteria. The photoproduction correction factors are therefore significantly higher than the respective DIS factors due to the inefficiency in detecting low E_T dijet photoproduction events.

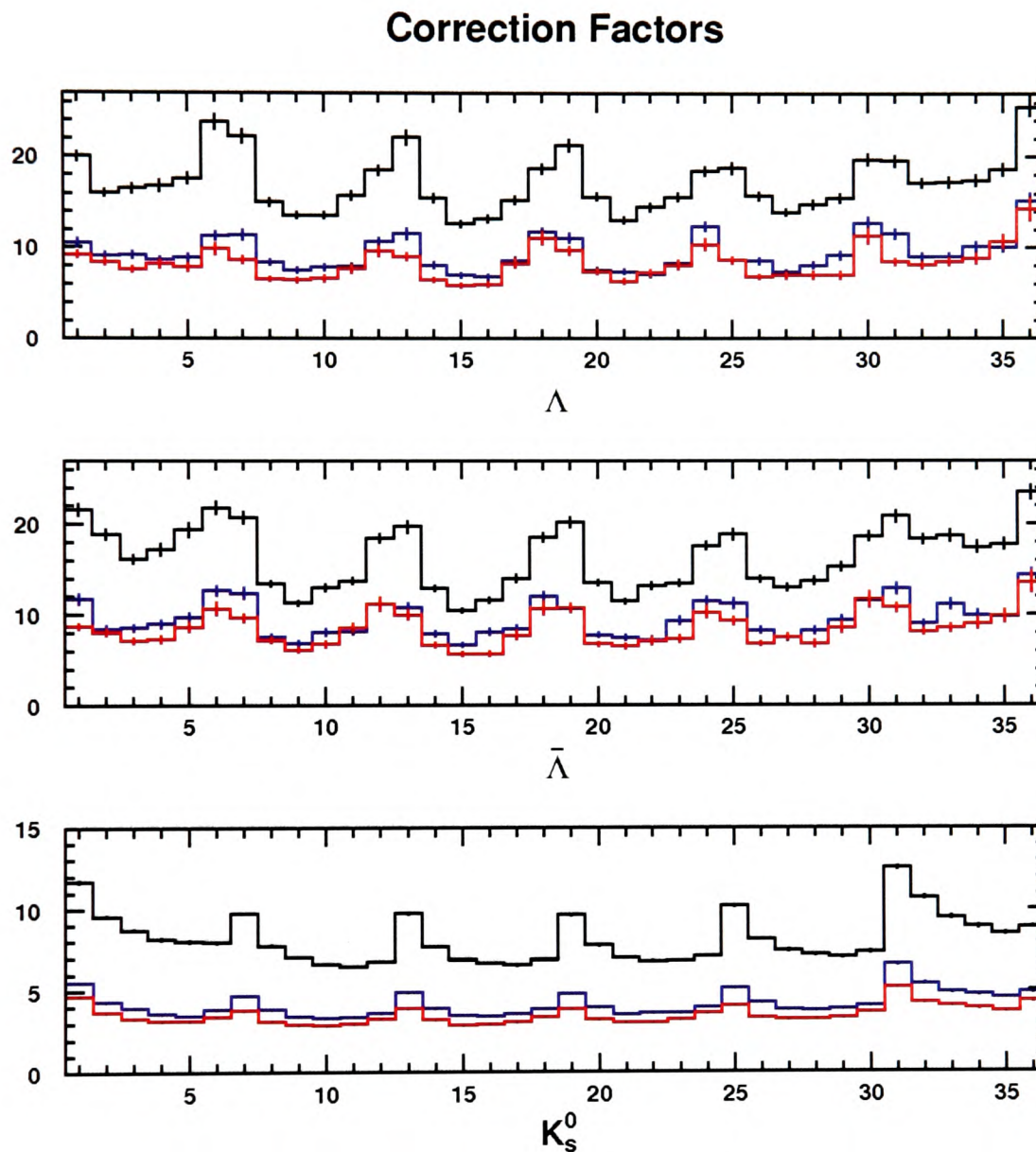


Figure 7.13: The correction factors obtained from MC to be applied to strange particles observed in the data depending on their P_T and η . The bin number here corresponds to $(\text{bin number in } P_T) + (6 \times (\text{bin number in } \eta - 1))$. Black is for photoproduction, blue is for $Q^2 > 25\text{GeV}^2$, red is for $5 < Q^2 < 25\text{GeV}^2$. Errors are statistical only.

Background Subtraction

There is some background in the reconstructed MC sample, due to random combinations of secondary tracks having the correct Λ or K_s^0 mass. The background is accounted for

using a sideband subtraction method, as described below.

For each of the 36 bins of the histogram containing the $P_T - \eta$ of the reconstructed MC strange particle candidates, a separate histogram is filled containing the reconstructed mass of the Λ , $\bar{\Lambda}$ or K_s^0 (all the same selection criteria are applied, except for the mass window selection of Equations 7.5 and 7.6). Each of these mass peaks is fitted to a Gaussian and 1st order polynomial. The polynomial part of the fit is integrated over the signal region (as defined by Equations 7.5 and 7.6) to give the number of background events in each bin. This is subtracted from the number of events in the $P_T - \eta$ histogram. Typical fits for obtaining the background can be seen in Fig. 7.14.

Once the background has been subtracted, the generator level $P_T - \eta$ histograms for Λ , $\bar{\Lambda}$ and K_s^0 are divided by the respective histograms of the reconstructed $P_T - \eta$ values. This gives 36×3 weighting factors to be applied to data Λ , $\bar{\Lambda}$ and K_s^0 candidates, depending on their position in $P_T - \eta$ space.

7.4.2 Further Corrections

To obtain the differential cross-sections in P_T and η no more corrections are necessary. It only remains to subtract the background from the data strange particle signals, which is done with the same sideband subtraction method: For each of the P_T and η bins a mass peak, with each entry weighted by the $P_T - \eta$ weighting factor, is filled and fitted to a Gaussian and 1st order polynomial, from which the background is found and subtracted.

The acceptance correction for Λ and K_s^0 does not however depend solely on the P_T and η of the particle. Therefore, in order to find the differential cross-section in other variables an additional correction must be made. To correct in a variable Y , the ratio is taken between the MC generator level Λ , $\bar{\Lambda}$ or K_s^0 Y histogram and the MC reconstructed Λ , $\bar{\Lambda}$ or K_s^0 Y histogram, after the weighting depending on $P_T - \eta$ position, and after background has been subtracted using the sideband subtraction method. Each bin of the $P_T - \eta$ weighted data Y histogram, after background is subtracted, is multiplied by the relevant ratio of generated to reconstructed MC Y distributions. This additional correction factor will be on average equal to one, averaged over all the Y bins.

The polarization, as discussed in Section 7.3, is obtained from the distribution $\cos \theta$ of

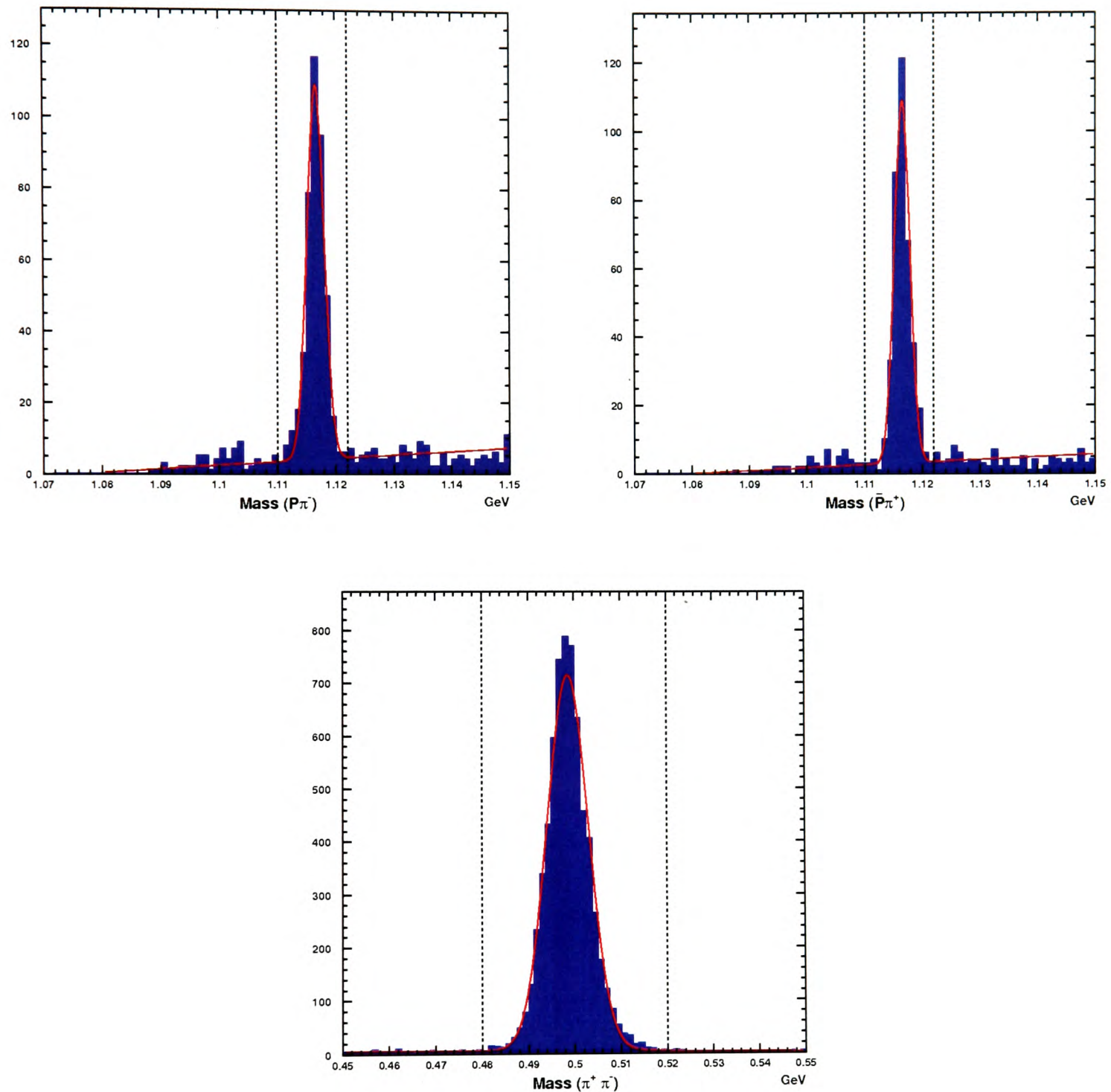


Figure 7.14: Typical mass peaks for Λ , $\bar{\Lambda}$ and K_s^0 for one bin of $P_T - \eta$ ($0.6 < P_T < 0.8 \text{ GeV}; -1.2 < \eta < -0.65$). The histogram is the ARIADNE sample with $Q^2 > 25 \text{ GeV}^2$. The associated fit of a Gaussian + 1st order polynomial is shown as the red line. The signal region is shown by the dotted lines.

the Λ decay proton. Table 7.2 displays the bins used in obtaining the $\cos \theta$ distributions. When obtaining the longitudinal polarization, only the first 6 bins are used, as the kinematics of Λ decay combined with the detector limitation of only well-measuring tracks with $P_T > 0.15\text{GeV}$ mean that if the $\pi^\pm$ is emitted in the opposite hemisphere to the direction of travel of the Λ it is much less likely to be detected.

Bin boundaries in $\cos \theta$	-1.0	-0.8	-0.6	-0.4	-0.2	0.0	0.2	0.4	0.6	0.8	1.0
---------------------------------	------	------	------	------	------	-----	-----	-----	-----	-----	-----

Table 7.2: Definition of the $\cos \theta$ bins used to obtain the polarization.

Differential cross-sections are obtained as a function of P_T and η for all three event samples. For the High Q^2 and Low Q^2 samples the differential cross-sections are also obtained as a function of x and Q^2 , and for the photoproduction sample as a function of x_γ . The bins used to obtain these cross-sections are shown in Tables 7.3, 7.4 and 7.5.

Bin boundaries in x	0.0003	0.0006	0.00085	0.0014	0.0025	0.0045	0.02
Bin boundaries in $Q^2(\text{GeV}^2)$	25.0	45.0	75.0	105.0	145.0	240.0	500.0

Table 7.3: Definition of the x and Q^2 bins for the High Q^2 event sample.

Bin boundaries in x	0.00005	0.000175	0.0003	0.0006	0.00085	0.0014	0.02
Bin boundaries in $Q^2(\text{GeV}^2)$	5.0	6.0	7.5	9.5	12.0	17.0	25.0

Table 7.4: Definition of the x and Q^2 bins for the Low Q^2 event sample.

Bin boundaries in x_γ	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
------------------------------	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----

Table 7.5: Definition of the x_γ bins.

7.4.3 Statistical Errors

The number of events in each bin of an uncorrected histogram is sufficiently high that it is assumed to obey Gaussian statistics. That is, if there are N_i events in bin i , there is a statistical error associated with that number, such that the Standard Deviation of N_i , $\sigma(N_i) = \sqrt{N_i}$.

The correction procedure requires various multiplying and dividing of histograms. In this case the final statistical errors are obtained by propagating the initial errors as follows. Suppose the errors on $(X, Z, \dots)$ are known, then the statistical error on $Y = f(X, Z, \dots)$ is given by:

$$\sigma_Y = \sqrt{\left(\frac{\partial Y}{\partial X}\right)^2 \sigma_X^2 + \left(\frac{\partial Y}{\partial Z}\right)^2 \sigma_Z^2 + \dots + \frac{\partial Y}{\partial X} \frac{\partial Y}{\partial Z} \sigma_{XZ} + \dots} \quad (7.14)$$

The covariance term, σ_{XZ} , is zero for independent variables X and Z .

The error on the background subtraction is not treated statistically. Instead the mass window over which the polynomial describing the background is integrated is varied. This is treated as a systematic error, as discussed later.

7.5 Tracks

As a measure of the amount of strangeness in an event, it is profitable to take a ratio of the number of strange particles to the total number of tracks. This necessitates knowing how many tracks are produced in an event, which may be corrected from what is observed in the detector to the hadron level in a similar way to the strange particle corrections. Tracks are only considered in the same P_T and η region as the strange particles (that is $0.6 < P_T < 2.5\text{GeV}$, $|\eta| < 1.2$) and are not corrected to include tracks beyond this region.

The description of the data track quantities by the MC at the detector level can be seen in Fig 7.15 for the High Q^2 sample, in Fig. 7.16 for the Low Q^2 sample and in Fig. 7.17 for the photoproduction sample. Note that not all the MC samples quoted in Tables 6.2 and 6.5 are appropriate to be used to correct tracks; some samples have a strange particle filter applied at the generator level and so are not used. Solely inclusive MC samples are used to correct tracks for detector effects, such that the ratio of events with $E_P = 820\text{GeV}$ to events with $E_P = 920\text{GeV}$ is the same as in the data. The optimal combination of direct to resolved events, obtained by fitting to the data x_γ distribution is also retained when correcting tracks in the photoproduction sample.

Although the MC is in good agreement with the data when describing the track variables of the High Q^2 and Low Q^2 event samples, for the photoproduction sample

the agreement is less good. Therefore, a simple one-dimensional correction may have a large model dependence. Thus, and also to be consistent with the method for correcting strange particles, a two dimensional correction is used.

As with the strange particles, two histograms of $P_T - \eta$ are filled (using the same grid as for the strange particle corrections). The first contains the $P_T - \eta$ position of all detector level tracks that are fitted to either a primary or a secondary vertex. The second contains the $P_T - \eta$ position of all generator level tracks that originate from the eP collision (as opposed to interactions with the material in the detector or beam pipe). The ratio of these histograms is taken to get a multiplicative factor depending on the position in $P_T - \eta$ to be applied to detector level tracks in the data.

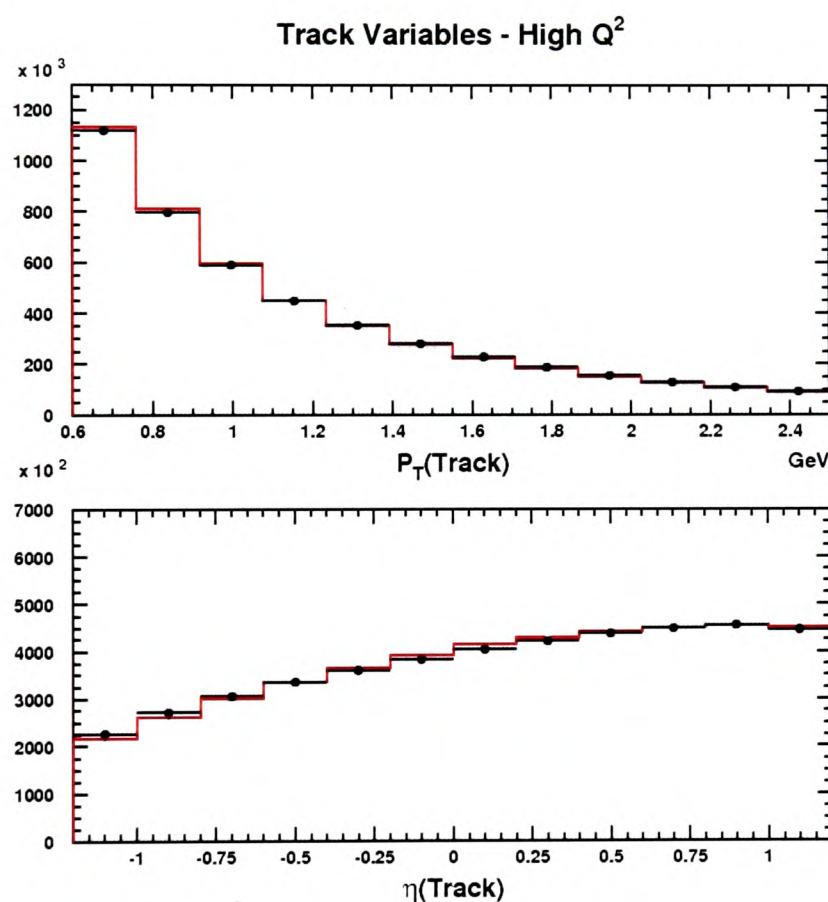


Figure 7.15: Detector level comparison of track variables for High Q^2 events, between data (black circles) and ARIADNE (red line). The MC is normalized to the same number of events as in the data histograms.

The correction factors as a function of P_T and η that are applied to reconstructed tracks are displayed in Fig. 7.18. The correction factors are significantly smaller than those required to correct strange particles. There is some dependence on the type of event in the correction factor, as observed by the difference in shape of the correction factor distributions as a function of P_T and η (cf. the correction factors for Λ , $\bar{\Lambda}$ and K_s^0 in Fig. 7.13, where the correction factor distributions have very similar shapes).

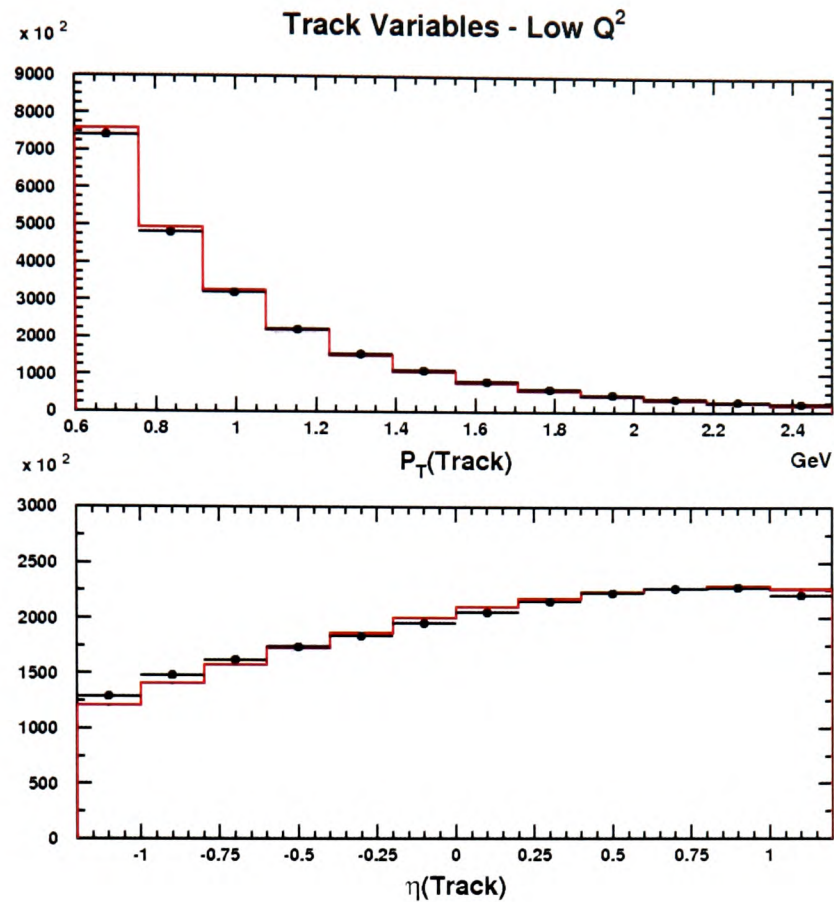


Figure 7.16: Detector level comparison of track variables for Low Q^2 events, between data (black circles) and ARIADNE (red line). The MC is normalized to the same number of events as in the data histograms.

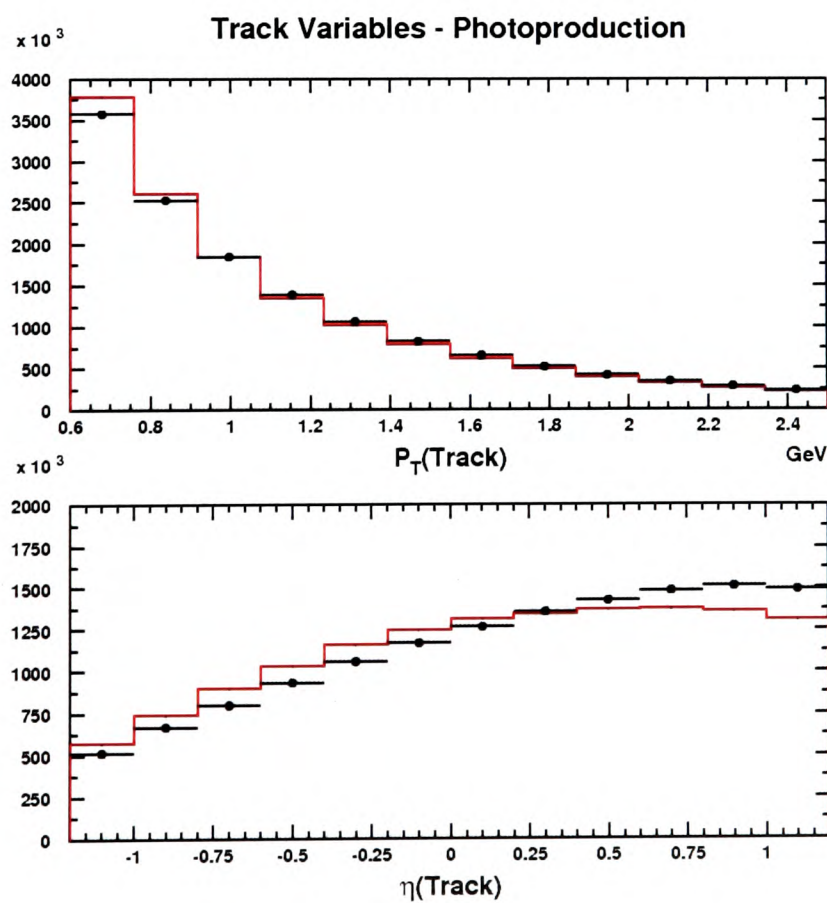


Figure 7.17: Detector level comparison of track variables for photoproduction events, between data (black circles) and PYTHIA (red line). The MC is normalized to the same number of events as in the data histograms.

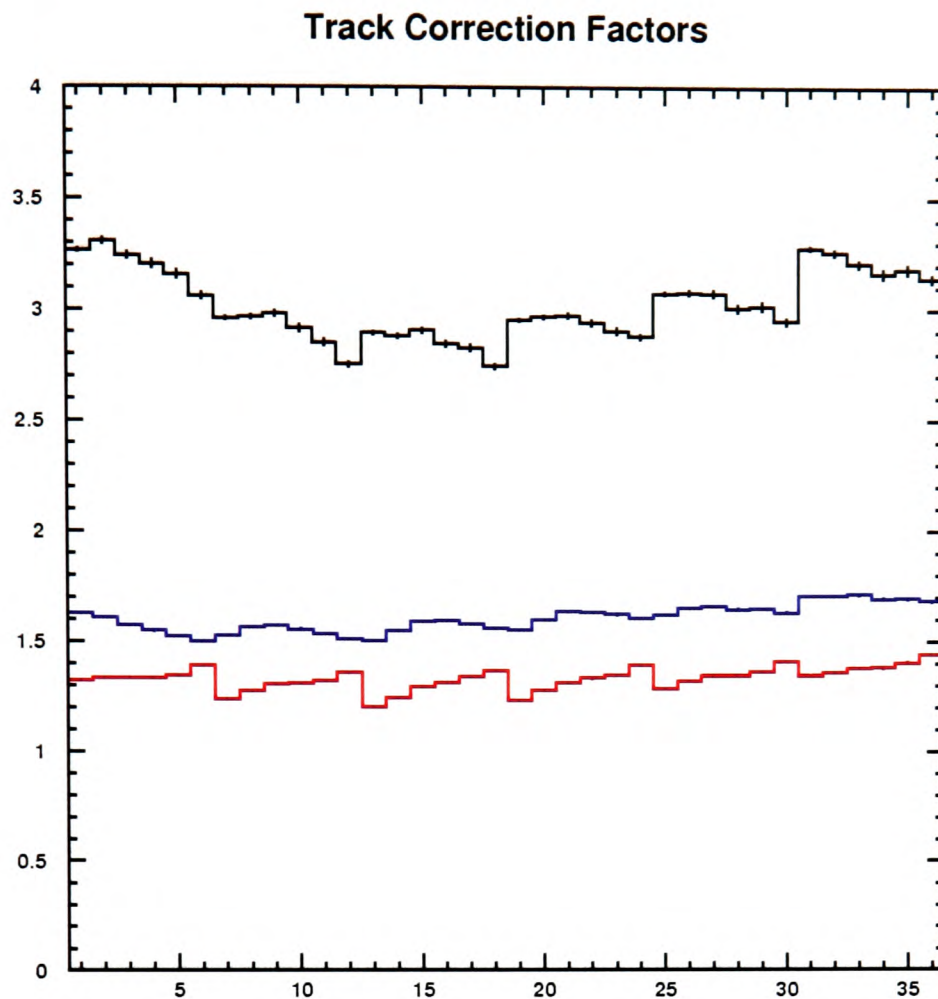


Figure 7.18: The correction factors obtained from MC to be applied to tracks observed in the data depending on their P_T and η . The bin number here corresponds to (bin number in P_T) + (6 $\times$ (bin number in η - 1)). Black is for photoproduction, blue is for $Q^2 > 25\text{GeV}^2$, red is for $5 < Q^2 < 25\text{GeV}^2$. Errors are statistical only.

This is thought to be due to a multiplicity bias introduced at the event selection level, particularly by the jet requirement of photoproduction events.

7.6 Further Variables

It can be advantageous to further split the phase space into regions where the physics processes producing strange particles may be different. Two such separations are investigated.

7.6.1 Fraction of E_T in highest E_T jet

The fireball region in photoproduction events was discussed in Section 2.2. Particularly distinctive about these events are the large number of low energy jets. This suggests an interesting way to split the phase space is by observing the fraction of the total

hadronic E_T in the highest energy jet. This fraction will be high (up to ~ 0.5) for ordinary photoproduction dijet events but low for fireball-like events. The distribution of the total E_T ² compared with the E_T of the highest E_T jet is shown in Fig. 7.19. Although this separation is originally designed for photoproduction events, it involves

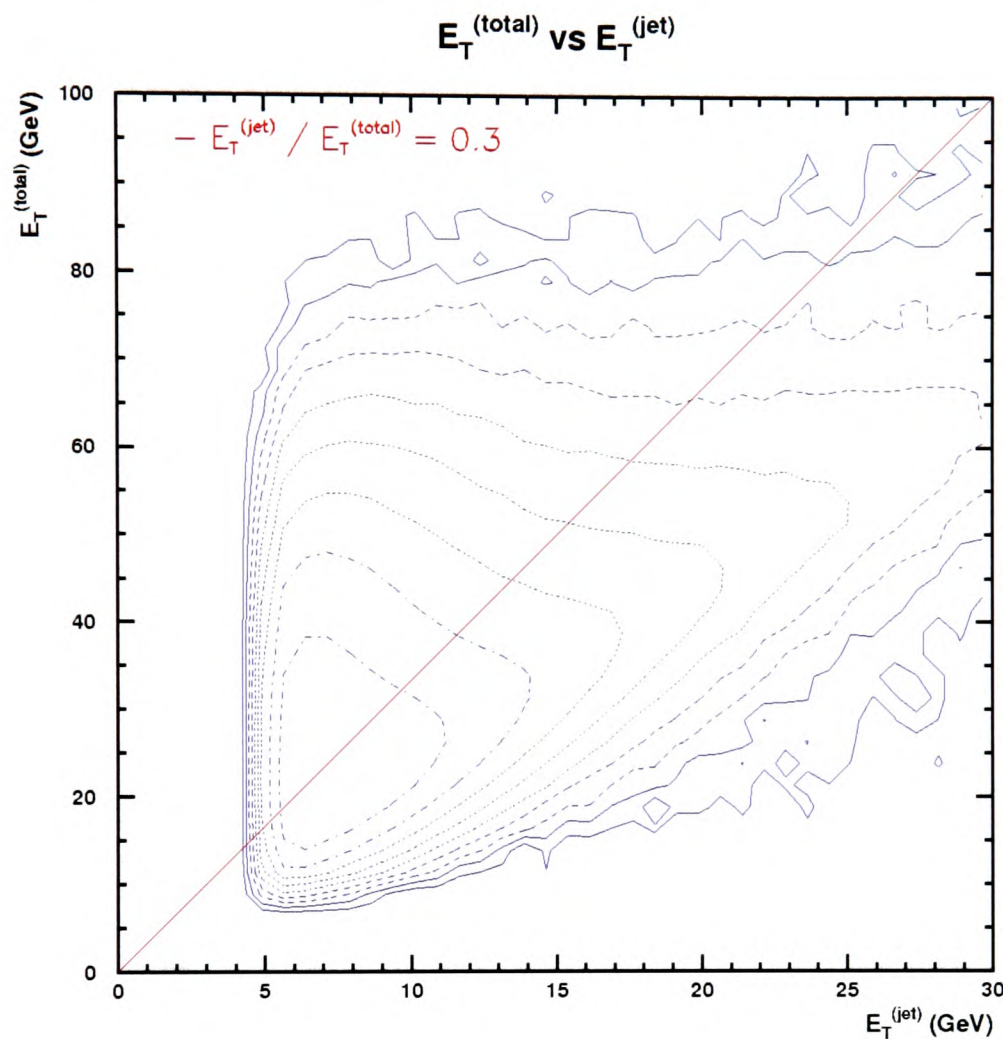


Figure 7.19: The distribution of the total E_T compared to the E_T of the highest E_T jet for photoproduction events. The red line shows where the separation is made into High $E_T^{(jet)} / E_T^{(total)}$ and Low $E_T^{(jet)} / E_T^{(total)}$.

simple enough quantities for it to be applied across the whole phase space, so it is also applied to DIS events. In the DIS samples the scattered electron is subtracted from the total E_T , to leave the hadronic E_T , as in photoproduction. The jet reconstruction in DIS is slightly different to photoproduction: The same jet algorithm is used in the DIS samples as in photoproduction (KTCLUS), but with a minimum jet E_T of 2GeV (cf. photoproduction events which all contain at least two jets with $E_T > 5\text{GeV}$, due to the event selection). Events are split into those events with $E_T^{jet} / E_T^{total} > 0.3$ and those events with $E_T^{jet} / E_T^{total} < 0.3$.

²The uncorrected scalar sum of the total E_T in the calorimeter is used.

7.6.2 $E_T - P_T$

A similar, even simpler, separation is designed for the High Q^2 DIS sample, without the need to reconstruct jets. E_T is the scalar sum of the hadronic E_T deposited in the calorimeter, whereas P_T is the vector sum³. Events where the transferred photon interacts with a quark generally give single-jet events which have a relatively low value of E_T/P_T . Events where the photon interacts with a gluon typically give more than one jet, and hence a larger value of E_T/P_T . The distribution of the hadronic E_T versus P_T can be seen in Fig. 7.20. The sample is split into those events with $E_T/P_T > 1.7$ (multi-jet enriched) and those events with $E_T/P_T < 1.7$ (single-jet enriched). This separation is only used for High Q^2 DIS events.

³The hadronic E_T and P_T are calculated using the CorAndCut routine, which corrects for back-splash and energy loss.

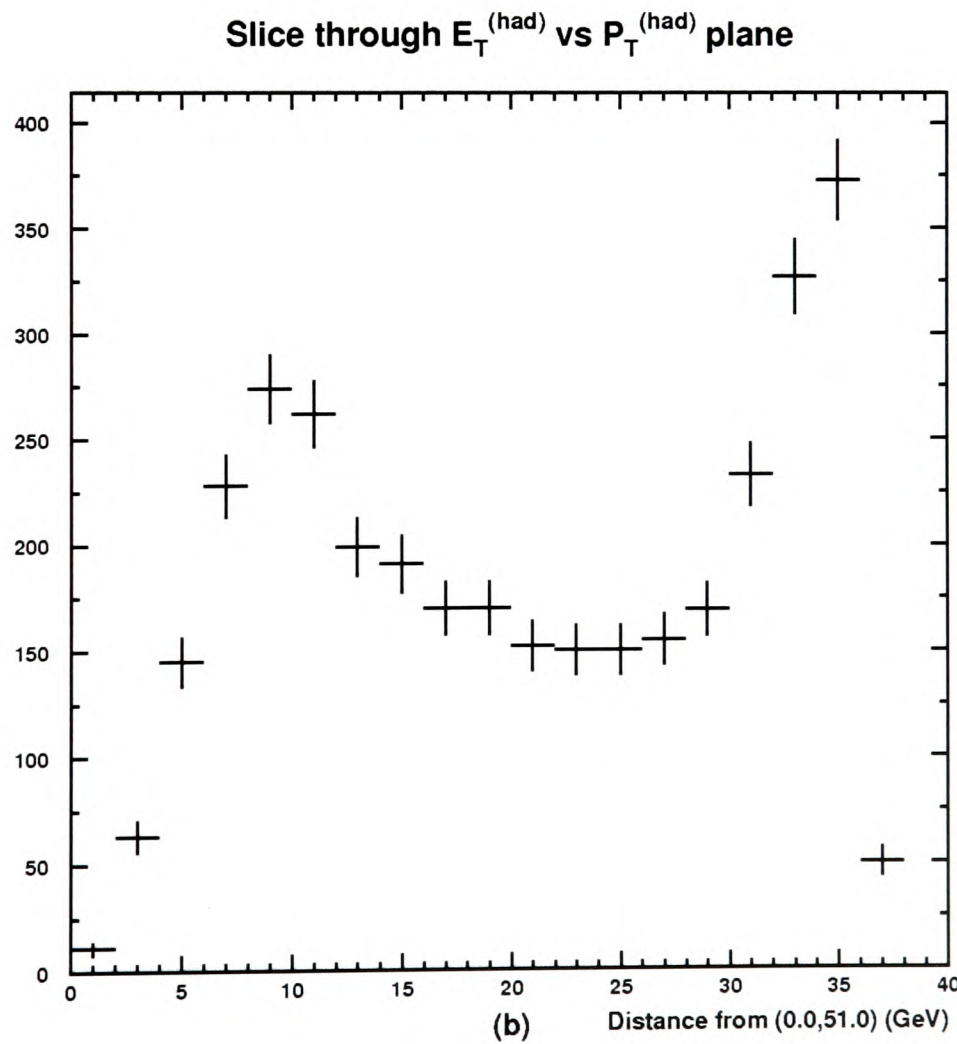
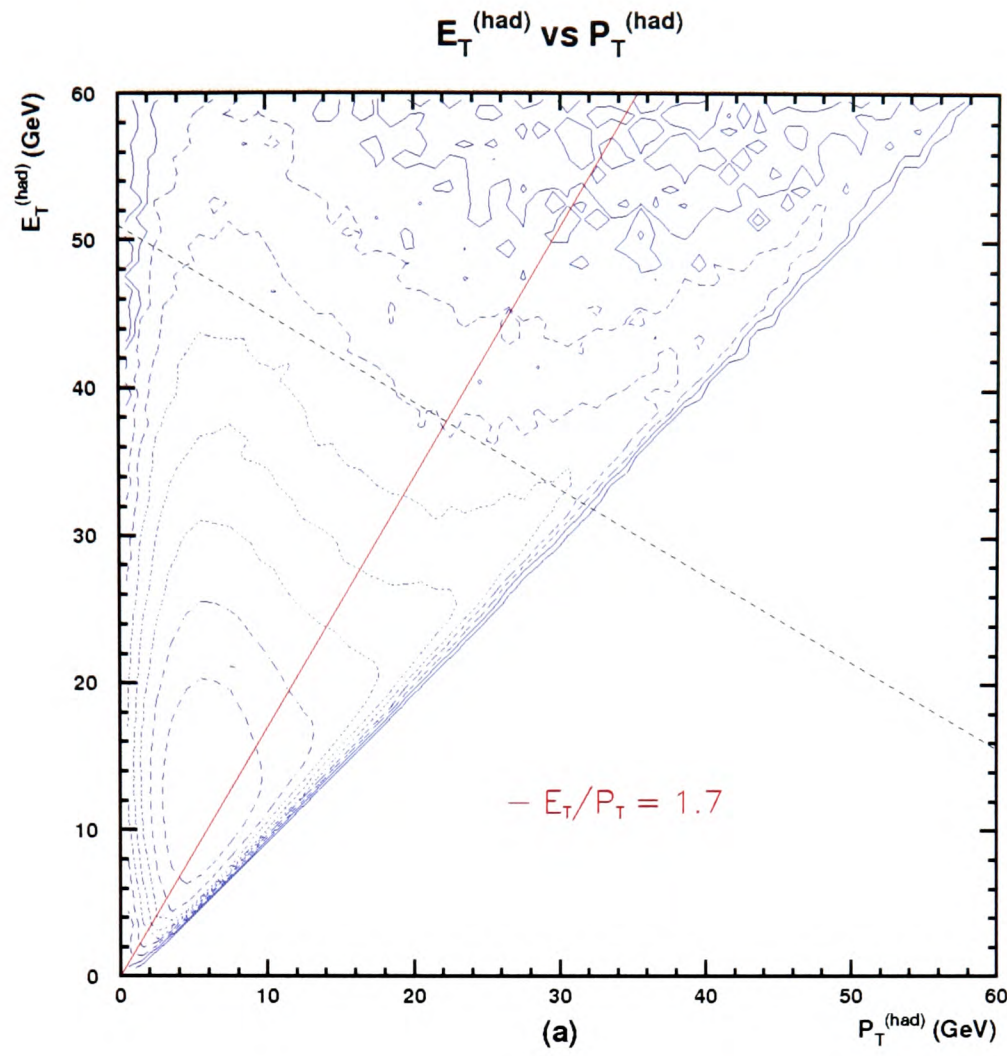


Figure 7.20: (a) The $E_T - P_T$ distribution for DIS events with $Q^2 \geq 25\text{GeV}^2$. The red line shows where the separation is made into High E_T/P_T and Low E_T/P_T . (b) A slice through (a) at the position indicated by the dotted black line showing the two distinct regions of the phase space.

Chapter 8

Results

8.1 Differential Cross-Sections

8.1.1 $5 \leq Q^2 \leq 25\text{GeV}^2$

The differential production cross-sections of Λ , $\bar{\Lambda}$ and K_s^0 with $0.6 < P_T < 2.5\text{GeV}$ and $|\eta| < 1.2$ have been measured for events within the kinematic range $5 \leq Q^2 \leq 25\text{GeV}^2$, $0.02 \leq y \leq 0.95$ as a function of Q^2 and x of the event and P_T and η of the particle concerned.

The production cross-sections for $(\Lambda + \bar{\Lambda})$, Λ , $\bar{\Lambda}$ and K_s^0 are shown in Figs. 8.1, 8.2, 8.3 and 8.4, together with the prediction from ARIADNE. An estimate of the systematic error on the data $(\Lambda + \bar{\Lambda})$ and K_s^0 cross-sections is included, added in quadrature to the statistical error. Systematic errors generally arise when the MC simulation is inadequately describing the detector response. This estimate of the systematic error is obtained by varying the DIS event selection criteria, and the cuts to select strange particles, by approximately the same order of magnitude as the MC is expected to disagree with the data. The differences between the cross-sections obtained with the original selection criteria and those obtained with the alternative selection criteria give the estimate of the systematic error. The particular variations are described in Table 8.1. More details of the effects of the individual variables on the total systematic error are shown in Appendix A.

For both Λ and K_s^0 the MC broadly describes the shape of the data differential cross-sections. However, the MC does somewhat overestimate the K_s^0 production.

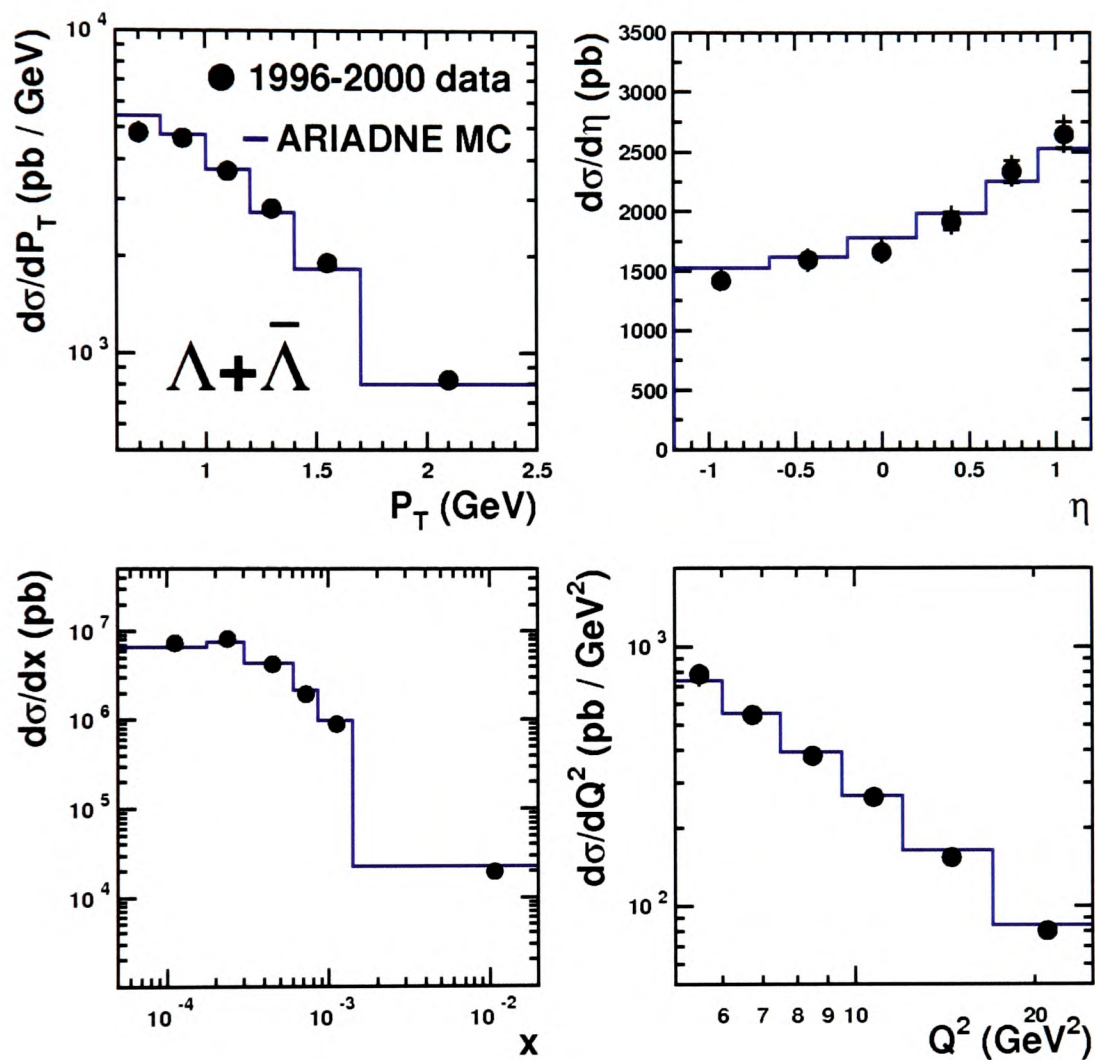


Figure 8.1: Differential cross-sections for $\Lambda + \bar{\Lambda}$ production in DIS events with $5 \leq Q^2 \leq 25 \text{ GeV}^2$. 1996-2000 data and ARIADNE MC are shown. The MC contains samples with $E_P = 820 \text{ GeV}$ and $E_P = 920 \text{ GeV}$ in the same proportion as the data. Statistical (inner error bars) and systematic and statistical errors added in quadrature are shown, unless smaller than the point size.

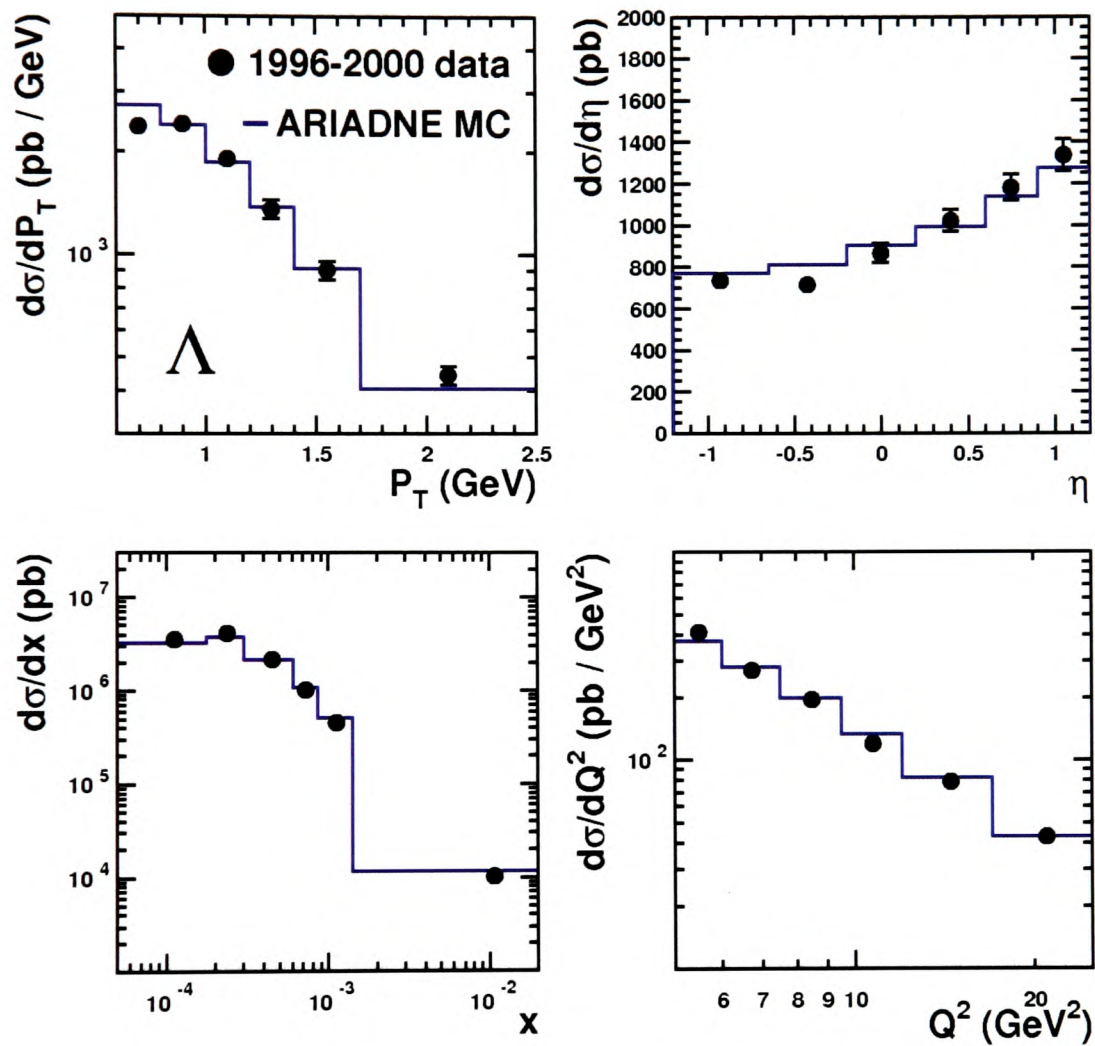


Figure 8.2: Differential cross-sections for Λ production in DIS events with $5 \leq Q^2 \leq 25 \text{ GeV}^2$. 1996-2000 data and ARIADNE MC are shown. The MC contains samples with $E_P = 820 \text{ GeV}$ and $E_P = 920 \text{ GeV}$ in the same proportion as the data. Statistical errors only are shown, unless smaller than the point size.

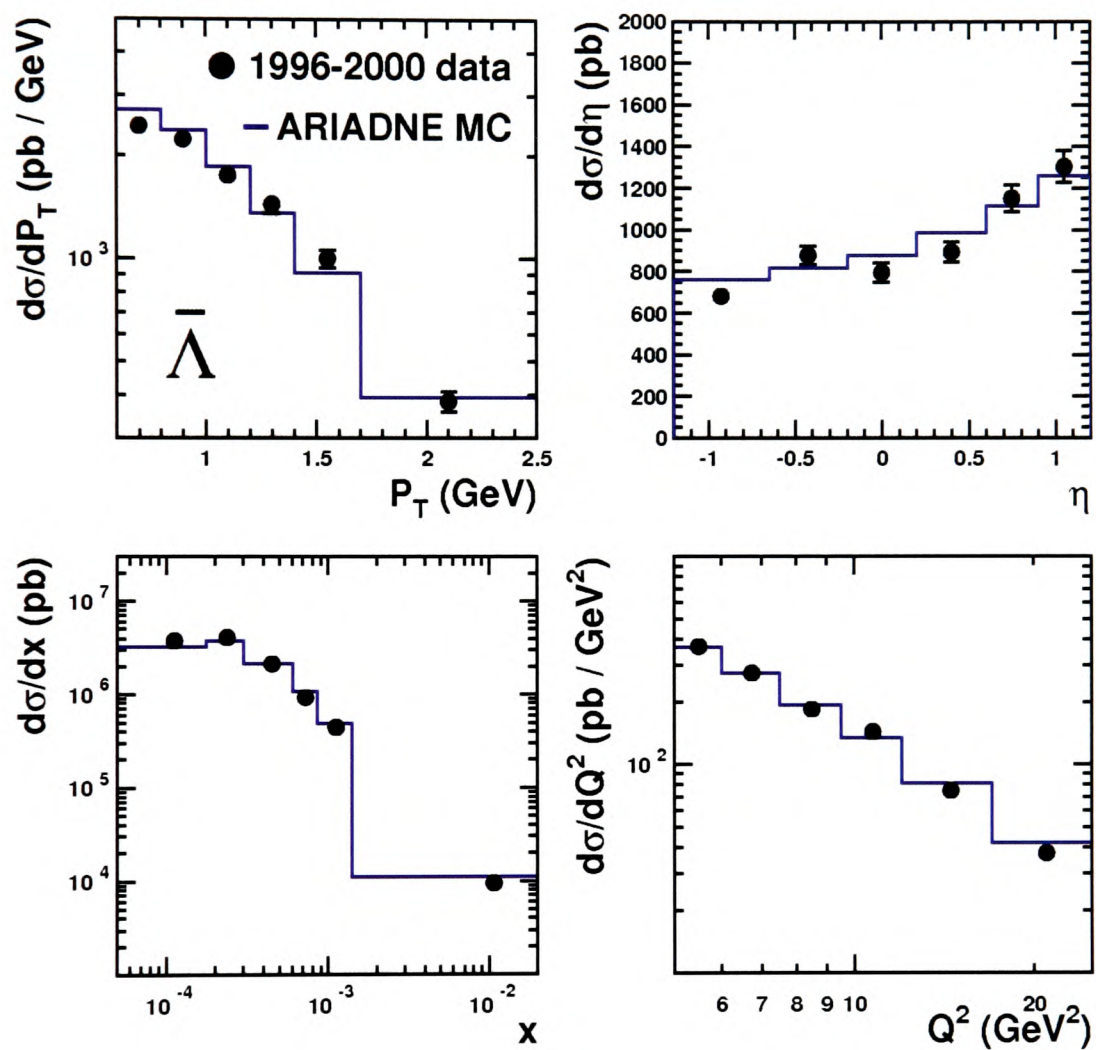


Figure 8.3: Differential cross-sections for $\bar{\Lambda}$ production in DIS events with $5 \leq Q^2 \leq 25 \text{ GeV}^2$. 1996-2000 data and ARIADNE MC are shown. The MC contains samples with $E_P = 820 \text{ GeV}$ and $E_P = 920 \text{ GeV}$ in the same proportion as the data. Statistical errors only are shown, unless smaller than the point size.

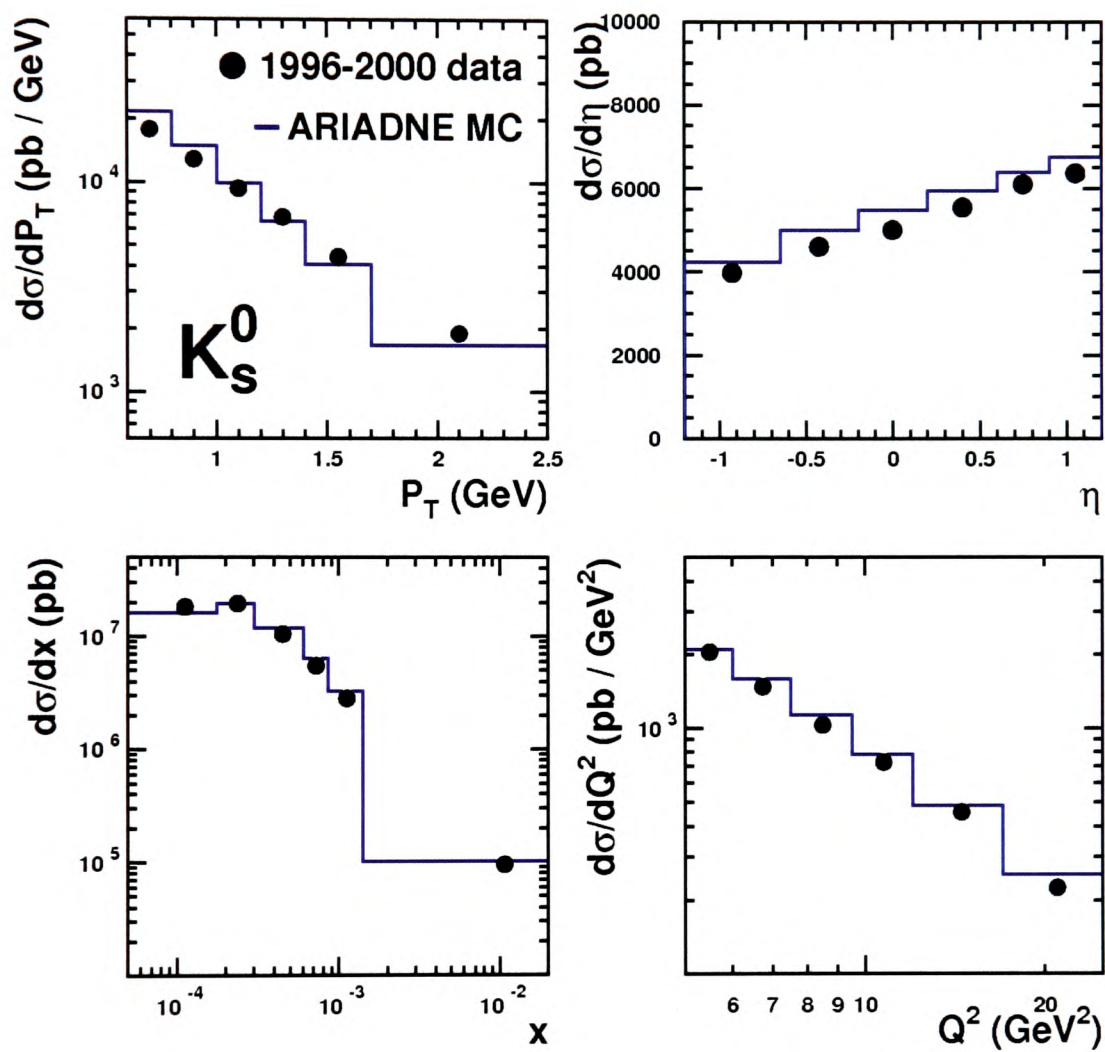


Figure 8.4: Differential cross-sections for K_s^0 production in DIS events with $5 \leq Q^2 \leq 25 \text{ GeV}^2$. 1996-2000 data and ARIADNE MC are shown. The MC contains samples with $E_P = 820 \text{ GeV}$ and $E_P = 920 \text{ GeV}$ in the same proportion as the data. Statistical (inner error bars) and systematic and statistical errors added in quadrature are shown, unless smaller than the point size.

Systematic ID	Default	Variation
Event Selection		
1	$y_{JB} \geq 0.02$	$y_{JB} \geq 0.03$
2	$y_{JB} \geq 0.02$	$y_{JB} \geq 0.01$
3	Q_{da}^2	Q_{el}^2
4	$ z_{vtx} \leq 50.0\text{cm}$	$ z_{vtx} \leq 55.0\text{cm}$
5	$ z_{vtx} \leq 50.0\text{cm}$	$ z_{vtx} \leq 45.0\text{cm}$
6	$E_e^{corr} \geq 10\text{GeV}$	$E_e^{corr} \geq 11\text{GeV}$
7	$E_e^{corr} \geq 10\text{GeV}$	$E_e^{corr} \geq 9\text{GeV}$
8	Various $E - P_z$ cuts	All $E - P_z$ cuts +2GeV
9	Various $E - P_z$ cuts	All $E - P_z$ cuts -2GeV
10	Box cut $26 \times 14\text{cm}$ (Low Q^2) $r_{el} \leq 36\text{cm}$ (High Q^2)	Box cut $27 \times 15\text{cm}$ $r_{el} \leq 37\text{cm}$
11	Box cut $26 \times 14\text{cm}$ (Low Q^2) $r_{el} \leq 36\text{cm}$ (High Q^2)	Box cut $25 \times 13\text{cm}$ $r_{el} \leq 35\text{cm}$
Strange Particle Selection		
12	$P_T^{track} \geq 0.15\text{GeV}$	$P_T^{track} \geq 0.12\text{GeV}$
13	$P_T^{track} \geq 0.15\text{GeV}$	$P_T^{track} \geq 0.18\text{GeV}$
14	$ \eta^{track} \leq 1.5$	$ \eta^{track} \leq 1.4$
15	$ \eta^{track} \leq 1.5$	$ \eta^{track} \leq 1.6$
16	$\theta^{coll} < 0.2$	$\theta^{coll} < 0.25$
17	$\theta^{coll} < 0.2$	$\theta^{coll} < 0.15$
18	$1.11 < M(\Lambda) < 1.122\text{GeV}$ $0.48 < M(K_s^0) < 0.52\text{GeV}$	$1.106 < M(\Lambda) < 1.126\text{GeV}$ $0.47 < M(K_s^0) < 0.53\text{GeV}$
19	$M(K_s^0) \geq 0.475\text{GeV}$ (Λ sample) $M(\Lambda) \geq 1.125\text{GeV}$ (K_s^0 sample)	$M(K_s^0) \leq 0.478\text{GeV}$ $M(\Lambda) \geq 1.130\text{GeV}$
20	$M(K_s^0) \geq 0.475\text{GeV}$ (Λ sample) $M(\Lambda) \geq 1.125\text{GeV}$ (K_s^0 sample)	$M(K_s^0) \leq 0.472\text{GeV}$ $M(\Lambda) \geq 1.120\text{GeV}$

Table 8.1: Variations in the selection criteria in order to estimate the systematic error of Λ and K_s^0 production in the High Q^2 and Low Q^2 samples.

8.1.2 $Q^2 \geq 25\text{GeV}^2$

The differential production cross-sections of Λ , $\bar{\Lambda}$ and K_s^0 with $0.6 < P_T < 2.5\text{GeV}$ and $|\eta| < 1.2$ have been measured for events within the kinematic range $Q^2 \geq 25\text{GeV}^2$, $0.02 \leq y \leq 0.95$ as a function of Q^2 and x of the event and P_T and η of the particle concerned.

The production cross-sections for $(\Lambda + \bar{\Lambda})$, Λ , $\bar{\Lambda}$ and K_s^0 are shown in Figs. 8.5, 8.6, 8.7 and 8.8, together with the prediction from ARIADNE.

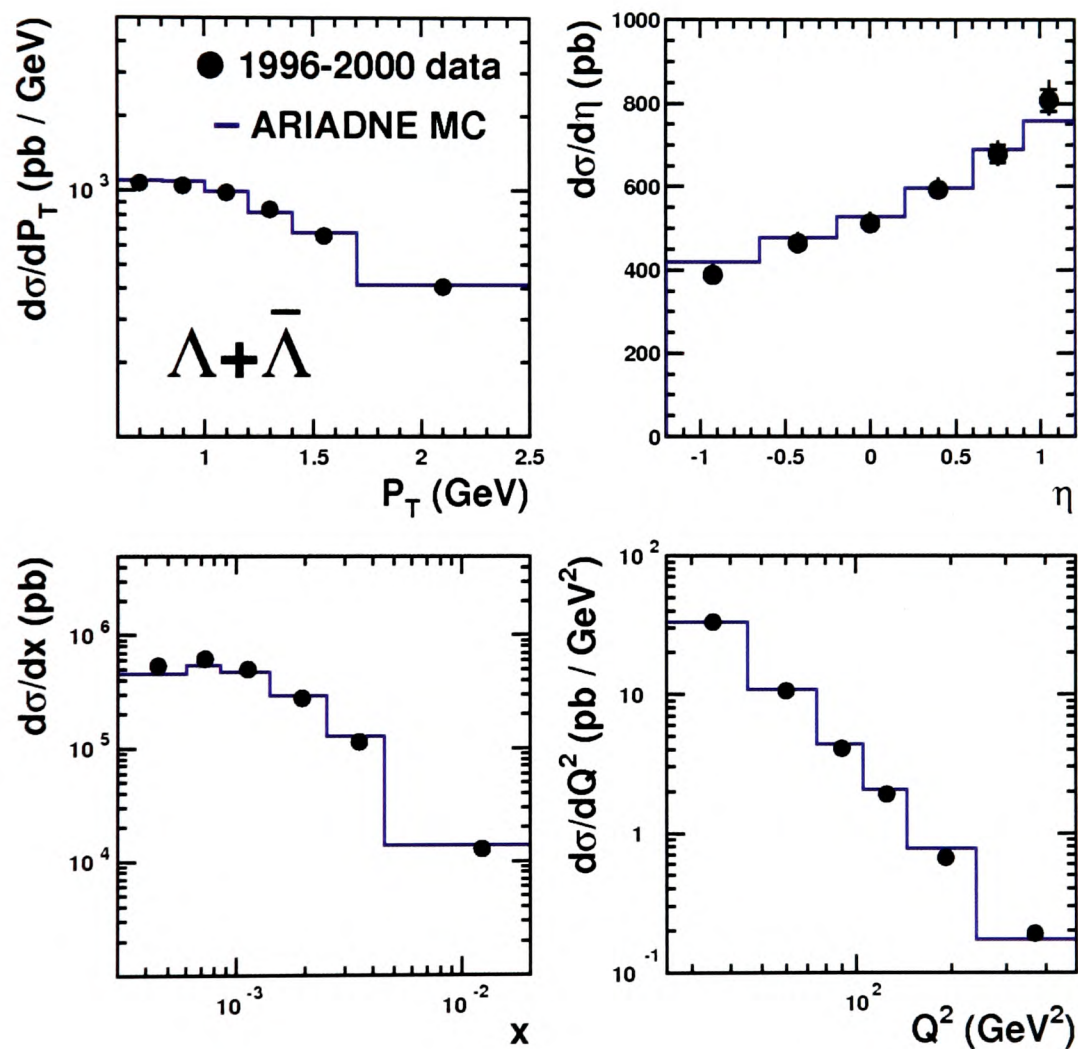


Figure 8.5: Differential cross-sections for $\Lambda + \bar{\Lambda}$ production in DIS events with $Q^2 \geq 25\text{GeV}^2$. 1996-2000 data and ARIADNE MC are shown. The MC contains samples with $E_P = 820\text{GeV}$ and $E_P = 920\text{GeV}$ in the same proportion as the data. Statistical (inner error bars) and systematic and statistical errors added in quadrature are shown, unless smaller than the point size.

The systematic errors are estimated in the same way as for the Low Q^2 sample, according to the variations in the event and particle selections displayed in Table 8.1. Further details are shown in Appendix A.

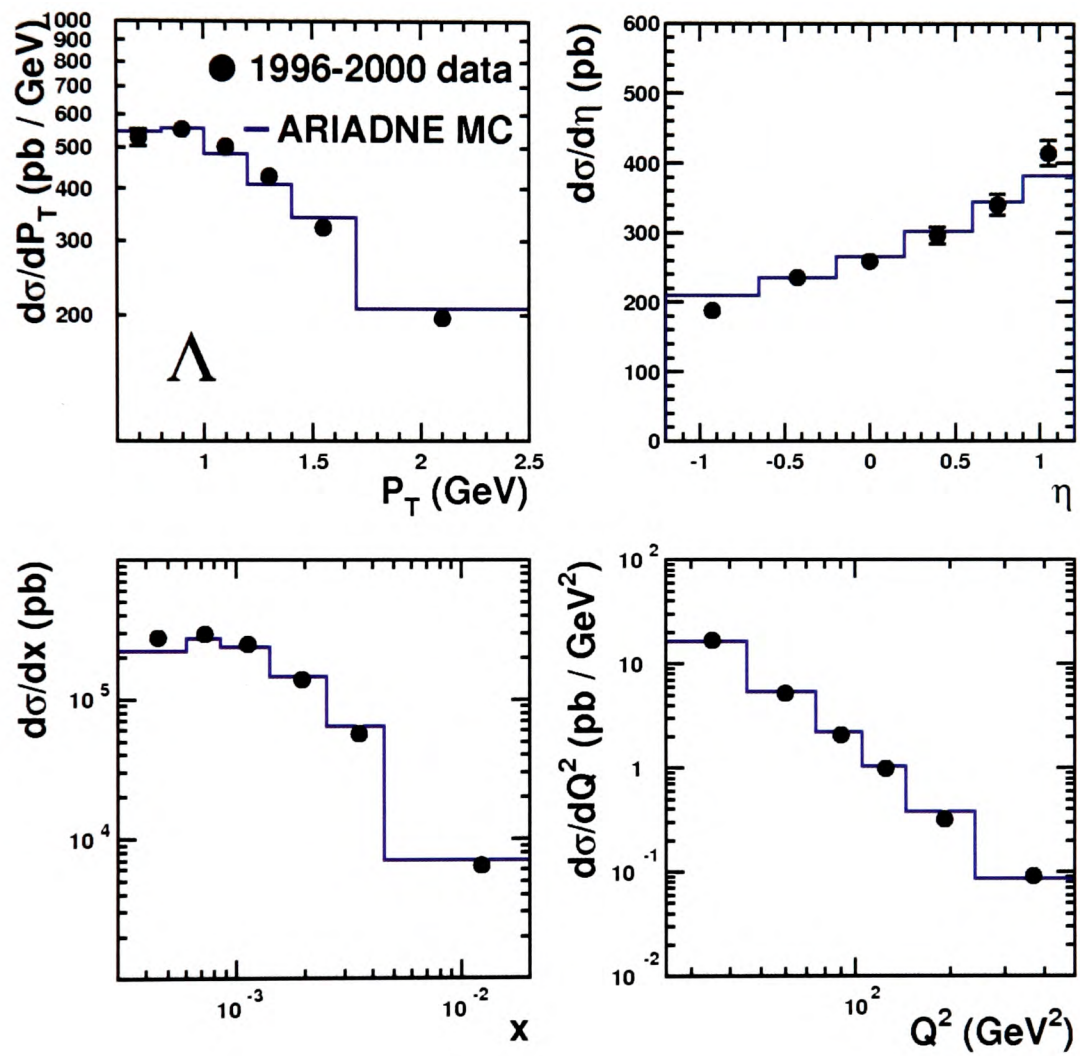


Figure 8.6: Differential cross-sections for Λ production in DIS events with $Q^2 \geq 25 \text{ GeV}^2$. 1996-2000 data and ARIADNE MC are shown. The MC contains samples with $E_P = 820 \text{ GeV}$ and $E_P = 920 \text{ GeV}$ in the same proportion as the data. Statistical errors only are shown, unless smaller than the point size.

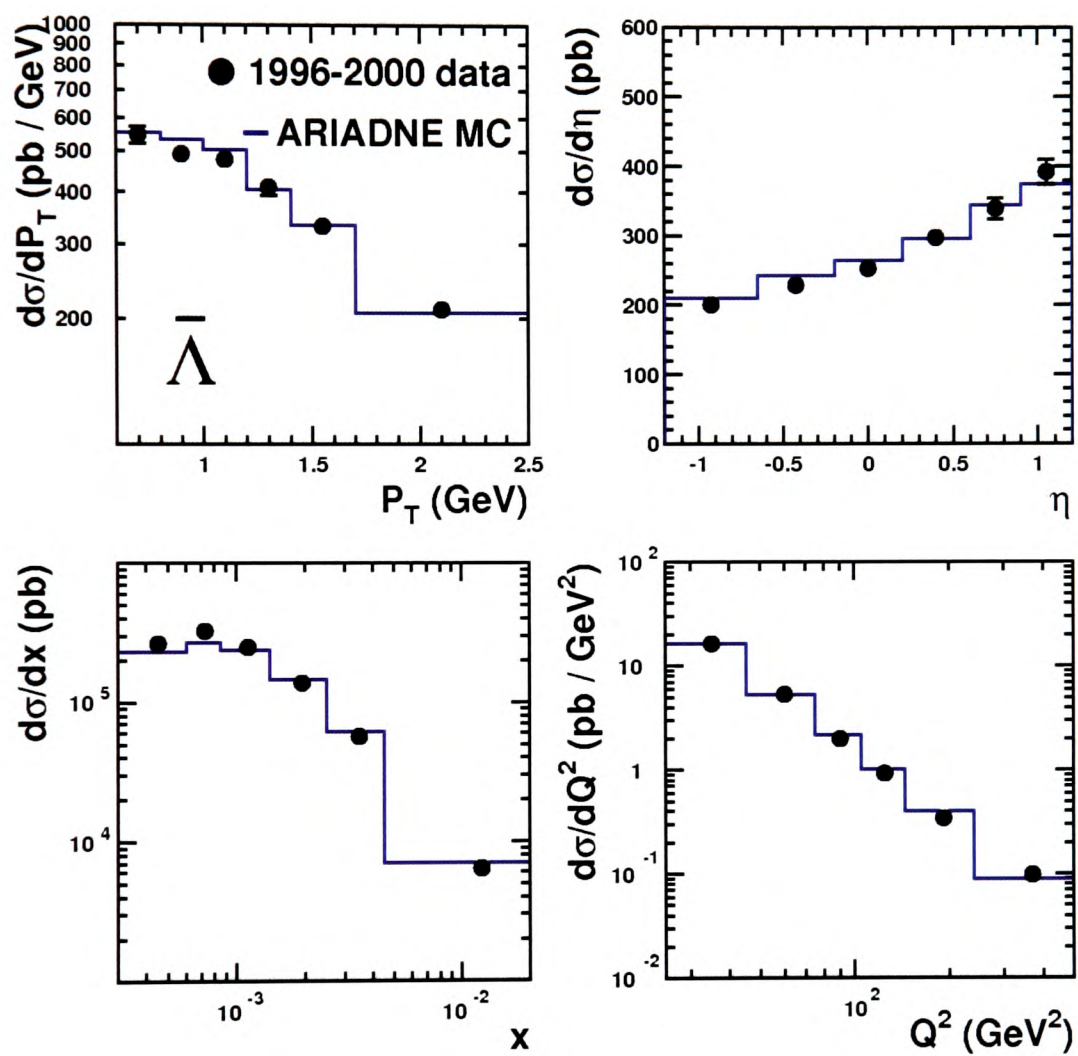


Figure 8.7: Differential cross-sections for $\bar{\Lambda}$ production in DIS events with $Q^2 \geq 25 \text{ GeV}^2$. 1996-2000 data and ARIADNE MC are shown. The MC contains samples with $E_P = 820 \text{ GeV}$ and $E_P = 920 \text{ GeV}$ in the same proportion as the data. Statistical errors only are shown, unless smaller than the point size.

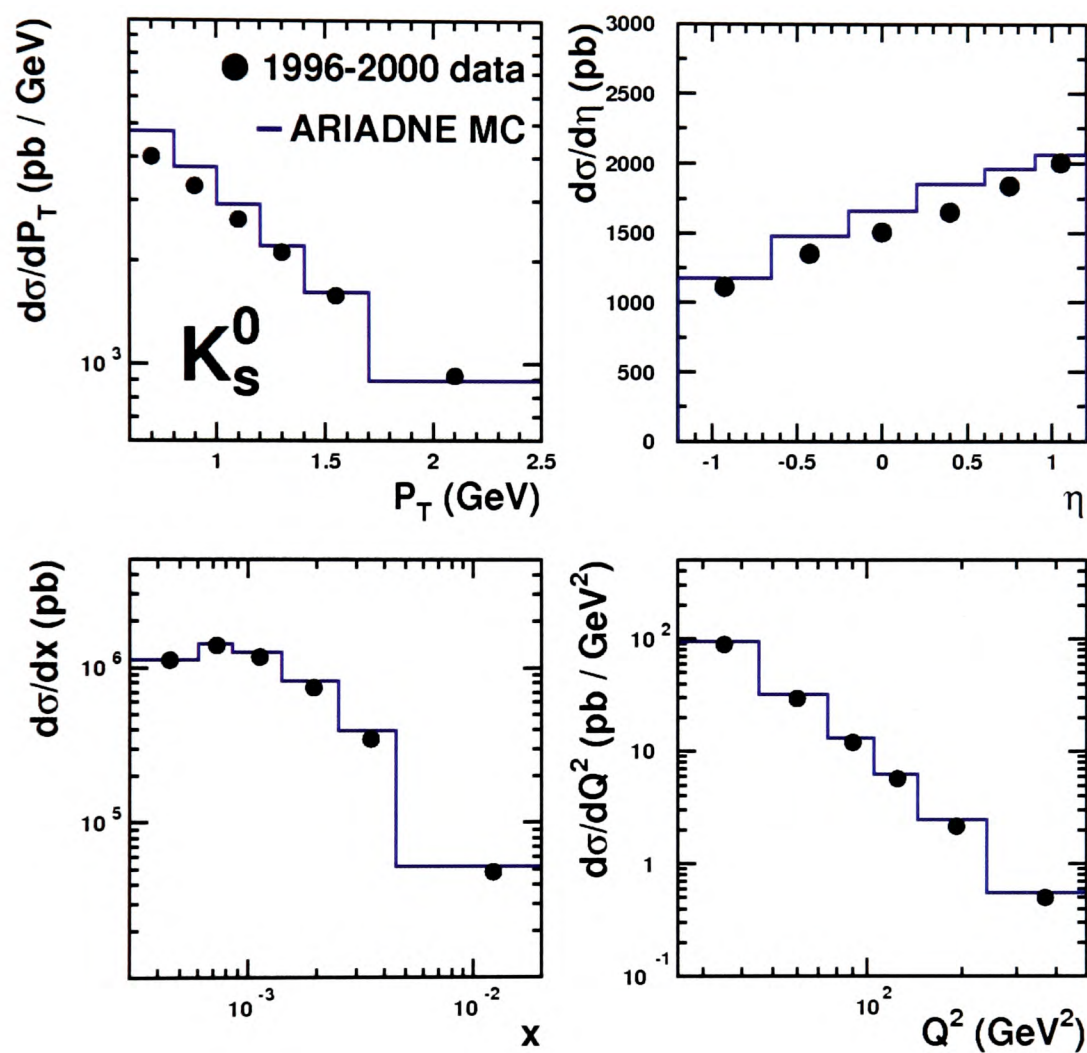


Figure 8.8: Differential cross-sections for K_s^0 production in DIS events with $Q^2 \geq 25 \text{ GeV}^2$. 1996-2000 data and ARIADNE MC are shown. The MC contains samples with $E_P = 820 \text{ GeV}$ and $E_P = 920 \text{ GeV}$ in the same proportion as the data. Statistical (inner error bars) and systematic and statistical errors added in quadrature are shown, unless smaller than the point size.

ARIADNE generally describes the shape of the differential cross-section distributions in the data, although as in the Low Q^2 sample, it overestimates the K_s^0 production cross-section.

8.1.3 Photoproduction

The differential production cross-sections of Λ , $\bar{\Lambda}$ and K_s^0 with $0.6 < P_T < 2.5\text{GeV}$ and $|\eta| < 1.2$ have been measured for events which have at least two jets both satisfying:

$$E_T^{jet1,2} > 5\text{GeV} \quad (8.1)$$

$$|\eta|^{jet1,2} < 2.4 \quad (8.2)$$

The cross-sections are measured as a function of x_γ^{obs} of the event and P_T and η of the particle concerned.

The production cross-sections for $(\Lambda + \bar{\Lambda})$, Λ , $\bar{\Lambda}$ and K_s^0 are shown in Figs. 8.9, 8.10, 8.11 and 8.12. The cross-sections predicted by PYTHIA are also shown, for comparison, normalized such that the total production cross-section for Λ , $\bar{\Lambda}$ and K_s^0 is the same as the data. To achieve this normalization, the Λ and $\bar{\Lambda}$ MC cross-sections are scaled by a factor 1.5 and the K_s^0 MC cross-sections by a factor 1.1.

The MC generally describes the shape of the cross-section distributions as a function of P_T and η , although it does not account sufficiently for the increasing strange particle production with increasing η . The shape of the cross-section as a function of x_γ is not well described, particularly with regards to the large amount of strange particle production occurring at low x_γ (~ 0.15).

No attempt is made to estimate the full systematic errors in the same way as for the High and Low Q^2 DIS samples. Variations in the photoproduction Λ and K_s^0 cross-sections due to differences in the particle selection criteria are expected to be at a similar level to the systematic errors in the DIS samples - relatively small. However, there is a potentially much bigger systematic error due to the lack of good agreement between the data and detector level MC distributions (as shown in Section 6.3). In order to estimate the effect that this will have on the final results, three sets of results are shown in the Figures. Black circles show the data corrected using direct and resolved photoproduction

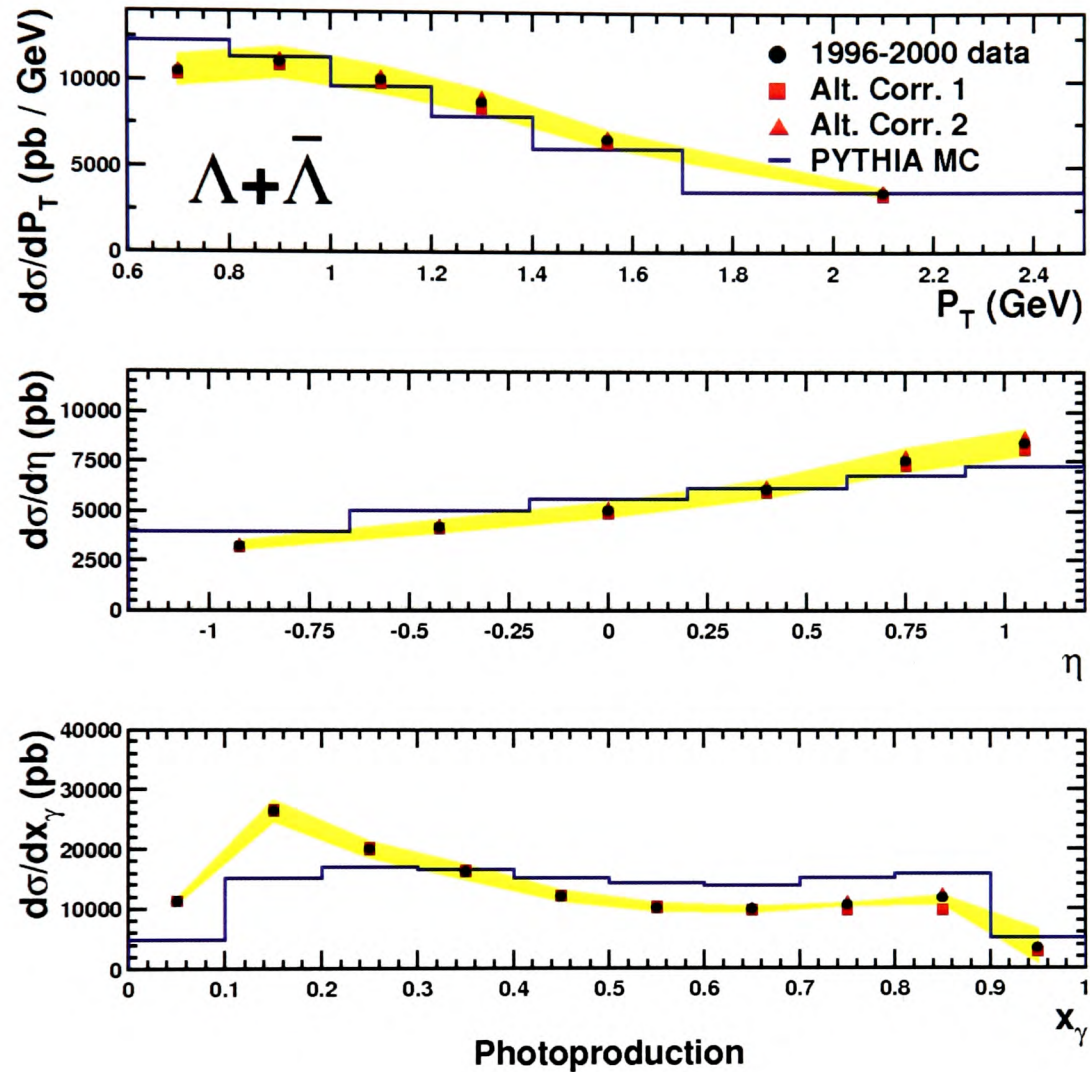


Figure 8.9: Differential cross-sections for $(\Lambda + \bar{\Lambda})$ production in photoproduction. 1996-2000 data and PYTHIA MC are shown. The MC includes direct and resolved samples combined according to the generated luminosities, and samples with $E_P = 820\text{GeV}$ and $E_P = 920\text{GeV}$ in the same proportion as the data. The MC is normalized to the same area as in the data histograms by multiplying by 1.5. Statistical errors for the data are included, but are smaller than the point sizes. Black circles show the data corrected with the optimal correction factors. Two alternative correction factors are used, as discussed in the text, which give rise to the red triangles and squares. The yellow band shows the systematic error due to the calorimeter energy scale.

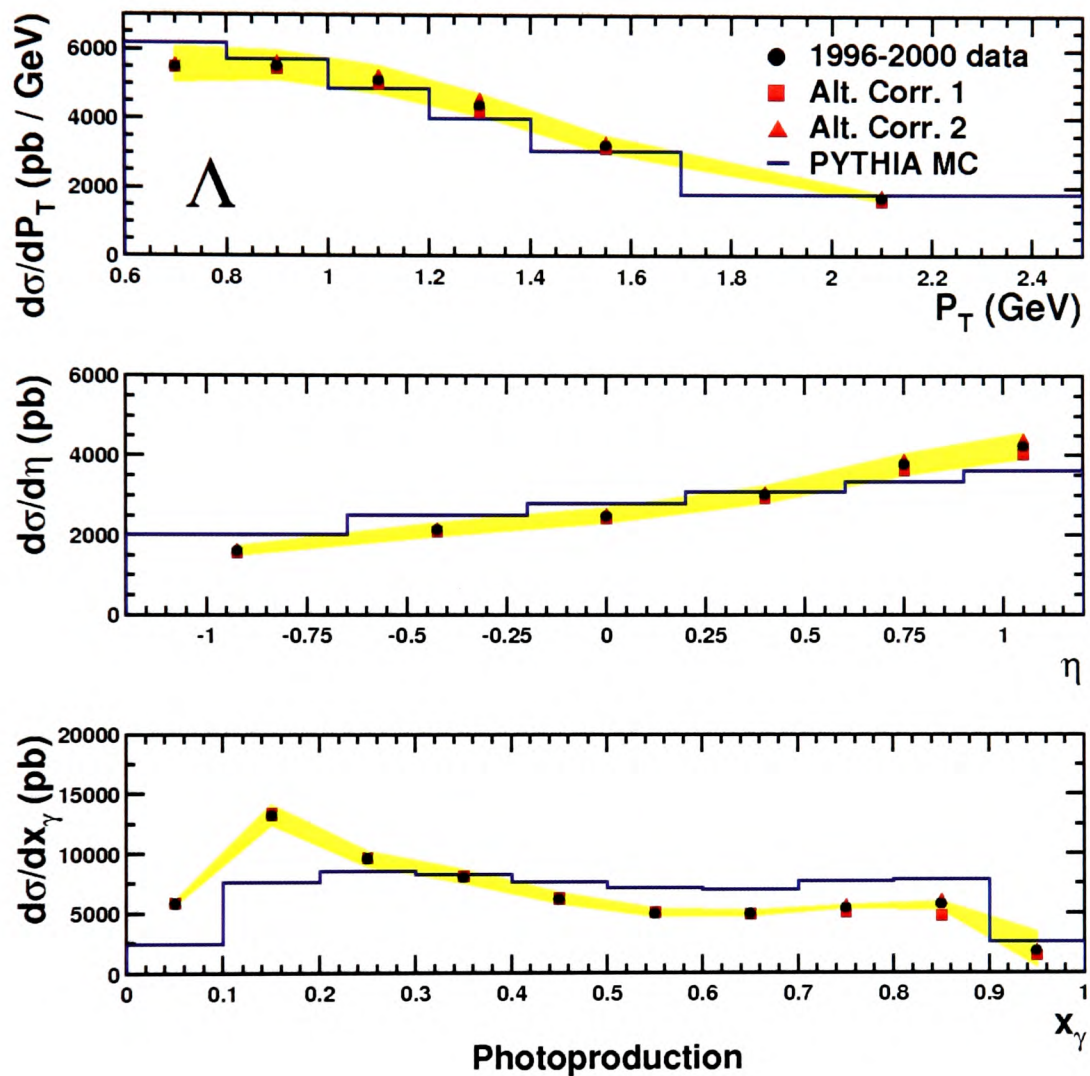


Figure 8.10: Differential cross-sections for Λ production in photoproduction. 1996-2000 data and PYTHIA MC are shown. The MC includes direct and resolved samples combined according to the generated luminosities, and samples with $E_P = 820\text{GeV}$ and $E_P = 920\text{GeV}$ in the same proportion as the data. The MC is normalized to the same area as in the data histograms by multiplying by 1.5. Statistical errors for the data are included, but are smaller than the point sizes. Black circles show the data corrected with the optimal correction factors. Two alternative correction factors are used, as discussed in the text, which give rise to the red triangles and squares. The yellow band shows the systematic error due to the calorimeter energy scale.

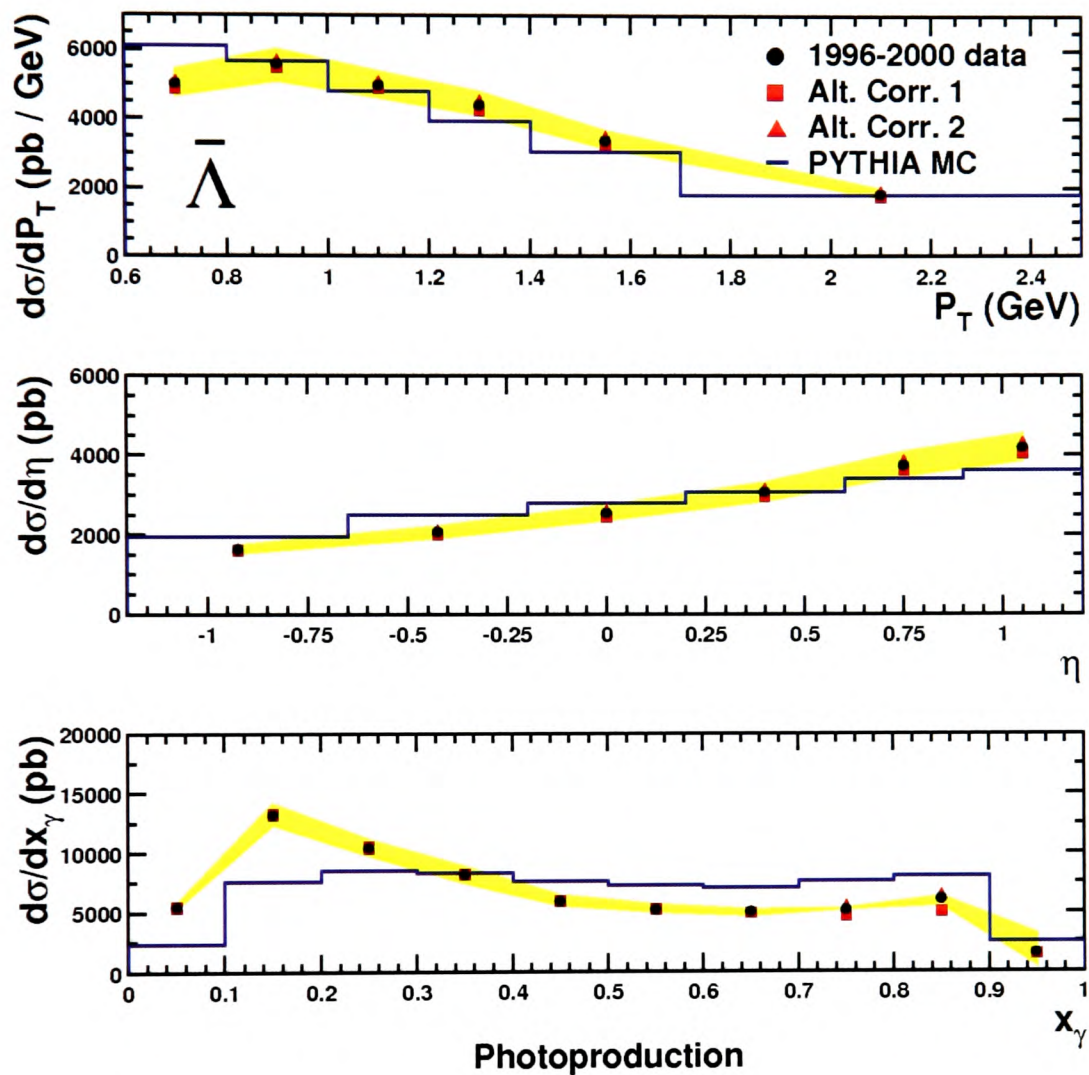


Figure 8.11: Differential cross-sections for $\bar{\Lambda}$ production in photoproduction. 1996-2000 data and PYTHIA MC are shown. The MC includes direct and resolved samples combined according to the generated luminosities, and samples with $E_P = 820\text{GeV}$ and $E_P = 920\text{GeV}$ in the same proportion as the data. The MC is normalized to the same area as in the data histograms by multiplying by 1.5. Statistical errors for the data are included, but are smaller than the point sizes. Black circles show the data corrected with the optimal correction factors. Two alternative correction factors are used, as discussed in the text, which give rise to the red triangles and squares. The yellow band shows the systematic error due to the calorimeter energy scale.

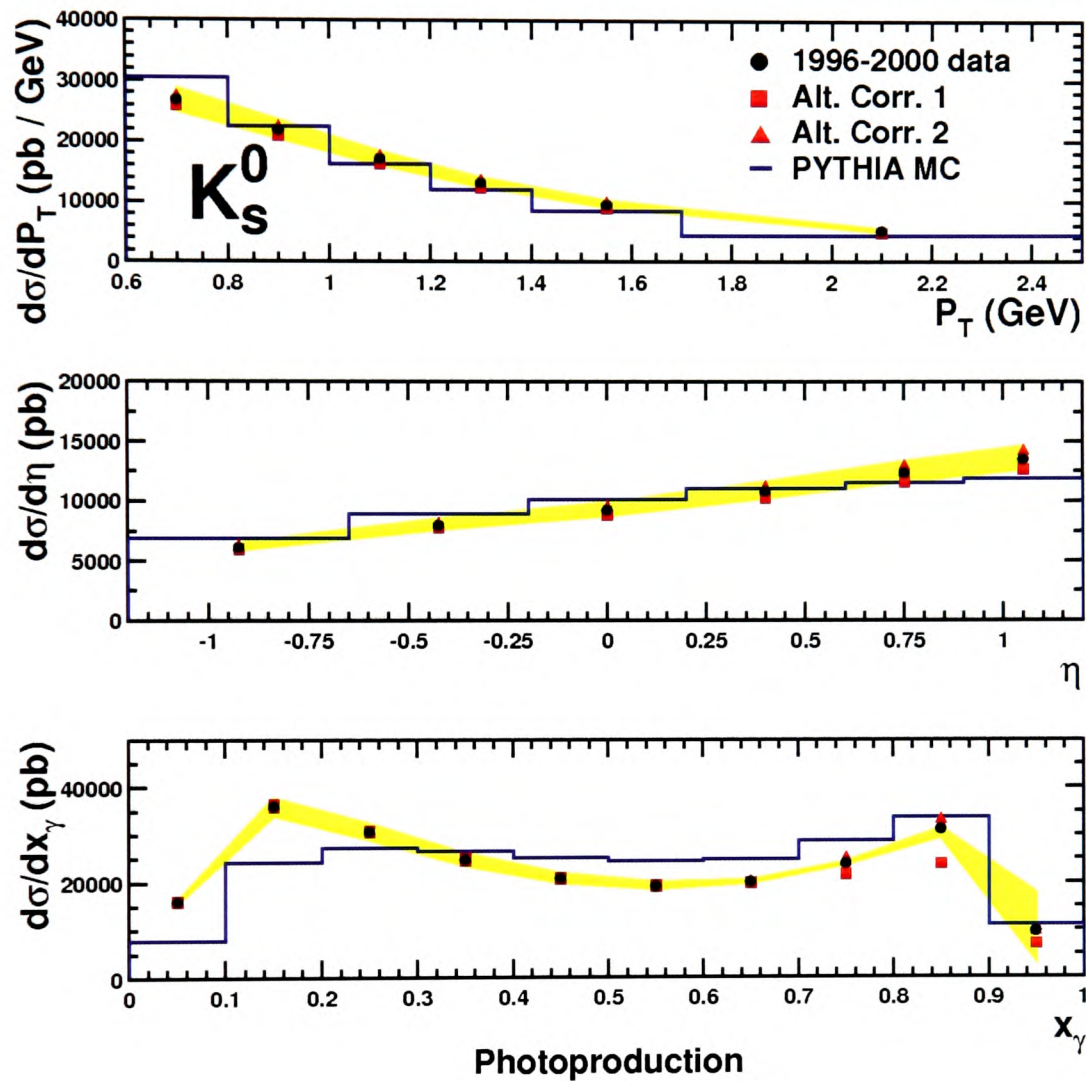


Figure 8.12: Differential cross-sections for K_s^0 production in photoproduction. 1996-2000 data and PYTHIA MC are shown. The MC includes direct and resolved samples combined according to the generated luminosities, and samples with $E_P = 820\text{GeV}$ and $E_P = 920\text{GeV}$ in the same proportion as the data. The MC is normalized to the same area as in the data histograms by multiplying by 1.1. Statistical errors for the data are included, but are smaller than the point size. Black circles show the data corrected with the optimal correction factors. Two alternative correction factors are used, as discussed in the text, which give rise to the red triangles and squares. The yellow band shows the systematic error due to the calorimeter energy scale.

MC samples combined according to the best fit to the detector level x_γ distribution in the data (Fig. 6.3). Red triangles show the data corrected with the same direct sample reweighted by a factor $\times 2$, added to the resolved sample (Alternative Correction 1). Red squares show the data corrected with just the resolved MC sample (Alternative Correction 2). The most significant differences occur at high x_γ , as expected, due to the predominance of the direct component in this region. When correcting with just the resolved MC sample, the cross-sections obtained are noticeably smaller. Similarly, when obtaining the correction factors from the direct enriched sample, the cross-sections obtained are bigger. Although the cross-sections depend on which MC sample is used to correct for detector effects, the variation is predominantly due to whether the whole event passes the trigger and offline event selection criteria, and not whether the Λ , $\bar{\Lambda}$ and K_s^0 are observed, given that the event containing them passes the cuts. This is demonstrated by using the same method to estimate any systematic effects in the $\Lambda - \bar{\Lambda}$ asymmetry and $(\Lambda + \bar{\Lambda})/K_s^0$ ratio shown later.

The yellow band shown on the plots gives an estimate of the systematic error due to the uncertainty in energy scale of the calorimeter. This is obtained by varying the E_T^{jet} and y_{jb} values in the data by $\pm 3\%$. Although the effect is significant in the cross-sections, the ratios $(\Lambda - \bar{\Lambda})/(\Lambda + \bar{\Lambda})$ and $(\Lambda + \bar{\Lambda})/K_s^0$ change very little, as may be seen later.

8.2 Polarization

The Λ and $\bar{\Lambda}$ polarization is obtained from taking the gradient of a plot of the angular distribution of the decay proton, as discussed in Section 7.3.

8.2.1 $5 \leq Q^2 \leq 25 \text{ GeV}^2$

The angular distributions from which the polarization is obtained for the Low Q^2 sample may be seen in Fig. 8.13 and 8.14. The 1st order polynomial fit is based on the central values with their statistical errors. Taking the gradient of the fit gives the polarization values shown in Table 8.2. The error of the fit is shown as the statistical error. An estimate of the systematic error, as obtained in Section 8.1 and detailed in Appendix A, is displayed in the Figure (although not included in the fit). The systematic error

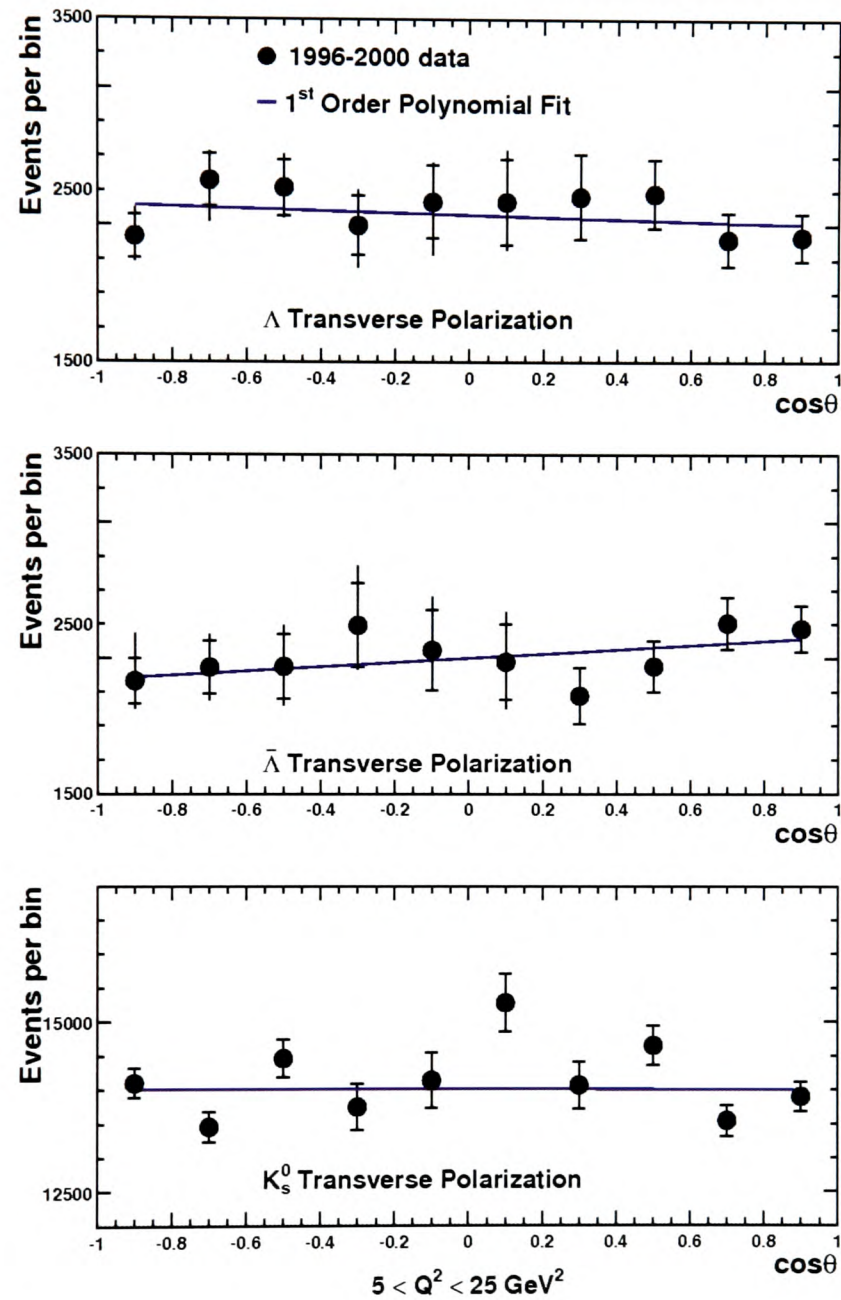


Figure 8.13: Angular distribution of the highest momentum decay particle from a strange particle in the Low Q^2 sample. θ is the angle between the momentum of this particle and $\hat{n} = \hat{p}_{beam} \times \hat{p}_\Lambda$ or $\hat{n} = \hat{p}_{beam} \times \hat{p}_{K_s^0}$. Statistical (inner error bars) and systematic and statistical errors added in quadrature are shown for Λ and $\bar{\Lambda}$. Statistical errors only are shown for K_s^0 .

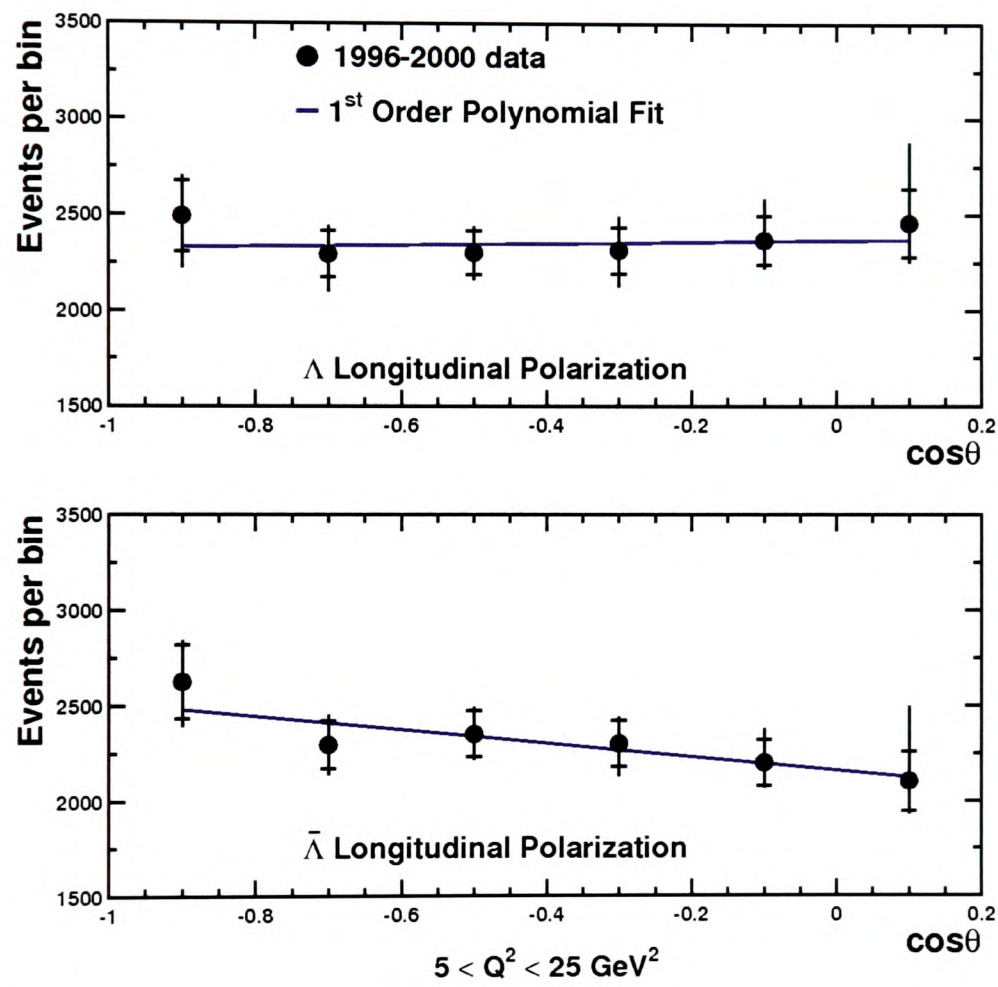


Figure 8.14: Angular distribution of the highest momentum decay particle from a strange particle in the Low Q^2 sample. θ is the angle between the momentum of this particle and $\hat{p}_\Lambda$. Statistical (inner error bars) and systematic and statistical errors added in quadrature are shown.

obtained from this method is also quoted in Table 8.2.

	Transverse (%)	χ^2/NDF	Longitudinal (%)	χ^2/NDF
Λ	$-4.0 \pm 5.3^{+4.7}_{-4.0}$	0.7	$2.7 \pm 12.4^{+16.0}_{-3.2}$	0.3
$\bar{\Lambda}$	$-8.5 \pm 5.5^{+4.7}_{-2.1}$	0.6	$25.6 \pm 13.1^{+2.6}_{-17.4}$	0.4
K_s^0	-0.05 ± 1.4	3.5	-	-

Table 8.2: Polarization values in the Low Q^2 sample, including both statistical and systematic errors.

As a further test of any systematic error in the polarization, the same method of obtaining the transverse Λ polarization is applied to the K_s^0 sample¹, where no polarization is expected. The K_s^0 polarization is also displayed in Table 8.2, and is consistent with zero, with a statistical error somewhat smaller than the statistical error on the Λ and $\bar{\Lambda}$ polarization values.

Due to the kinematic constraints of observing the Λ decay products, particularly the $\pi^\pm$, the full range of θ is not accessible for the longitudinal polarization angular distributions. This leads to the larger error seen in the longitudinal polarization compared to the transverse polarization.

No significantly non-zero transverse or longitudinal polarization is observed for either Λ or $\bar{\Lambda}$ in the Low Q^2 sample.

8.2.2 $Q^2 \geq 25\text{GeV}^2$

The angular distributions from which the polarization is obtained for the High Q^2 sample may be seen in Fig. 8.15 and 8.16. The 1st order polynomial fit is based on the central values with their statistical errors. Taking the gradient of the fit gives the polarization values shown in Table 8.3. The error of the fit is shown as the statistical error. An estimate of the systematic error, as obtained in Section 8.1 and detailed in Appendix A, is displayed in the Figure (although not included in the fit). The systematic error obtained from this method is also quoted in Table 8.3.

The K_s^0 transverse polarization, expected to be zero, is also quoted in Table 8.3. and

¹To measure the K_s^0 polarization the angular distribution of the π^+ or π^- with the most momentum is used, *cf* the angular distribution of the proton or antiproton used to obtain the Λ and $\bar{\Lambda}$ polarization.

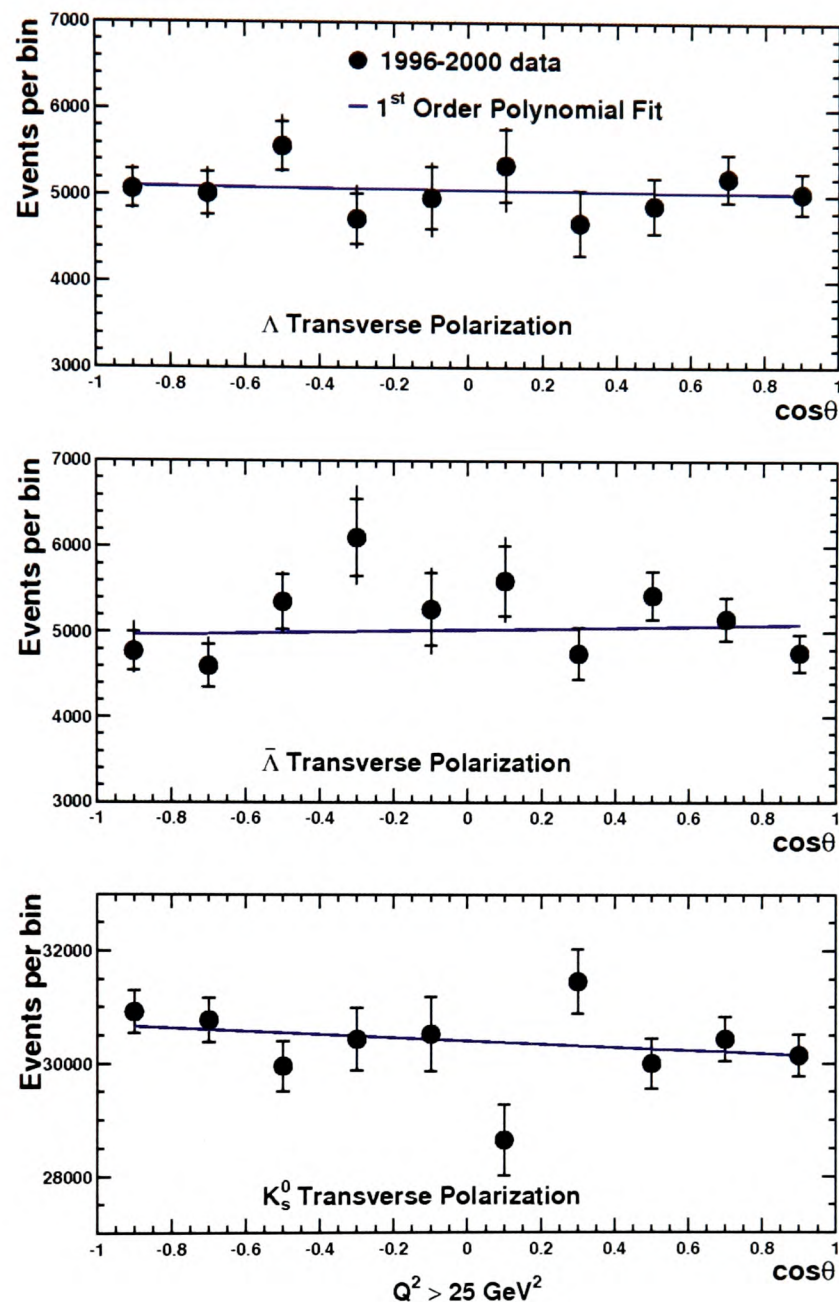


Figure 8.15: Angular distribution of the highest momentum decay particle from a strange particle in the High Q^2 sample. θ is the angle between the momentum of this particle and $\hat{n} = \hat{p}_{beam} \times \hat{p}_\Lambda$ or $\hat{n} = \hat{p}_{beam} \times \hat{p}_{K_s^0}$. Statistical (inner error bars) and systematic and statistical errors added in quadrature are shown for Λ and $\bar{\Lambda}$. Statistical errors only are shown for K_s^0 .

	Transverse (%)	χ^2/NDF	Longitudinal (%)	χ^2/NDF
Λ	$-1.3 \pm 4.3^{+4.0}_{-0.8}$	0.8	$4.3 \pm 9.6^{+4.9}_{-6.9}$	0.9
$\bar{\Lambda}$	$-2.2 \pm 4.2^{+2.4}_{-1.3}$	2.2	$6.4 \pm 9.8^{+20.3}_{-2.6}$	0.4
K_s^0	-1.5 ± 1.1	1.8	-	-

Table 8.3: Polarization values in the High Q^2 sample, including both statistical and systematic errors.

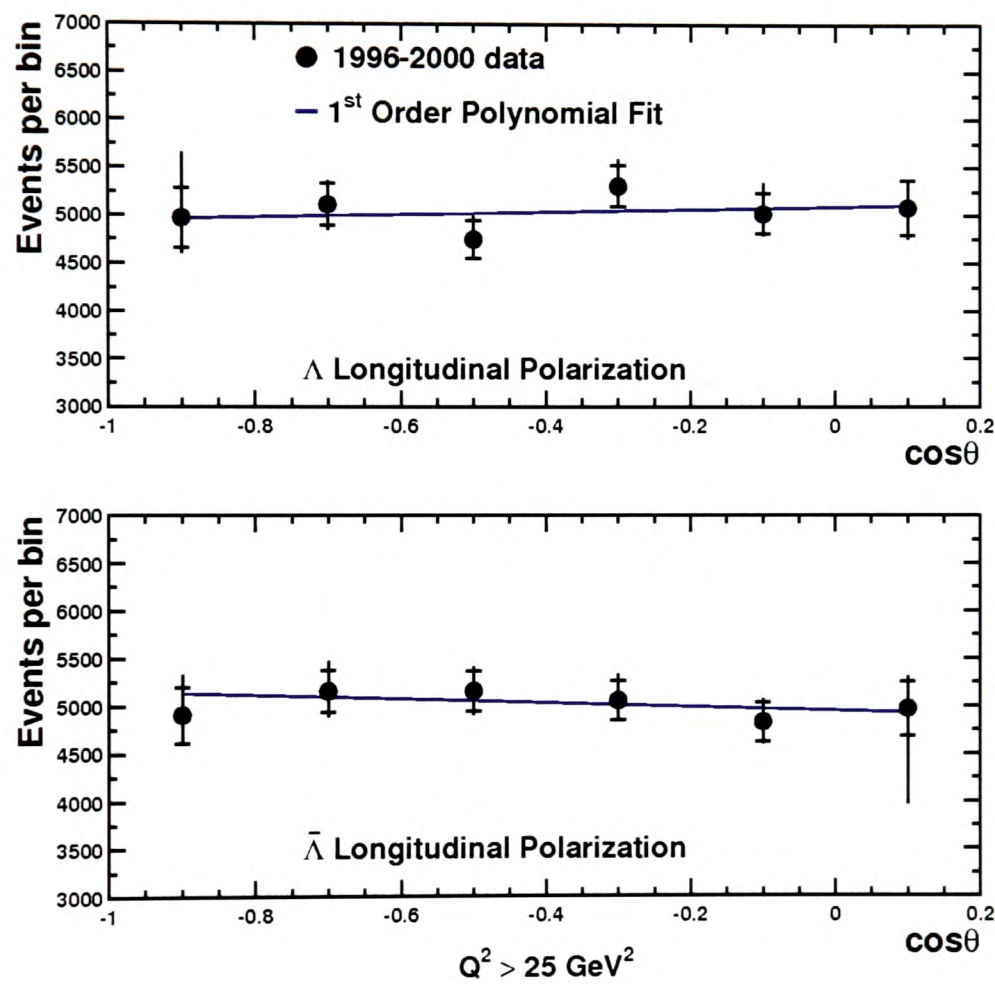


Figure 8.16: Angular distribution of the highest momentum decay particle from a strange particle in the High Q^2 sample. θ is the angle between the momentum of this particle and $\hat{p}_\Lambda$. Statistical (inner error bars) and systematic and statistical errors added in quadrature are shown.

is consistent with zero, as expected, giving another measure of the possible systematic error. As in the Low Q^2 sample, this is significantly smaller than the statistical error on the Λ and $\bar{\Lambda}$ polarization values.

The Λ and $\bar{\Lambda}$ transverse and longitudinal polarization are consistent with zero for events with $Q^2 \geq 25\text{GeV}^2$.

8.2.3 Photoproduction

The angular distributions from which the polarization is obtained for the photoproduction sample may be seen in Fig. 8.17 and 8.18. The 1st order polynomial fit is based

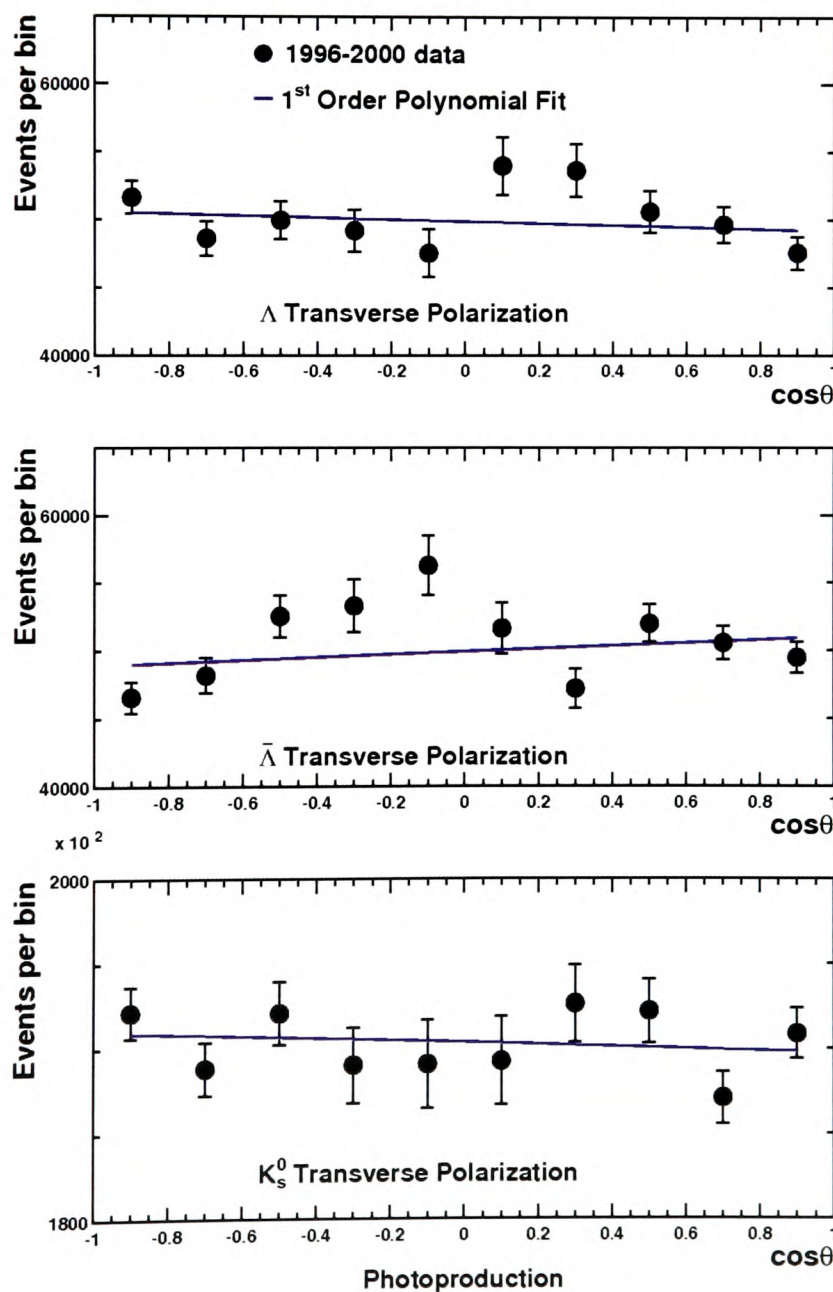


Figure 8.17: Angular distribution of the highest momentum decay particle from a strange particle in the photoproduction sample. θ is the angle between the momentum of this particle and $\hat{n} = \hat{p}_{beam} \times \hat{p}_\Lambda$ or $\hat{n} = \hat{p}_{beam} \times \hat{p}_{K_s^0}$. Errors shown are statistical only.

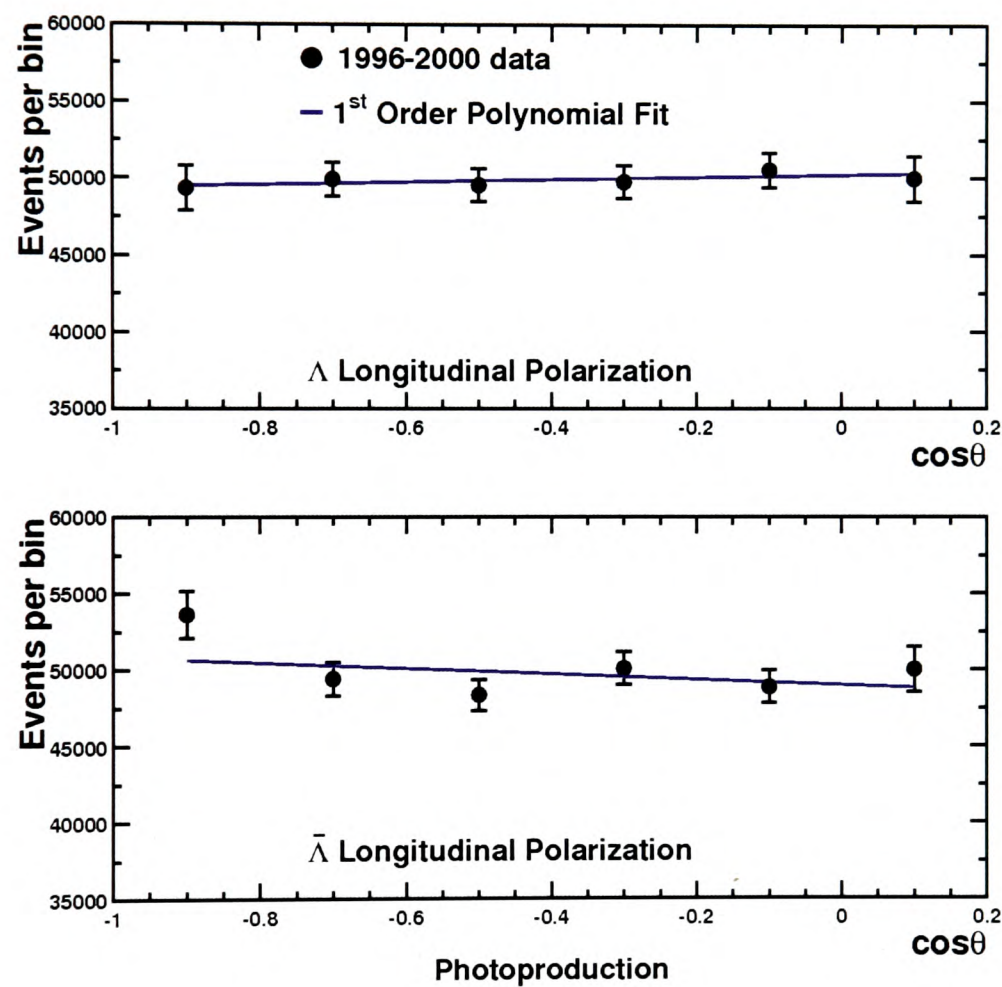


Figure 8.18: Angular distribution of the highest momentum decay particle from a strange particle in the photoproduction sample. θ is the angle between the momentum of this particle and $\hat{p}_\Lambda$. Errors shown are statistical only.

on the central values with their statistical errors. Taking the gradient of the fit gives the polarization values shown in Table 8.4. The error of the fit is shown as the statistical error.

	Corrections	Transverse (%)	χ^2/NDF	Longitudinal (%)	χ^2/NDF
Λ	Direct + Resolved	-2.2 ± 2.2	2.0	1.3 ± 5.0	0.1
Λ	Resolved Only	-2.2 ± 2.3	1.7	3.8 ± 4.0	0.4
Λ	Resolved + (Direct $\times 2$)	-1.8 ± 2.2	2.3	-1.1 ± 4.0	0.1
$\bar{\Lambda}$	Direct + Resolved	-3.3 ± 2.1	3.7	6.6 ± 4.4	2.2
$\bar{\Lambda}$	Resolved Only	-3.4 ± 2.2	3.1	3.6 ± 4.6	1.8
$\bar{\Lambda}$	Resolved + (Direct $\times 2$)	-3.3 ± 2.1	4.0	6.7 ± 4.5	1.8
K_s^0	Direct + Resolved	-0.50 ± 0.83	1.3	-	-
K_s^0	Resolved Only	-0.30 ± 0.67	1.6	-	-
K_s^0	Resolved + (Direct $\times 2$)	-0.68 ± 0.7	1.3	-	-

Table 8.4: Polarization values in the photoproduction sample. The different corrections provide some measure of the systematic error, and are discussed in the text.

It was noted in Sections 6.3 and 7.1 that the the photoproduction event variables are not well described by the MC. In order to estimate the effect of this on the polarization results, corrections from three different MC samples are used. The central result is when the data is corrected using direct and resolved photoproduction MC samples combined according to the best fit to the detector level x_γ distribution in the data. Alternative corrections come from the same sample with the direct photoproduction contribution reweighted by a factor $\times 2$, added to the resolved sample, and just using the resolved sample on its own. The polarization obtained using correction factors from all of these MC samples are shown in Table 8.4. Changing the MC sample used to obtain the correction factors in this way has little effect on the polarization values obtained, suggesting that any systematic error arising from the lack of good agreement between MC and data at the detector level is small.

As no polarization is expected in the K_s^0 sample, the same method of obtaining the Λ polarization is applied to the K_s^0 , as for the DIS samples, as another means of estimating the systematic error. The K_s^0 polarization is also displayed in Table 8.4, and is consistent with zero, as expected, to much greater precision than the Λ and $\bar{\Lambda}$ polarization measurements, again suggesting that the systematic error is small.

To account for the systematic error in the energy scale of the calorimeter, E_T^{jet} and

y_{jb} were varied in the data by $\pm 3\%$. This affected the transverse Λ polarization by $\sim 1\%$ and the longitudinal Λ polarization by $\sim 4\%$.

There is no evidence for either any transverse or longitudinal polarization in the photoproduction Λ and $\bar{\Lambda}$ sample.

8.3 Baryon - Antibaryon Asymmetry

The baryon - antibaryon asymmetry in the Λ system is defined as²:

$$\mathcal{A} = \frac{\sigma(\Lambda) - \sigma(\bar{\Lambda})}{\sigma(\Lambda) + \sigma(\bar{\Lambda})} \quad (8.3)$$

The differential cross-sections presented in Section 8.1 are used to obtain this asymmetry as a function of the same variables. The average asymmetry obtained is also quoted.

8.3.1 $5 \leq Q^2 \leq 25 \text{ GeV}^2$

The baryon asymmetry in the Low Q^2 sample as a function of P_T , η , x and Q^2 can be seen in Fig. 8.19, with the expectation from the ARIADNE MC shown for comparison. An estimate of the systematic error, as obtained in Section 8.1 and detailed in Appendix A, is included in the Figure. As the statistical error of the MC sample is not totally negligible, it is also included. ARIADNE expects a slightly non-zero positive $\Lambda - \bar{\Lambda}$ asymmetry, with which the data are always consistent.

The average asymmetry obtained is:

$$\text{Data : } \frac{\sigma(\Lambda) - \sigma(\bar{\Lambda})}{\sigma(\Lambda) + \sigma(\bar{\Lambda})} = 1.2 \pm 1.6\% \quad (8.4)$$

$$\text{ARIADNE : } \frac{\sigma(\Lambda) - \sigma(\bar{\Lambda})}{\sigma(\Lambda) + \sigma(\bar{\Lambda})} = 1.0 \pm 0.2\% \quad (8.5)$$

The data sample is split into those events where a high proportion of the total hadronic transverse energy is in the highest E_T jet, and the remainder, where the highest E_T jet has a small proportion of the total E_T (as defined in Section 7.6). The detector corrections for the full sample are applied to the two subsamples ('High' and 'Low') and the resulting $(\Lambda - \bar{\Lambda})/(\Lambda + \bar{\Lambda})$ ratios as a function of P_T and η are shown in Fig. 8.20.

²Note that some papers refer to twice this value as the asymmetry.

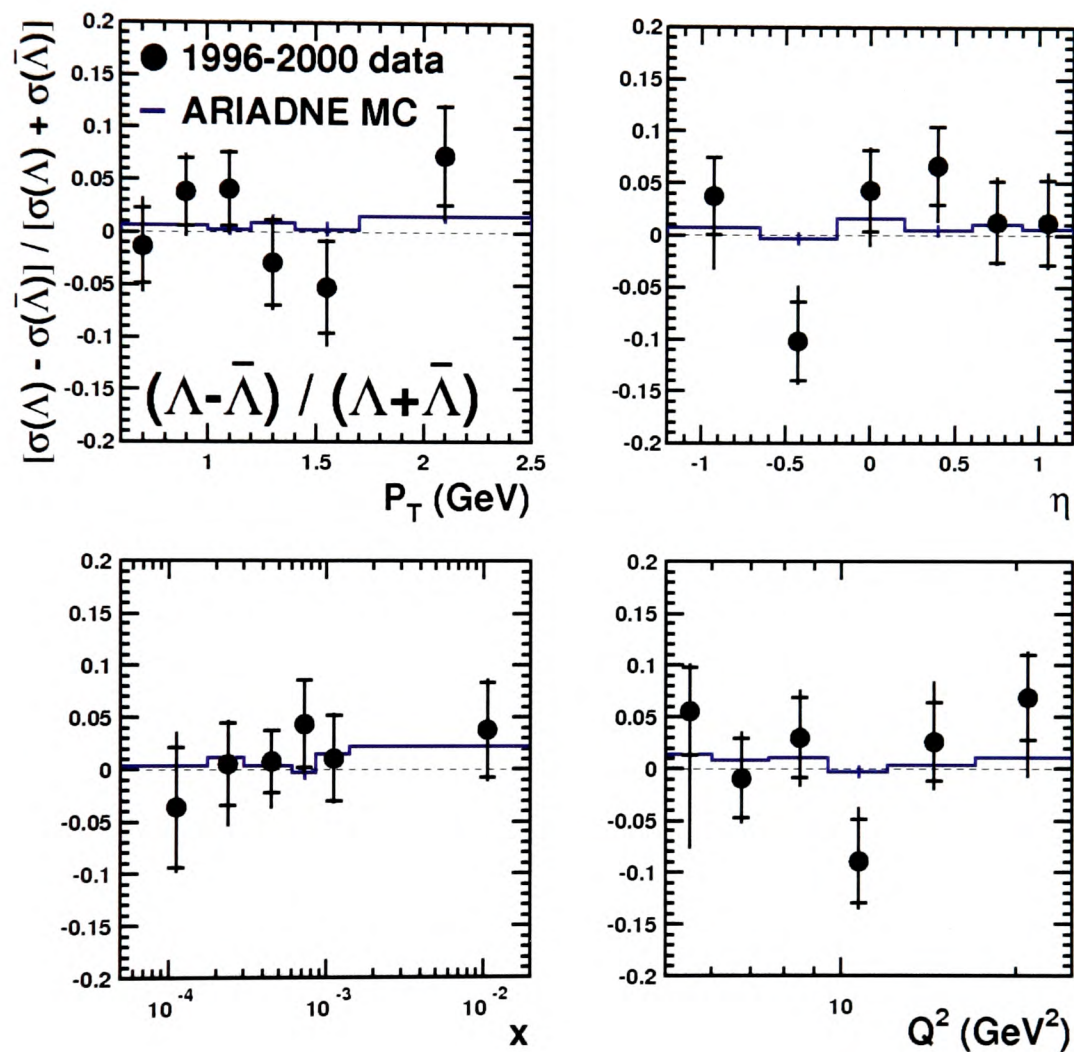


Figure 8.19: $\Lambda - \bar{\Lambda}$ asymmetry in the Low Q^2 sample. Statistical (inner error bars) and systematic and statistical errors added in quadrature are shown for data. Statistical errors are shown for MC, which contains samples with $E_P = 820\text{GeV}$ and $E_P = 920\text{GeV}$ in the same proportion as the data.

The same correction method is applied to reconstructed ARIADNE Λ and $\bar{\Lambda}$, with events similarly divided according to detector level total E_T and E_T of the highest E_T jet.

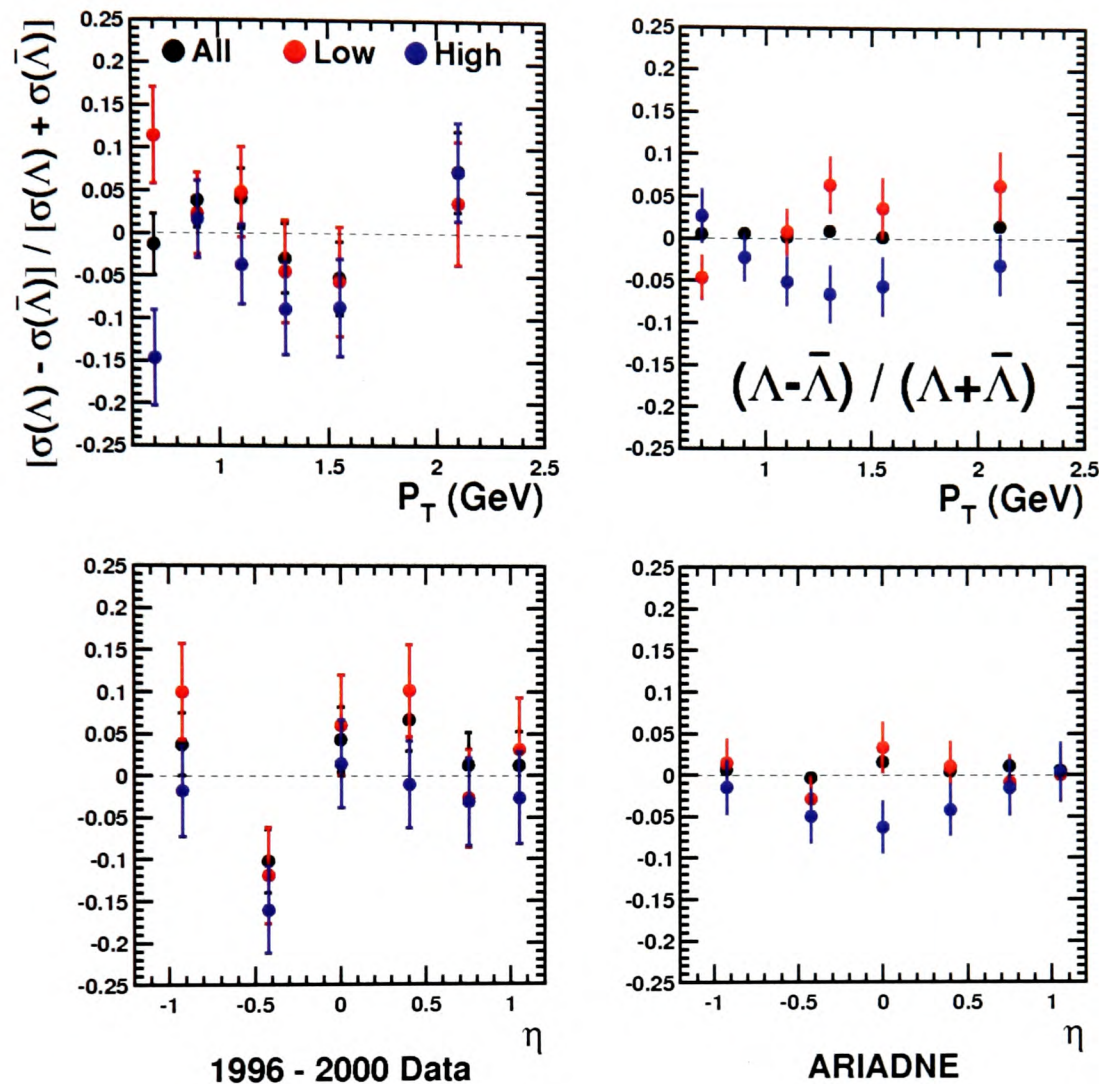


Figure 8.20: $(\Lambda - \bar{\Lambda})/(\Lambda + \bar{\Lambda})$ asymmetry in the Low Q^2 sample. Black points show the asymmetry for the full sample; red points show the asymmetry for those events where a small proportion of the total E_T is carried by the highest E_T jet; blue points show the asymmetry for those events where a large proportion of the total E_T is carried by the highest E_T jet, as discussed in the text. Statistical errors only are included.

Dividing the sample into High and Low fractions of the total E_T in the highest E_T jet does not alter significantly the $(\Lambda - \bar{\Lambda})/(\Lambda + \bar{\Lambda})$ distributions.

8.3.2 $Q^2 \geq 25\text{GeV}^2$

The baryon asymmetry in the High Q^2 sample as a function of P_T , η , x and Q^2 can be seen in Fig. 8.21, with the expectation from the ARIADNE MC shown for comparison. An estimate of the systematic error, as obtained in Section 8.1 and detailed in Appendix A, is included in the Figure. As the statistical error of the MC sample is not totally

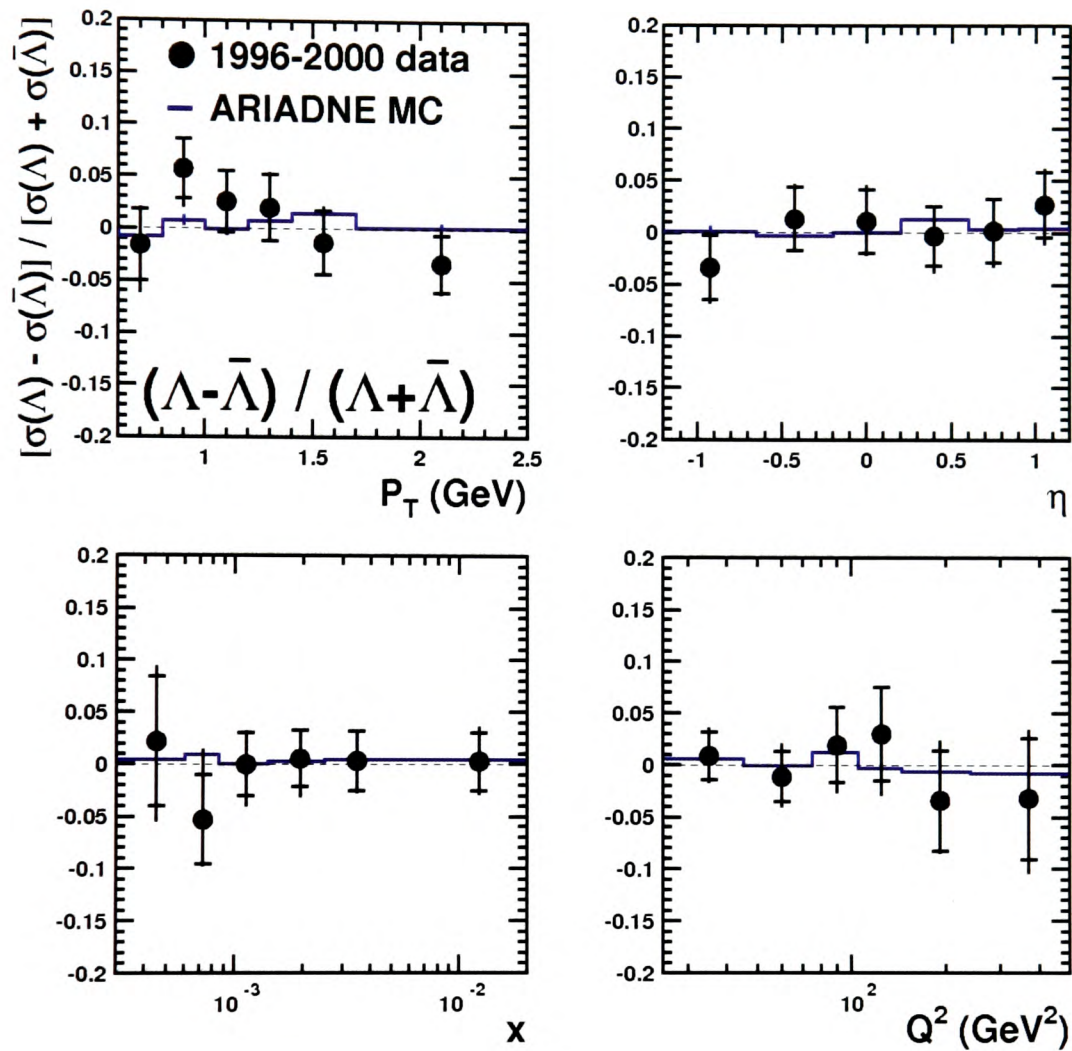


Figure 8.21: $\Lambda - \bar{\Lambda}$ asymmetry in the High Q^2 sample. Statistical (inner error bars) and systematic and statistical errors added in quadrature are shown for data. Statistical errors are shown for MC. All the available High Q^2 MC is shown, to minimize any statistical error.

negligible, it is also included. ARIADNE expects a slightly non-zero positive $\Lambda - \bar{\Lambda}$ asymmetry, with which the data are always consistent.

The average asymmetry obtained is:

$$\text{Data : } \frac{\sigma(\Lambda) - \sigma(\bar{\Lambda})}{\sigma(\Lambda) + \sigma(\bar{\Lambda})} = 0.3 \pm 1.3\% \quad (8.6)$$

$$\text{ARIADNE : } \frac{\sigma(\Lambda) - \sigma(\bar{\Lambda})}{\sigma(\Lambda) + \sigma(\bar{\Lambda})} = 0.4 \pm 0.2\% \quad (8.7)$$

The data sample is split into those events where a high proportion of the total hadronic transverse energy is in the highest E_T jet, and the remainder, where the highest E_T jet has a small proportion of the total E_T (as defined in Section 7.6). The detector corrections for the full sample are applied to the two subsamples ('High' and 'Low') and the resulting $(\Lambda - \bar{\Lambda})/(\Lambda + \bar{\Lambda})$ ratios as a function of P_T and η are shown in Fig. 8.22. The same correction method is applied to reconstructed ARIADNE Λ and $\bar{\Lambda}$, with events similarly divided according to detector level total E_T and E_T of the highest E_T jet.

Dividing the sample into High and Low fractions of the total E_T in the highest E_T jet does not alter significantly the $(\Lambda - \bar{\Lambda})/(\Lambda + \bar{\Lambda})$ distributions.

8.3.3 Photoproduction

The baryon asymmetry in the photoproduction sample as a function of x_γ , P_T and η can be seen in Fig. 8.23, with the expectation from the PYTHIA MC shown for comparison. As the statistical error of the MC sample is not totally negligible, it is included on the Figure. The systematic error due to the inadequacies of the MC simulation are estimated by comparing the results obtained from data corrected for detector effects with correction factors from different MC samples. Data corrected with the optimal MC combination of direct and resolved photoproduction samples are shown as black circles. Red triangles show the data corrected with the same direct sample reweighted by a factor $\times 2$, added to the resolved sample (Alternative Correction 1). Red squares show the data corrected with just the resolved MC sample (Alternative Correction 2). The effects of using these different MC samples to correct the data are smaller than the statistical uncertainty. The yellow band shown on the plots gives an estimate of the systematic error due to the uncertainty in the energy scale of the calorimeter.

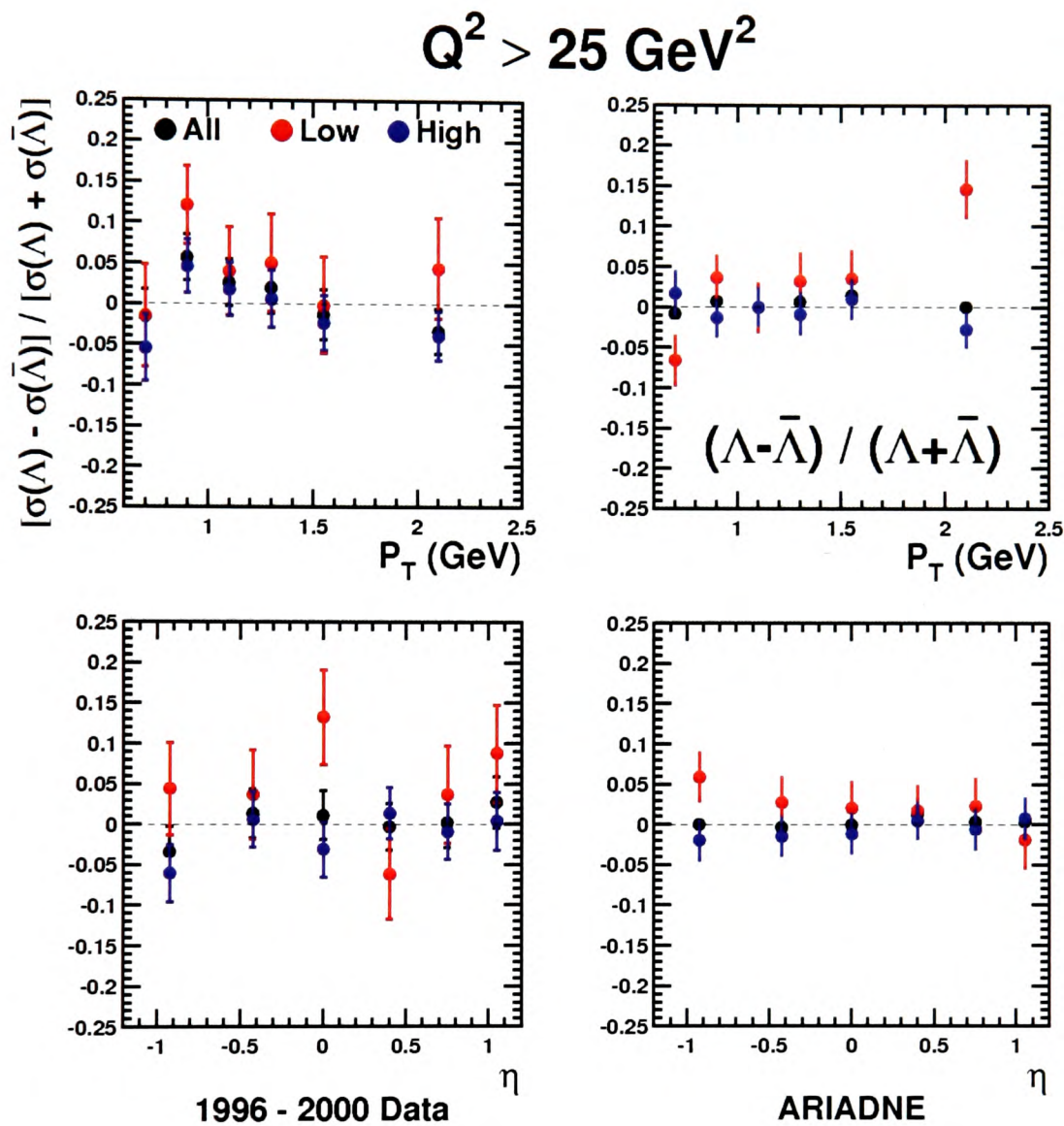


Figure 8.22: $(\Lambda - \bar{\Lambda})/(\Lambda + \bar{\Lambda})$ asymmetry in the High Q^2 sample. Black points show the asymmetry for the full sample; red points show the asymmetry for those events where a small proportion of the total E_T is carried by the highest E_T jet; blue points show the asymmetry for those events where a large proportion of the total E_T is carried by the highest E_T jet, as discussed in the text. Statistical errors only are included. All the available MC is used for the strange particle production in the MC plots.

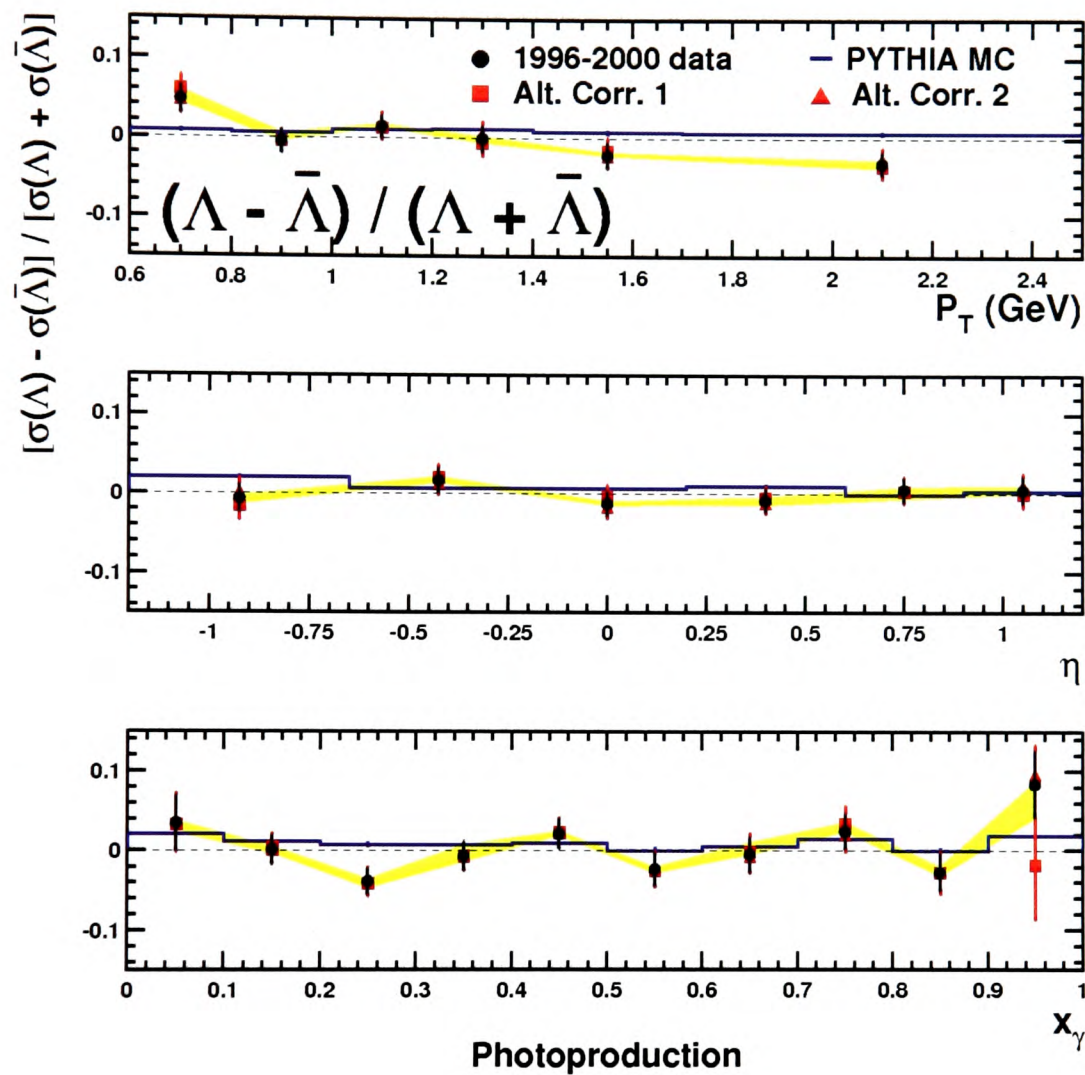


Figure 8.23: $\Lambda - \bar{\Lambda}$ asymmetry in the photoproduction sample. Statistical errors are shown for both data and MC. Black circles show the data corrected with the optimal correction factors. Two alternative correction factors are used, as discussed in the text, which give rise to the red triangles and squares. The yellow band shows the systematic error due to the calorimeter energy scale.

PYTHIA expects a slightly non-zero $\Lambda - \bar{\Lambda}$ asymmetry, at the level of $\sim +0.5\%$. The data are always consistent with this.

The average asymmetry obtained is:

$$\text{Data : } \frac{\sigma(\Lambda) - \sigma(\bar{\Lambda})}{\sigma(\Lambda) + \sigma(\bar{\Lambda})} = -0.02 \pm 0.6\% \quad (8.8)$$

$$\text{PYTHIA : } \frac{\sigma(\Lambda) - \sigma(\bar{\Lambda})}{\sigma(\Lambda) + \sigma(\bar{\Lambda})} = 0.6 \pm 0.1\% \quad (8.9)$$

The data sample is split into those events where a high proportion of the total transverse energy is in the highest E_T jet, and the remainder, where the highest E_T jet has a small proportion of the total E_T (as defined in Section 7.6). The detector corrections for the full sample are applied to the two subsamples ('High' and 'Low') and the resulting $(\Lambda - \bar{\Lambda})/(\Lambda + \bar{\Lambda})$ ratios are shown in Fig. 8.24. The same correction method is applied to reconstructed PYTHIA Λ and $\bar{\Lambda}$, with events similarly divided according to detector level total E_T and E_T of the highest E_T jet.

Dividing the sample into High and Low fractions of the total E_T in the highest E_T jet does not alter significantly the $(\Lambda - \bar{\Lambda})/(\Lambda + \bar{\Lambda})$ distributions.

8.4 Baryon - Meson Ratio

The baryon - meson ratio in the $\Lambda - K_s^0$ system is defined as:

$$\mathcal{R} = \frac{\sigma(\Lambda) + \sigma(\bar{\Lambda})}{\sigma(K_s^0)} \quad (8.10)$$

The differential cross-sections presented in Section 8.1 are used to obtain this ratio as a function of the same variables.

8.4.1 $5 \leq Q^2 \leq 25\text{GeV}^2$

The baryon - meson ratio in the Low Q^2 sample as a function of P_T , η , x and Q^2 can be seen in Fig. 8.25, with the expectation from the ARIADNE MC shown for comparison. An estimate of the systematic error, as obtained in Section 8.1 and detailed in Appendix A, is included in the Figure.

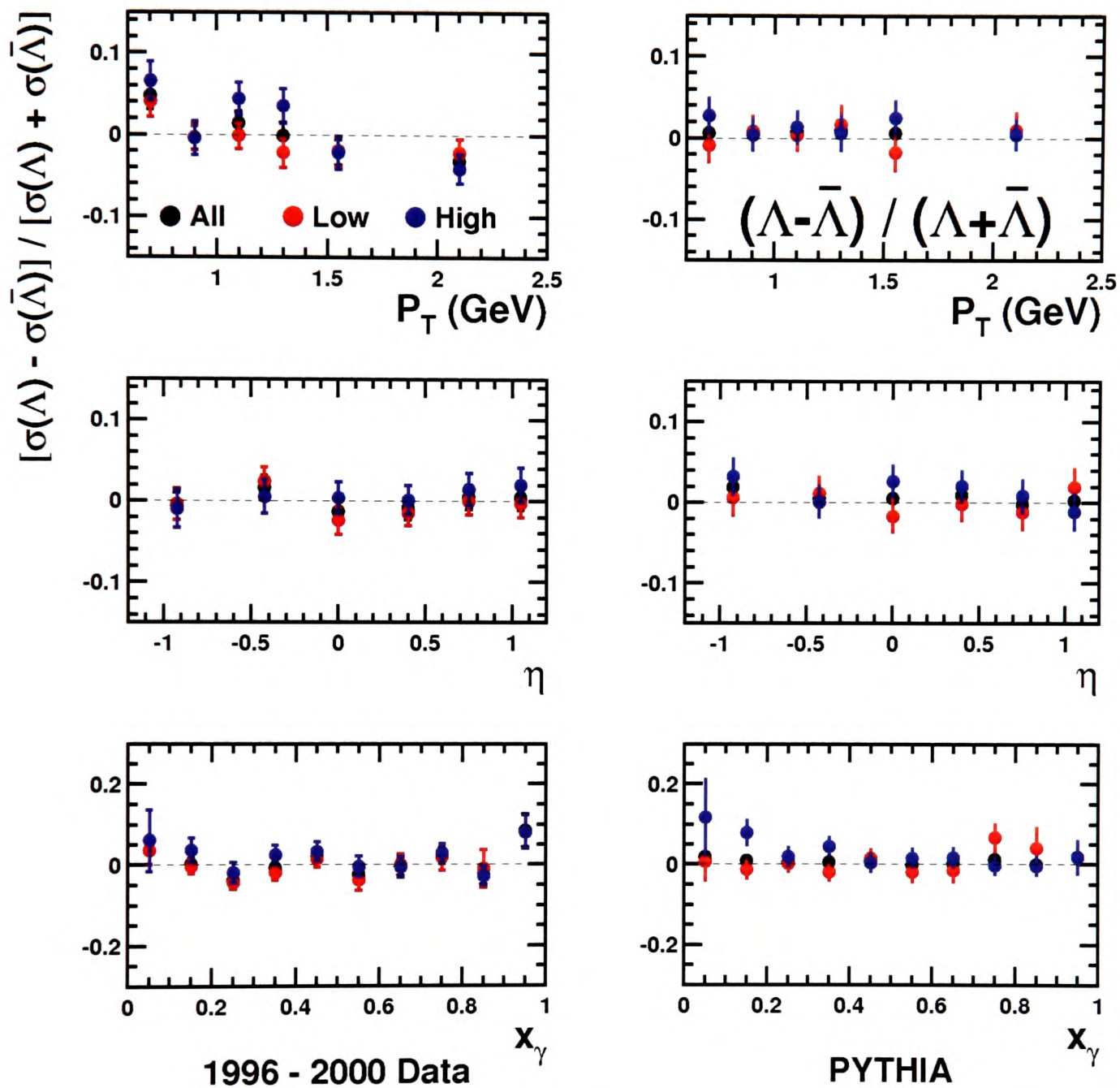


Figure 8.24: $(\Lambda - \bar{\Lambda})/(\Lambda + \bar{\Lambda})$ asymmetry in the photoproduction sample. Black points show the asymmetry for the full sample; red points show the asymmetry for those events where a small proportion of the total E_T is carried by the highest E_T jet; blue points show the asymmetry for those events where a large proportion of the total E_T is carried by the highest E_T jet, as discussed in the text. Statistical errors only are included. Note the contracted scale for the x_γ distributions. The highest x_γ bin of the Low sample is omitted due to insufficient statistics.

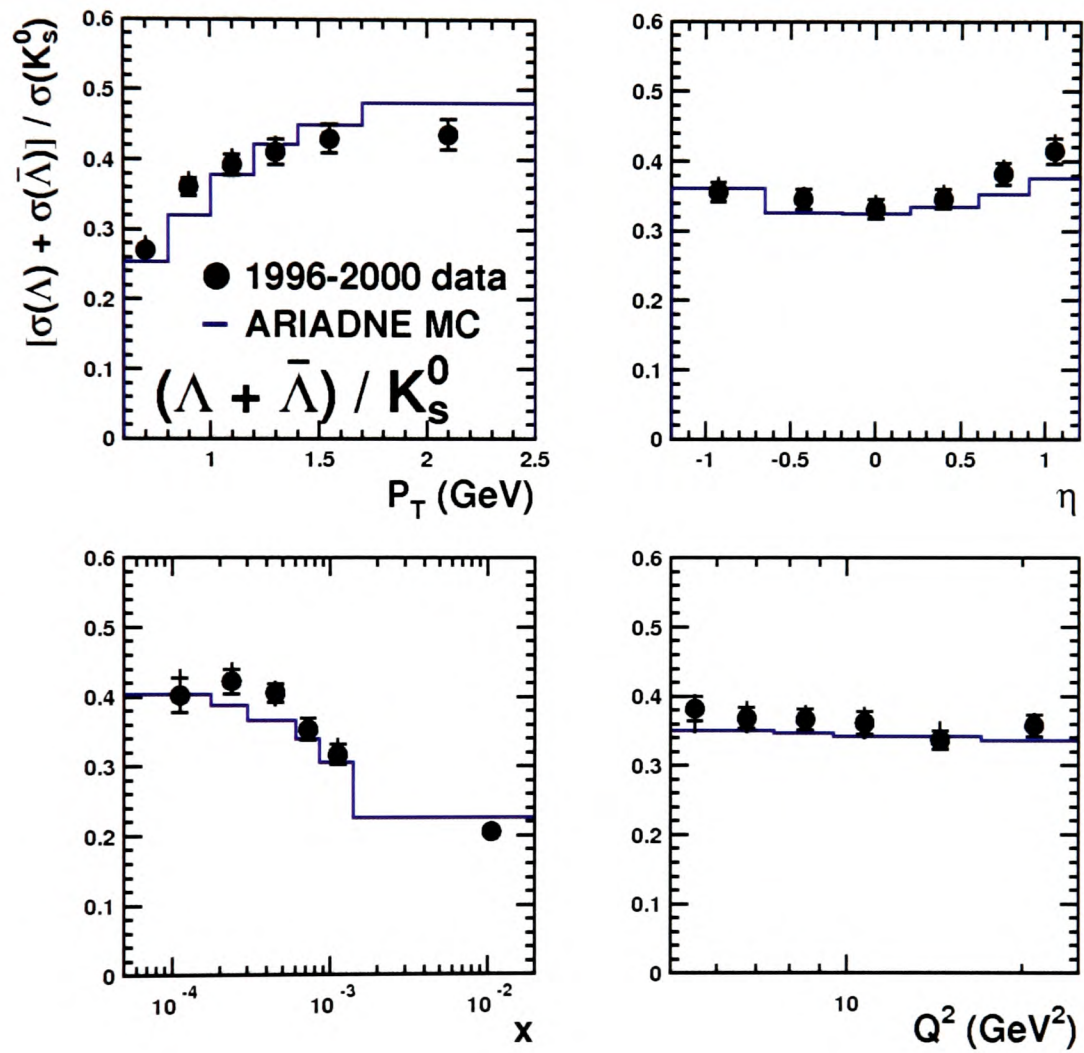


Figure 8.25: $(\Lambda + \bar{\Lambda})/K_s^0$ ratio for the Low Q^2 sample. Statistical (inner error bars) and systematic and statistical errors added in quadrature are shown for data. The MC contains samples with $E_P = 820\text{GeV}$ and $E_P = 920\text{GeV}$ in the same proportion as the data.

The data generally give a slightly larger value of the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio than ARIADNE. The general shapes of how the ratio varies as a function of the four variables is described, but with meager accuracy. The $(\Lambda + \bar{\Lambda})/K_s^0$ ratio tends to increase significantly (from ~ 0.27 to ~ 0.44) as the P_T of the particle increases from $0.6\text{GeV} - 2.5\text{GeV}$. Both the data and the MC see the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio slightly lower in the central region of the detector and increasing at higher and lower η . However, the data is more skewed towards the forward direction. There is a rise in the ratio as the x of the event decreases. In the highest x bin ($0.0014 - 0.02$) the ratio is as low as ~ 0.21 . As Q^2 increases both data and MC see the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio decrease slowly.

The data sample is split into those events where a high proportion of the total transverse energy is in the highest E_T jet, and the remainder, where the highest E_T jet has a small proportion of the total E_T (as defined in Section 7.6). The detector corrections for the full sample are applied to the two subsamples ('High' and 'Low') and the resulting $(\Lambda + \bar{\Lambda})/K_s^0$ ratios as a function of P_T and η are shown in Fig. 8.26. The same correction method is applied to reconstructed ARIADNE Λ and K_s^0 , with events similarly divided according to detector level total E_T and E_T of the highest E_T jet.

No statistically significant change in the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio is seen for event samples with High and Low fractions of the total E_T in the highest E_T jet.

8.4.2 $Q^2 \geq 25\text{GeV}^2$

The baryon - meson ratio in the High Q^2 sample as a function of P_T , η , x and Q^2 can be seen in Fig. 8.27, with the expectation from the ARIADNE MC shown for comparison. An estimate of the systematic error, as obtained in Section 8.1 and detailed in Appendix A, is included in the Figure.

The data generally give a slightly larger value of the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio than ARIADNE. As in the Low Q^2 sample, although the general trends in how the ratio varies are simulated, the accuracy is slight. The rise in the ratio as P_T increases is observed, as are the similar features to the Low Q^2 sample as a function of η - a lower ratio in the central region, and the ratio more skewed to the forward direction in the data than the MC. As x decreases, the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio increases significantly more in the data

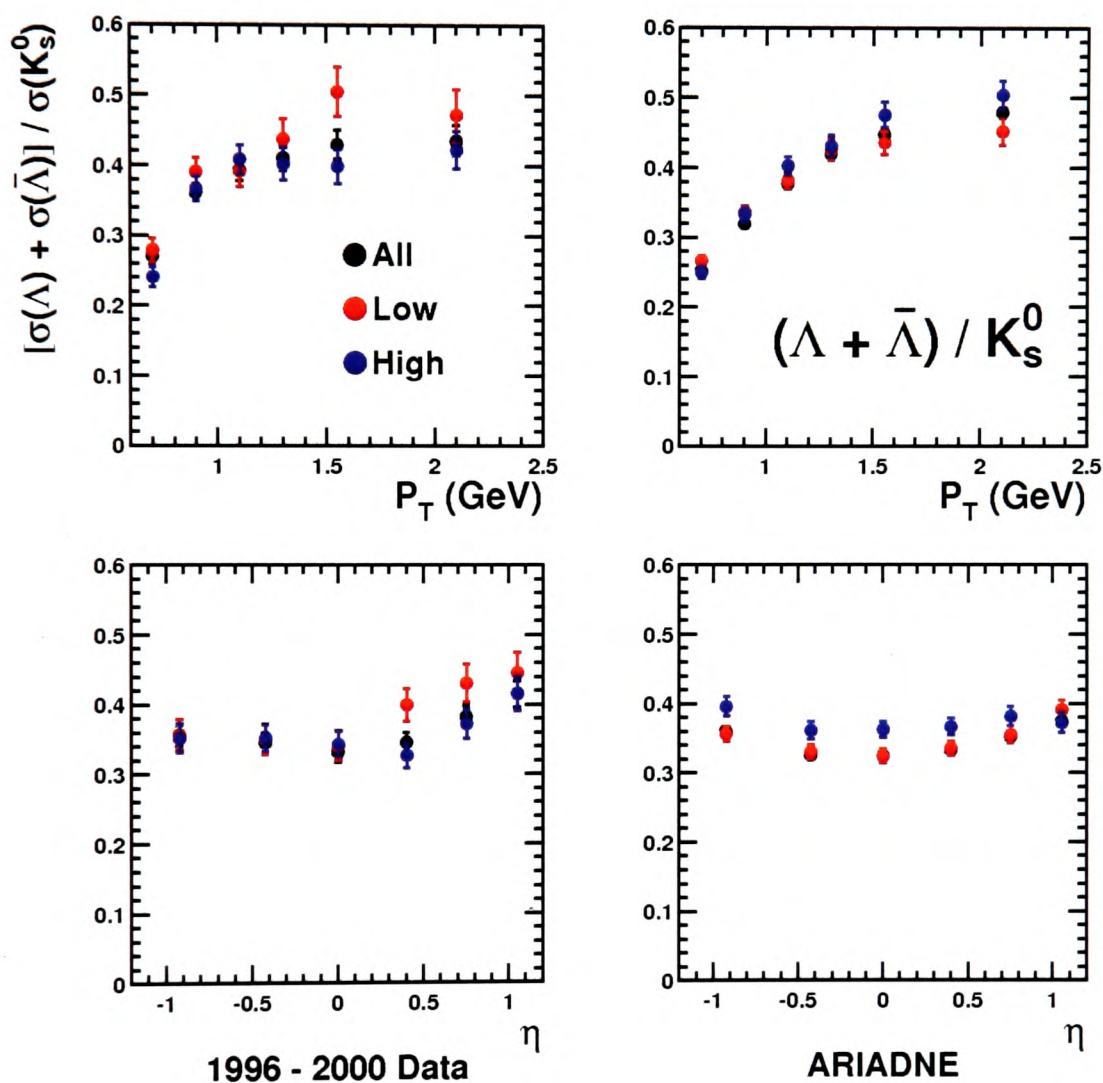


Figure 8.26: $(\Lambda + \bar{\Lambda})/K_s^0$ ratio for the Low Q^2 sample. Black points show the ratio for the full sample; red points show the ratio for those events where a small proportion of the total E_T is carried by the highest E_T jet; blue points show the ratio for those events where a large proportion of the total E_T is carried by the highest E_T jet, as discussed in the text. Statistical errors only are shown.

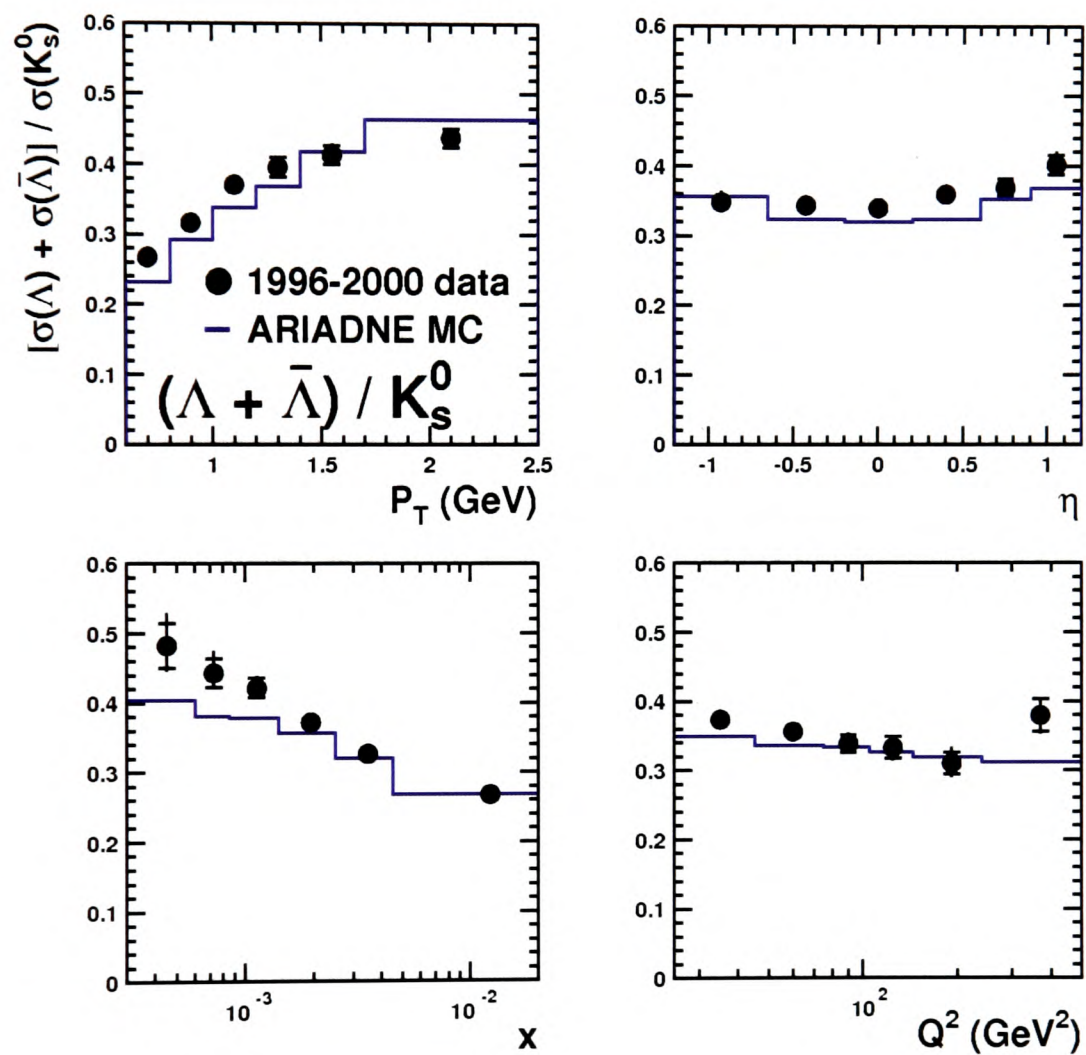


Figure 8.27: $(\Lambda + \bar{\Lambda})/K_s^0$ ratio for the High Q^2 sample. Statistical (inner error bars) and systematic and statistical errors added in quadrature are shown for data. The MC contains samples with $E_P = 820\text{GeV}$ and $E_P = 920\text{GeV}$ in the same proportion as the data.

than the MC. The values range from ~ 0.27 to ~ 0.48 . The ratio as a function of Q^2 continues to decrease slowly as Q^2 increases, aside from one anomalous (but statistically less significant) point with a larger ratio in the highest Q^2 bin ($240\text{GeV}^2 - 500\text{GeV}^2$).

The data sample is split into those events where a high proportion of the total transverse energy is in the highest E_T jet, and the remainder, where the highest E_T jet has a small proportion of the total E_T (as defined in Section 7.6). The detector corrections for the full sample are applied to the two subsamples ('High' and 'Low') and the resulting $(\Lambda + \bar{\Lambda})/K_s^0$ ratios as a function of P_T and η are shown in Fig. 8.28. The same correction method is applied to reconstructed ARIADNE Λ and K_s^0 , with events similarly divided according to detector level total E_T and E_T of the highest E_T jet.

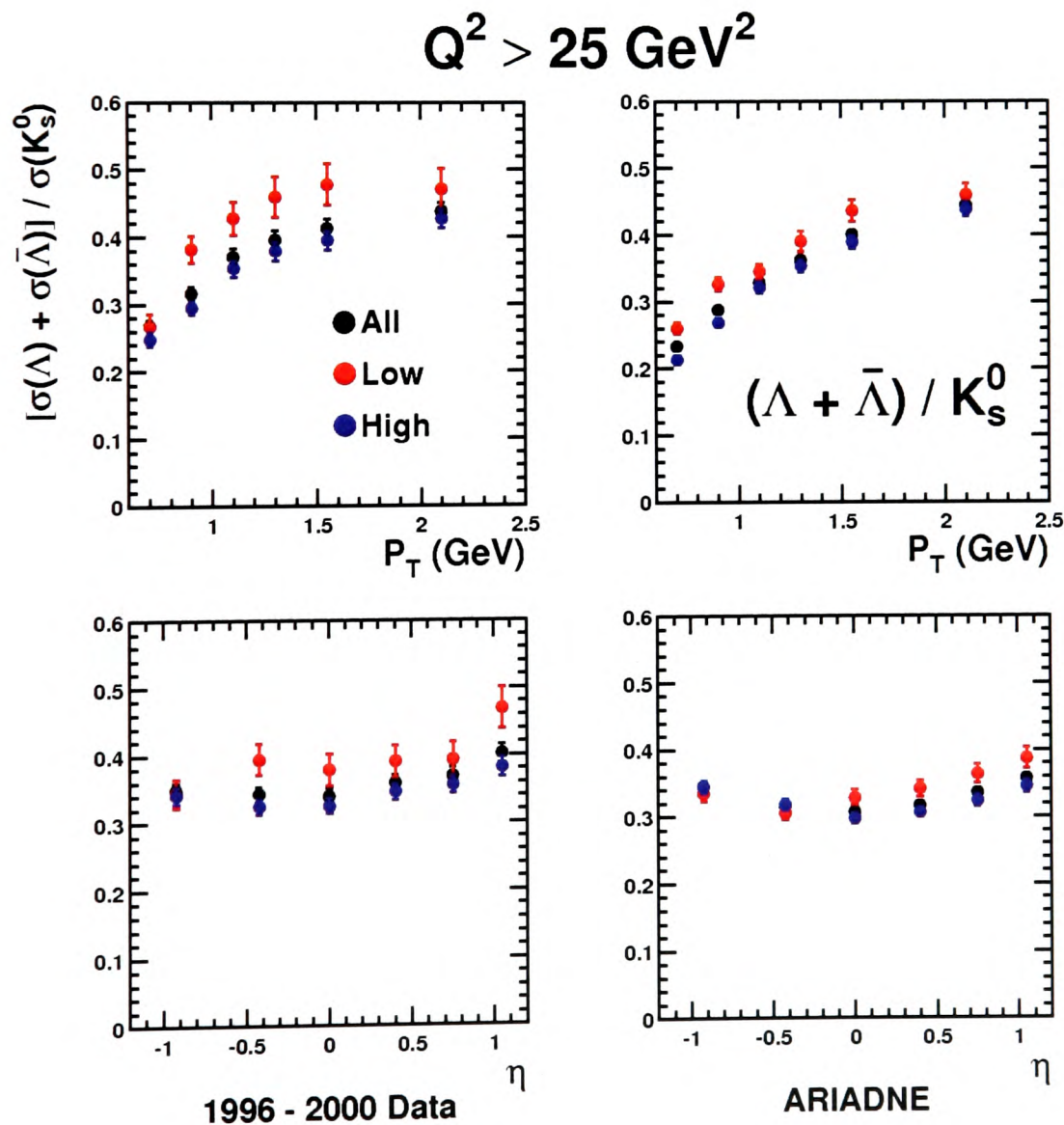


Figure 8.28: $(\Lambda + \bar{\Lambda})/K_s^0$ ratio for the High Q^2 sample. Black points show the ratio for the full sample; red points show the ratio for those events where a small proportion of the total E_T is carried by the highest E_T jet; blue points show the ratio for those events where a large proportion of the total E_T is carried by the highest E_T jet, as discussed in the text. Statistical errors only are shown. All the available MC is used for the strange particle production in the MC plots.

There is a tendency for the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio to be slightly higher for events with a Low fraction of the total E_T in the highest E_T jet in both the data and MC, but the available statistics limit a strong conclusion.

The High Q^2 sample may also be split into events with a High and Low values of E_T/P_T (the hadronic transverse energy and momentum) as described in Section 7.6. Events with High E_T/P_T typically correspond to multi-jet events, where the transferred photon generally interacts with a gluon. Events with Low E_T/P_T typically correspond to single-jet events, where the transferred photon generally interacts with a quark. The detector corrections for the full sample are applied to the two subsamples ('High' and 'Low') and the resulting $(\Lambda + \bar{\Lambda})/K_s^0$ ratios as a function of P_T , η , x and Q^2 are shown in Fig. 8.29. The same correction method is applied to reconstructed ARIADNE Λ and K_s^0 , with events similarly divided according to detector level E_T/P_T . Results for the MC are shown in Fig. 8.30.

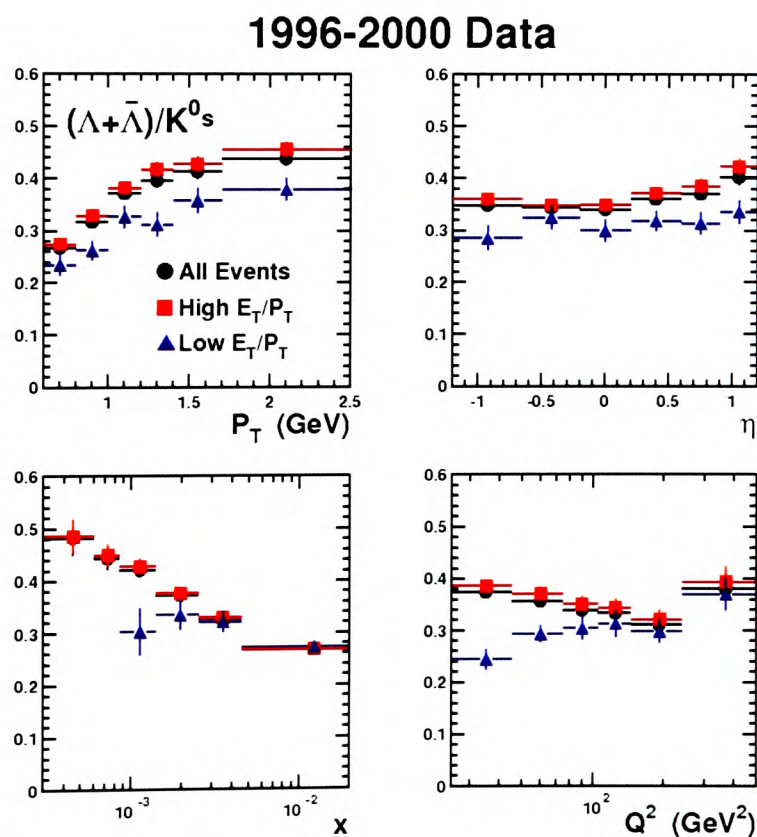


Figure 8.29: $(\Lambda + \bar{\Lambda})/K_s^0$ ratio for the High Q^2 data sample. Black points show the ratio for the full sample; red points show the ratio for those events where $E_T/P_T > 1.7$ (multi-jet enriched); blue points show the ratio for those events where $E_T/P_T < 1.7$ (single-jet enriched). Statistical errors only are shown. The two lowest points in x for the Low E_T/P_T sample are omitted due to insufficient statistics.

As a function of P_T , single-jet events show a slightly lower value of $(\Lambda + \bar{\Lambda})/K_s^0$ than multi-jet events in both the data and MC. As a function of η the data show a lower

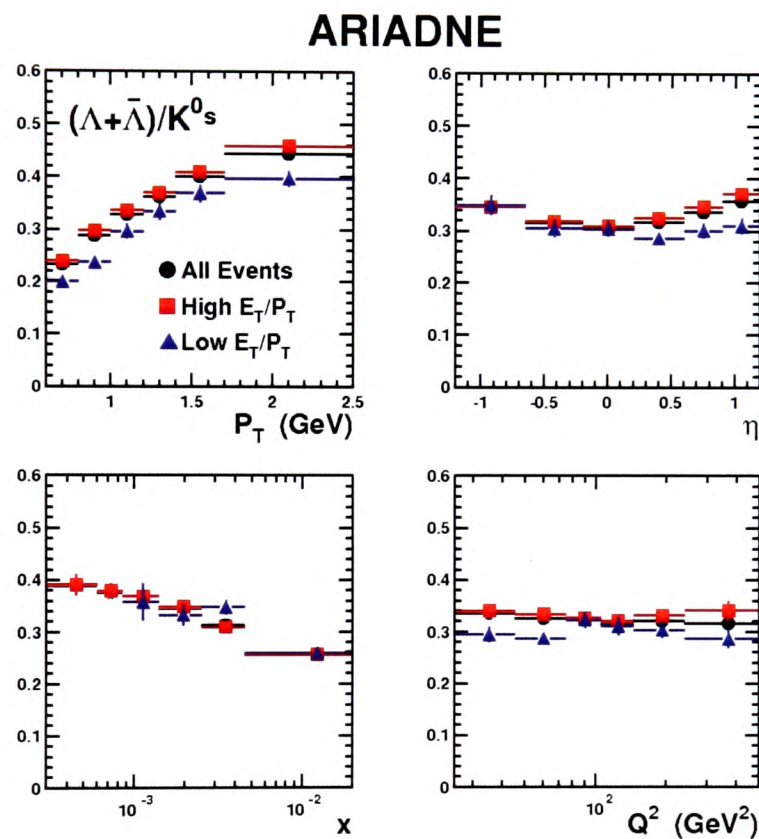


Figure 8.30: $(\Lambda + \bar{\Lambda})/K_s^0$ ratio for the High Q^2 ARIADNE sample. Black points show the ratio for the full sample; red points show the ratio for those events where $E_T/P_T > 1.7$ (multi-jet enriched); blue points show the ratio for those events where $E_T/P_T < 1.7$ (single-jet enriched). Statistical errors only are shown. All the available MC is used. The two lowest points in x for the Low E_T/P_T sample are omitted due to insufficient statistics.

value of $(\Lambda + \bar{\Lambda})/K_s^0$ in single-jet events than multi-jet events across the whole range of η ($-1.2 < \eta < +1.2$). The MC only shows a difference in the ratio for $\eta \gtrsim 0$. The data $(\Lambda + \bar{\Lambda})/K_s^0$ ratio as a function of x begins to decrease in single-jet events, when $x \lesssim 0.003$, which is not seen in the MC. The Q^2 profile of the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio tends to increase as Q^2 increases for single jet events, but tends to decrease for multi-jet events (aside from the anomalous point at the highest Q^2). The MC gives an approximately constant ratio as a function of Q^2 .

The difference between data and MC is most pronounced at low x and low Q^2 . Therefore, a subsample of events with $25 \leq Q^2 \leq 120 \text{ GeV}^2$ and $x \leq 0.002$ is investigated. The $(\Lambda + \bar{\Lambda})/K_s^0$ ratios obtained for data and MC in this region, separated into high and low E_T/P_T are shown in Fig. 8.31. The effect of splitting events in this way has a clear

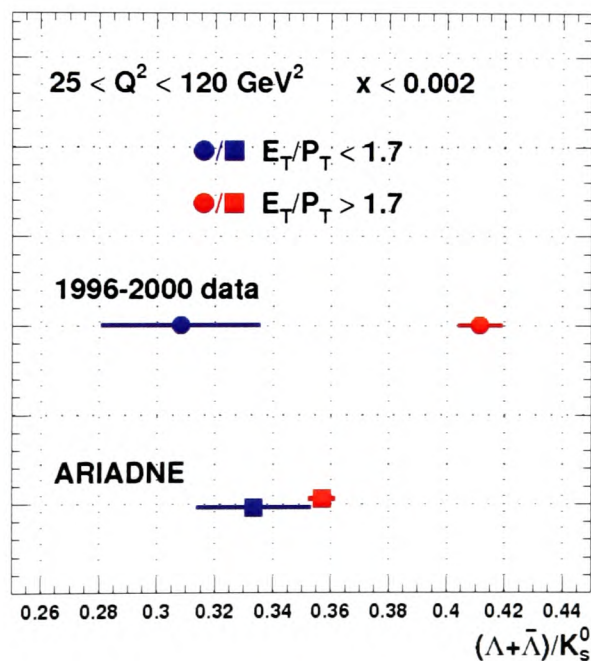


Figure 8.31: $(\Lambda + \bar{\Lambda})/K_s^0$ ratio for the data (circles) and MC (squares) events in the region $25 \leq Q^2 \leq 120 \text{ GeV}^2$ and $x \leq 0.002$. Red points show the ratio for those events where $E_T/P_T > 1.7$ (multi-jet enriched); blue points show the ratio for those events where $E_T/P_T < 1.7$ (single-jet enriched). Statistical errors only are shown. All the available MC is used.

effect on the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio in this region of x and Q^2 in the data. A lower value of the ratio is obtained in the single-jet enriched sample: $\frac{\Lambda + \bar{\Lambda}}{K_s^0} = 0.31 \pm 0.03$. A higher value of the ratio is obtained in the multi-jet enriched sample: $\frac{\Lambda + \bar{\Lambda}}{K_s^0} = 0.41 \pm 0.01$. This difference is not seen in the ARIADNE $(\Lambda + \bar{\Lambda})/K_s^0$ ratio.

To investigate further the events where this difference is seen, the η^{max} distributions

are examined for data and MC in four regions:

- $25 \leq Q^2 \leq 120 \text{ GeV}^2$ AND $x \leq 0.002$ with $E_T/P_T > 1.7$
- $25 \leq Q^2 \leq 120 \text{ GeV}^2$ AND $x \leq 0.002$ with $E_T/P_T < 1.7$
- $Q^2 > 120 \text{ GeV}^2$ OR $x > 0.002$ with $E_T/P_T > 1.7$
- $Q^2 > 120 \text{ GeV}^2$ OR $x > 0.002$ with $E_T/P_T < 1.7$

$\eta^{\max}$ is the η value of the furthest forward hadronic energy deposit in the detector. Standard DIS events, where a coloured quark or gluon receives a 4-momentum transfer from the electron, have a colour field connecting the proton remnant with the struck quark or gluon. This gives rise to hadrons produced throughout the area of the colour field, which leads to a large value of $\eta^{\max}$. Diffractive events, where a colour-neutral object (the pomeron) receives the 4-momentum transfer, have no such colour field, and so can give rise to events with smaller values of $\eta^{\max}$. The $\eta^{\max}$ distributions are shown in Fig. 8.32.

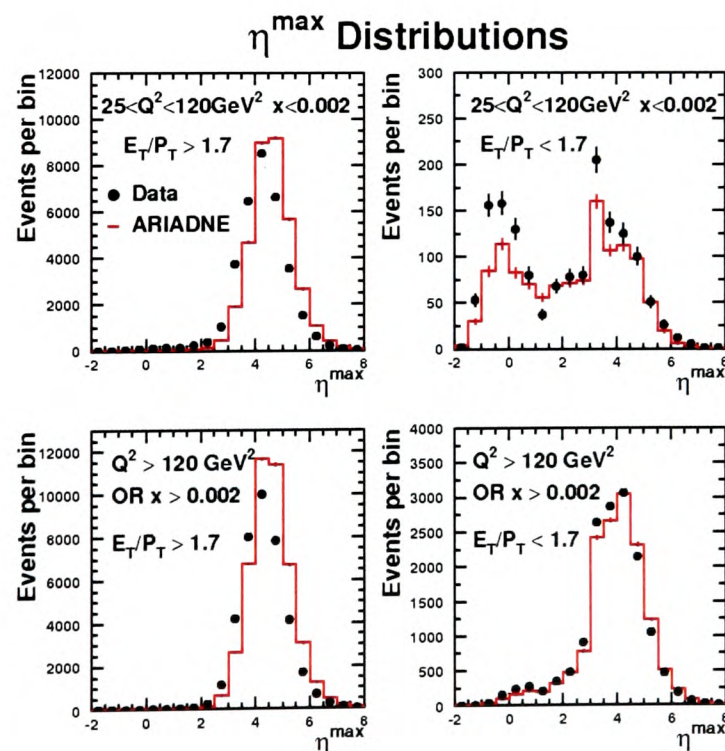


Figure 8.32: Detector level $\eta^{\max}$ distributions for events containing a Λ , $\bar{\Lambda}$ or K_s^0 . ARIADNE (red line) is normalized to the same luminosity as the data (black circles). Statistical errors only are shown. All the available MC is used.

The diffractive corner at low x and low Q^2 is the only place where there is a significant difference between single-jet and multi-jet events. At other x and Q^2 the number of jets in the event makes little difference to the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio.

8.4.3 Baryon-meson ratio across the $x - Q^2$ plane

The variables x and Q^2 in DIS events are not independent, but are correlated to some degree. In an attempt to separate any x and Q^2 dependence on the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio, the High Q^2 and Low Q^2 samples are combined to obtain the ratio as a function of x in four bins of Q^2 and as a function of Q^2 in four bins of x . The bin definitions are displayed in Tables 8.5 and 8.6. The MC was used to obtain the average x and Q^2 values displayed in the tables. The $(\Lambda + \bar{\Lambda})/K_s^0$ ratio with this $x - Q^2$ separation are shown

Q^2 bin (GeV ²)	Average Q^2 (GeV ²)	x Bin boundaries				
5.0 - 9.5	6.9	0.00005	0.00023	0.00032	0.00062	0.006
9.5 - 25.0	15	0.00012	0.00048	0.00075	0.0014	0.01
25.0 - 100.0	46	0.00025	0.00098	0.0015	0.003	0.02
100.0 - 500.0	188	0.0014	0.0035	0.006	0.01	0.02

Table 8.5: Bin boundaries to obtain x dependence in bins of Q^2 .

x bin	Average x	Q^2 Bin boundaries (GeV ²)				
0.00002 - 0.0003	0.00019	5.0	6.0	7.5	10.0	21.0
0.0003 - 0.0006	0.00044	5.0	8.0	12.0	25.0	50.0
0.0006 - 0.0014	0.00095	5.0	10.0	25.0	40.0	100.0
0.0014 - 0.02	0.0040	5.0	25.0	70.0	200.0	600.0

Table 8.6: Bin boundaries to obtain Q^2 dependence in bins of x .

in Fig. 8.33 and Fig. 8.34.

For each of the Q^2 bins, the ratio decreases from ~ 0.42 to ~ 0.24 as x increases, with a similar trend in the MC. As a function of Q^2 the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio now increases, once the x dependence is removed.

8.4.4 Photoproduction

The baryon - meson ratio in the photoproduction sample as a function of x_γ , P_T and η can be seen in Fig. 8.35, with the expectation from the PYTHIA MC shown for comparison (no normalization of the MC sample is applied for these plots). The systematic error due to the inadequacies of the MC simulation are estimated by comparing the results obtained from data corrected for detector effects with correction factors from different MC samples. Data corrected with the optimal MC combination of direct and resolved photoproduction

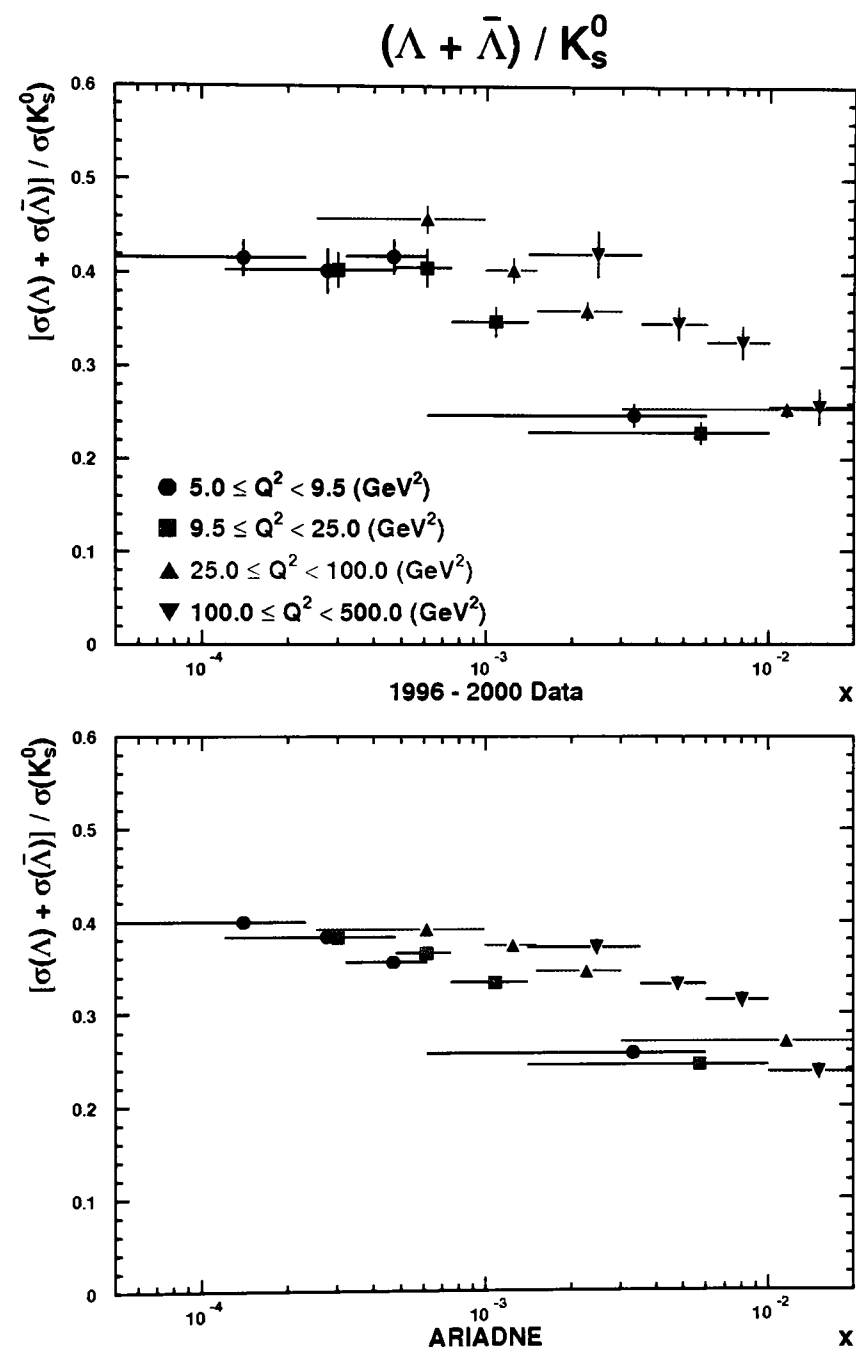


Figure 8.33: $(\Lambda + \bar{\Lambda})/K_s^0$ ratio as a function of x in four bins of Q^2 . Statistical errors are included for both data and MC.

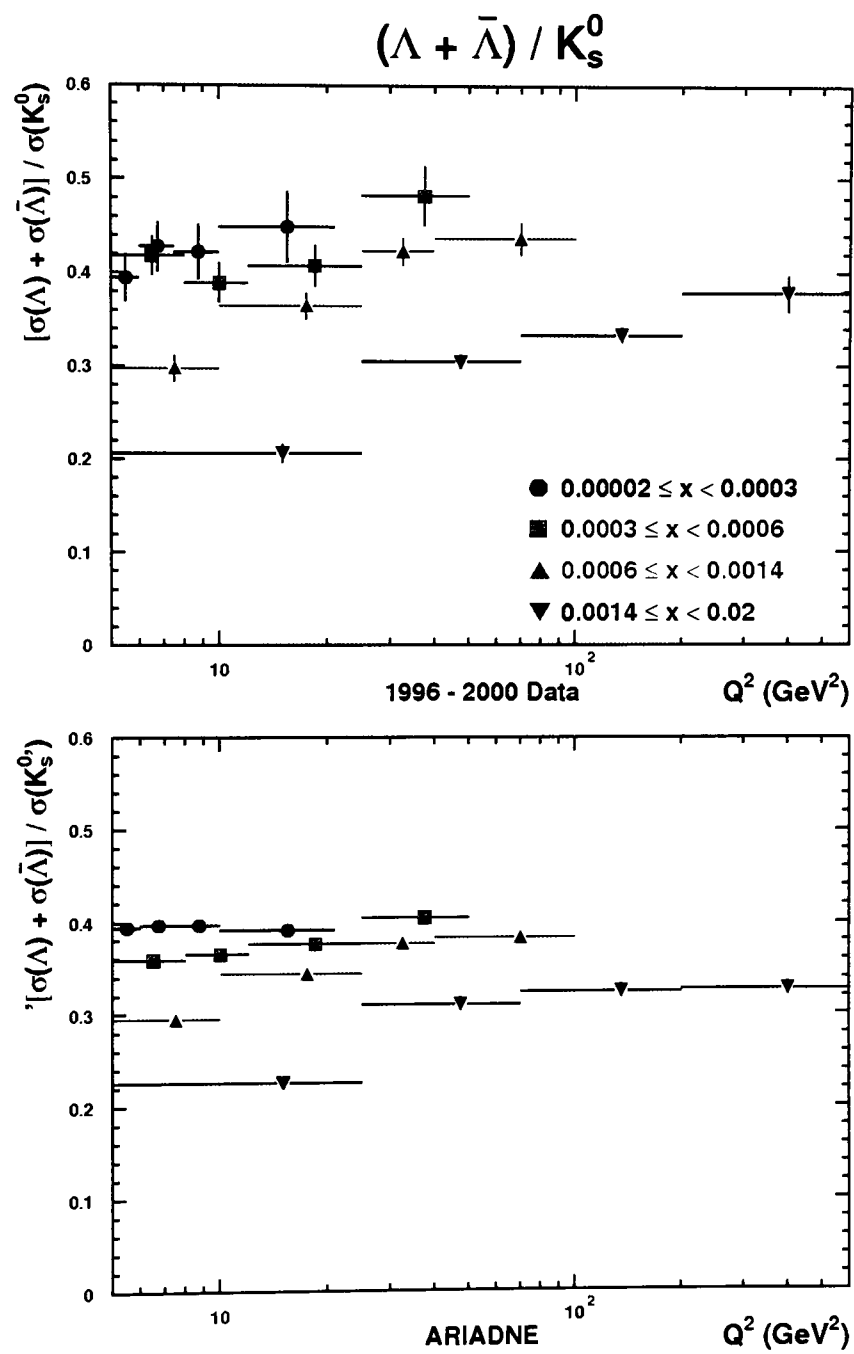


Figure 8.34: $(\Lambda + \bar{\Lambda})/K_s^0$ ratio as a function of Q^2 in four bins of x . Statistical errors are included for both data and MC.

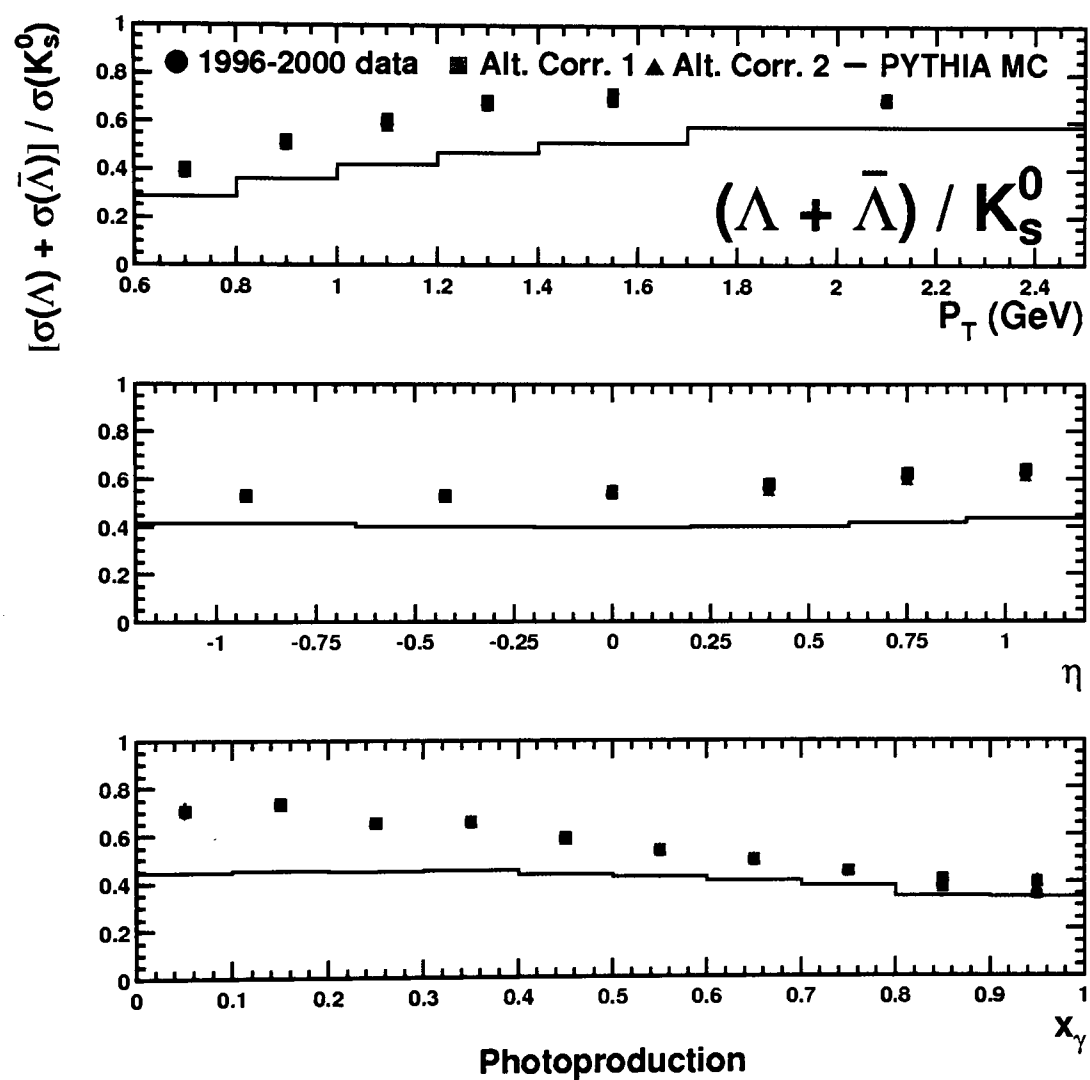


Figure 8.35: $(\Lambda + \bar{\Lambda})/K_s^0$ ratio for the photoproduction sample. Statistical errors are included, but are smaller than the point size. Black circles show the data corrected with the optimal correction factors. Two alternative correction factors are used, as discussed in the text, which give rise to the red triangles and squares. The yellow band shows the systematic error due to the calorimeter energy scale.

samples are shown as black circles. Red triangles show the data corrected with the same direct sample reweighted by a factor $\times 2$, added to the resolved sample (Alternative Correction 1). Red squares show the data corrected with just the resolved MC sample (Alternative Correction 2). The effect of using these different MC samples to correct the data is small. The yellow band shown on the plots gives an estimate of the systematic error due to the uncertainty in the energy scale of the calorimeter.

The data generally give a significantly larger value of the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio than PYTHIA. This abundance of baryon to meson production occurs mainly at low x_γ .

The data sample is split into those events where a high proportion of the total transverse energy is in the highest E_T jet, and the remainder, where the highest E_T jet has a small proportion of the total E_T (as defined in Section 7.6). The detector corrections for the full sample are applied to the two subsamples ('High' and 'Low') and the resulting $(\Lambda + \bar{\Lambda})/K_s^0$ ratios are shown in Fig. 8.36. The same correction method is applied to reconstructed PYTHIA Λ and K_s^0 , with events similarly divided according to detector level total E_T and E_T of the highest E_T jet.

In the data, events with a small proportion of the total E_T in the highest E_T jet have a larger $(\Lambda + \bar{\Lambda})/K_s^0$ ratio than events with a large proportion of the total E_T in the highest E_T jet. This is not seen in the PYTHIA MC.

8.5 Ratio of Strange Particles to Tracks

A measure of the amount of strangeness in an event is obtained by finding the ratios $(\Lambda + \bar{\Lambda})/(N_{Tracks})$ and $K_s^0/(N_{Tracks})$, where only strange particles and charged tracks in the region $0.6 < P_T < 2.5\text{GeV}$ and $|\eta| < 1.2$ are considered. The number of charged tracks in an event is corrected for detector effects as described in Section 7.5.

8.5.1 $5 \leq Q^2 \leq 25\text{GeV}^2$

The ratios of strange particles to charged tracks in the Low Q^2 sample are shown in Fig. 8.37.

The $(\Lambda + \bar{\Lambda})/(N_{Tracks})$ and $K_s^0/(N_{Tracks})$ ratios are approximately constant as a func-

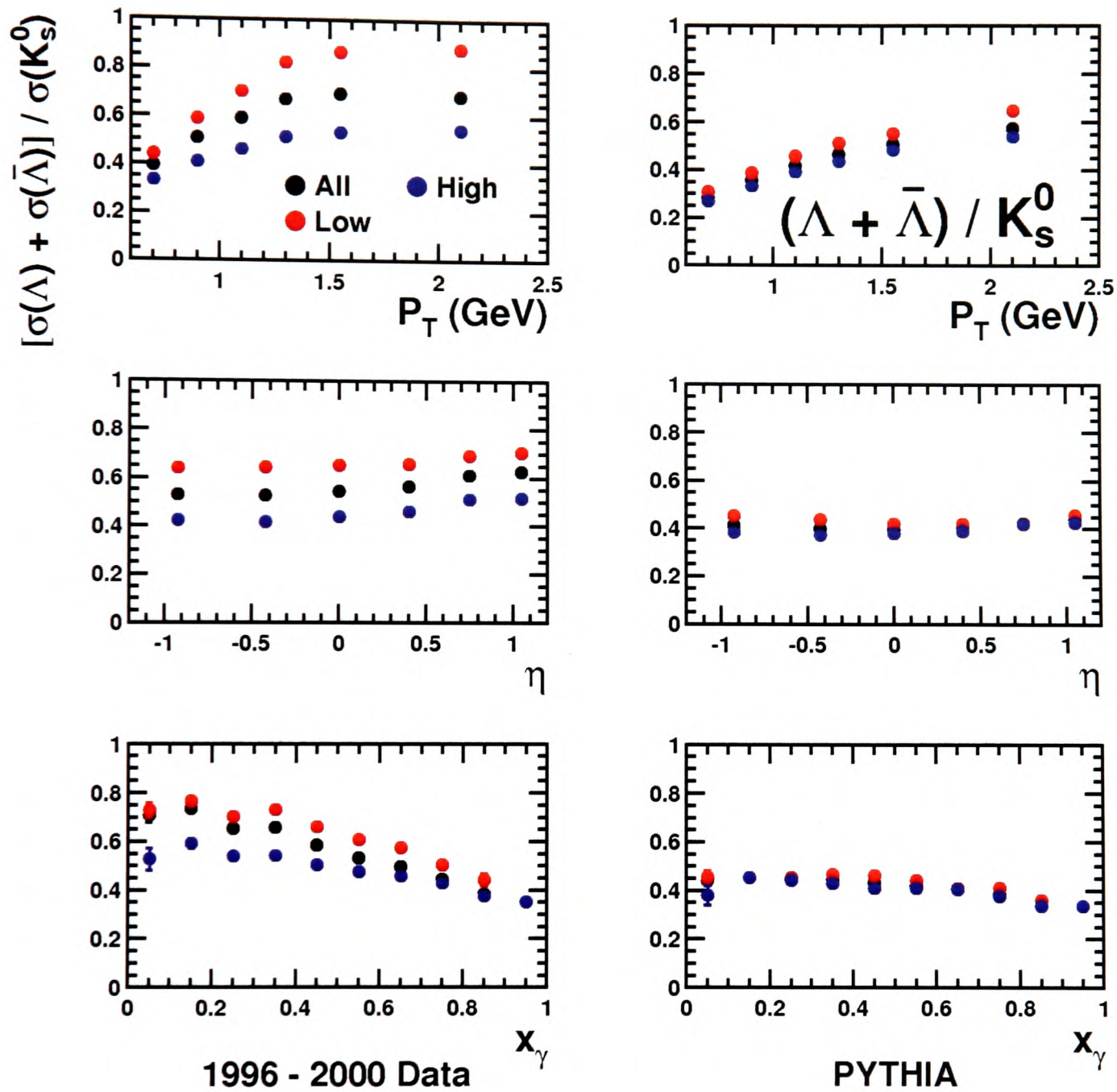


Figure 8.36: $(\Lambda + \bar{\Lambda})/K_s^0$ ratio for the photoproduction sample. Black points show the ratio for the full sample; red points show the ratio for those events where a small proportion of the total E_T is carried by the highest E_T jet; blue points show the ratio for those events where a large proportion of the total E_T is carried by the highest E_T jet, as discussed in the text. Statistical errors are included but are generally smaller than the point size.

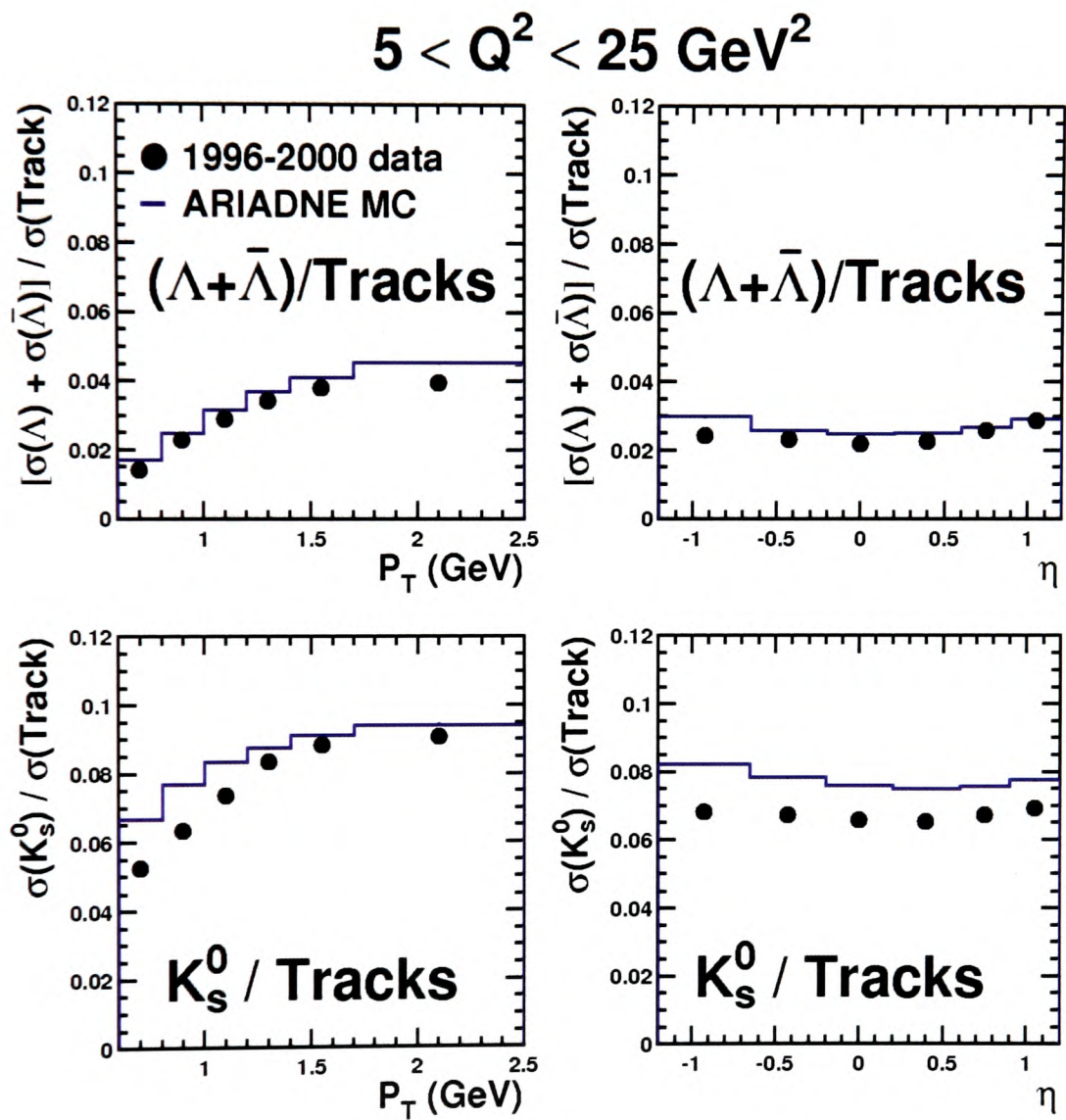


Figure 8.37: Ratios of strange particles to total number of tracks as a function of P_T and η in the Low Q^2 sample. Statistical errors only are shown. The MC contains samples with $E_P = 820\text{GeV}$ and $E_P = 920\text{GeV}$ in the same proportion as the data.

tion of η . Both ratios do increase as P_T increases, the data more steeply than the MC in the K_s^0 case. The MC gives a higher value of the $K_s^0/(N_{Tracks})$ ratio than the data.

If the data are split into events with a large proportion of the total E_T in the highest E_T jet, and events with a small proportion of the total E_T in the highest E_T jet, the strange particle to track ratios are affected as shown in Fig. 8.38.

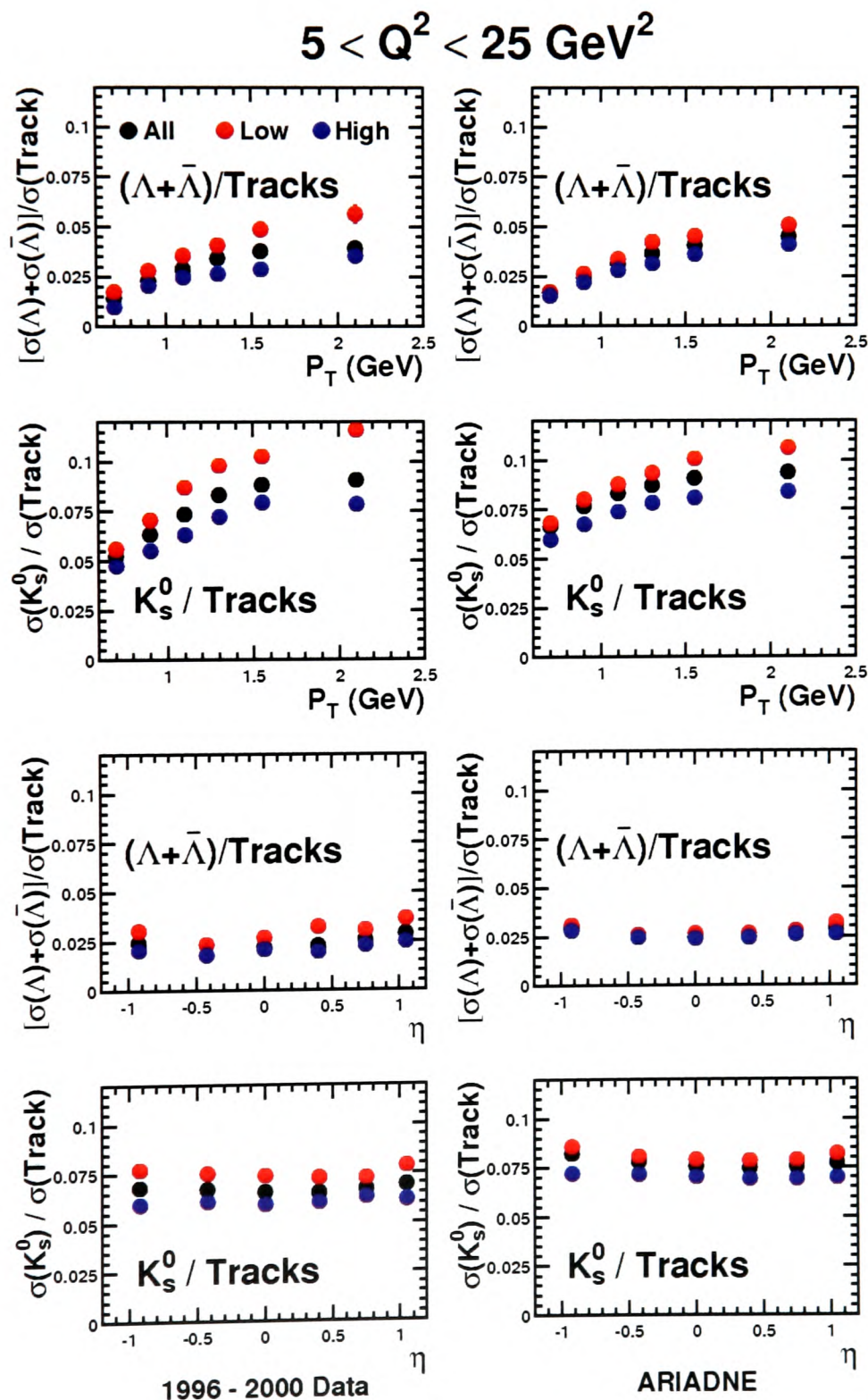


Figure 8.38: Ratios of strange particles to total number of tracks as a function of P_T and η in the Low Q^2 sample. Black points show the ratio for the full sample; red points show the ratio for those events where a small proportion of the total E_T is carried by the highest E_T jet; blue points show the ratio for those events where a large proportion of the total E_T is carried by the highest E_T jet, as discussed in the text. Statistical errors only are shown.

8.5.2 $Q^2 \geq 25\text{GeV}^2$

The ratios of strange particles to tracks in the High Q^2 sample are shown in Fig. 8.39.

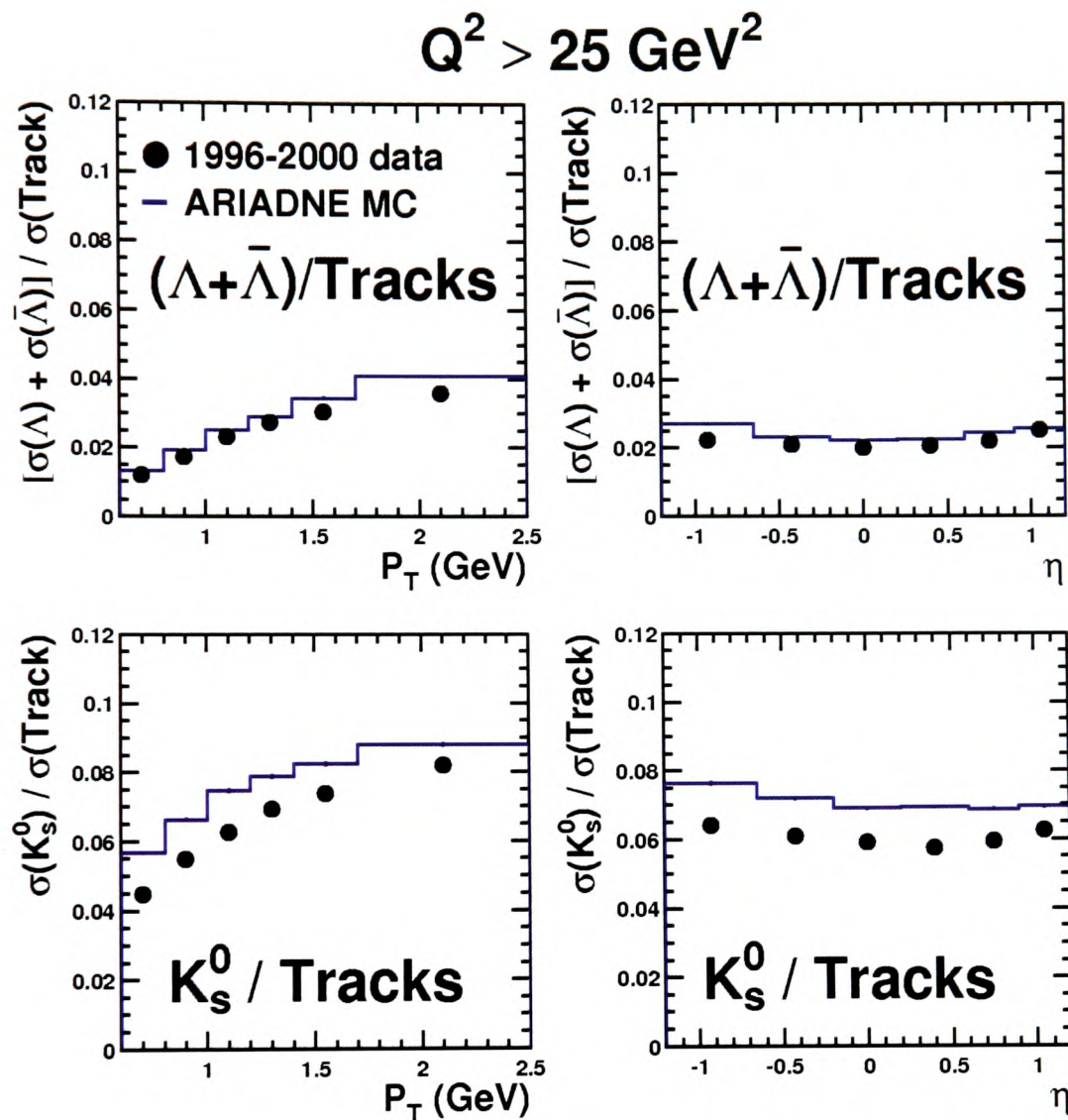


Figure 8.39: Ratios of strange particles to total number of tracks as a function of P_T and η in the High Q^2 sample. Statistical errors only are shown. The MC contains samples with $E_P = 820\text{GeV}$ and $E_P = 920\text{GeV}$ in the same proportion as the data.

As in the Low Q^2 sample, the $(\Lambda + \bar{\Lambda})/(N_{Tracks})$ and $K_s^0/(N_{Tracks})$ ratios are approximately constant as a function of η , and increase as P_T increases. The MC gives a higher value of the $K_s^0/(N_{Tracks})$ ratio than the data.

If the data are split into events with a large proportion of the total E_T in the highest E_T jet, and events with a small proportion of the total E_T in the highest E_T jet, the strange particle to track ratios are affected as shown in Fig. 8.40.

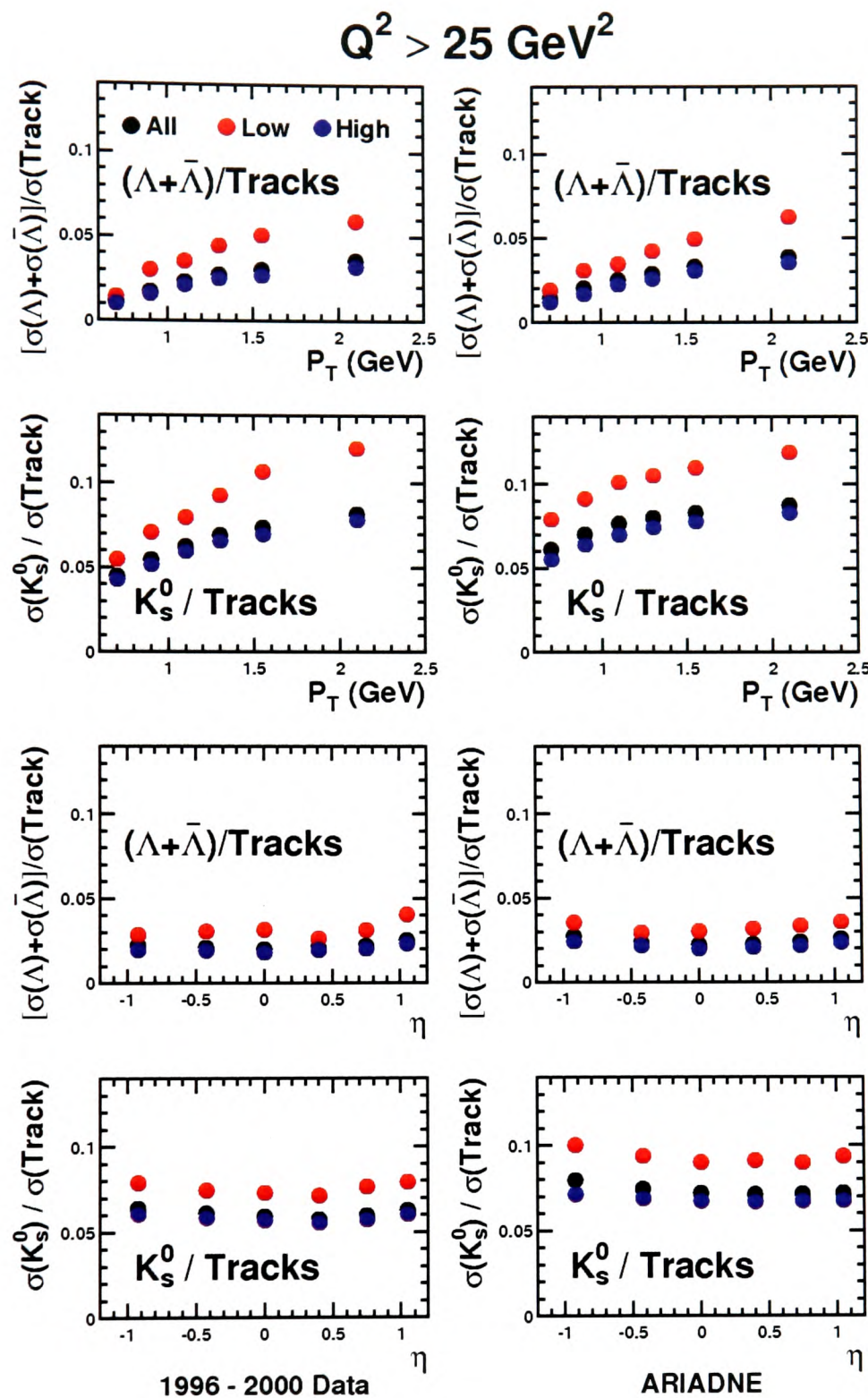


Figure 8.40: Ratios of strange particles to total number of tracks as a function of P_T and η in the High Q^2 sample. Black points show the ratio for the full sample; red points show the ratio for those events where a small proportion of the total E_T is carried by the highest E_T jet; blue points show the ratio for those events where a large proportion of the total E_T is carried by the highest E_T jet, as discussed in the text. Statistical errors only are shown. All the available MC is used for the strange particle production in the MC plots.

8.5.3 Photoproduction

The ratios of strange particles to tracks in the photoproduction sample are shown in Fig. 8.41.

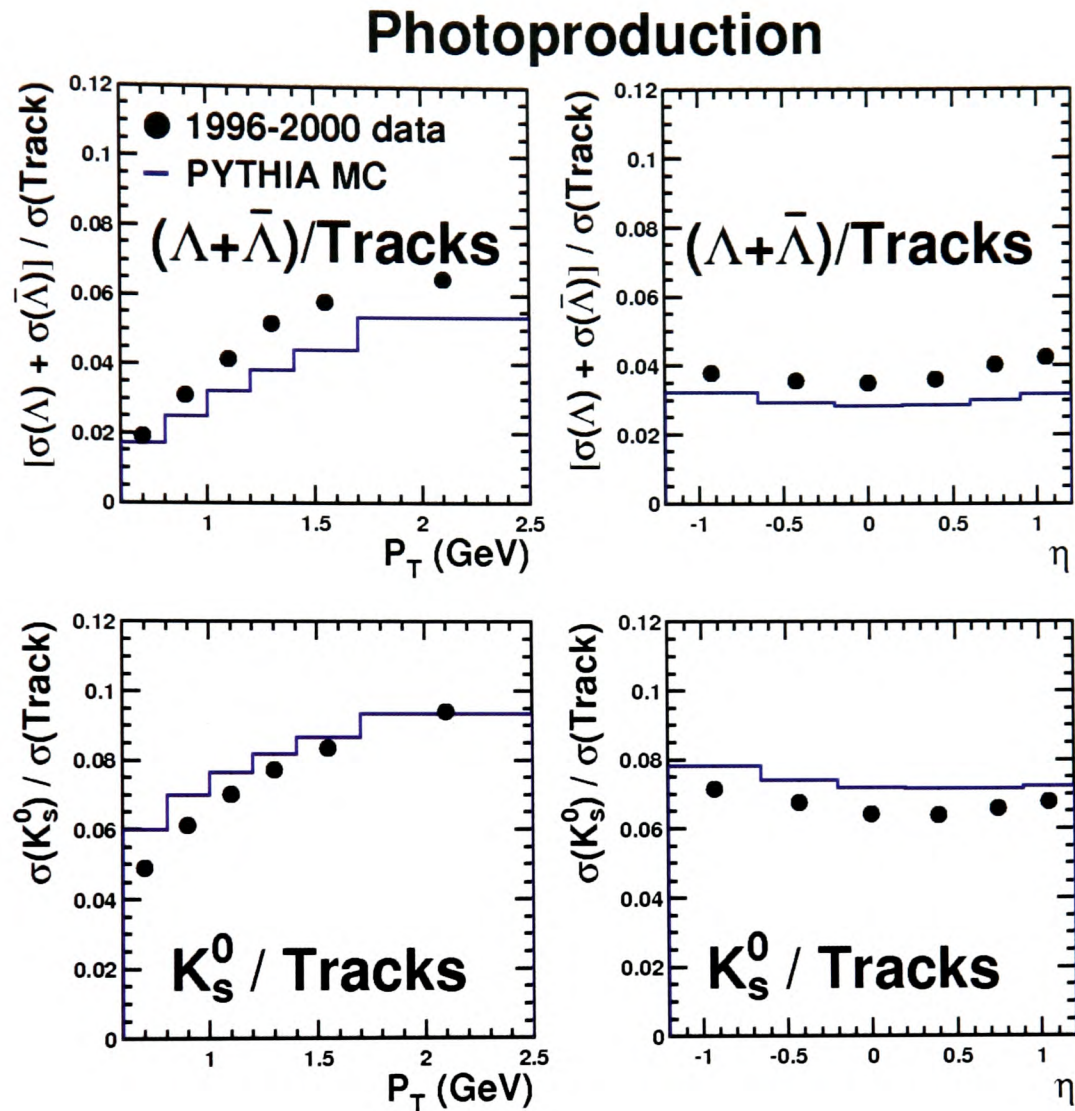


Figure 8.41: Ratios of strange particles to total number of tracks as a function of P_T and η in the photoproduction Q^2 sample. Statistical errors only are shown.

As in the DIS samples, the $(\Lambda + \bar{\Lambda})/(N_{Tracks})$ and $K_s^0/(N_{Tracks})$ ratios are approximately constant as a function of η , but increase as P_T increases. The MC gives a slightly higher value of the $K_s^0/(N_{Tracks})$ ratio than the data, but a lower value of the $(\Lambda + \bar{\Lambda})/(N_{Tracks})$ ratio than the data.

If the data are split into events with a large proportion of the total E_T in the highest E_T jet, and events with a small proportion of the total E_T in the highest E_T jet, the strange particle to track ratios are affected as shown in Fig. 8.42.

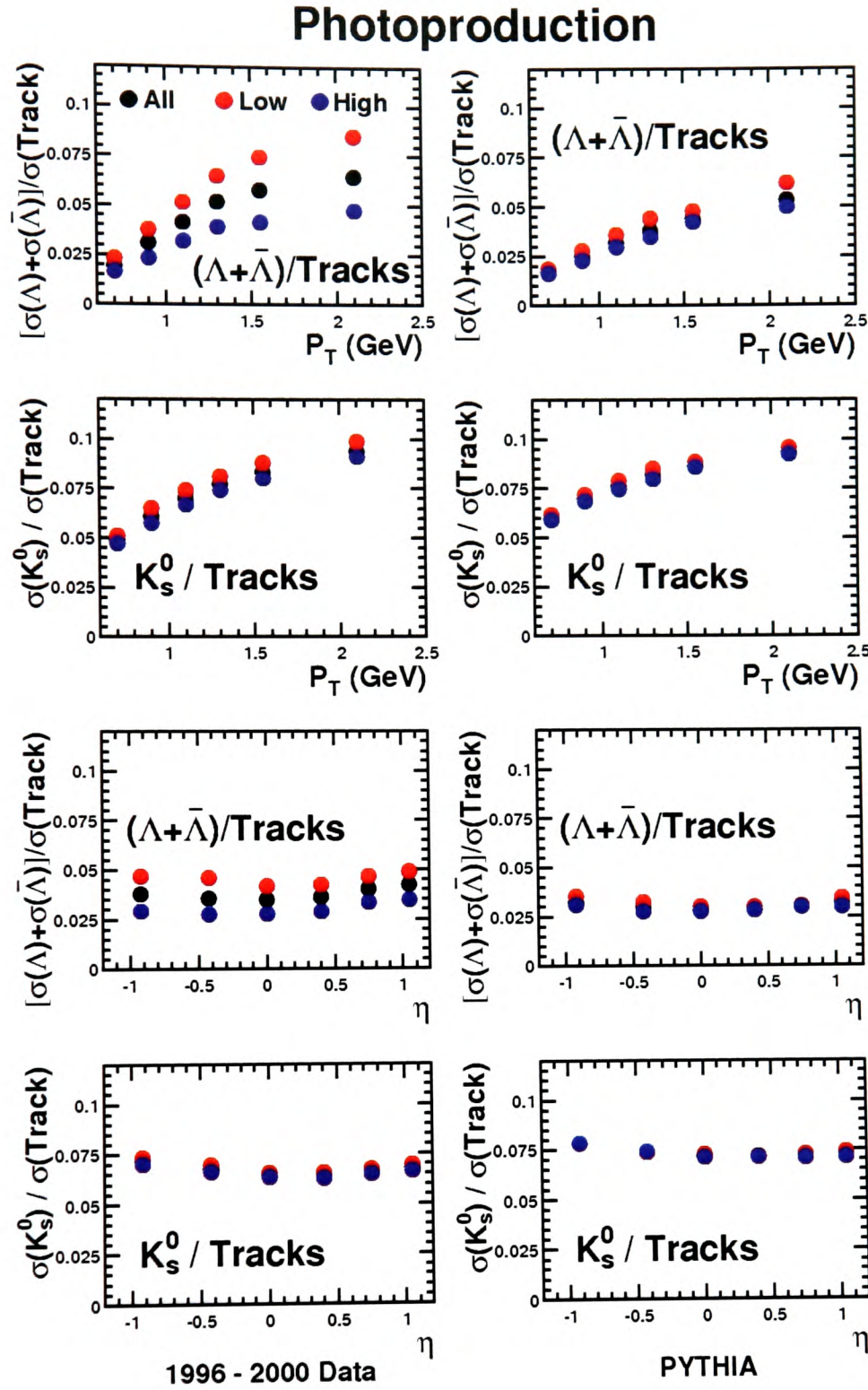


Figure 8.42: Ratios of strange particles to total number of tracks as a function of P_T and η in the photoproduction sample. Black points show the ratio for the full sample; red points show the ratio for those events where a small proportion of the total E_T is carried by the highest E_T jet; blue points show the ratio for those events where a large proportion of the total E_T is carried by the highest E_T jet, as discussed in the text. Statistical errors only are shown. All the available MC is used for the strange particle production in the MC plots.

Chapter 9

Conclusions

9.1 Cross-sections

The differential cross-sections of Λ , $\bar{\Lambda}$ and K_s^0 have been measured in DIS and in photo-production.

The shapes and magnitude of the cross-sections as functions of P_T , η , x and Q^2 are approximately simulated by ARIADNE in DIS events. For all the particles, the cross-sections decrease rapidly as a function of the event Q^2 , due to the propagator of the transferred photon behaving as $1/q^2$. The correlation between x and Q^2 leads to a decrease in the cross-sections as x increases. More strange particles are produced in the forward region ($\eta > 0$) than the backward region. The momenta of the proton and electron beam are asymmetric, resulting in the centre-of-mass of the total eP system moving in the forward direction. However, at the very low x values of most events, the centre-of-mass of the electron-parton system is travelling in a backwards direction. The struck parton and the proton generally remain connected by a colour field, out of which hadrons predominantly emerge (the fragmentation region of the proton). As a function of increasing P_T , the strange particle production cross-sections decrease, which is consistent with scattering experiments generally, from Rutherford scattering to other ZEUS measurements, eg. [64].

The K_s^0 production cross-sections are generally overestimated by the MC, whereas the Λ and $\bar{\Lambda}$ MC cross-sections are closer to the data. The MC does contain various parameters that control both the suppression of strange quarks relative to up and down quarks, and the production of baryons relative to mesons. Careful tuning of these pa-

rameters could achieve a better description of the data by the MC. However, different experiments at different energies prefer different values of, for example, the strangeness suppression factor [65], suggesting that these parameters are far from universal and not indicative of the physics.

The strange particle cross-sections in the dijet photoproduction sample show similar trends as a function of P_T and η , with the shapes of the differential cross-sections fairly well simulated by PYTHIA. However, the cross-section as a function of x_γ is not well described by the MC. The data show a significant peak in the Λ and $\bar{\Lambda}$ cross-sections at low x_γ ($x_\gamma \sim 0.15$), and a smaller peak at high x_γ ($x_\gamma \sim 0.85$). The peak at high x_γ is more pronounced for K_s^0 production. PYTHIA is particularly unable to simulate the large cross-sections at low x_γ . The PYTHIA version used in this thesis contains Multiple Interactions (MI), which are included to give a better description of low E_T jets, which are seen particularly in events with low x_γ . Including MI increases the production cross-sections at low x_γ (see, for example, Fig. 1.19), but by an insufficient amount to account for strange particle production in events where the two jets have $E_T > 5.0\text{GeV}$. Inclusive jet production at this E_T^{jet} is also underestimated, even with MI included [29]. Again, parameters in the implementation of MI in the MC may exist that can be tuned to give a better description of the cross-sections but, as will be shown later, this is unlikely to describe the underlying physics.

9.2 Polarization

9.2.1 Transverse Polarization

The transverse polarization measurements give an indication of any preferred frame in Λ and $\bar{\Lambda}$ production. In the model of DeGrand and Miettinen [17] the sign of the polarization gives an indication of the initial direction of the strange quark. In all three of the event samples investigated no transverse polarization significantly different from zero is observed. Therefore the conclusion is made that either there is no preferred initial direction of the strange quark, or that any polarization that does arise is smaller than the resolution of the analysis (the error on the measurements is $\sim \pm 8\%$ in the DIS samples, and $\sim \pm 3\%$ in photoproduction). The resolution of this analysis is somewhat

smaller than polarizations that have been measured previously. HERMES measured Λ polarizations of up to $\sim 10\%$ [18], in inclusive scattering of a virtual photon on nuclear targets. Heller *et al.* observed Λ polarizations of up to $\sim 20\%$ [19] in proton beryllium scattering.

The strange quarks that are contained in Λ and $\bar{\Lambda}$ can come from a variety of possible sources, as discussed in Section 2.2. If the dominant production mechanism of strange hadrons is from either strange quarks in the resolved photon, or in the proton sea, then a polarization (of the opposite sign for each beam) would be expected. If neither of these processes dominate, then the polarization of the individual particles would average to a much smaller value when looking at the whole sample. Additionally, strange quarks may originate from the fragmentation, where again, the lack of a preferred frame results in the polarization averaging to zero.

9.2.2 Longitudinal Polarization

The longitudinal polarization of Λ and $\bar{\Lambda}$ is expected to be zero if unpolarized beams are used, and it is always observed to be consistent with zero across the kinematic range investigated in this analysis. The upgraded accelerator, HERA-II, now provides a polarized lepton beam (at the level of $\sim 40\%$). Some fraction of this polarization is expected to transfer to any produced Λ and $\bar{\Lambda}$. Given the same luminosity, triggers, and tracking detectors as used in this analysis, ZEUS can measure Λ longitudinal polarization with a statistical resolution of $\sim 10\%$ in DIS events and $\sim 5\%$ in photoproduction. The statistics are likely to improve due to increased luminosity from HERA, and due to the addition of the Micro Vertex Detector (MVD) to ZEUS, which will allow the reconstruction of strange particles that decay much closer to the interaction point. There may be some restraints on the improvement in the available statistics due to changes in the triggers, however. Overall, the prospects are good for measuring the longitudinal polarization in HERA-II to a statistical precision of a few percent. Additional systematic errors will potentially come from imperfect understanding of the new tracking environment, but should be small.

9.3 Baryon - Antibaryon Asymmetry

In all the event samples and subsamples, across all the variables investigated, no significant $(\Lambda - \bar{\Lambda})$ asymmetry is observed, leading to the conclusion that in the HERA eP collisions there is no substantial transfer of the Baryon Number (BN) from the proton beam to the strange particle system in the detector region.

Baryon Number is clearly related to valence quarks, given the definition that baryons are composed of 3 valence quarks, and antibaryons of 3 antiquarks. Both ARIADNE and PYTHIA MC programs give small but positive asymmetry values ($\frac{(\Lambda - \bar{\Lambda})}{(\Lambda + \bar{\Lambda})} \lesssim 1\%$), which it is believed arise from a small number of Λ containing a u or d valence quark. The separation of DIS events into events with a large fraction of the total E_T in the highest E_T jet and events with a small fraction of the total E_T in the highest E_T jet will effectively separate out a single-jet enriched sample and a multi-jet enriched sample respectively. If the hard eP sub-process involves a quark (or antiquark) from the proton, a single-jet event is more likely than if a gluon from the proton was involved. This separation can therefore test the extent to which the different quark and antiquark distributions in the proton affect the $(\Lambda - \bar{\Lambda})$ asymmetry. No significant differences in the asymmetry distributions are seen, however, suggesting that valence quarks do not play a sizable role in baryon production at this rapidity.

A previous public measurement of baryon asymmetry at HERA is a preliminary result from H1, observing the proton - antiproton asymmetry in photoproduction [66]. The results, showing a positive asymmetry at a level of $4\% \pm \sim 1.5\%$ (removing an extra factor of 2, due to an alternative definition of the asymmetry) can be seen in Fig. 9.1. Although these are not brazenly inconsistent with the measurements presented in this thesis, they do tend to show a somewhat higher value of the baryon asymmetry - cf. the average asymmetry in photoproduction in ZEUS, $\frac{(\Lambda - \bar{\Lambda})}{(\Lambda + \bar{\Lambda})} = -0.02\% \pm 0.6\%$ (stat. only). The proton - antiproton H1 result has been interpreted by Garvey, Kopeliovich and Povh [20] as support for the model where BN is carried by a gluonic junction. This model predicts an average BN asymmetry in the detector region of $\sim 3.5\%$, which is slightly higher than that observed in the Λ system in ZEUS. This paper also notes that the asymmetry of specific baryons (i.e. Λ) is not necessarily identical with the overall

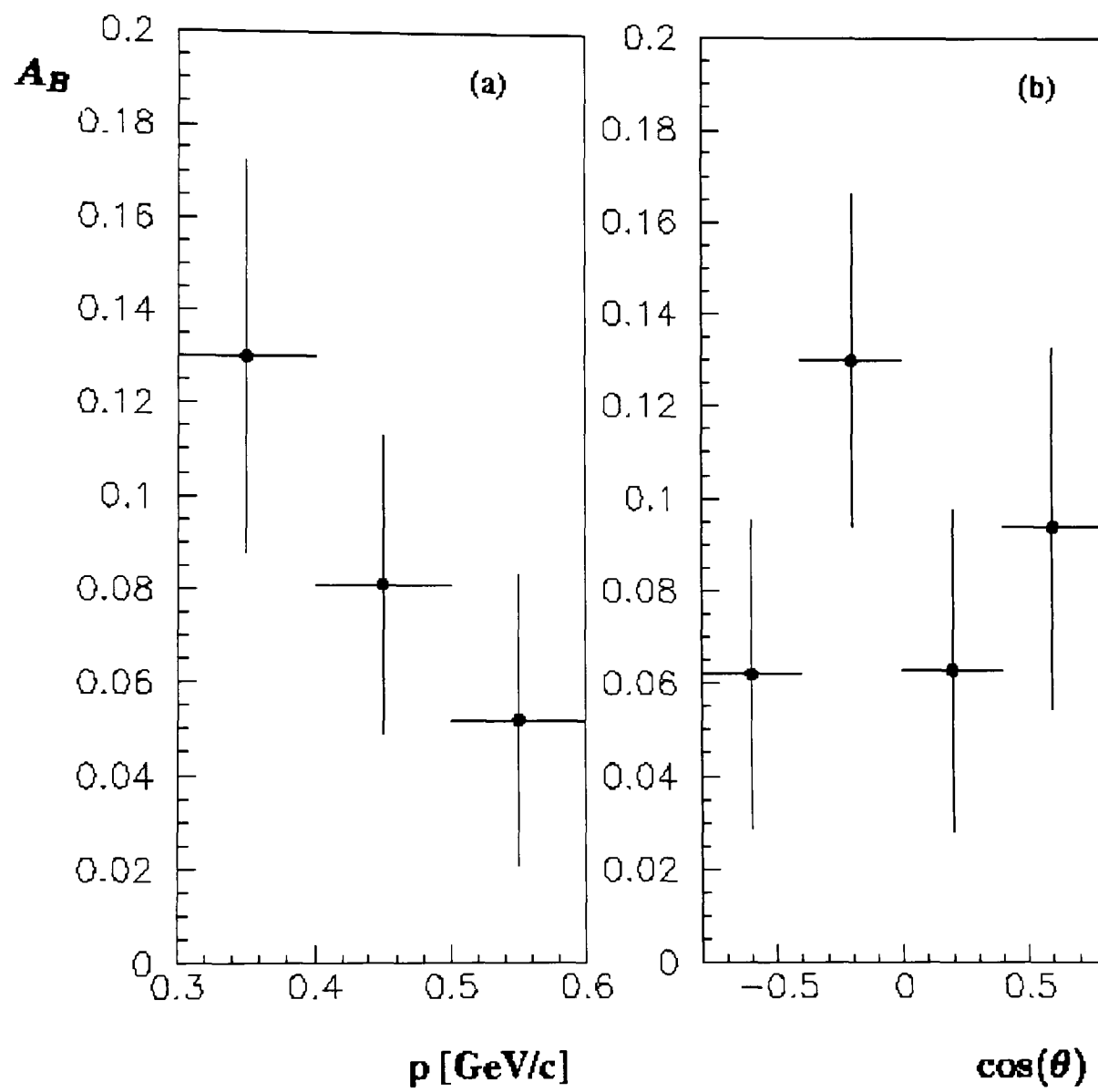
H1 Preliminary

Figure 9.1: Proton-antiproton asymmetry, $2\frac{(p-\bar{p})}{(p+\bar{p})}$ in photoproduction at HERA measured by H1, shown as a function of momentum and azimuthal angle.

BN asymmetry, although the specific model propounded by Kopeliovich and Povh in [22] (and models generally that solely involve gluons) does not expect any flavour dependence. This model does agree with the data presented here in that no dependence on Q^2 is predicted.

Baryon asymmetries have also been measured in the heavy ion collisions at RHIC [23], where surprisingly large excesses of baryon compared with antibaryon were seen. Two models are able to give adequate descriptions of this baryon - antibaryon asymmetry. The gluonic junction model previously mentioned, which associates baryon number with a junction of the colour field connecting the quarks, rather than the valence quarks themselves, and the partonic rescattering model [24], which obtains the necessary baryon number transport from the beam to the detector by multiple scattering of the valence quarks. The gluonic junction model seems to slightly overestimate the BN transport observed in the Λ system at ZEUS. Although it is not known exactly how the partonic rescattering model will transfer to the HERA environment, multiple rescattering of partons is likely to be much less significant in the hugely less dense environment of eP collisions than the Au-Au collisions at RHIC.

9.4 Baryon - Meson Ratio

The traditional view of hadron production in eP collisions is that a parton (quark or gluon) involved in the hard subprocess which receives a large enough 4-momentum transfer to escape from the proton will fragment into a jet of hadrons. Extra quarks are formed when the colour field connecting the struck parton to the proton remnant becomes strong enough for quark-antiquark pairs to be produced from the vacuum. The quarks then combine according to a one-dimensional overlap of their wavefunctions to form mesons and baryons. With this model, what factors will influence when a baryon is produced rather than a meson, and is it sufficient to explain the various trends in the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio that are observed?

In both DIS and photoproduction the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio increases as a function of P_T . As a function of pseudorapidity $(\Lambda + \bar{\Lambda})/K_s^0$ is lowest in the central detector region ($\eta \sim 0$), and increases slightly in the backward and forward direction. These trends are

broadly simulated by the MC programs. The wider P_T distributions of heavier particles has been observed before (eg. [67]) and is also seen when taking the ratios of strange particles to charged tracks in this analysis.

In the DIS samples, the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio shows a substantial increase when x decreases, and increases very gradually when Q^2 decreases. This behaviour is also shown by ARIADNE, but is somewhat difficult to interpret in the light of the results from strange particle production in e^+e^- collisions. The results from e^+e^- colliders show an increase in the ratio as the centre of mass energy increases (see Table 2.1), which is plausible, given the greater energy available, increasing the phase space available for the heavier Λ more than K_s^0 .

In the DIS events at HERA, x and Q^2 are not independent. The distributions of the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio as a function of x in four bins of Q^2 , and as a function of Q^2 in four bins of x are easier to interpret, as they reduce the ambiguity of which variable is driving the physics.

When divided into small ranges of x to investigate solely the Q^2 dependence, it is observed that the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio increases as a function of Q^2 for every value of x , as might be expected were the available energy important as suggested by e^+e^- results. In the highest x bin ($x = 0.004$), $(\Lambda + \bar{\Lambda})/K_s^0$ increases from ~ 0.2 to ~ 0.38 across the full Q^2 range. Treating Q^2 in ZEUS as equivalent to $s/2$ in e^+e^- (the factor two arises as the energy is split equally between two partons in e^+e^- , whereas Q^2 may be transferred to only one parton), one observes that $(\Lambda + \bar{\Lambda})/K_s^0$ is slightly higher in the eP collisions at ZEUS than in e^+e^- collisions.

When $(\Lambda + \bar{\Lambda})/K_s^0$ is examined as a function of x in various bins of Q^2 it is observed that the ratio increases from ~ 0.24 to ~ 0.42 as x decreases, a trend that is approximately mirrored by ARIADNE. It is noted that at low x the gluon plays an increasingly dominant role in the proton PDFs (Fig. 1.4). The Lund String Model [50], employed by ARIADNE to perform the hadronisation, treats gluons as energy-momentum kinks on a colour string joining two quarks, which leads to the prediction that if the struck parton is a gluon, it is more likely to become a baryon than if the struck parton is a quark [68].

In general the data ratios are well described by the ARIADNE MC, except for a small

area of the phase space at low x and low Q^2 where diffractive events are prominent. In these diffractive events the data give a substantially lower value of $(\Lambda + \bar{\Lambda})/K_s^0$ than the MC. Aside from finding this diffractive corner, dividing the DIS sample into single-jet and multi-jet events does not have any great effect on $(\Lambda + \bar{\Lambda})/K_s^0$, so supporting the model of local production of hadrons based on a one-dimensional overlap of quark wavefunctions.

9.4.1 The Insufficiency of Multiple Interactions

The $(\Lambda + \bar{\Lambda})/K_s^0$ ratio in photoproduction is considerably greater than in DIS, rising to a maximum value of ~ 0.7 . The greatest difference between data and PYTHIA is seen at low x_γ . This is the region where MI in the MC have most effect. However, the effect of MI is to introduce more interactions of the same type to try to reduce the deficit in the MC cross-sections at low x_γ . This approach, however, cannot alter ratios such as $(\Lambda + \bar{\Lambda})/K_s^0$, and so is immediately called into question when seeing this large difference with the data in describing $(\Lambda + \bar{\Lambda})/K_s^0$. Dividing the photoproduction sample into simple dijet events (those with a high proportion of the total E_T in the highest E_T jet) and events with more jets or without a clearly defined jet structure (the fireball region) has a dramatic effect on $(\Lambda + \bar{\Lambda})/K_s^0$. The ratio is significantly lower for the simple dijet events than the multi-jet events in the data, but this effect is not visible in the MC. This may be interpreted using the recombination (or coalescence) model developed to explain the baryon to meson ratios observed at RHIC [26]. Where a simple dijet process occurs then simple fragmentation (from a one-dimensional overlap of quark wavefunctions) is the best model, as in DIS. When no such jet structure is present then hadrons form by a more-than-one-dimensional overlap of quark wavefunctions, only possible when the quarks are so close together in position and momentum. This model of hadron production increases the baryon production relative to mesons in dense areas of the phase space, as observed by ZEUS.

9.5 Strange Particle to Track Ratio

By taking the ratios $(\Lambda + \bar{\Lambda})/N_{Tracks}$ and K_s^0/N_{Tracks} a measure of the amount of strangeness in eP events has been obtained. This is particularly interesting for the fireball region (where there is no clear jet structure). An excess of strangeness in this region would point to a highly non-trivial production mechanism [29]. However, observing particularly the ratio of K_s^0/N_{Tracks} in photoproduction, no such excess is seen. This ratio is very similar for both the simple dijet region and the fireball region, and these are also similar to the ratios obtained in both the DIS samples. The $(\Lambda + \bar{\Lambda})/N_{Tracks}$ ratio in photoproduction does show an excess in the fireball region, but this is due to the different method of baryon production discussed above, rather than an excess of strangeness.

It is also noted that the DIS samples do show a larger ratio of strange particles to tracks in multi-jet enriched events compared with single-jet enriched events, although this behaviour is simulated by the ARIADNE MC.

9.6 Final Conclusions

The data obtained in this thesis observe the production of neutral strange hadrons in the eP collisions provided by HERA. The production cross-sections of Λ and K_s^0 particles in events with $Q^2 > 5\text{GeV}^2$ are generally well simulated by the ARIADNE MC, where the hadronisation is assumed to be independent of the hard sub-process, and to proceed by the Lund model. The hadronisation is controlled by such parameters as the strangeness-suppression factor and various constants governing baryon production relative to mesons, where these parameters are assumed to be universal for a fast-moving parton fragmenting to a jet of hadrons. The DIS results in this thesis therefore add some support to this view.

Neutral strange particle production in photoproduction is not so well described by the MC (PYTHIA), particularly in the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio at low x_γ , where the data give a significantly higher ratio than the MC. The difference between data and MC is exacerbated when observing events with a small proportion of the total E_T in the

highest E_T jet (that is, those events without a clear jet structure). The hadronisation mechanism in the photoproduction MC is the same as that for the DIS MC, which leads to the conclusion that this difference between data and MC in photoproduction is caused by a different hadronisation mechanism in the data. Similar observations at the heavy ion collisions at RHIC are interpreted as the hadronisation being dominated by a three-dimensional overlap of quark wavefunctions - hence the fragmentation of a parton is dependent on its environment (the colour field), distinct from the DIS case above. The results in this thesis give the first evidence that such a mechanism may be occurring in the eP collisions at HERA.

The additional studies into the Λ polarization, the $\Lambda - \bar{\Lambda}$ asymmetry, and the ratio of the observed strange particles to charged tracks provide some sensitivity to other processes that may be involved - for example a higher than expected baryon number asymmetry could suggest the association of baryon number with a gluonic junction, or an excess in the K_s^0/N_{Tracks} ratio in the low x_γ region could be indicative of instanton production. None of these are observed.

Appendix A

Systematic Errors

Systematic errors may arise from an insufficient understanding of the detector, leading to an inadequate description of the detector response. In order to estimate the effect of this, each event selection cut and strange particle selection cut is varied by approximately the same order of magnitude as the expected disagreement between the data and MC. The analysis is repeated with the new selection criteria, and the difference between the original cross-sections and the new cross-sections is taken as the systematic error for the particular variable under investigation. The systematic errors from each of the variables are assumed to be uncorrelated.

The particular variations in the selection criteria used to obtain the systematic errors of Λ and K_s^0 production in the High Q^2 and Low Q^2 samples are described in Table 8.1. The effect of each of these variations on the production cross-sections are shown in this appendix.

Differences in the cross-sections from variations in the selection criteria may indicate a systematic shift. Alternatively, the difference may arise from a statistical effect from using a slightly different data sample. No attempt is made to separate these effects, so the total systematic error shown is expected to be slightly conservative.

For each bin of the $(\Lambda + \bar{\Lambda})$ and K_s^0 differential cross-sections the effect of each systematic test is displayed as the difference between the original cross-section value and the cross-section with the new selection cut, divided by the original cross-section. These are displayed in Figs. A.1 - A.8 for the Low Q^2 sample.

The largest systematic variations for the Low Q^2 sample occur when using Q_{el}^2 instead

of Q_{da}^2 (#3) and varying the minimum electron energy requirement (#6 and #7). These give rise to variations in the cross-sections of up to 10% in the lowest x bin, but are generally $\lesssim 5\%$.

The total systematic error is obtained by adding in quadrature the differences between the original cross-section value and the cross-section with the new selection cut for each variable. Additionally, a $\pm 2\%$ systematic error is included to account for the error on the luminosity measurement [69]. The errors on the branching ratios of $\Lambda \rightarrow P\pi$ and $K_s^0 \rightarrow \pi^+\pi^-$ are $< 1\%$ [10] and are neglected. The total systematic error is added in quadrature to the statistical error, to give an estimate of the total error.

The systematic error is also obtained for the $(\Lambda - \bar{\Lambda})/(\Lambda + \bar{\Lambda})$ asymmetry and the $(\Lambda + \bar{\Lambda})/K_s^0$ ratio. Although the ratio of the strange particle cross-sections is taken in order to obtain the central values and statistical errors, the differences in the final ratios, rather than the cross-sections are used to obtain the systematic error. This preserves the advantage of taking ratios in minimizing the systematic error.

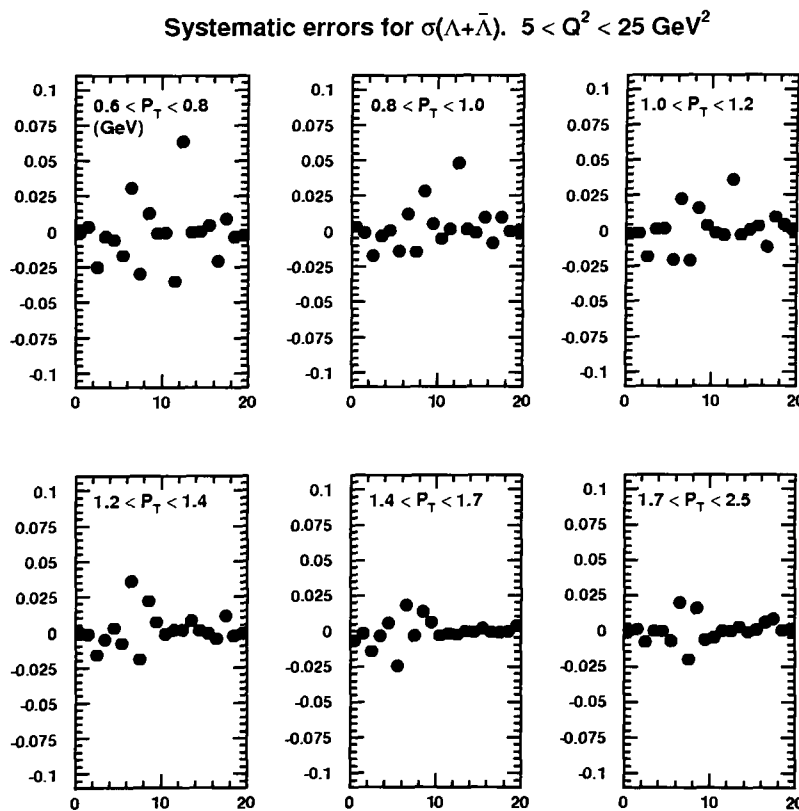


Figure A.1: Effect of the individual variations in obtaining the systematic error for the $(\Lambda + \bar{\Lambda})$ differential cross-section as a function of P_T , shown as $(\sigma' - \sigma)/\sigma$. Each bin corresponds to one systematic variation, as detailed in Table 8.1.

The same systematic variations are investigated for the High Q^2 sample, with the results shown in Figs. A.9 - A.16.

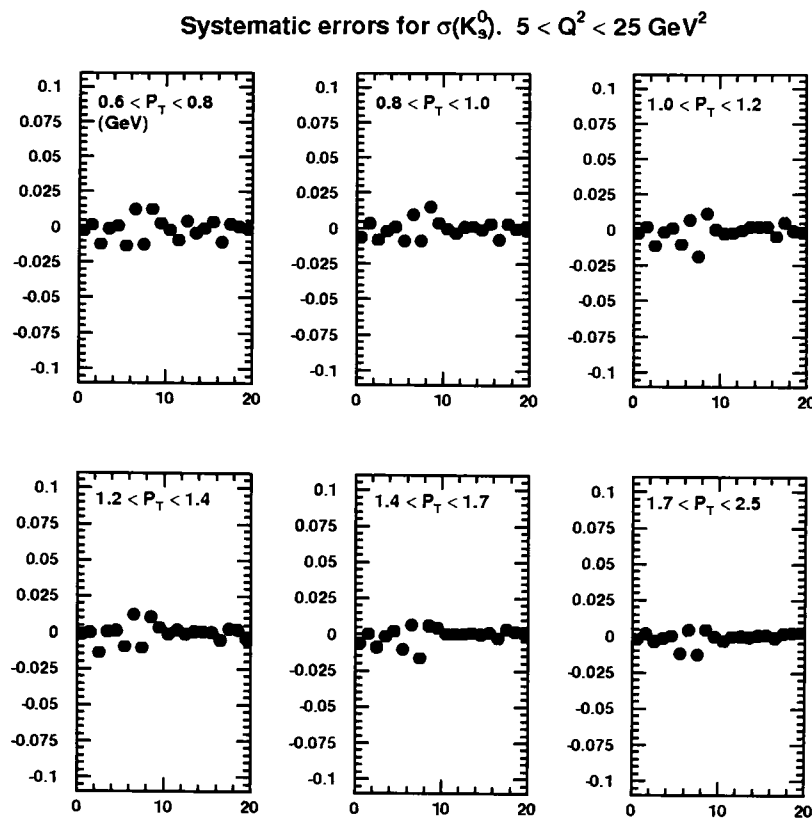


Figure A.2: Effect of the individual variations in obtaining the systematic error for the K_s^0 differential cross-section as a function of P_T , shown as $(\sigma' - \sigma)/\sigma$. Each bin corresponds to one systematic variation, as detailed in Table 8.1.

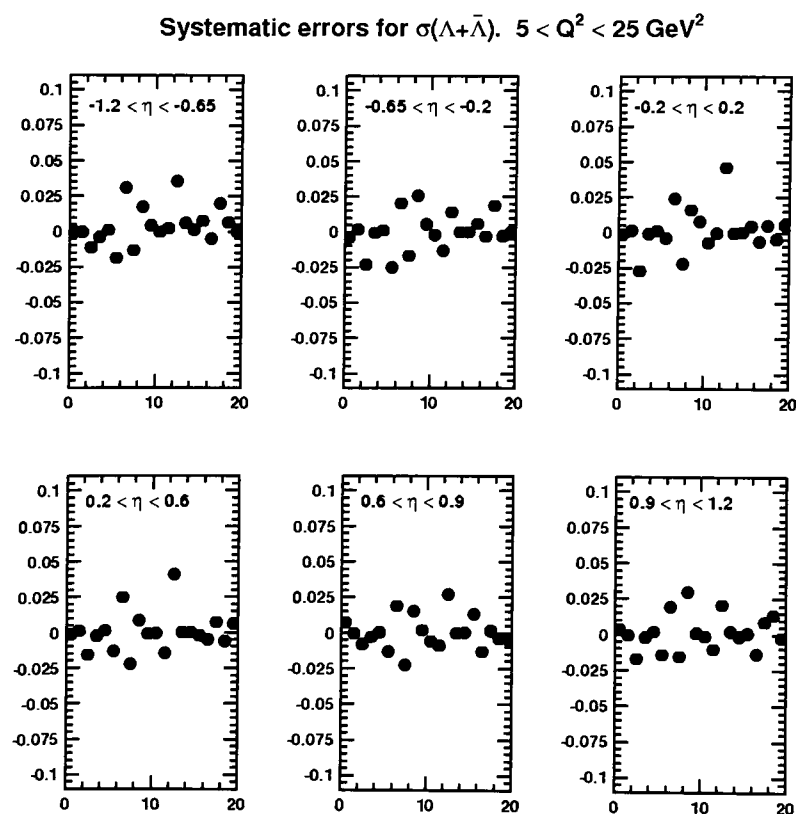


Figure A.3: Effect of the individual variations in obtaining the systematic error for the $(\Lambda + \bar{\Lambda})$ differential cross-section as a function of η , shown as $(\sigma' - \sigma)/\sigma$. Each bin corresponds to one systematic variation, as detailed in Table 8.1.

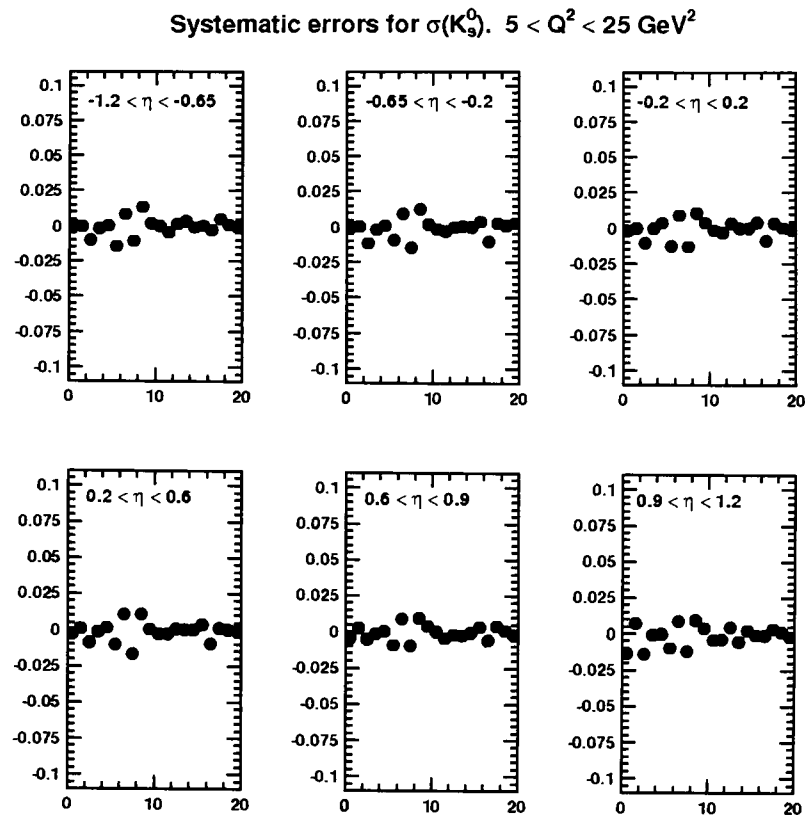


Figure A.4: Effect of the individual variations in obtaining the systematic error for the K_s^0 differential cross-section as a function of η , shown as $(\sigma' - \sigma)/\sigma$. Each bin corresponds to one systematic variation, as detailed in Table 8.1.

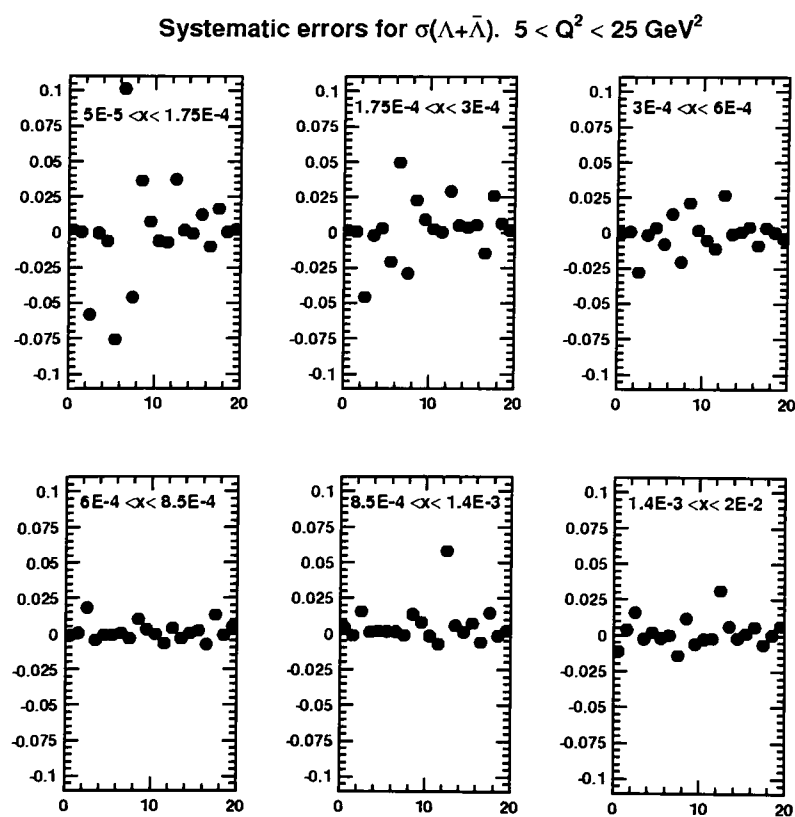


Figure A.5: Effect of the individual variations in obtaining the systematic error for the $(\Lambda + \bar{\Lambda})$ differential cross-section as a function of x , shown as $(\sigma' - \sigma)/\sigma$. Each bin corresponds to one systematic variation, as detailed in Table 8.1.

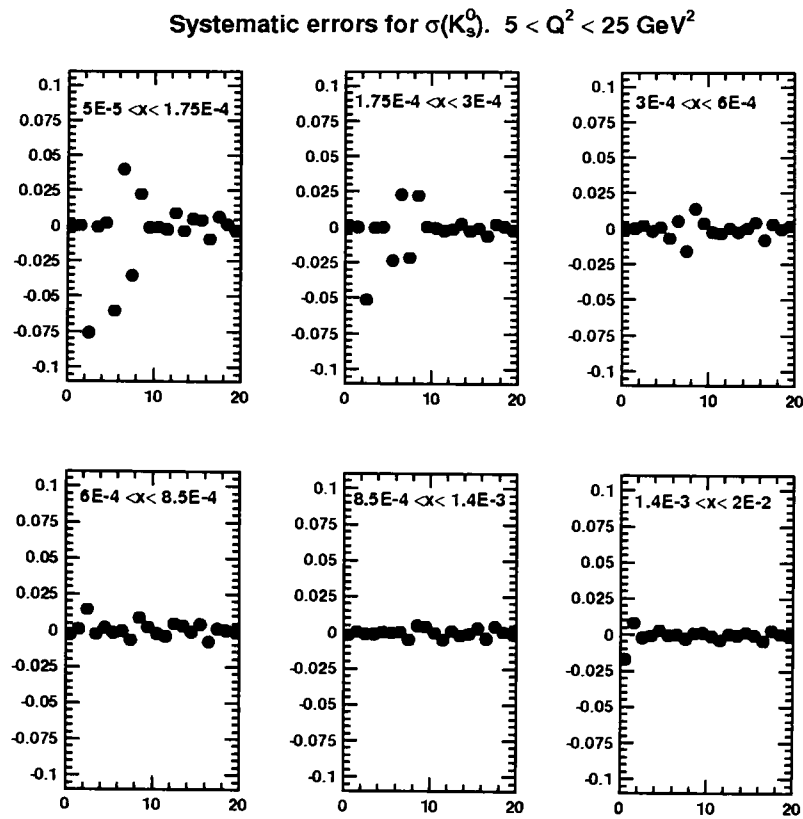


Figure A.6: Effect of the individual variations in obtaining the systematic error for the K_s^0 differential cross-section as a function of x , shown as $(\sigma' - \sigma)/\sigma$. Each bin corresponds to one systematic variation, as detailed in Table 8.1.

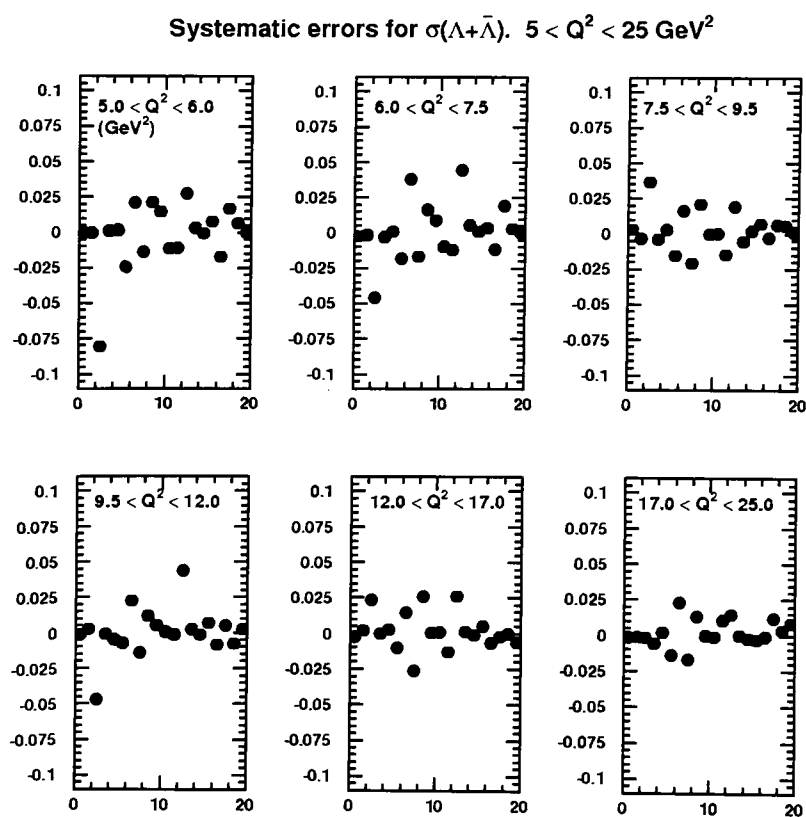


Figure A.7: Effect of the individual variations in obtaining the systematic error for the $(\Lambda + \bar{\Lambda})$ differential cross-section as a function of Q^2 , shown as $(\sigma' - \sigma)/\sigma$. Each bin corresponds to one systematic variation, as detailed in Table 8.1.

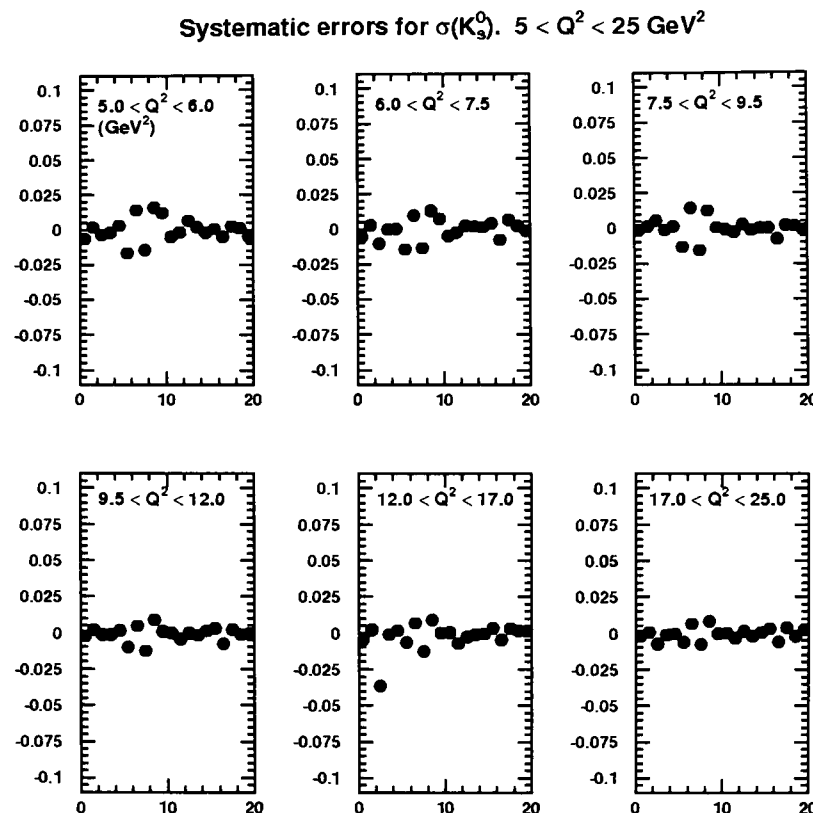


Figure A.8: Effect of the individual variations in obtaining the systematic error for the K_s^0 differential cross-section as a function of Q^2 , shown as $(\sigma' - \sigma)/\sigma$. Each bin corresponds to one systematic variation, as detailed in Table 8.1.

The systematic variations for the High Q^2 sample are generally smaller than in the Low Q^2 sample, due to the scattered electron being easier to detect in higher Q^2 events. The largest systematic errors are in the lowest x bins, but the variations are generally $\lesssim 5\%$.

One additional systematic error is included for the High Q^2 sample. The MC sample used to correct the Low Q^2 sample contains the same fraction of events with $E_P = 820\text{GeV}$ to events with $E_P = 920\text{GeV}$ as the data. However, in the High Q^2 MC sample this is not the case, as can be seen in Table 6.2, due to the time-consuming nature of generating MC, and hence the necessity of using already existing MC samples to minimize the statistical error.

The effect of this is estimated by comparing the correction factors obtained when using the full MC sample with those obtained when using a MC sample with the correct ratio of events with $E_P = 820\text{GeV}$ to events with $E_P = 920\text{GeV}$. These correction factors can be seen in Fig. A.17, and the ratio of the correction factors from the two samples in Fig. A.18. Although the correction factors from the two samples are generally within the statistical errors, fitting the ratio to a 1st order polynomial shows that the

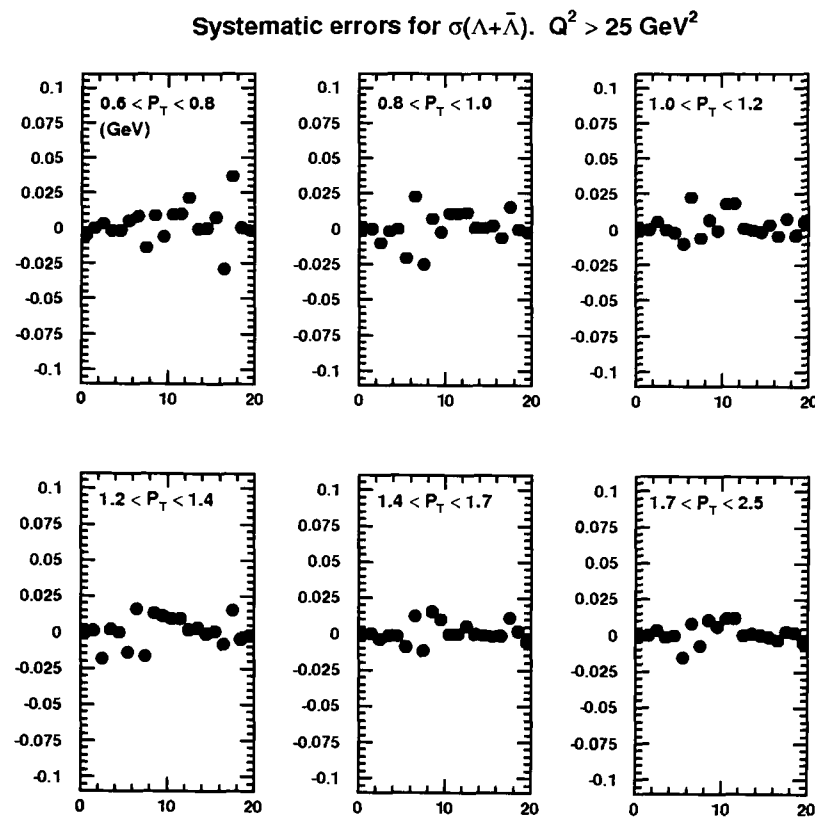


Figure A.9: Effect of the individual variations in obtaining the systematic error for the $(\Lambda + \bar{\Lambda})$ differential cross-section as a function of P_T , shown as $(\sigma' - \sigma)/\sigma$. Each bin corresponds to one systematic variation, as detailed in Table 8.1.

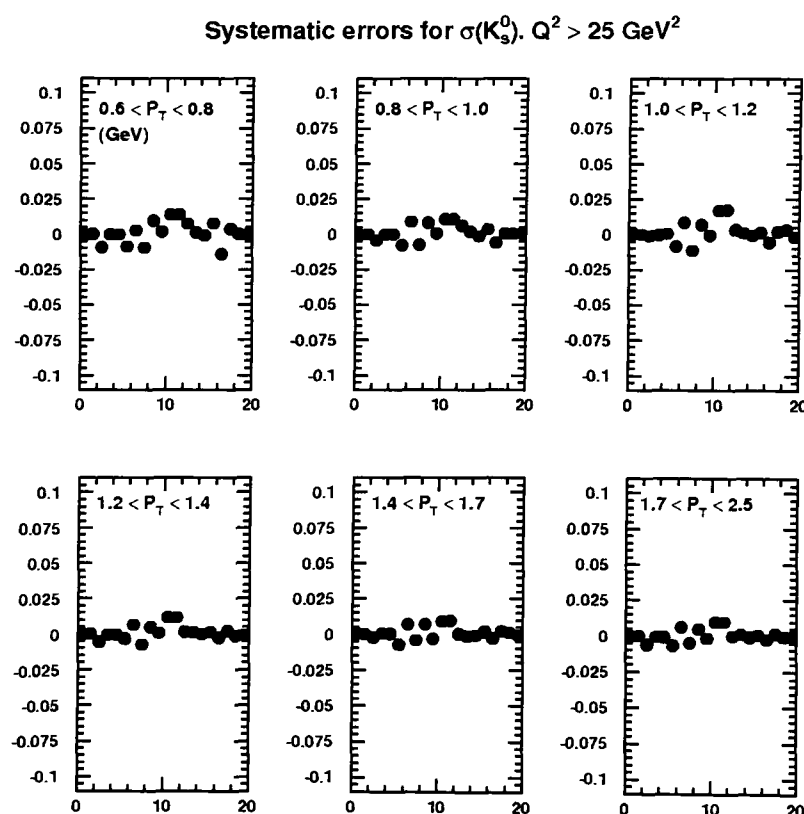


Figure A.10: Effect of the individual variations in obtaining the systematic error for the K_s^0 differential cross-section as a function of P_T , shown as $(\sigma' - \sigma)/\sigma$. Each bin corresponds to one systematic variation, as detailed in Table 8.1.

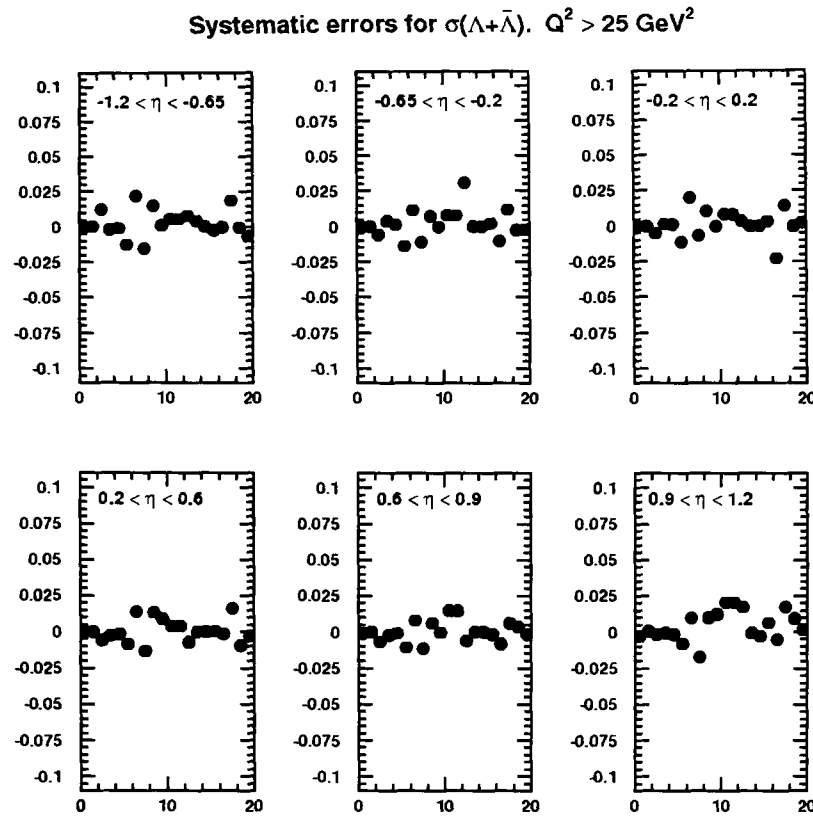


Figure A.11: Effect of the individual variations in obtaining the systematic error for the $(\Lambda + \bar{\Lambda})$ differential cross-section as a function of η , shown as $(\sigma' - \sigma)/\sigma$. Each bin corresponds to one systematic variation, as detailed in Table 8.1.

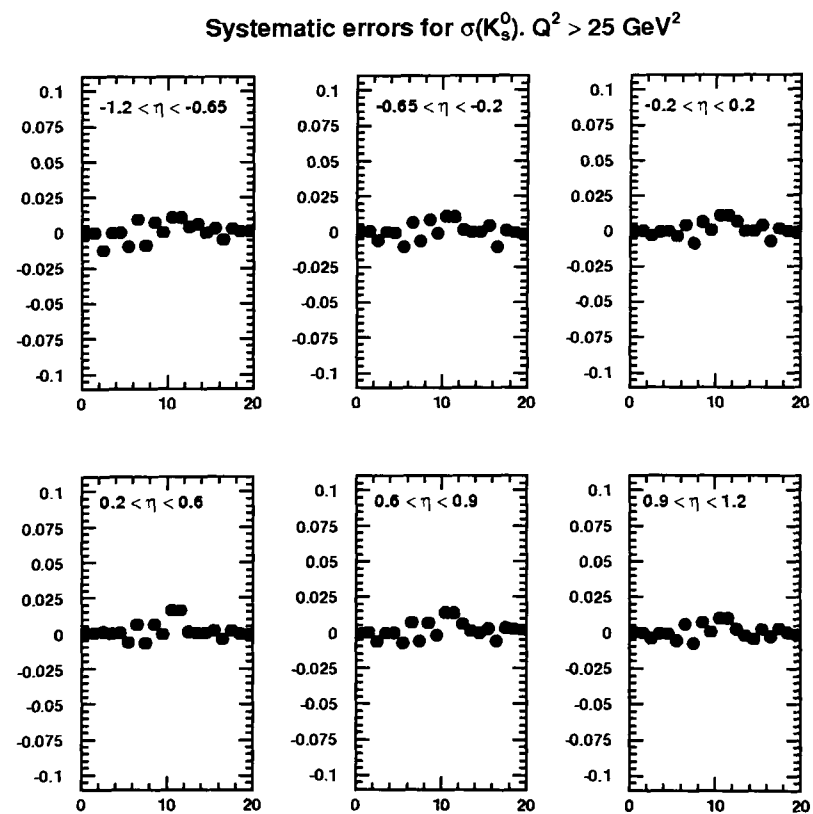


Figure A.12: Effect of the individual variations in obtaining the systematic error for the K_s^0 differential cross-section as a function of η , shown as $(\sigma' - \sigma)/\sigma$. Each bin corresponds to one systematic variation, as detailed in Table 8.1.

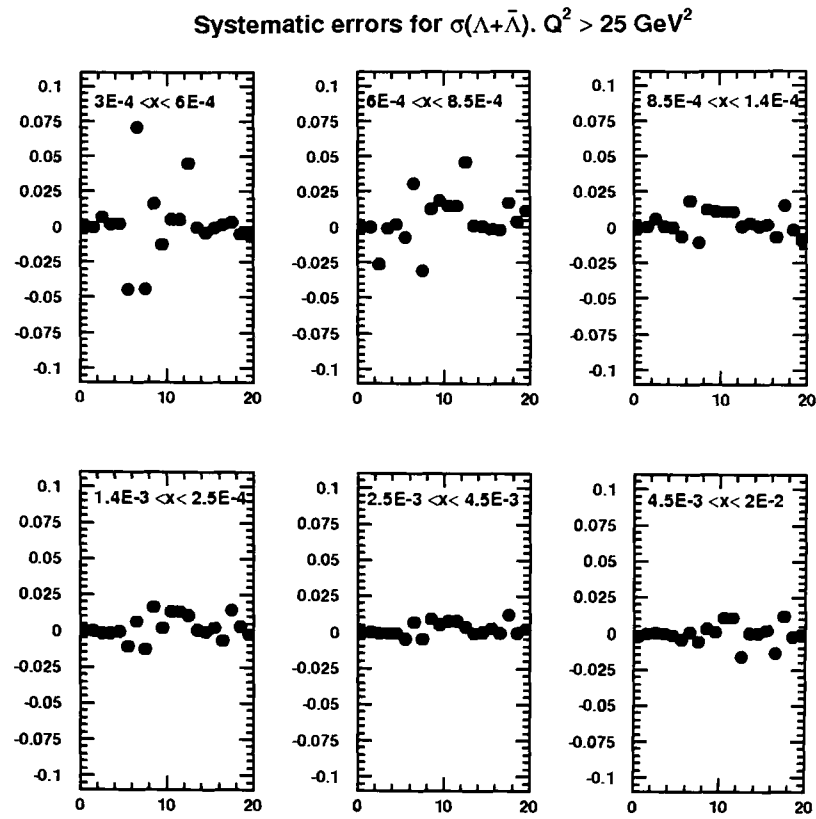


Figure A.13: Effect of the individual variations in obtaining the systematic error for the $(\Lambda + \bar{\Lambda})$ differential cross-section as a function of x , shown as $(\sigma' - \sigma)/\sigma$. Each bin corresponds to one systematic variation, as detailed in Table 8.1.

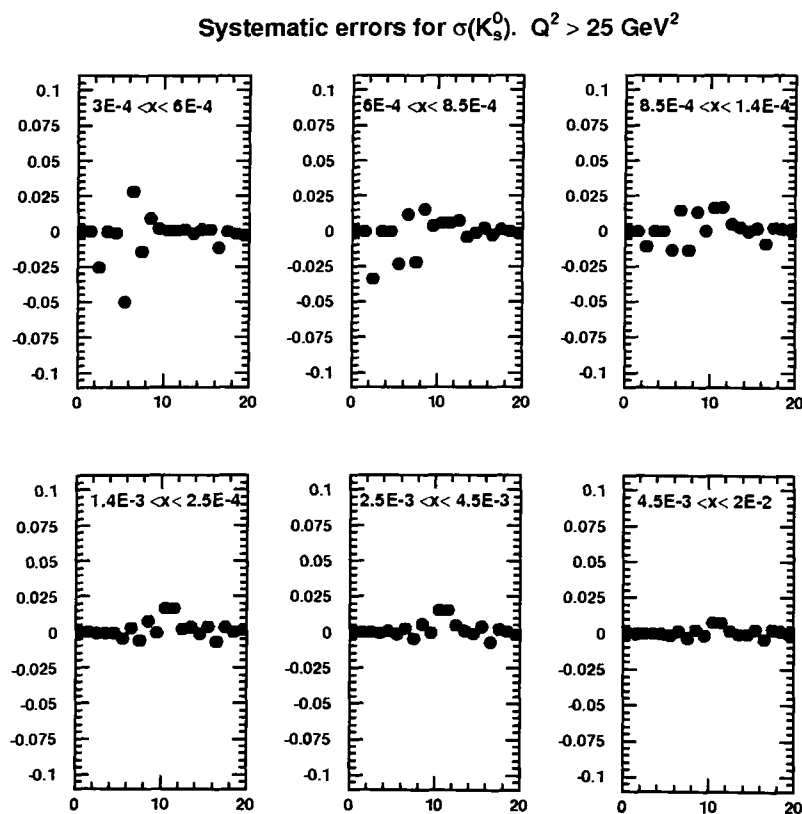


Figure A.14: Effect of the individual variations in obtaining the systematic error for the K_s^0 differential cross-section as a function of x , shown as $(\sigma' - \sigma)/\sigma$. Each bin corresponds to one systematic variation, as detailed in Table 8.1.

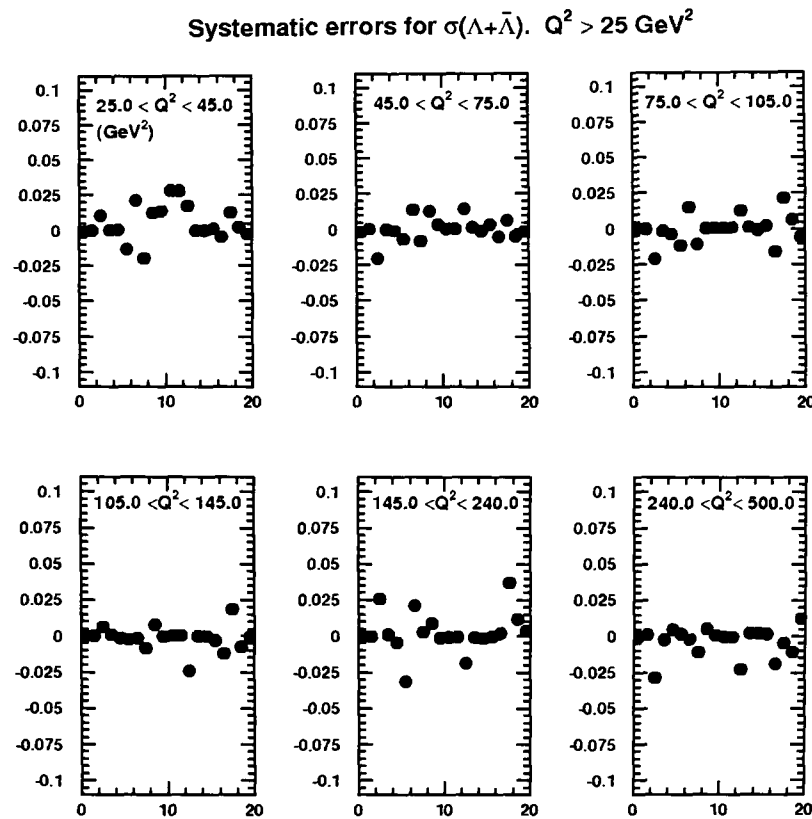


Figure A.15: Effect of the individual variations in obtaining the systematic error for the $(\Lambda + \bar{\Lambda})$ differential cross-section as a function of Q^2 , shown as $(\sigma' - \sigma)/\sigma$. Each bin corresponds to one systematic variation, as detailed in Table 8.1.

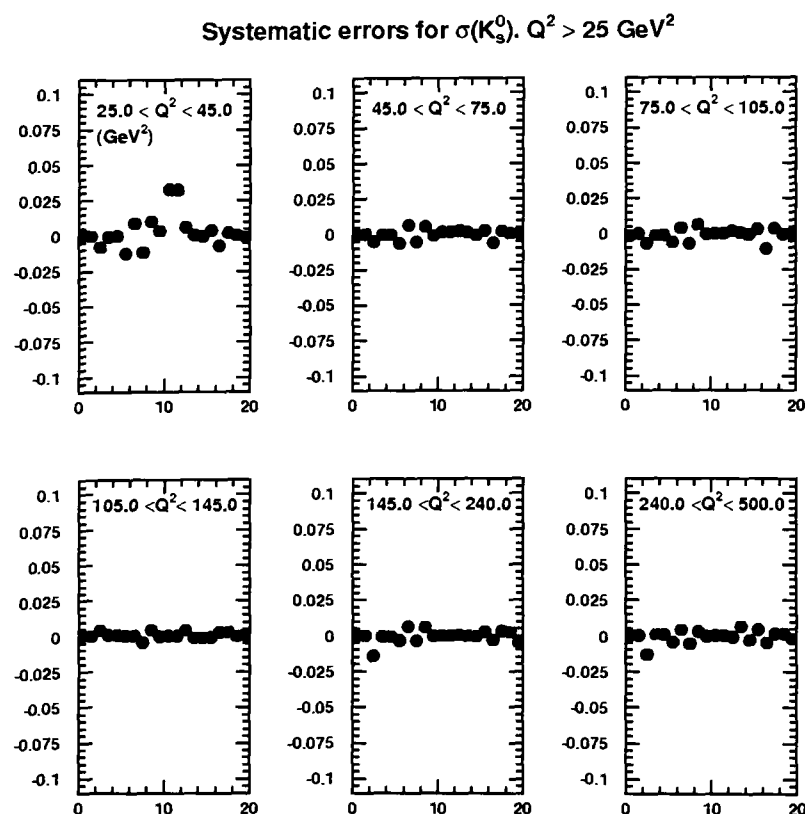


Figure A.16: Effect of the individual variations in obtaining the systematic error for the K_s^0 differential cross-section as a function of Q^2 , shown as $(\sigma' - \sigma)/\sigma$. Each bin corresponds to one systematic variation, as detailed in Table 8.1.

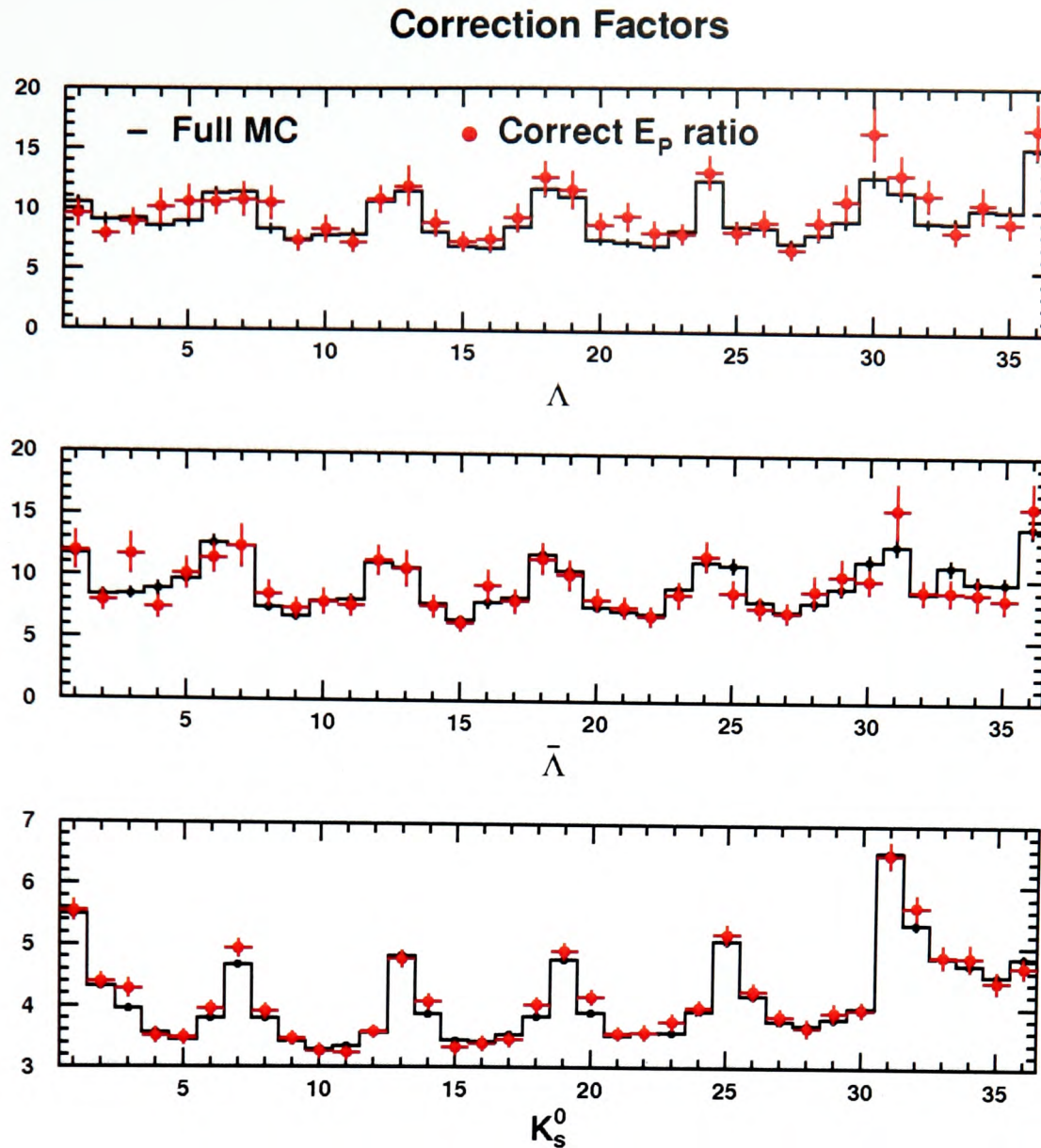


Figure A.17: The correction factors obtained from MC to be applied to strange particles observed in the data depending on their P_T and η . The bin number here corresponds to $(\text{bin number in } P_T) + (6 \times (\text{bin number in } \eta - 1))$. Black is for the full High Q^2 MC sample, red is for a smaller sample with the same ratio of events with $E_P = 820\text{GeV}$ to events with $E_P = 920\text{GeV}$ as the data. Errors are statistical only.

average correction factor from the full sample is 0.98 ± 0.01 of the average correction factor from the sample with the correct ratio of events with $E_P = 820\text{GeV}$ to events with $E_P = 920\text{GeV}$. Therefore, an additional systematic error of $+2\%$ is added to the High Q^2 Λ and K_s^0 cross-sections.

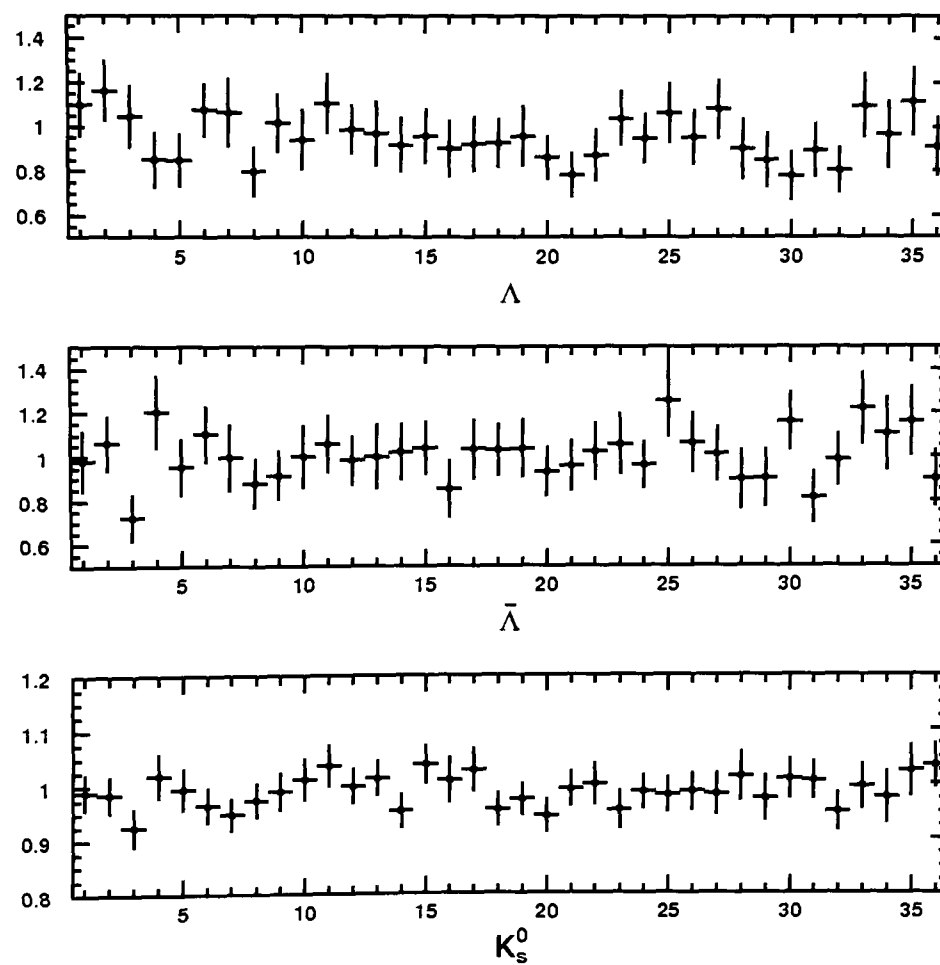


Figure A.18: The ratio of correction factors obtained from the full High Q^2 MC sample to the correction factors obtained from the MC sample with the same ratio of events with $E_P = 820\text{GeV}$ to events with $E_P = 920\text{GeV}$ as the data. The bin number here corresponds to $(\text{bin number in } P_T) + (6 \times (\text{bin number in } \eta - 1))$. Errors are statistical only.

Bibliography

- [1] R.C.E. Devenish and A.M. Cooper-Sarkar, Deep Inelastic Scattering, OUP, (2004)
- [2] C.G. Callan and D.J. Gross, Phys. Rev. Lett. **22** (1969) 156
- [3] J.D. Bjorken, Phys. Rev. **179** (1969) 1547
- [4] T. Eichten et al., Phys. Lett. **B46** (1973) 274
- [5] TASSO Coll., R. Brandelik et al., Phys. Lett. **B86** (1979) 243
- [6] ZEUS Coll., S. Chekanov et al., Eur. Phys. J. **C 21** (2001) 3
- [7] Yu.L. Dokshitzer, Sov. Phys. JETP **46** (1977) 641;
G. Altarelli and G. Parisi, Nucl. Phys. **B126** (1977) 298;
V.N. Gribov and L.N. Lipatov, Sov. J. Nucl. Phys. **15** (1972) 438
- [8] ZEUS Coll., S. Chekanov et al., Phys. Rev. **D 67** (2002) 012007
- [9] ZEUS Coll., J. Breitweg et al., Eur. Phys. J. **C 1** (1998) 109
- [10] K. Hagiwara et al., Phys. Rev. **D 66** (2002) 010001
- [11] ZEUS Coll., S. Chekanov et al., Phys. Lett. **B 591** (2004) 7
- [12] ZEUS Coll., S. Chekanov et al., Phys. Lett. **B 578** (2004) 33
- [13] ZEUS Coll., J. Breitweg et al., Eur. Phys. J. **C 2** (1998) 77
- [14] ZEUS Coll., M. Derrick et al., Z. Phys. **C 68** (1995) 569
- [15] G. Bunce et al., Phys. Rev. Lett. **36** (1976) 1113
- [16] A. Panagiotou, Int. J. Mod. Phys. **A5** (1990) 1197
- [17] T.A. DeGrand and H.I. Miettinen, Phys. Rev. **D24** (1981) 2419
- [18] O. Grebenyuk, Proceedings of X International Workshop on Deep Inelastic Scattering, ‘Transverse Polarization of Λ and $\bar{\Lambda}$ produced inclusively in eN scattering at HERMES’ (2002)
- [19] K. Heller et al., Phys. Rev. Lett. **41** (1978) 607

- [20] G.T. Garvey, B.Z. Kopeliovich and B. Povh, *Comment Mod. Phys.* **A5** (2001) 47
- [21] G.C. Rossi and G. Veneziano, *Nucl. Phys.* **B123** (1997) 507; *Phys. Rep.* **63** (1980) 149
- [22] B.Z. Kopeliovich and B. Povh, *Z. Phys.* **C75** (1997) 693
- [23] PHENIX Coll. K. Adcox et al., *Phys. Rev. Lett.* **89** (2002) 092302
- [24] S.A. Bass, B. Müller and D.K. Srivastava, *Phys. Rev. Lett.* **91** (2003) 502302
- [25] H.Z. Huang and J. Rafelski, pre-print hep-ph/0501187, ‘Hadronization and Quark Probes of Deconfinement at RHIC’, 2005
- [26] R.J. Fries et al., pre-print nucl-th/0306027, ‘Hadron production in heavy ion collisions: Fragmentation and recombination from a dense parton phase’, 2003
- [27] R.J. Fries et al., *Phys. Rev. Lett.* **90** (2003) 202303
- [28] ZEUS Coll., J. Breitweg et al., *Eur. Phys. J.* **C 4** (1998) 591
- [29] C. Nath, R. Walczak, Y. Yamazaki, *J. Phys.* **G 25** (1999) 1440
- [30] C. Nath, ‘Measurement of Inclusive Jet Cross Sections in High Total Transverse Energy Photoproduction at HERA’, DPhil Thesis, Oxford University, 1998
- [31] A. Ringwald and F. Schrempp, *J. Phys.* **G 25** (1999) 1297
- [32] G. A. Voss and B. H. Wiik, *Ann. Rev. Nucl. Part. Sci.* **44**, 413 (1994): HERA, A proposal for a large Electron-Proton Colliding Beam Facility at DESY, DESY HERA 81-10.
- [33] ZEUS Coll., U. Holm (ed.), *The ZEUS Detector, Status Report* (unpublished), DESY (1993) available on <http://www-zeus.desy.de/bluebook/bluebook.html>
- [34] B. Foster et al., *Nucl. Inst. Meth.* **A338** (1994) 254
- [35] R. Hall-Wilton et al., ‘The CTD Tracking Resolution’, ZEUS-Note-99-024
- [36] H. Bethe and W. Heitler, *Proc. Roy. Soc. Lond.* **A 146** (1934) 83
- [37] S. Bentvelsen, J. Engelen and P. Kooijman, *Proc. of the Workshop ‘Physics at HERA’*, vol. 1, Eds. W. Buchmuller and G. Ingelman, DESY (1991) 23
- [38] F. Jacquet and A. Blondel, ‘Proceedings of the study of an eP facility for Europe’, DESY 79-48 p391
- [39] J.E. Huth et al., ‘Proceedings of the DPF Summer Study on High Energy Physics’, E.L. Berger (Ed.) (World Scientific, Singapore, 1992) p.134
- [40] S. Catani et al., *Nucl. Phys.* **B406** (1993) 187
- [41] S.D. Ellis and D.E. Soper, *Phys. Rev.* **D48** (1993) 3160

- [42] M. Seymour, pre-print hep-ph/9707349, ‘Jet Phenomenology’, Contribution to ‘Proceedings of Les Rencontres de la Valee d’Acoste: Results and Perspectives in Particle Physics’, La Tuile, Italy, March 2-8, 1997
- [43] G.F. Hartner et al., ‘VCTRACK (3.07/04): Offline Output Information’, ZEUS-note-97-064
- [44] G.F. Hartner, ‘VCTRACK Briefing: Program and Math’, ZEUS-Note-98-058
- [45] R. Brun et al., ‘GEANT 3.13’, CERN DD/EE/84-1, 1987
- [46] ZEUS trigger simulation library, Els de Wolf (ed.) et al.
- [47] T. Sjöstrand et al., Comp. Phys. Commun. **135** (2001) 238
- [48] C.F. von Weizsacker, Z. Phys. **88** (1934) 612
- [49] E.J. Williams, Phys. Rev. **45** (1934) 729
- [50] B. Andersson et al., Phys. Rep. **97** (1983) 33
- [51] G. Corcella et al., JHEP **0101** (2001) 010 [hep-ph/0011363]; hep-ph/0210213.
- [52] H. Spiesberger et al., <http://www.desy.de/hspiesb/djangoh.html>
- [53] A. Kwiatkowski et al., Comp. Phys. Commun. **69** (1992) 155
- [54] L. Lönnblad, Comp. Phys. Commun, **71** (1992) 15
- [55] B. Andersson et al., Z. Phys. **C69** (1996) 379
- [56] ZEUS Coll., S. Chekanov et al., Phys. Lett. **B510** (2001) 36
- [57] ZEUS Coll., J. Breitweg et al., Eur. Phys. J. **C12** (2000) 53
- [58] F. Wilson, ‘Simulation of the CTD FLT in 1995’, ZEUS-Note-95-002
- [59] R. Sinkus and T. Voss, Nucl. Instr. Meth. **A 391** (1997) 360
- [60] C. Gwenlan, ‘Jets and Energy Flow in Photoproduction using the ZEUS Detector at HERA’, PhD Thesis, University College London, 2003
- [61] S. T. Boogert, ‘Photoproduction of K_s^0 mesons and Λ baryons in electron proton collisions at ZEUS’, DPhil Thesis, Oxford University, 2002
- [62] D.H. Perkins, Introduction to High Energy Physics (3rd Edition), Addison-Wesley, (1987)
- [63] <http://wwwasd.web.cern.ch/wwwasd/paw/>
- [64] ZEUS Coll., S. Chekanov et al., Phys. Rev. **D69** (2004) 012004
- [65] CDF Coll., F. Abe et al., Phys. Rev. **D40** (1989) 3791

- [66] H1 Coll., C. Adloff et al., Proceedings of 29th International Conference on High Energy Physics, ‘Measurement of the Baryon-Antibaryon Asymmetry in Photoproduction at HERA’ (1998)
- [67] H. Aihara et al., Phys. Rev. Lett. **53** (1984) 2378
- [68] B. Andersson, G. Gustafson and T. Sjöstrand, Nucl. Phys. **B197** (1982) 45
- [69] ZEUS Coll., <http://www-zeus.desy.de/physics/lumi/>