# ZEUS PROGRESS REPORT

## ZEUS UK COLLABORATION

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# ZEUS Progress Report

ZEUS UK Collaboration

# 1 Introduction

At the time of our last report to the PPESP, the HERA $ep$ collider had been in operation for two years and several physics results were presented. Here we report on progress since then. The past two years saw a continued improvement in the performance of both HERA and ZEUS, with ZEUS recording integrated luminosities of 4.1 $\text{pb}^{-1}$ and 7.1 $\text{pb}^{-1}$ in 1994 and 1995 respectively. This has allowed a significant expansion of the range ZEUS physics results.

The principal contribution of the UK to the equipment of the ZEUS detector has been the central tracking detector (CTD). This was built in the UK and is fully equipped with trigger and read-out electronics designed and manufactured in the UK. Due to the efforts of the ZEUS UK collaboration over the last two years, the CTD is fully commissioned and has for some time been playing a major rôle in the whole of the ZEUS physics programme; indeed, data is taken only when the CTD is operational. Thus, whilst operating the CTD will continue to require resources, the emphasis of ZEUS UK has now shifted towards increased participation in physics analyses. This is reflected in the structure of this report. After a brief review of the status of the detector, and of the offline analysis environment and software, where UK involvement also continues at a high level, the majority of the report focuses on ZEUS physics. We concentrate on those areas where UK involvement has been particularly significant, although it should be emphasised that every single analysis on ZEUS relies in some way on data from the CTD.

Over the next few years, important luminosity upgrades are planned for HERA, as well as running with polarised electron and positron beams. These projects will open up exciting prospects of new physics. The implications are discussed in the final section of this report. In particular, studies of charm and to some extent bottom production will allow precision QCD studies to be performed, as well as providing the possibility of surprises in the shape of new physics. Tagging of these processes will require a modest detector upgrade. We expect to return to the PPESP to request support in the future.

# 2 Detector status and performance

*All UK Groups*

The CTD is a large volume cylindrical drift chamber covering the central region ($15^o < \theta < 164^o$). It provides charged particle tracking, momentum measurement and particle identification from $dE/dx$, as well as triggering information. We give a brief description of the important advances made in the operation and understanding of the detector over the last two years. The impact on physics analyses of these and future improvements will also be elaborated in subsequent sections.

The ZEUS trigger is continually being improved to remove the high rate of background events as the luminosity increases at HERA. These improvements depend critically on the successful operation of the CTD trigger system at all three levels of the ZEUS trigger. The luminosity is now high enough that it is no longer sufficient to trigger on $ep$ collisions in general: it is necessary to trigger on specific channels. In many physics channels, high quality track reconstruction in the trigger is essential. Indeed, even particle mass reconstruction currently takes place online using tracking information in the third level trigger.

Since January 1994, new trigger branches have been introduced at the first and second levels of the trigger (FLT,SLT) which are essential for the acceptance of many very different physics channels. For example, the CTD-FLT now works successfully with the ZEUS leading proton spectrometer to tag very low activity events such as elastic $\rho$ production ($ep \rightarrow e\rho p$, Fig. 1a). In addition, the CTD-SLT is fully operational and is an integral part of the majority of physics triggers. Contrast the very quiet event of Fig. 1a with, for example, a high $E_T$ jet photoproduction event shown in Fig. 1b which is triggered on a combination of calorimeter and tracking information. This flexibility allows ZEUS to take data efficiently and with low backgrounds over the enormous range of event topologies demanded by the breadth of physics at HERA.

Also over the past two years, the detailed understanding of the performance of the CTD has greatly improved. This has lead to a momentum resolution of $\sigma_{P_T}/P_T = 0.004 p_T(\mathrm{GeV}) \oplus 0.016$, and vertex resolution of 2 cm in $z$ and better than 2 mm in $x$ and $y$. This understanding is fully incorporated in the simulation of the detector, which allows the experiment to fully utilise the data for physics. Information on $dE/dx$ is now used in many analyses. In Fig. 2a we show the $dE/dx$ distribution for tracks in a sample of deep inelastic scattering (DIS) events. Fig. 2b and 2c show the $D^*$ signal obtained before and after cuts on $dE/dx$ respectively. Clearly $dE/dx$ information greatly improves the signal to background ratio.

Another important area in which CTD information is essential is the *in situ* determination of the energy calibration of the uranium calorimeter. The level of knowledge of this calibration has been an important source of uncertainty in many analyses. Matching tracks in the CTD with calorimeter energy deposits provides information which has been crucial in the determination and reduction of this uncertainty.

In the forward region, the transition radiation detectors, two of which were constructed in Glasgow, have been commissioned and tested in 1993 and 1994, and the rear tracking detector is now routinely used in track reconstruction in ZEUS. Both these detectors rely upon electronics designed and constructed by the ZEUS UK group.

Maintaining the CTD, electronics and DAQ are major UK activities in which all groups participate.

# 3 Analysis environment

*All UK Groups*

The high data rates, detector complexity and diversity of physics at ZEUS, as well as the global spread of the collaboration, place stringent requirements on the environment in which physics analysis takes place. Three areas in particular are critical:

- CPU power and networking must be sufficient to allow prompt reconstruction of the data and provide access to the data for physics analyses.
- The understanding of the detector must allow high quality reconstruction during the running period and must be present in a flexible and well defined software environment.
- This understanding must also be available in terms of a detailed Monte Carlo simulation of the detector, and access to large numbers of simulated and reconstructed events must be provided.

The collaboration has met these requirements by providing a central computing system (ZARAH) to replace the DESY IBM mainframe. ZARAH currently consists principally of SGI Challenge XL multiprocessor machines, an AMPEX tape robot, an open storage management system providing access to tape silos, and over 800GB of disk storage space. The design is such that the system is easily expandable (ZEUS plans a modest yearly CPU and disk increase to keep pace with acquired data) and is in principal portable to any UNIX system. As well as reconstructing the data ZARAH provides access from physicists' workstations to all reconstructed data and Monte Carlo samples via a batch facility. International access to this data depends critically upon wide-area network (WAN) connections, and the UK network connections need to be enhanced if this facility is to be fully exploited from the UK.

The collaboration has also developed a production facility for Monte Carlo events (known as 'Funnel') which allows the simulation program to 'soak up' background CPU power on UNIX machines at collaborating institutes all over the world. Where network connections permit the Monte Carlo events are retrieved and made available on ZARAH over the network. Otherwise, tape transport is used. This facility was developed with UK involvement and is currently able to provide at least a million simulated events per week for physics analysis. It is installed in the UK and runs on the WAN in the UK using machines in the collaborating institutes. Whilst our colleagues in Italy for instance can ship events back via a high speed network connection, unfortunately the poor network connections to the UK force the final stage of data transfer to be made via data tapes.

As well as providing the expertise to simulate and analyse CTD data, UK physicists participated in the development of the offline software environment and currently make an important contribution to the maintenance and development of the entire ZEUS detector simulation and event display programme.

# 4 Proton structure

*Bristol, Glasgow, Imperial, Oxford, RAL*

The first HERA papers on the proton structure function $F_2$ appeared in 1993 [1], and were based on the data collected in the first year of running at HERA. These data were the first to show the strong rise of $F_2$ as Bjorken $x$ decreases to $10^{-2}$ and below. This rise of $F_2$ at low $x$ came as a surprise to many in the high energy physics community. Its interpretation in terms of parton distributions and QCD evolution has been the source of much theoretical activity [2]. This activity continues, and has been renewed each time new and more precise structure function data are published.

The second ZEUS paper on $F_2$ [3] was based on the data taken during 1993. With the increased statistics and improved understanding of the detector, the $F_2$ measurements (see Fig. 3) confirmed the rise of $F_2$ at low $x$, while extending the coverage in $Q^2$. The systematic errors, as well as statistical errors, were reduced by a factor of 2-3. The $F_2$ data from the second paper were used to extract the gluon density of the proton [4]. One of the methods used was developed by a ZEUS UK physicist [5]. A next-to-leading-order GLAP [6] fit to the ZEUS and NMC data was performed, and the gluon distribution was extracted at $Q^2$ of 20 GeV$^2$ down to $x$ of $4 \times 10^{-4}$, as shown in Fig. 4. The scaling violations are dominated by the contribution from the gluon. The handling of correlated systematic errors, usually lacking in global fits of parton distributions, gives an estimate of the uncertainty on the gluon distribution obtained within the GLAP framework.

The most recent $F_2$ measurement from ZEUS [7] uses subsets of the data taken in 1994 to begin to probe the region between the DIS regime ($Q^2 > 4$ GeV$^2$) and the photoproduction regime ($Q^2 \approx 0$). For one of the data sets used, the interaction point was shifted forward (i.e. in the proton direction) in order to accept lower $Q^2$ events in the detector. The second data set consists of events with tagged initial state QED radiation which effectively lowers the $Q^2$ of the interaction. These two data sets extend the $Q^2$ coverage down to 1.5 GeV$^2$. The rise of $F_2$ at low $x$ corresponds to a rise of the $\gamma^* p$ cross section as a function of the $\gamma^* p$ CMS energy ($W$), as shown in Fig. 5. Also shown are data from fixed target experiments [8] and the total photoproduction (i.e. $Q^2 = 0$) cross section measurements from HERA [9], which indicate that at low $Q^2$ $F_2$ rises relatively slowly as a function of $W$, in agreement with Regge predictions [10]. However, already at $Q^2 = 1.5$ GeV$^2$ the rise in $F_2$ is more pronounced and indeed the GRV [11] parton distributions are able to describe the data even at this low $Q^2$. Further investigation of this low-$Q^2$ region promises to give us greater insight into QCD and the transition between real and virtual photons.

The current ZEUS $F_2$ analysis uses the full 1994 data set, which represents a five-fold increase in the statistics from 1993. The precision and coverage in the kinematic region will once again improve significantly.

To investigate the low-$Q^2$ transition region directly, a beam pipe calorimeter (BPC) was installed and operated in 1995 (data was also taken with a prototype BPC in 1994). The BPC allows access to a $Q^2$ region $0.2 < Q^2 < 0.7$ GeV$^2$ at $x$ values as low as $2 \times 10^{-6}$. With these data, ZEUS will be able to measure the transition region between hard and soft physics.

Our involvement in the $F_2$ analyses has been extensive with UK physicists leading the DIS working group since 1993. In addition to vital technical contributions, several complete $F_2$ analyses have been performed by members of the UK collaboration. Furthermore, CTD information will become increasingly important in the measurement of $F_2$ as luminosity increases. Already, the vertex provided by the CTD is critical to the good $Q^2$ resolution of the measurement. Tracks are used to improve the electron identification in the high $Q^2$ region and in the near future, CTD information will be used to improve the hadronic measurements, which will be important in the higher $x$ regions where HERA and fixed target data overlap. These improvements will come both indirectly, by checking the calorimeter energy scale (as mentioned in section 2), and directly, by providing an additional measure of the hadronic momenta.

Finally, vastly improved constraints can be placed on QCD and the gluon density inside the proton by measuring further structure functions. ZEUS will attempt a measurement of $F_L$ during low energy HERA running in 1996, and is currently engaged in measuring $F_2^{charm}$. These are topics of longer term interest in which the UK collaboration is investing significant effort.

# 5 QCD and photon structure

*Glasgow, UCL*

The study of collisions between protons and the almost real photons radiated from the positron beam at HERA provides a unique window on the strong interactions of the photon.

Inclusive jet photoproduction cross sections have been published [12] and compared to next-to-leading order QCD calculations [13]. ZEUS has demonstrated the ability to distinguish 'resolved' and 'direct' interactions: the photon either resolves into a hadron-like object before the interaction, or interacts directly as a pointlike particle with a parton in the proton [14]. ZEUS has developed a separation defined in terms of the momentum fraction of the photon, $x_\gamma^{OBS}$, appearing in the two observed final state jets of highest transverse energy [15]. Resolved and direct jet cross sections have been measured [15], as illustrated in Fig. 6. The resolved cross sections give information on the partonic (in particular gluonic) content of the photon, whereas the direct processes provide constraints on the low-$x$ gluon content of the proton complementary to those obtained in DIS [16]. QCD predicts that direct photon processes are dominated by $t$-channel spin-1/2 quark exchange whereas resolved processes are dominated by $t$-channel spin-1 gluon exchange. This leads to a resolved cross section more strongly peaked in the forward direction than the direct cross section. The cross section has been measured as a function of $|\cos\theta^*|$, where $\theta^*$ is the scattering angle in the jet-jet centre-of-mass system. The comparison with the predictions bears out this fundamental prediction of QCD, as shown in Fig. 7.

The BPC allows the study of of photoproduction to be continued as the photon moves off mass-shell, towards the DIS regime. First results from the BPC prototype data of 1994, have been presented at the European Physical Society conference [17] and are shown in Fig.8. The two-component structure seen in the (uncorrected) $x_\gamma^{OBS}$ distribution reflects the presence of both resolved (low-$x_\gamma^{OBS}$) and direct (high-$x_\gamma^{OBS}$) components in both regions of photon virtuality. The resolved component is expected to fall off faster than the direct as photon virtuality increases, as is seen in the data. More quantitative measurements with the 1995 data will extend our understanding of both the photon and of QCD.

The UK involvement in all the above analyses is strong and the measurements are being repeated and extended using the increased luminosity now available. The analyses will result in quantitative tests of QCD in an extremely interesting kinematic region and place important constraints on the structure of the photon.

These measurements require high jet statistics in various kinematic regions, some of which are at relatively low $E_T$. As HERA luminosity increases, the ability to retain these events amidst the high rates of background and of less interesting low $E_T$ physics depends critically on tracking information in the trigger. In the past two years, the CTD-FLT allowed ZEUS to retain relatively low calorimeter energy thresholds even though HERA luminosity increased by a factor of more than 10 since

1993. The CTD-SLT vertex information allows a similar relaxing of cuts at the second level, and in the future the ability to match CTD tracks to calorimeter clusters at the second level will be vital. At the third level of the trigger, a jet finding algorithm is run, which needs the CTD vertex information in order to determine the rapidity of the jets.

The dominant systematic uncertainty in the jet cross section measurements is the uncertainty in the absolute energy response of the calorimeter. As mentioned in section 2, CTD data are vital for controlling and reducing this uncertainty.

A topic of great interest at high luminosities is prompt photon production, where one of the jets is replaced by a high $E_T$ isolated photon [18]. Prompt photon production provides complementary information on proton and photon structure to jet production, and in addition allows studies of QCD radiation and fragmentation effects. Differentiating this signal from $e$ and/or $\pi^{\pm}$ signals relies heavily on information from the CTD, whereas calorimeter information is being used to determine the remaining background from $\pi^0$ production. This analysis is currently underway, again with strong UK involvement.

# 6 Diffraction

*Bristol, Glasgow, Imperial, UCL*

Given the fact that for almost real photons the $\gamma p$ cross section rises only slowly with $W$, whereas for virtual photons at $Q^2$ of 1.5 GeV$^2$ the cross section rises rapidly (see section 4), a natural way to extend the study of the virtual photon is to examine diffractive vector meson production, $\gamma p \rightarrow Vp$. In these processes a hard scale may be provided by the four-momentum transfer $t$ between the proton and the photon, or by the production of a particle of high mass (for example the $J/\Psi$ meson), or as in inclusive DIS, by $Q^2$, the photon virtuality. At ZEUS the ability exists to the control the scale involved in the collision and so investigate the transition between the perturbative and non-perturbative descriptions of diffraction.

Data on the elastic photoproduction of light vector mesons by real and virtual photons, shown in Fig.9, follows a similar trend to the inclusive measurements (Fig.5). ZEUS has shown that the total cross section $\sigma(\gamma p \rightarrow Vp)$, where $V$ is either $\rho$, $\omega$ or $\phi$ rises slowly with $W$ [19, 20]. This process also exhibits an exponentially falling distribution in four momentum transfer at the proton vertex, and $s$ channel helicity conservation. These properties are consistent with a diffractive production mechanism. The data are well described by the Vector Dominance Model (VDM) [10]. In contrast, the cross section $\sigma(\gamma^* p \rightarrow Vp)$ with photon virtuality $Q^2 > 2$ GeV$^2$ grows rapidly with $W$ [21]. ZEUS have also measured the cross section for $J/\Psi$ photoproduction, $\sigma(\gamma p \rightarrow J/\Psi p)$ [22]. For $W$ greater than about 50 GeV the cross section rises more rapidly with $W$ than that of the lower mass vector mesons. From these data it appears that when no hard scale is involved, VDM can describe the data, whereas when a hard scale is present VDM fails and QCD models give a better qualitative description of the data. The behaviour of the cross sections in QCD models is related to the rise in the gluon distribution at low-$x$ determined by HERA $F_2$ measurements. Further studies will be important in the future investigation of low-$x$ QCD.

The UK group participated in the production of the above results at all levels from the design and implementation of triggers to the development of the analysis methods and the publication of results. This involvement continues with the analysis of the latest data.

A further avenue which HERA provides for the study of diffraction is the measurement of so-called 'diffractive hard scattering' processes. These processes are characterised by a large four-momentum transfer across a rapidity gap. Such events have been observed at ZEUS [23] in the shape of an excess of dijet photoproduction events with a large rapidity gap between the two jets. Because of the high momentum transfer, the exchanged pomeron is amenable to calculation in perturbative QCD [24] and these processes should provide a valuable insight into the diffractive mechanism in QCD. The potential for these measurements at high luminosities at HERA is currently being investigated within the 'Future physics at HERA' workshop.

# 7 QCD and DIS hadronic final states

*Glasgow, Imperial, RAL, UCL*

In order to make more detailed studies of QCD in DIS than those available from inclusive structure function measurements, it is necessary to study the hadronic final state.

A natural frame in which to study the dynamics of the hadronic final state in DIS is the Breit frame [25]. In the quark parton model the $z$-component of the momentum of the incoming quark is $Q/2$ before and $-Q/2$ after the interaction with the exchanged virtual boson. In the direction of the struck quark (the current region) in the Breit frame the particle spectra are expected to have no dependence on $x$ and a dependence on $Q^2$ similar to those observed in $e^+e^-$ annihilation at energy $s = Q^2$ [26]. ZEUS have published the charged particle multiplicity and scaled momentum spectra in the current region of the Breit frame [27]. The results (Fig.10), show that these fragmentation properties of the struck quark in DIS are similar to those of quarks created in $e^+e^-$ annihilation for $Q > 10$ GeV. The measurements have recently been extended to higher $Q^2$ and a preliminary investigation of the target fragmentation region has been performed.

At the large centre of mass energies at HERA multi-jet structures are very pronounced [28] for the first time in DIS. It is therefore possible to determine the $Q^2$ dependence of $\alpha_s$ from the dijet production rate [29]. The measurement was performed at high $Q^2$ and $x$ to remove theoretical uncertainties arising from the parton density functions. In addition, in order to use the next-to-leading order (NLO) calculation [30, 31] to extract $\alpha_s$ (in the JADE scheme) it was found necessary to cut on the partonic scaling variables of the dijet system to ensure the region of phase space was away from collinear and infrared singularities. The value of $\alpha_s$ was determined in three regions of $Q^2$ and was found to be consistent with a variation with $Q^2$ (Fig. 11). The value of $\alpha_s$ when extrapolated to the $Z^0$ mass was found to be $\alpha_s(Z^0) = 0.117 \ \pm\ 0.005\ (stat)\ ^{+0.004}_{-0.005}\ (syst_{exp})\ \pm 0.007\ (syst_{theory})$. An important issue in this analysis was the determination of the region of phase space in which NLO calculations can safely be applied.

Calculations of event properties and cross sections in perturbative QCD commonly make use of resummed quark and gluon splitting functions. These lead to predictions for multiplicities in terms of a cascade of partons. In different kinematic regions, the evolution of this cascade can be approximated by either the BFKL [32] or GLAP [6] scheme. Whilst the GLAP scheme successfully describes large amounts of data, (for example scaling violations in $F_2$), no unambiguous evidence for the validity of the BFKL evolution exists to date. At low $x$, the BFKL approach predicts more transverse energy ($E_T$) in the hadronic final state in the central region of the hadronic centre of mass system than does the GLAP approach. This corresponds to the very forward region of the detectors in the HERA laboratory frame. Fig.12 shows the transverse energy flow as a function of pseudorapidity, $\eta$, as measured in the ZEUS laboratory frame [33]. The $E_T$ level is almost flat at $\approx 2$ GeV/(unit of $\eta$). Also shown are the partonic calculations from Golec-Biernet et al. [34] which seem to indicate a preference towards the BFKL approach over GLAP. Present studies suggest that non-perturbative hadronization effects also influence these results, and so it is not possible to comment definitively upon whether these plots are signatures for BFKL evolution. Much experimental, phenomenological and theoretical work is in progress in order to eliminate the remaining ambiguities.

# 8 Standard model and beyond

*Imperial, Oxford, RAL*

As the luminosity delivered by HERA continues to increase, measurements of low cross-section processes such as charged current DIS and $W$ boson production become more viable. Furthermore the potential increases for discovering new and exotic particles (such as leptoquarks and excited fermions) predicted to exist in extensions to the Standard Model.

The topology of charged current events and those in which massive particles are produced (e.g. $W$ and $Z$ bosons, excited quarks) tends to be very different to the bulk of events observed in ZEUS. A detailed understanding of all regions and components of the ZEUS detector is therefore essential. Moreover, many of the analysis techniques developed in the process will become standard techniques throughout ZEUS as present analyses are extended at high luminosities. For example, electron identification in the forward and barrel regions using charged tracks in the CTD will be important for measurement of $F_2$ at high $Q^2$, and correcting the energy measurement of highly energetic jets which 'punch-through' into the backing calorimeter will be important for high $E_T$ photoproduction and charged current measurements.

ZEUS has published neutral current and charged current differential cross-sections at high $Q^2$ based on 1993 e$^-$p data [37]. The results, shown in Fig.13, show the weak and electromagnetic forces becoming comparable in strength at $Q^2 \sim 10^4$ GeV$^2$, consistent with Standard Model expectations. A fit to the charged current data gives a mass for the propagator consistent with the W mass. The statistical and systematic errors have improved using 1994 data and will continue to do so as more data are collected.

In 1994 HERA operated as both an $e^-p$ and $e^+p$ collider. As shown in Fig.14, the ratio of $\sigma(e^+p)/\sigma(e^-p)$ in neutral current DIS decreases as $Q^2$ approaches $10^4$ GeV$^2$, illustrating the difference of the $Z^0$ coupling to $e^+$ and $e^-$. The charged current data show that the valence quark contribution to the proton structure function dominates as expected. More luminosity using polarised and unpolarised electron and positron beams will enable the quark couplings to be unfolded from such measurements, and preliminary studies are underway as part of the 'Future Physics at HERA' workshop.

Real W and Z bosons are predicted to be produced at HERA with a cross-section of around 1 pb. As well as being an interesting physics process in itself, W and Z production is an important background to a number of exotic physics processes, for example very massive right-handed neutrinos, for which a search is presently being carried out. Majorana neutrinos decay into $e^-W^+$ and $e^+W^-$ with equal branching fractions. The most distinctive events have a final state consisting of two jets with high dijet invariant mass, and an electromagnetic cluster in the calorimeter which is associated with a CTD track with charge opposite to that of the lepton beam. The analysis of $W$ production has so far concentrated on optimising algorithms to select $W$ events through their leptonic ($e\nu$, $\mu\nu$ and $\tau\nu$) and hadronic decay channels. All decay modes are considered in order to achieve a statistically significant sample of events as well as providing an important cross-check. To achieve this a good understanding of the detector and backgrounds, particularly those from QCD processes in the $W \rightarrow$ jets channel, is required. A candidate $e^+p \rightarrow WX$, $W \rightarrow e^+\nu$ event is shown in Fig.15. The event has a well-identified positron in the calorimeter with a matched CTD track, and a large missing $p_T$.

# 9 Future plans

The eventual goal of HERA is to provide high luminosity running with polarised and unpolarised electrons and positrons. Electron running will restart in 1997, and in the years following that major luminosity upgrades are planned, in order to achieve integrated luminosities at a level of 150-200 pb$^{-1}$/year. In addition, spin rotators will be installed. The 1996 data taking period will be used to measure $F_L$. This requires the operation of HERA at lower proton beam energies.

This plan for HERA operation reflects the requirements of the physics programme of the ZEUS collaboration. In defining this programme, ZEUS UK has played an important and influential rôle. As described in the previous sections, all UK institutes have areas of particular expertise and interest, which they will continue to pursue. Specifically:

- The Bristol, Imperial and Oxford groups will continue high precision measurements of proton structure. This includes measuring $F_L$ with the low energy running in 1996, and $F_2^{charm}$. In addition, studies of diffractive vector meson production, in particular $J/\Psi$, will continue.

- Bristol, Glasgow and UCL will pursue measurements of high $E_T$ photoproduction. Particular goals for the near future are the measurement of prompt photon production and higher precision jet measurements in order to pin down the photon structure and to test QCD. Additionally studies of hard diffraction and the nature of the pomeron at high momentum transfers will be extended.

- Glasgow, RAL and UCL will continue with the analysis of DIS hadronic final states, providing further insights into QCD.

- Studies of electroweak and exotic physics are naturally expanding rapidly as luminosity increases. The strong involvement of the Imperial, Oxford and RAL groups will grow as this continues. Charged current physics will be a particular beneficiary of the reintroduction of electrons in 1997.

The many important results so far produced have been achieved with an integrated luminosity of 10 pb$^{-1}$, a fraction of the annual HERA design luminosity, so the prospects for the future are exciting indeed. Higher precision and higher statistics will ensure that the already substantial impact of ZEUS data on the current understanding of QCD, and particle physics in general, continues to increase. It must be emphasised that this level of involvement in both the detector and the physics analysis requires funding for travel and maintenance at levels similar to the current ones.

In order to exploit the anticipated luminosity upgrades, the ZEUS collaboration is addressing the issue of an upgrade to the tracking detectors, e.g. the introduction of a silicon vertex detector. ZEUS tracking is dominated by the UK contribution, and ZEUS UK would expect to participate in any future upgrades in this area, albeit at a modest level.

With dramatically increased luminosity and the advent of polarisation we anticipate ZEUS remaining at the forefront of fundamental scientific research well into the next century.

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# Appendices

## A ZEUS Journal Publications

(Since last PPESP report)

1. M. Derrick et al., Measurement of Total and Partial Photon Proton Cross Sections at 180 GeV Centre of Mass Energy Zeit. f. Phys., C63 (1994) 391-408.
2. M. Derrick et al., Observation of jet production in deep inelastic scattering with a large rapidity gap at HERA Phys. Letters B332 (1994) 228.
3. P. Morawitz and H. Dreiner, Signals for supersymmetry at HERA Nucl. Phys B428 (1994) 31.
4. M. Derrick et al., Comparison of energy flows in deep inelastic scattering with and without a large rapidity gap Phys. Lett. B338 (1994) 483.
5. B. Foster et al., The design and construction of the ZEUS central tracking detector Nucl. Instr. and Meth. A338 (1994) 254.
6. C.J.S. Morgado et al., The performance of the FADC System for the ZEUS Central Tracking Detector IEEE Trans. on Nuclear Science 41 (1994) 1250.
7. S.B. Galagadera et al., The Timing and Control System of the ZEUS Tracking Detector Data Acquisition Electronics IEEE Trans. on Nuclear Science 41 (1994) 1255.
8. D.G. Cussans & H.F. Heath Optimisation of the pulse arrival time determination in the ZEUS central tracking detector FADC system Nucl Inst. and Meth, A362 (1995) 277.
9. M. Derrick et al., Measurement of the Proton Structure Function F2 from the 1993 HERA Data Zeit. f. Phys., C65 (1995) 379.
10. M. Derrick et al., A Search for Excited Fermions in *ep* Collisions at HERA Zeit. f. Phys., C65 (1995) 627.
11. M. Derrick et al., Inclusive Jet Differential Cross Sections in Photoproduction at HERA Phys. Lett. B342 (1995) 417.
12. M. Derrick et al., Extraction of the Gluon Density of the Proton at Small X Phys. Lett. B345 (1995) 576.
13. M. Derrick et al., Observation of Hard Scattering in Photoproduction Events with a Large Rapidity Gap at HERA Phys. Lett. B346 (1995) 399.
14. M. Derrick et al., Measurement of Multiplicity and Momentum Spectra in the Current Region of the Breit Frame at HERA Zeit. f. Phys. C67 (1995) 93.
15. M. Derrick et al., Study of $D^*(2010)\pm$ Production in $ep$ Collisions at HERA Phys. Lett. B349 (1995) 225.

16. M. Derrick et al., Jet production in high $Q^2$ deep-inelastic $ep$ scattering at HERA Zeit. f. Phys. C67 (1995) 81.

17. M. Derrick et al., Dijet Cross Sections in Photoproduction at HERA Phys. Lett. B348 (1995) 665.

18. M. Derrick et al., Inclusive Transverse Momentum Distributions of Charged Particles in Diffractive and Non-Diffractive Photoproduction at HERA Zeit. f. Phys., C67 (1995) 227.

19. M. Derrick et al., Measurement of the Cross Section for the reaction $\gamma p \rightarrow J/\psi p$ with the ZEUS Detector at HERA Phys. Lett. B350 (1995) 120.

20. M. Derrick et al., Measurement of Charged and Neutral Current $ep$ Deep Inelastic Scattering Cross Sections at High $Q^2$ Phys. Rev. Lett. 75 (1995) 1006.

21. M. Derrick et al., Study of the Photon Remnant in Resolved Photoproduction at HERA Phys. Lett. B354 (1995) 163.

22. M. Derrick et al., Neutral Strange Particle Production in Deep Inelastic Scattering at HERA Zeit. f. Phys. C68 (1995) 29.

23. M. Derrick et al., Measurement of the Diffractive Structure Function in Deep Inelastic Scattering at HERA Zeit.f. Phys. C68 (1995) 569.

24. M. Derrick et al., Diffractive Hard Photoproduction at HERA and Evidence for the Gluon Content of the Pomeron Phys. Lett. B356 (1995) 129.

25. M. Derrick et al., Exclusive $\rho_0$ Production in Deep Inelastic $ep$ Scattering at HERA Phys. Lett. B356 (1995) 601.

26. M. Derrick et al., Measurement of Elastic $\rho_0$ Photoproduction at HERA Zeit. f. Phys. C69 (1995) 39.

27. M. Derrick et al., Measurement of $\alpha_s$ from Jet Rates in Deep Inelastic Scattering Phys. Lett. B363 (1995) 201.

28. M. Derrick et al., Measurement of the Proton Structure Function $F_2$ at low $x$ and low $Q^2$ at HERA; accepted by Zeit. f. Phys. - MS 206.

29. M. Derrick et al., Rapidity Gaps between Jets in Photoproduction at HERA Phys. Lett. B369 (1996) 55.

30. M. Derrick et al., Inclusive Charged Particle Distribution in Deep Inelastic Scattering Events at HERA; accepted by Zeit. f. Phys. - MS 120.

31. M. Derrick et al., Measurement of Elastic phi-Photoproduction at HERA; accepted by Physics Letters B - Ref. 3879.

32. J. M. Butterworth, J. R. Forshaw and M. H. Seymour, Multiparton Interactions in Photoproduction at HERA; accepted by Zeit. f. Phys. - MS 213.

33. M. Derrick et al., Measurement of the Diffractive Cross Section in Deep Inelastic Scattering; accepted by Zeit. f. Phys. - MS 293.

## B Conference Talks

**Talks given at major national and international meetings since the last report by UK personnel**

1. Topical Conference on Diffractive Processes, Eilat, Israel, Feb 18-23/96, 'Rapidity gaps in Photoproduction', L. Sinclair, Glasgow.
2. DESY Theory Workshop: Strong and Weak Forces beyond Perturbation Theory, Sept 27-29/95, 'HERA results' , R. Devenish, Oxford.
3. DESY Theory Workshop: Strong and Weak Forces beyond Perturbation Theory, Sept 27-29/95, 'Jets and hadronic final states', A. Doyle , Glasgow.
4. 'Proton, Photon and Pomeron Structure', Workshop on HERA Physics, Durham, Sept 17-23/95, 'ZEUS DIS results' M. Lancaster, Oxford.
5. Computing in High Energy Physics, CHEP95, Rio de Janiero, Brazil, Sept. 18-22/95, 'The ZEUS Central Tracking Detector Second Level Trigger' H. Uijterwaal, Oxford.
6. Workshop on Weak Interactions and Neutrinos, Talloires, France, Sep 4-8/95, 'Exotic searches at HERA', V. Noyes, Oxford.
7. 1995 Int. Europhysics Conf. on HEP, Brussels, Belgium, 'Structure of the virtual photon', M. Utley, Glasgow.
8. Workshop on prospects for spin physics at HERA, Zeuthen, Berlin, 1995, R. Cashmore (Oxford).
9. ATLAS physics meeting, June 8-11/95, 'HERA physics', E. Gallo, Imperial College London.
10. Workshop on DIS and QCD, Paris, France, April 24-28/95, 'ZEUS Results' B. Foster, Bristol.
11. Workshop on DIS and QCD, Paris, France, April 24-28/95, 'Prospects for very high luminosity at HERA', R. Cashmore, Oxford.
12. Workshop on DIS and QCD, Paris, France, April 24-28/95, 'Vector mesons' , A. Whitfield, Imperial College London.
13. Workshop on DIS and QCD, Paris, France, April 24-28/95, '$F_2$ results' , M. Lancaster, Oxford.
14. Photon '95, Sheffield University, U.K., 8-13 April 1995. 'Photon and Proton Structure', J. Butterworth, University College London.
15. Photon '95, Sheffield University, U.K., 8-13 April 1995. '$F_2^p$ and the gluon' , I. Fleck, Glasgow.
16. Los Angeles Int. Sym. on vector boson self-interactions, Feb 1-3/95, 'W and Z Boson production at HERA', R. Walczak, Oxford.

17. Les Rencontres de Physique, La Thuile, March 5-11/95, 'DIS Results at HERA', R. Yoshida, Bristol.

18. Workshop on TRISTAN Physics at high luminosities, KEK Tsukuba, Japan, Nov. 16/95, 'Photon structure as seen at HERA', J. Butterworth, University College London.

19. QCD Institute at DESY, Sept 26-27/94, 'Proton Structure Functions', R. Devenish, Oxford.

20. 24th Inter. Sympos. on Multiparticle Dynamics, Salerno, Italy, Sept 12-19/94, '$F_2$ and Diffraction', A. Prinias, Imperial College London.

21. 27th Int. Conf. on High Energy Physics, Glasgow, July 20-27/94, 'ZEUS $F_2$ and Gluon', M. Lancaster, Oxford.

22. DESY Extended Scientific Council Meeting, June 2/94, '$F_2$ and Diffraction', A. Doyle, Glasgow.

23. Workshop on DIS at HERA, Paris, May 19-20/94, '$F_2$', M. Lancaster, Oxford.

24. 4th Annual Conference on Electronics for Future Colliders, Chestnut Ridge, NY, May 11-12/94, 'Electronics of the ZEUS Central Tracking Detector', R.J. Tapper, Bristol.

25. DESY Minischool on Diffraction at HERA, May 4-7/94, 'Results from ZEUS', R. Devenish, Oxford.

26. UK HEP Conference, 1994, Bristol, April 14-15/94, 'Results from HERA', B. Foster, Bristol.

27. Moriond, QCD and High Energy Hadronic Interactions 'Hadron Final States (DIS)' N. Brook, Glasgow.

28. Moriond, QCD and High Energy Hadronic Interactions 'Photoproduction at ZEUS' P. Bussey, Glasgow.

29. Eilat Workshop, Eilat, Israel, Feb 6-11/94, 'A look at the Breit frame', N. Brook, Glasgow.

30. Eilat Workshop, Eilat, Israel, Feb 6-11/94, 'High $E_T$ Photoproduction at ZEUS' J. Butterworth, University College London.

31. DESY PRC, Public ZEUS report, 26/1/95 B. Foster (Bristol)

32. DESY PRC, Public ZEUS report, 16/1/96 R. Cashmore (Oxford).

Note: In addition to the talks listed here, numerous contributions to the Workshop on Future Physics at HERA have come from ZEUS UK physicists, and ZEUS UK has provided the following conveners at major conferences and workshops:

- Workshop on Future Physics at HERA, 1995-1996: R. Cashmore, A. Doyle.

- 1995 Int. Europhysics Conf. on HEP, Brussels, Belgium: R. Devenish.
- Photon '95, Sheffield University, U.K., 1995: P. Bussey, R. Devenish, N. McCubbin.
- 'Proton, Photon and Pomeron Structure', Workshop on HERA Physics, Durham, UK, 1995: N. Brook, R. Devenish.
- Workshop on QCD and HERA Physics, Cambridge, UK, 1995: M. Lancaster.
- Workshop on DIS and QCD, Paris, France, 1995: R. Cashmore, R. Devenish.

# C UK Theses

(Submitted since last PPESP report.)

1. V. A. Noyes (née Jamieson), "Measurement of scaled momentum distributions in the Breit frame at HERA using the ZEUS detector"
   Glasgow, (1994). Winner of the *Award of the Association of Friends and Sponsors of DESY* for the best thesis submitted in 1994 based on research at the laboratory.
2. P. L. Makkar, "Studies of deep inelastic scattering at HERA"
   University College London, (1994).
3. C. D. Catterall, "Hadronic final states in deep inelastic electron proton scattering at a centre of mass energy of 300 GeV"
   University College London, (1995).
4. S.S. Wilson, "An investigation into the semi instrumented ZEUS tracking trigger and a study of leptoquarks at ZEUS"
   Bristol, (1994).
5. J.A. O'Mara, "A determination of the gluon momentum density within the proton and studies of systematic errors and trigger rates for the measurement of the proton structure function $F_2$"
   Bristol, (1995).
6. S. George, "Design of the SDC second level silicon tracking trigger and study of strange meson production in deep inelastic scattering with the ZEUS detector at HERA"
   Bristol, (1995).
7. P. E. Luffman "Performance of track reconstruction in the ZEUS CTD and studies of QCD in e-p collisions at HERA"
   Oxford, (1993).
8. P. P. O. Morawitz "The ZEUS first level tracking trigger and studies of supersymmetry at HERA"
   Oxford, (1993).

9. A. F. Byrne "An initial study of diffractive physics in e-p collisions at HERA and performance of the tracking trigger for the ZEUS experiment"
Oxford, (1994).

10. A. Prinias "The measurement of the proton $F_2$ structure function using the ZEUS detector"
Imperial, (1994).

# D ZEUS UK Collaboration

**Bristol University** S. Campbell-Robson[1], A. Cassidy[1], W. N. Cottingham, N. Dyce, B. Foster, S. George[1], R.Gilmore, R. Hall-Wilton[1], M. E. Hayes[1], G. P. Heath, H. F. Heath, D. Piccioni[1], D. Roth[1], R. J. Tapper, R. Yoshida

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**Imperial College London** T. C. Bacon, N.Brümmer, I. Butterworth, J. E. Cole[1], V. L. Harris[1], G. Howell[1], B. H. Y. Hung[1], L. Lamberti, K. R. Long, D. B. Miller, A. Prinias, J. K. Sedgbeer, D. Sideris[1], A. F. Whitfield[1]

**Oxford University** D. S. Bailey[1], H. E. Blaikley[1], R. J. Cashmore, A. M. Cooper-Sarkar, R. C. E. Devenish, J.K. Edmonds[1], N. Harnew, M. A. Lancaster, L. Lindemann, J. D. McFall[1], C. Nath[1], V. A. Noyes, A. Quadt[1], J. Tickner[1], H. Uijterwaal, R. Walczak, D. S. Waters[1], F. F. Wilson, T. Yip[1]

**Rutherford Appleton Laboratory** J. C. Hart, N. A. McCubbin, T. P. Shah

**University College London** J. M. Butterworth, C. D. Catterall, T. W. Jones, P. B. Kaziewicz[1], J. B. Lane, R. L. Saunders[1], J. Shulman, M. R. Sutton[1], M. Wing[1]

We are grateful to the engineers and support staff at the ZEUS UK institutes, who have provided invaluable help. For help over the past two years we would particularly like to acknowledge:

**Bristol:** S. Nash, R. Head
**Glasgow:** C. Raine, A. J. Flavell
**Imperial:** A. K. Jamdagni
**UCL:** T. J. Fraser, M. Postranecky, I. A. Vine
**Oxford:** S. Berry, P. D. Gronbech, G. Harris, C. Hunter, I. McArthur, P. Shield, C. Sutton, S. Topp-Jorgensen
**RAL:** R. W. Barnard, R. Carter, I. Church, C. Day, S. B. Galagadhera, M. D. Gibson, R. N. J. Halsall, R. Hatley, P. A. Hawthorne, A. C. Hopgood, J. Hiddleston, M. D. Jeffs, S. Madani Bozorg, M. C. Morrissey, C. Moss, B. T. Payne, S. P. H. Quinton, R. L. Thompson

[1]Graduate Student

# E ZEUS Organisation

**ZEUS Organisation**

Executive → Spokesman: R. Klanner / Deputy : A. Caldwell ← ZEUS Planning Group

Physics Coordinator
**R. Cashmore**

Technical Coordinator
B. Loehr

| | |
|---|---|
| DIS: | G. Wolf |
| | **R. Yoshida** |
| | E. Gallo |
| Heavy Flavours and Soft Photoproduction: | G. Iaccobucci |
| | B. Burow |
| Hard photoproduction: | C. Foudas |
| | **J. Butterworth** |
| | J. Terron |
| Exotics and High $Q^2$: | U. Katz |
| | B. Straub |

*Other UK Physics Coordinators since 1994:*

**A. Doyle, R. Devenish**

| | |
|---|---|
| Calorimetry: | J. Labs |
| Tracking: | **N. McCubbin** |
| Trigger: | R. Carlin |
| Reconstruction: | T. Haas |
| Monte Carlo: | M. Botje |
| DAQ: | C. Youngman |
| Run Coordinators: | M. Kuze |
| | **M. Lancaster** |
| | A. Staiano |
| | S. Kartk |
| Safety: | G. Knust |

*Other UK coordinators since 1994:*

**B. Foster, C. Morgado, R. Yoshida**

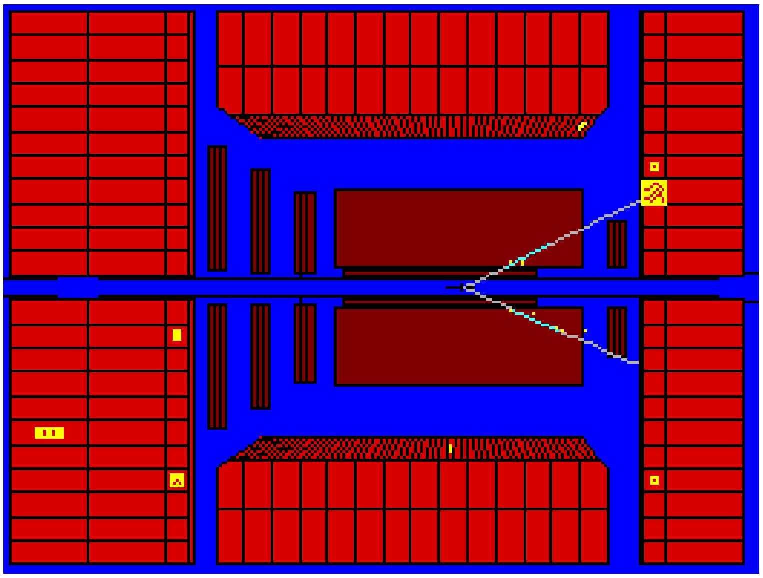

Figure 1: a)

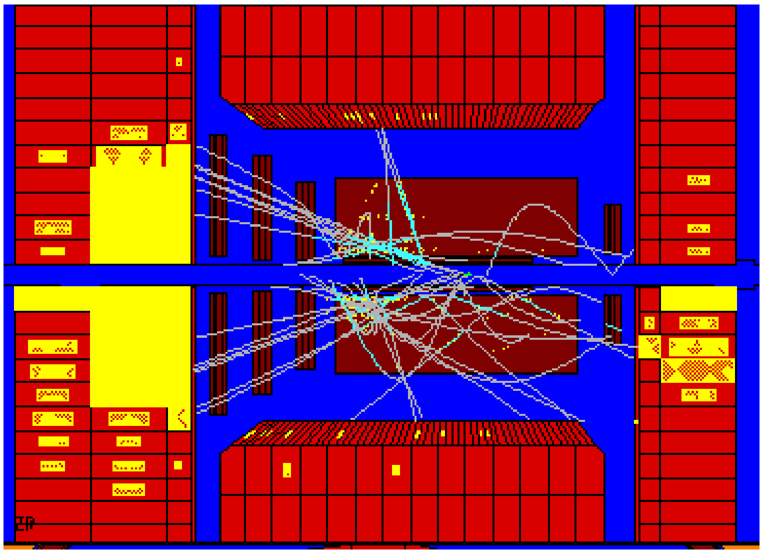

Figure 1: b)

Figure 1: a) Diffractive $\rho$ candidate b) High $E_T$ photoproduction.

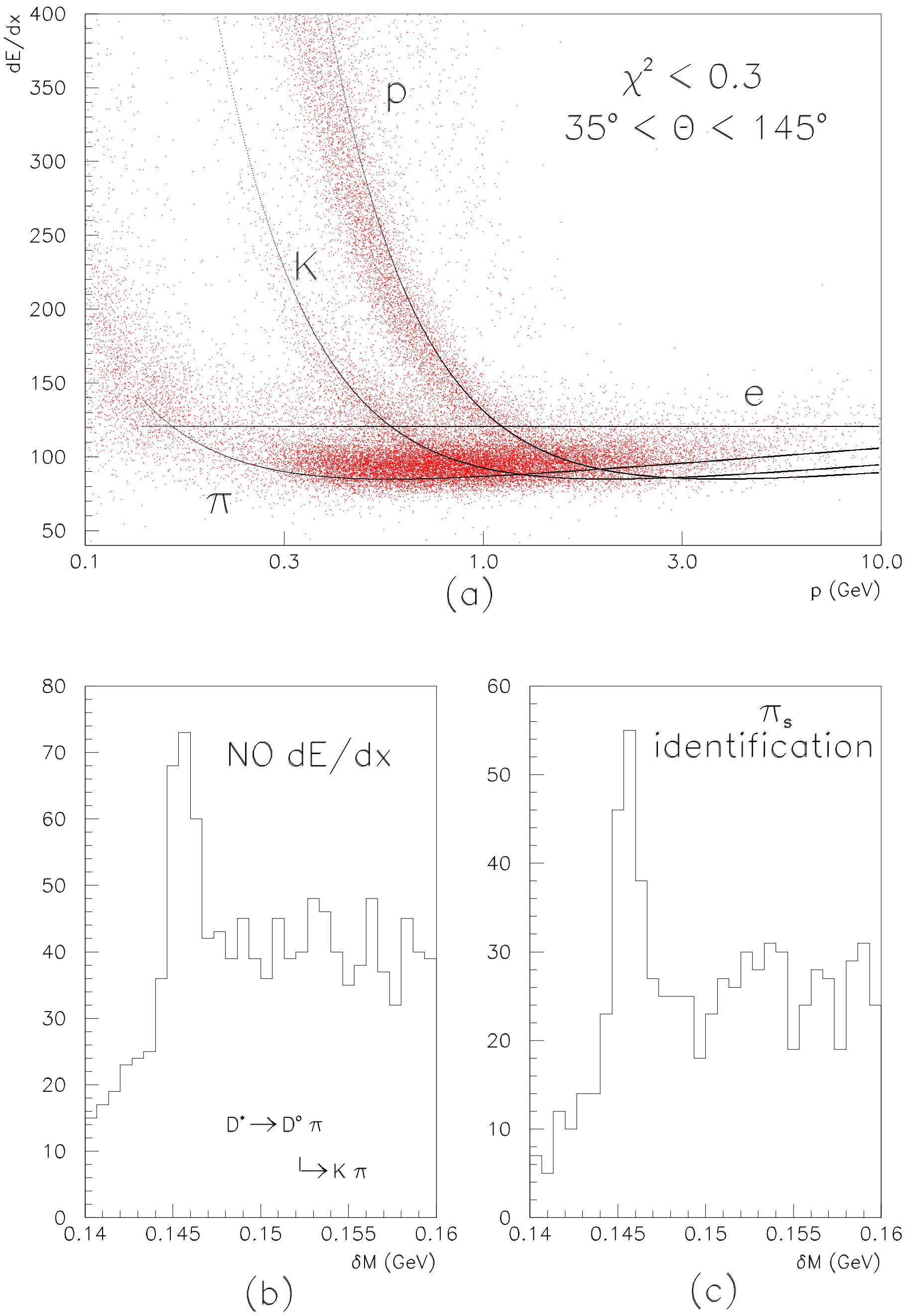


Figure 2: a) $dE/dx$ information for CTD tracks in DIS events, with the positions of the $e$, $K$, $\pi$ and $p$ bands indicated. b) $D^*$ signal before and c) after a $dE/dx$ cut is applied to identify the $\pi$.

# ZEUS 1993 $F_2$

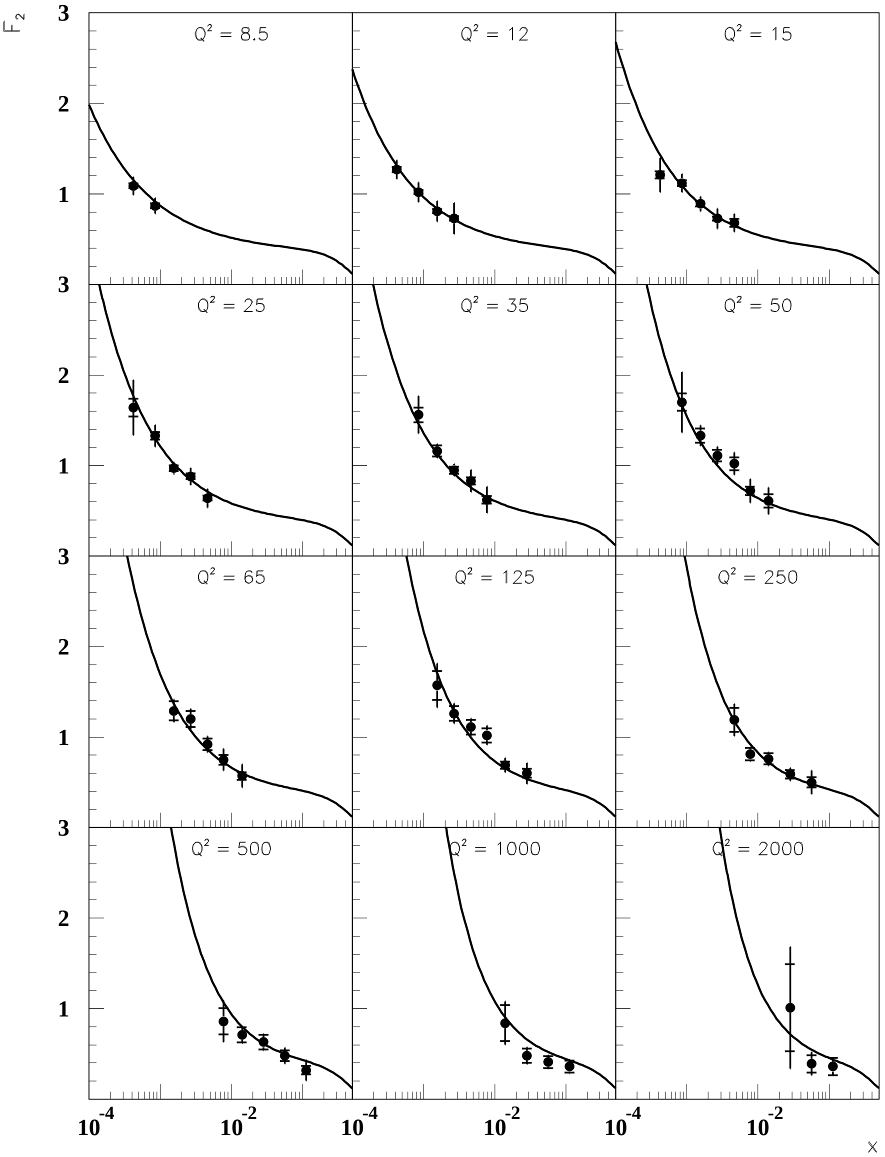


Figure 3: ZEUS 1993 $F_2$ versus Bjorken $x$. The curve is the result of a NLO GLAP fit to the data.

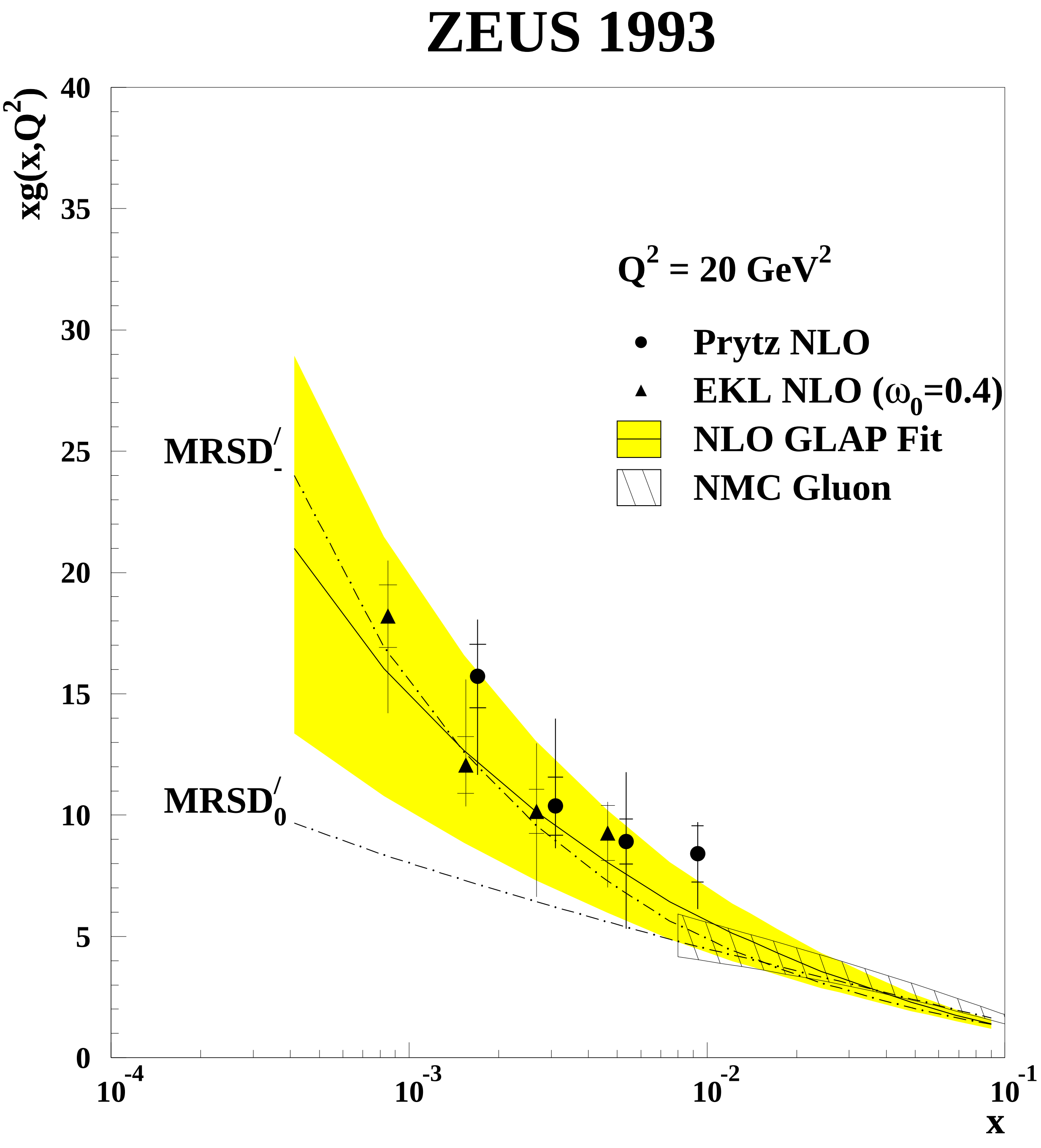


Figure 4: The gluon momentum density as a function of x at $Q^2 = 20\ GeV^2$ determined from the ZEUS data using the methods of Prytz [35] and EKL [36] in NLO. The error bars show the experimental statistical (inner error) and systematic error added together in quadrature. The solid line shows the result of the NLO GLAP global fit with the associated error indicated by the shaded region. The gluon parameterisations of MRSD$'_-$ and MRSD$'_0$ are shown as dash-dotted lines. The hatched region shows the gluon distribution determined by the NMC experiment.

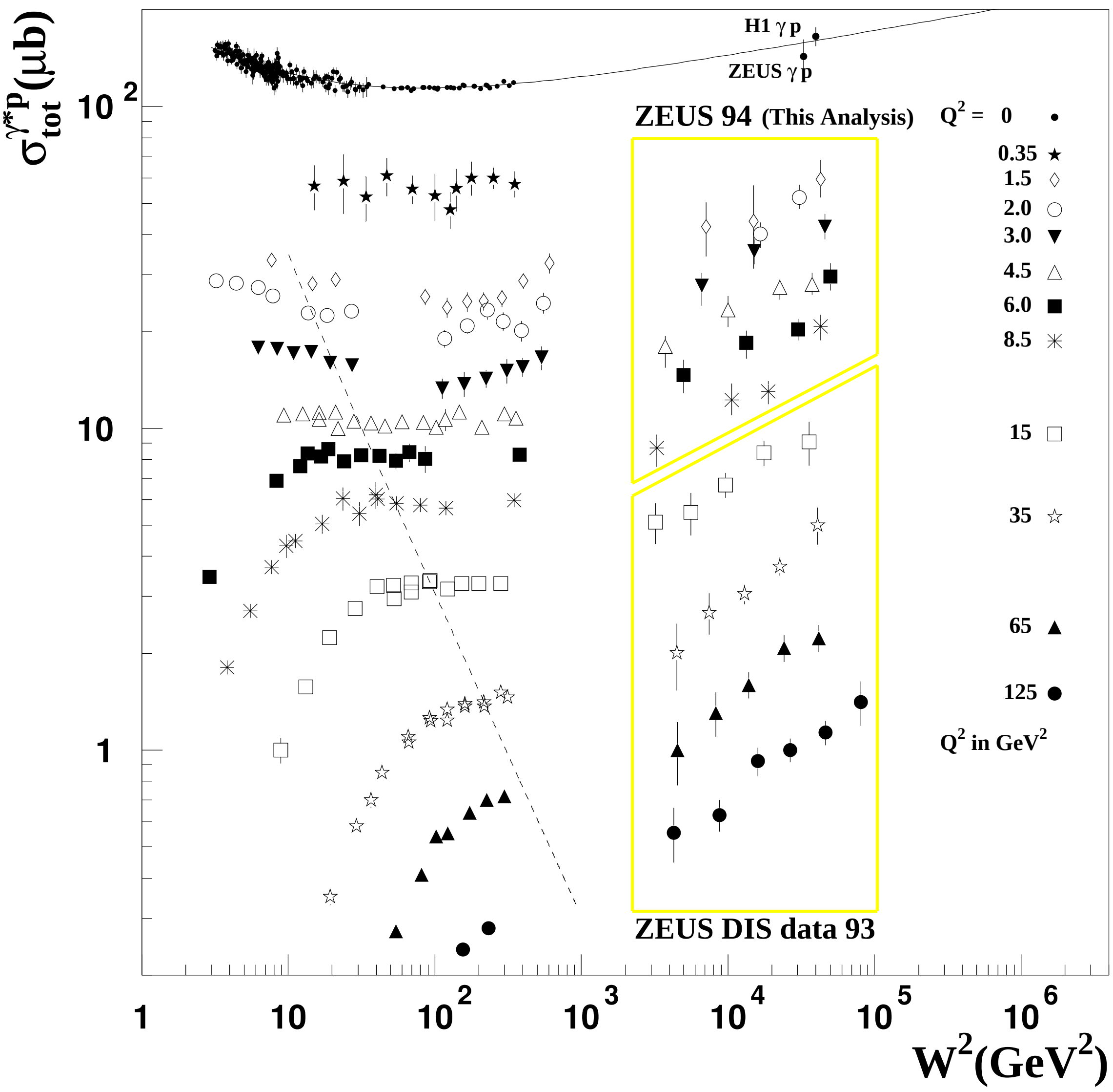


Figure 5: The total virtual photon-proton cross section versus $W^2$ for different $Q^2$ values. The cross section values obtained from the $F_2$ values described in this paper and the $F_2$ values from the 1993 data are shown in addition to data from previous low energy experiments [8]. The region to the right of the dashed line corresponds to $x < 1/(2m_p R_p)$. Also shown is the $W^2$ behaviour of the measured cross section for real photoproduction together with the prediction of Donnachie and Landshoff [10] (solid line).

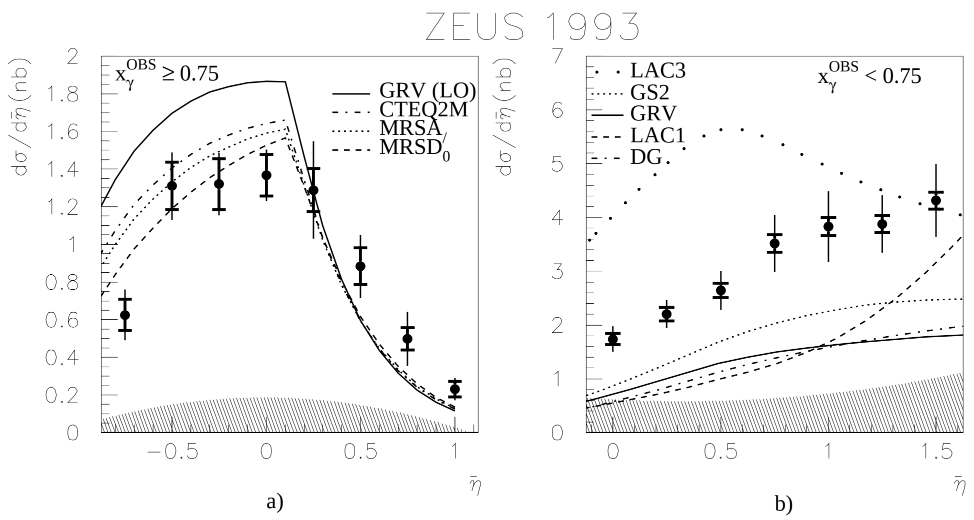


Figure 6: $d\sigma/d\bar{\eta}$ for $ep \to eX + 2$ jets, $\Delta\eta < 0.5, E_T^{jet} > 6$ GeV, $0.2 < y < 0.8, Q^2 < 4$ GeV$^2$: a) Direct and b) resolved photoproduction. The solid circles are corrected ZEUS data. The inner error bars indicate the statistical errors, the outer error bars show the systematic uncertainty excluding the the correlated uncertainty from measurement of energy in the calorimeter and the integrated luminosity, which are shown as a shaded band. In a) the data are compared to LO QCD calculations using several parton distribution sets for the proton. In b) the data are compared to LO QCD calculations using several parton distributions for the photon.

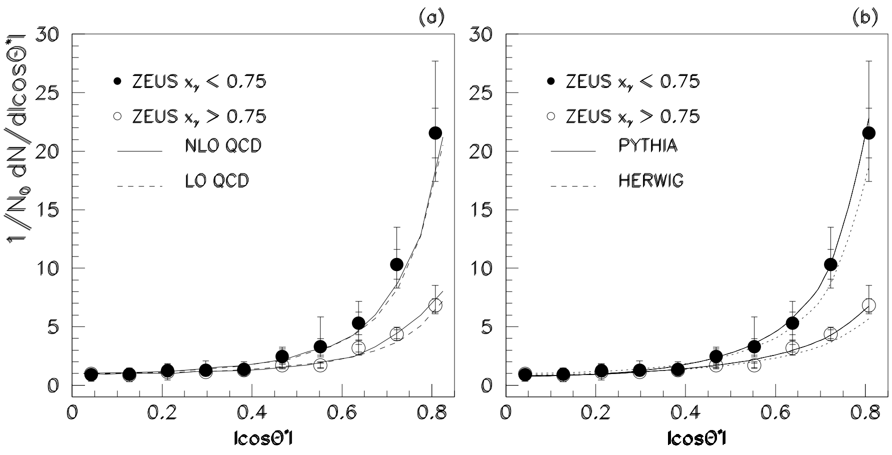


Figure 7: Corrected $|\cos\theta^*|$ distribution, normalized to unity at $|\cos\theta^*| = 0$ for resolved (solid dots) and direct (open circles) photoproduction. In (a), the ZEUS data are compared to the NLO QCD predictions (solid line) and LO predictions (dashed line). In (b), the solid line is the PYTHIA distribution and dotted line is the HERWIG distribution.

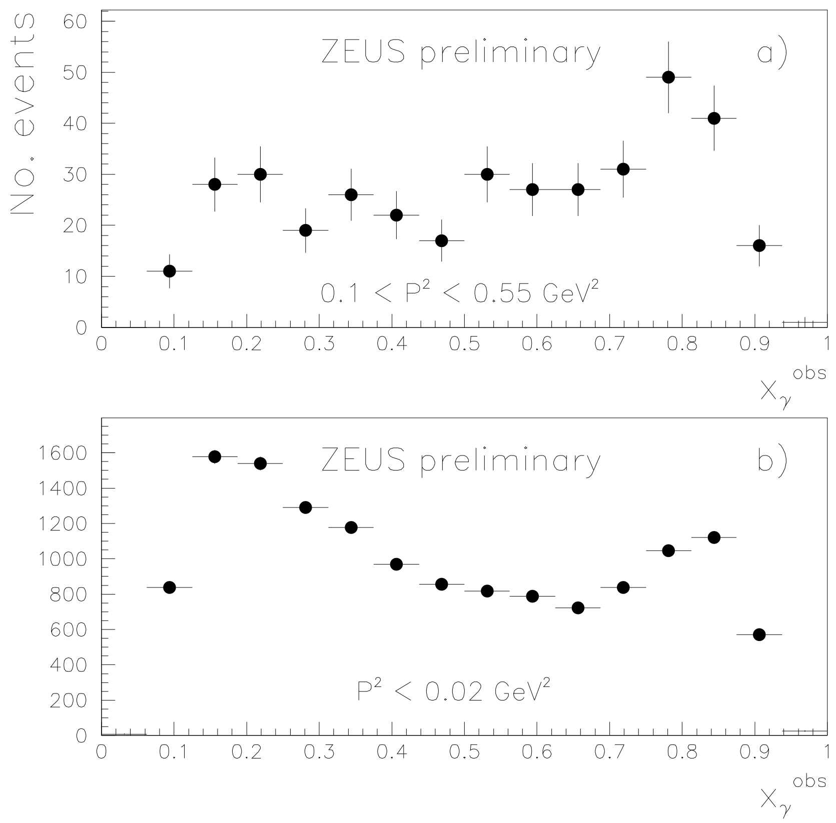


Figure 8: Uncorrected $x_\gamma^{OBS}$ distributions for a) virtual and b) quasi-real photons

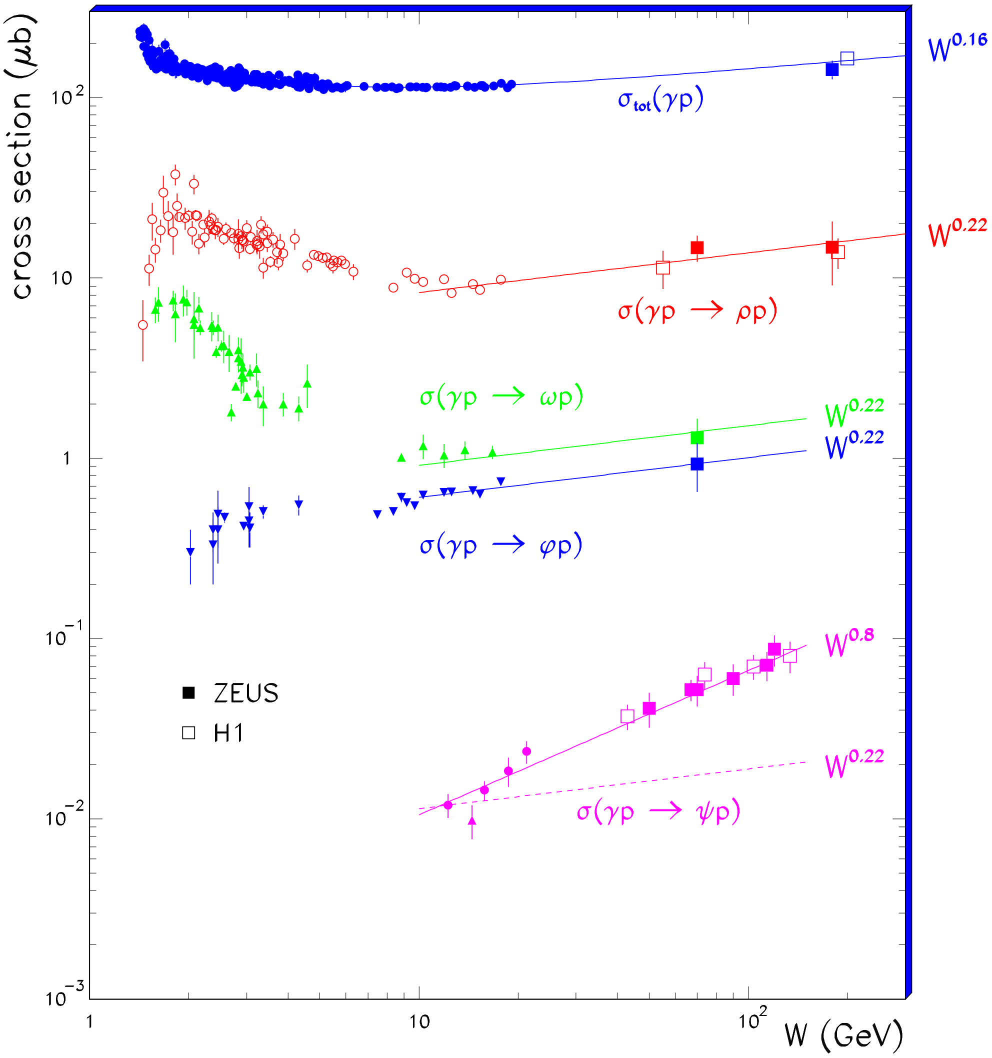


Figure 9: Vector meson photoproduction cross sections plotted against $\gamma p$ c.m.s. energy $W$

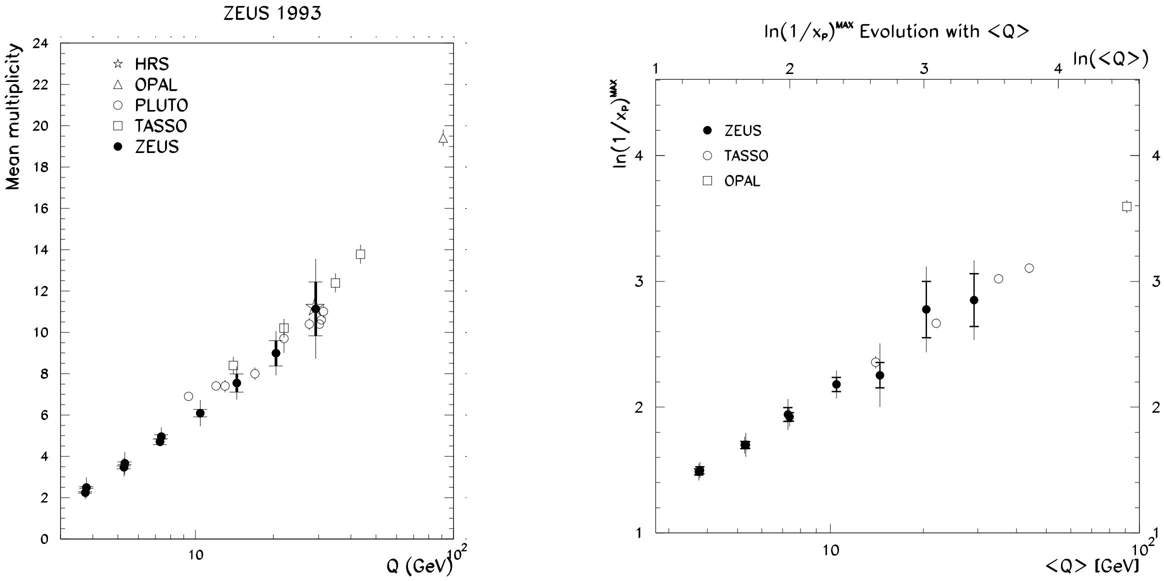


Figure 10: On the left is twice the measured ZEUS multiplicity in the current region compared to the results from HRS, OPAL, PLUTO and TASSO. All data have been corrected for $K_S^0$ and $\Lambda$ decays. The right hand figure is the evolution of the peak position of the $\log(1/x_p)$ spectrum, where $x_p = 2p/Q$, with $Q$. The ZEUS data are compared to results from OPAL and TASSO.

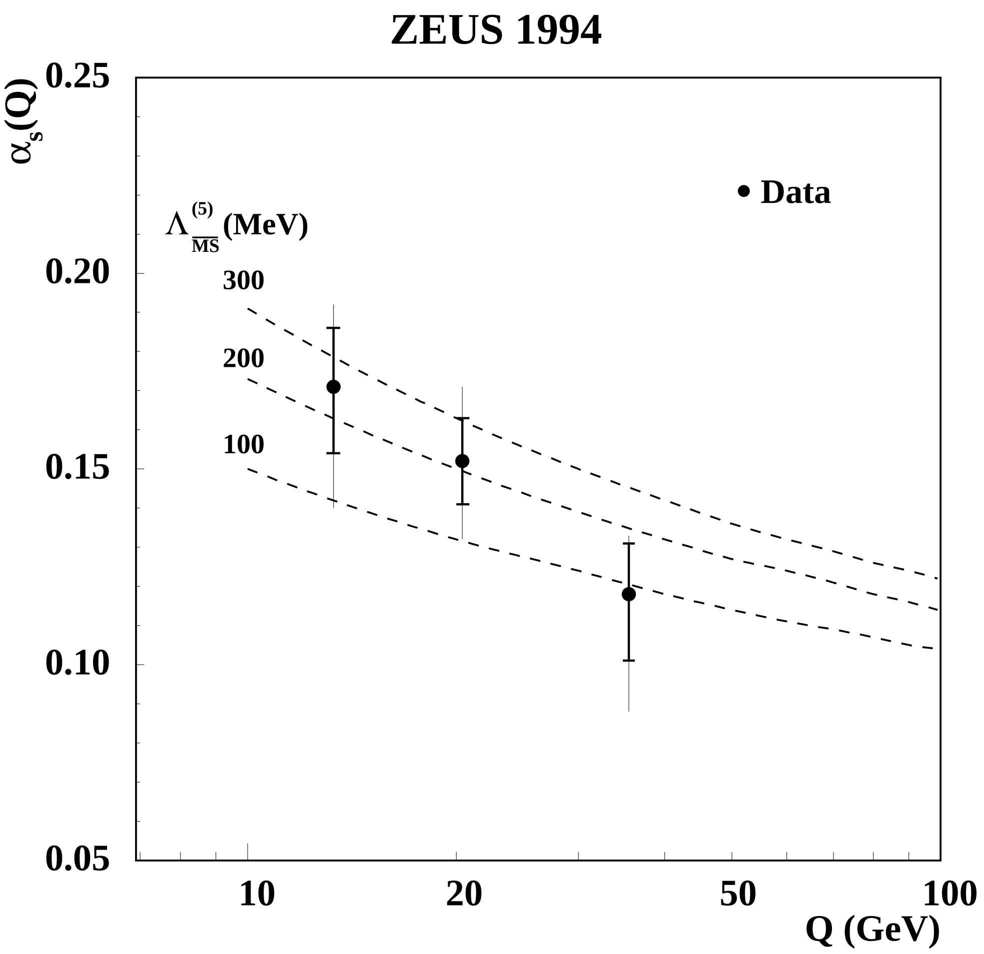


Figure 11: Measured values of $\alpha_s(Q)$ for three different $Q^2$ regions. The statistical error corresponds to the inner bar and the thin bar reflects the statistical and systematic error added in quadrature. The systematic errors are strongly correlated. The dashed curves represent $\alpha_s$ with $\Lambda^{(5)}_{\overline{MS}} = 100$, 200, and 300 MeV.

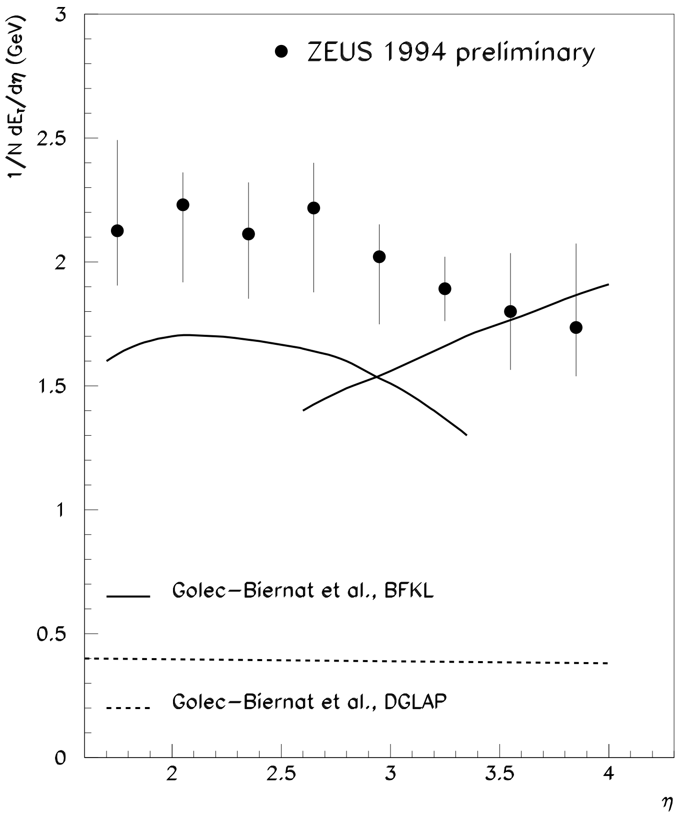


Figure 12: Mean transverse energy per unit rapidity in the forward region of the HERA lab. system. Also shown are the partonic calculations of Golec-Biernet et al. for BFKL (where the two solid lines represent the calculation under two different kinematic approximations) and GLAP evolution.

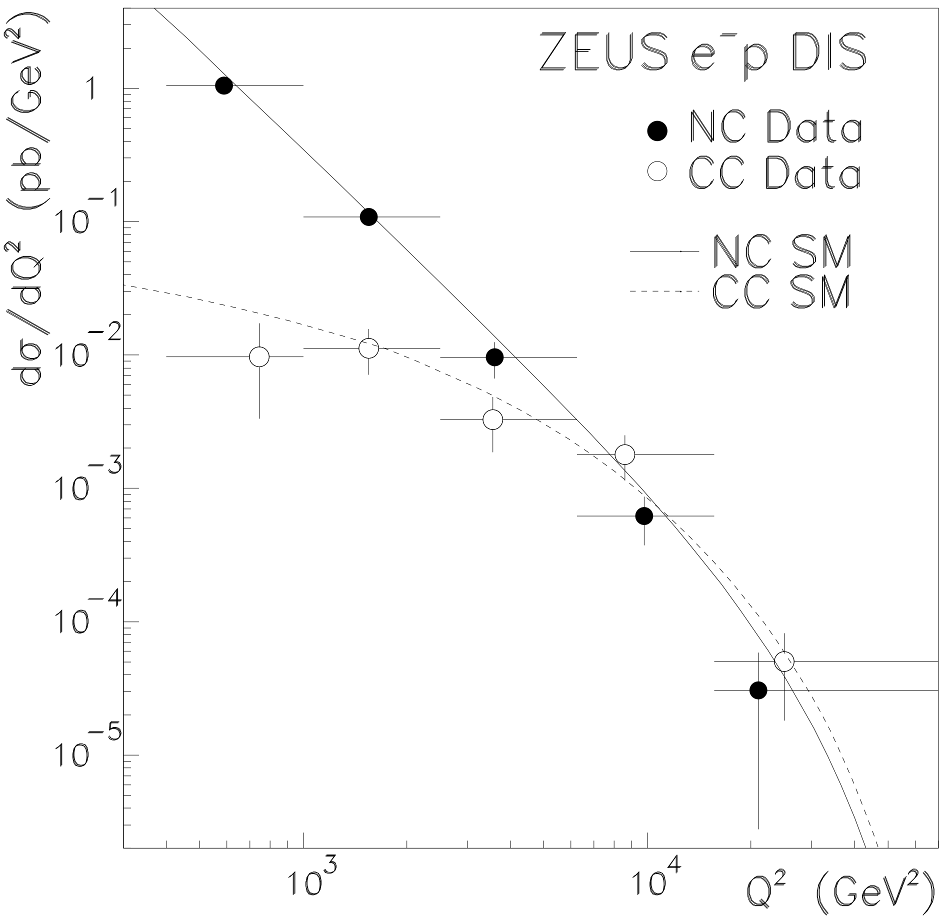


Figure 13: $d\sigma/dQ^2$ for neutral and charged current DIS data collected in 1993, compared to Standard Model expectations.

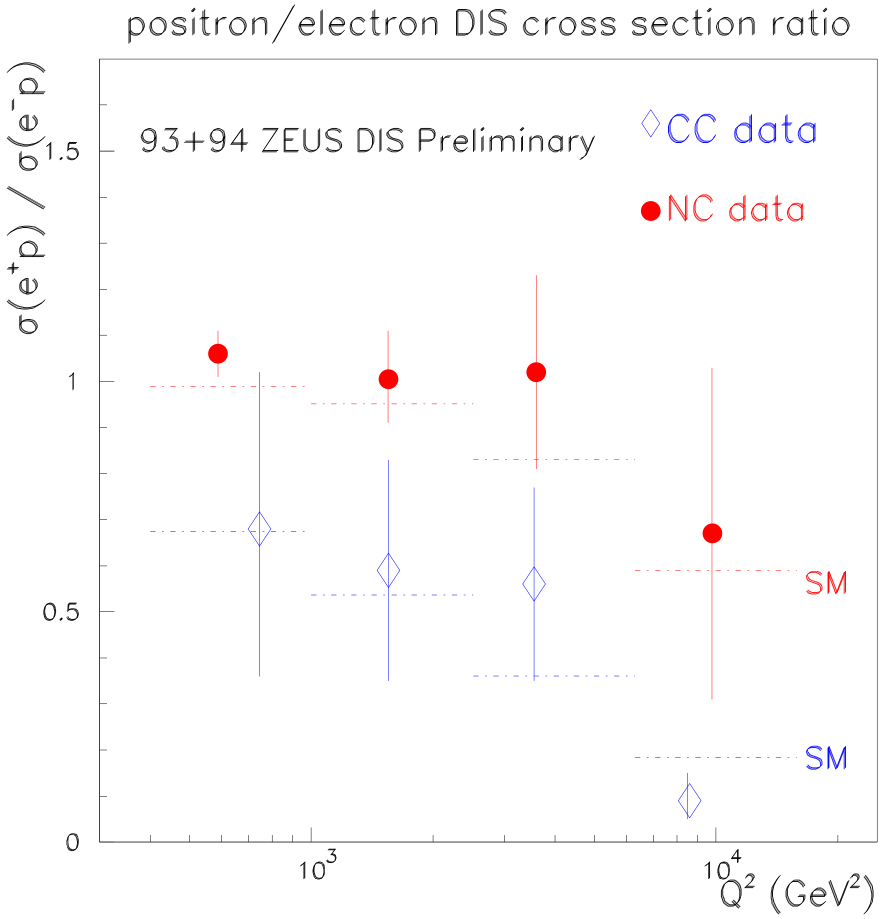


Figure 14: Positron/electron cross-section ratios vs $Q^2$ for neutral and charged current DIS data.

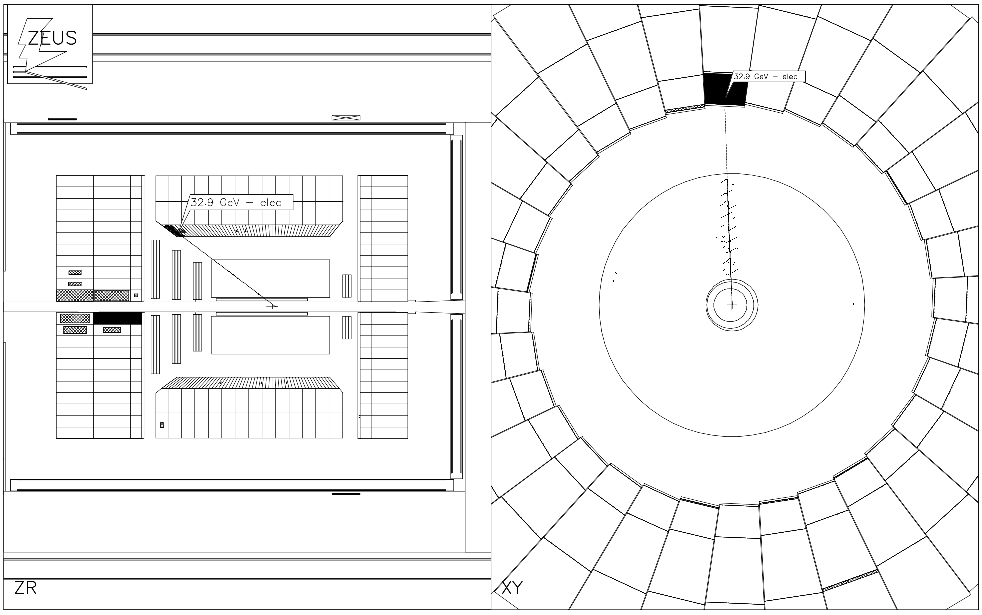


Figure 15: A candidate $e^+p \rightarrow W^+X$ event where the $W^+$ subsequently decays to $e^+\bar{\nu}$. The event has a well identified electron with energy 32.9 GeV and $p_T$=20.4 GeV, and a $\not{p}_T$=19.3 GeV.