ZEUS PROGRESS REPORT

ZEUS UK COLLABORATION

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1 Introduction

The performance of the HERA collider has improved steadily over the two years since our last report to the PPESP. The change to a two year interval between long winter shutdowns contributed significantly to the large increase in luminosity. The ZEUS detector operated essentially unchanged during the years 1996 and 1997 which means that we now have a data sample corresponding to $53.5\,\mathrm{pb}^{-1}$ (delivered) with the same detector configuration and trigger. This large sample is being actively analysed, but most of the physics results reported in this document come from the $5.11\,\mathrm{pb}^{-1}$, $12.3\,\mathrm{pb}^{-1}$ delivered in 1994, 1995 respectively. Many of the HERA results published to date are on various aspects of QCD in deep inelastic scattering and large E_T photoproduction and they have already contributed significantly to our understanding of the strong interaction. As already reported to the PPESP, the HERA collider is to be upgraded to provide significantly higher luminosities from the year 2000 and the ZEUS detector will be upgraded to take advantage of this. The increase in luminosity will give access to quantitative electroweak physics at large Q^2 and increase the discovery potential of HERA to effects beyond the standard model.

The principal contribution of the UK to the equipment of the ZEUS experiment 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. The UK groups have responsibility for the operation and maintenance of the CTD. It is essential that we continue to have the resources to keep this vital component operating at the highest level. Tracking information is so important for all ZEUS physics analyses that the experiment does not collect data unless the CTD is active.

This report is structured as follows: CTD status and infrastructure are covered in section 2; offline activities in section 3; the HERA and ZEUS upgrades in section 4; physics results with ZEUS UK involvement in section 5 and future plans and resources requested in section 6. Lists of publications, theses and the membership of ZEUS-UK groups are contained in the appendices.

ZEUS UK physicists continue to hold important positions in the management and leadership of the experiment. In addition to those shown in the organogram in appendix E, V. Noyes is coordinating physics studies for the HERA upgrade and also coordinating the UK contribution to the ZEUS microvertex detector project. R.J. Cashmore has responsibility for ZEUS long term physics planning.

It is interesting to note that in a citation study of journal papers published in December 1997, HERA results feature in 4 of the top 10 topics cited on collider physics. The subjects were F_2, large rapidity gaps in DIS, $\sigma_{tot}(\gamma p)$ (in all cases both H1 and ZEUS papers). The other papers were 3 on LEP physics (EW parameters, Z^0 line shape, jet properties) and 3 from the Tevatron (top quark, W boson, jet properties).

2 Detector status and infrastructure

The Central Tracking Detector (CTD) is a large volume cylindrical drift chamber covering the central region ($15° < \theta < 164°$). Its 4608 sense wires are arranged into nine superlayers, superlayer one being the innermost. The wires in odd-numbered superlayers run parallel to the chamber axis, whilst those in the even-numbered layers have a small stereo angle ($\sim 5^o$). Taken together they provide sufficient information to reconstruct tracks in 3 dimensions. The CTD provides charged particle tracking, momentum measurement and identification through dE/dx. It also participates in all three levels of the ZEUS trigger.

The CTD has performed very reliably during data-taking over the last two years. Dead channels remain at less than 2% with no signs of aging and the detector has caused minimal down-time for the ZEUS experiment as a whole. The chamber resolution and efficiency have remained essentially stable over the past 4 years.

2.1 Triggering

ZEUS operates a three-level trigger, of which the first level is a hardware-based system whose principal aim is to reduce backgrounds that do not come from the interaction point. CTD information is vital for this, and the detector uses dedicated, pipelined processor cards which provide tracking data to the global first level trigger. Before 1996 the CTD First Level Trigger only used information from the innermost superlayer to form its decision. Processors for superlayers three and five were added to the CTD trigger for the 1996 data-taking period. The inclusion of the extra superlayers reduced the rate in trigger slots requiring calorimeter and CTD information by around 10%. The extra information also gives us the flexibility to implement more trigger types in the future, particularly in matching regional calorimeter energies to tracking activity.

The ZEUS global second level trigger applies software cuts to clean the event sample further and identify certain classes of physics event. The CTD second level trigger, which makes use of data from all five axial superlayers and the z-by-timing data from layers 1,3,5, enables detailed information on the tracking and vertexing to be used in many physics filters at this level. In 1996 the CTD transputer network was successfully reconfigured in order to reduce the trigger latency, and further software improvements were undertaken during 1997.

The third-level trigger (TLT) runs in Unix work-stations using an appropriate version of the off-line reconstruction code. The steady improvement in price-performance of these machines means that since 1996 we have been able to run a version of the CTD reconstruction code which has a performance only slightly below that of the off-line version. For example, the resolution of the $D^* - D$ mass difference achieved at the TLT is $\sim 2\,\mathrm{MeV}$ compared to $\sim 1\,\mathrm{MeV}$ off-line. The TLT also produces early warning of any changes in critical CTD parameters, e.g. t0, the FADC start time.

2.2 Infrastructure, Slow Controls and Monitoring

An important task since the last PPESP report has been the upgrading and simplification of the CTD run-control programme which interfaces to the main ZEUS

DAQ system and run-control. In the process the use of obsolescent, non-supported packages has been removed.

The HV control system has continued to perform well. The HV control programme has been re-written to improve its robustness and user-interface. The HV ramping time has also been reduced. The gas system has also performed very reliably. Since 1997 we have chosen the HV, and hence chamber gain, according to the atmospheric pressure in order to optimise the pulse-height (and hence dE/dx) within the dynamic range of the FADC system.

The Data-Quality-Monitoring (DQM) is carried out via a system of automatic job-submission and the results are studied within a few hours of data-taking. We have striven, successfully, to streamline this process and reduce the human effort required. The DQM is performed almost entirely by graduate students, based either at DESY or in the UK.

We have begun to address the issue of maintaining the operation of the CTD through to 2005 - the "CTD 2005" challenge. This entails a thorough review of *all* components (electronics, hardware, and software) on which the operation of the CTD relies. We have to ensure that we have adequate spares, maintainable hardware and software etc. It also covers personnel: we must take account of the retirement before 2005 of several of the UK engineers who played a crucial role in bringing the CTD project to fruition. Occasional access to their expertise has been vital to the successful running of the CTD, and we must ensure that their knowledge is transferred or remains accessible.

3 Off-line activities

3.1 Tracking

As already remarked, the CTD is essential to all ZEUS physics analyses. The off-line reconstruction code has been rather stable over the last two years, though the dE/dx algorithm has been improved for those tracks with relatively few hits. We have continued to refine the Monte Carlo description of the detector, which now appears to be well-tuned in all critical parameters. UK physicists continue to provide leadership for the whole ZEUS central tracking effort.

3.2 Funnel

The ZEUS Monte Carlo facility, Funnel, runs the ZEUS detector and trigger simulation and event reconstruction programs on clusters of Unix machines distributed worldwide at the home laboratories of participating Institutes. Funnel is crucial to the physics analysis performed within the ZEUS Collaboration. The UK provides two of the four members of the team responsible for Funnel. The detector simulation program is maintained and regularly updated by a UK physicist. This task involves integrating new detector component geometries and their associated code into the main detector simulation program. The task of ensuring that all three programs run on all the platforms available for the running of Funnel worldwide is also the responsibility of a UK person. Currently the Funnel code runs on DEC Alpha, SUN, SGI and DEC ULTRIX machines and it is foreseen that it will run on PCs under LINUX.

It is also possible that HP Unix will be added to the list of supported platforms which would open the possibility of using CSF at RAL.

The UK also provides some of the Funnel computing power. DEC Alpha machines at University sites perform the CPU intensive task of detector simulation while a server machine at RAL performs the trigger and full event reconstruction. The responsibility for the server machine was taken over by the ZEUS members of PPD when the central OSF service was closed in September 1997. During 1997 the UK produced about 2.6 million events out of a worldwide total of 54.6 million. In addition the UK machines at DESY make a significant contribution to the events that are generated there (in 1997 they contributed at least 10% of the DESY total of 17 million).

3.3 File store

In the UK we have made use of the Central Unix File Store (CUFS) at RAL to maintain up to date copies of ZEUS software at DESY. These files are NFS mounted and exported to all UK sites from RAL.

4 HERA and ZEUS upgrades

4.1 Luminosity upgrade

The performance of the HERA accelerator has continued to improve as shown in Fig. 1, particularly over the last two years. In 1997 the instantaneous luminosity reached a value of $1.4 \times 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ which is close to the design value of $1.5 \times 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The total delivered luminosity reached $36.4\,\mathrm{pb}^{-1}$, exceeding the 1997 goal by a factor of 1.4 and is close to what is considered as an achievable annual luminosity. To go significantly beyond this requires an upgrade to the HERA accelerator and experimental interaction regions.

The data accumulated to date have mainly been used to explore the structure of the proton and photon and to extend our understanding of QCD. These results have attracted wide attention and surpassed the expectations of the original HERA proposal. It must be noted however that the precision measurements made so far are still 'low-Q^2' physics compared with the electroweak scale $Q^2 = m_W^2$. The integrated luminosity delivered so far has precluded detailed studies of the high Q^2 region that HERA was built to explore. Some of the unique features of HERA, such as electron polarisation and the capability to compare $\mathrm{e}^+\mathrm{p}$ and $\mathrm{e}^-\mathrm{p}$ running are only relevant in the electroweak regime.

The recent "Future Physics at HERA Workshop" [1] reached a clear conclusion that a luminosity upgrade, giving an integrated luminosity at the level of $1\,\mathrm{fb}^{-1}$ by 2005, would open up a range of unique electroweak physics, exciting possibilities beyond the Standard Model and even more sensitive tests of QCD. In particular it is imperative that the observed excess of events at high x and Q^2 [2] be confirmed or ruled out.

Given this strong motivation the HERA machine group together with members of the ZEUS-UK collaboration have studied different alternatives to achieve the desired luminosity upgrade. The solution which is both technically most viable and has least impact on the ZEUS detector is to install superconducting combined-function magnets into the ZEUS interaction region and to rebuild focusing magnets nearby. Such an upgrade will yield instantaneous luminosities of $7.4 \times 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ leading to delivered integrated luminosities of $150\,\mathrm{pb}^{-1}$ per year per experiment. Spin rotators will also be installed, allowing longitudinally polarised electron/positron beams.

The present schedule foresees that the interaction region upgrades will be installed in the next long shutdown between 1999 and 2000.

4.2 ZEUS Microvertex Detector

The ZEUS collaboration will take full advantage of the opportunities offered by the luminosity upgrade by installing a silicon microvertex detector (MVD) close to the interaction region during the 1999/2000 shutdown.

Charged particle tracking has proved a vital ingredient in the success of the experiment so far. The introduction of the MVD will significantly enhance the tracking capabilities of the detector. It will improve the definition of the primary vertex and will provide the ability to identify events containing secondary vertices displaced from the interaction point by distances $\mathcal{O}(100\ \mu\mathrm{m})$. Most notably this will bring a tenfold increase in the detection efficiency of charmed hadrons. This, together with the increase in statistics, will particularly benefit analyses in which the UK groups are currently taking a leading role:

- the charm structure function of the proton, F_2^{charm}, will be measured with increased precision over an extended kinematic region. This provides a powerful direct determination of the gluon density inside the proton at low x.
- identification of charm within high E_T jets in photoproduction will allow the investigation of the charm content of the photon; and
- in searches for physics beyond the Standard Model the ability to resolve secondary vertices and the enhanced measurement of very forward going particles will be vital.

The MVD design has to be compatible with the redesign of the ZEUS interaction region for the luminosity upgrade. The detailed layout is currently being finalised but will contain a 60 cm long barrel detector, the cross-section of which is shown in Fig. 2. The outer and middle barrel layers form concentric cylinders with average radii of 124 and 87 mm, respectively. Each barrel-layer is composed of two layers of single-sided silicon strip detectors $60 \times 60\,\mathrm{mm}^2$ in dimension with strips along z and $r - \phi$. The inner layer is constrained by the dimensions of the proposed elliptical beampipe. The centre of this carbon-fibre beampipe is shifted by 17.5 mm with respect to the CTD axis to accommodate the fan of synchrotron radiation. This has led to an inner layer with azimuthal coverage of 300°, constructed from identical silicon detectors arranged around the beampipe. To complement tracking in the forward direction, the MVD will also contain detectors arranged in wheels perpendicular to the beam axis providing measurements in both r and ϕ coordinates.

The base material of the detectors is n-type silicon. The readout uses single sided p+ implanted strips with 20 μm pitch. The readout pitch is 120 μm, and uses capacitive charge division between the p+ strips. The readout strips are AC coupled with respect to the p+ implanted strips. Several firms have been invited to submit tenders and the first delivery of detectors is expected in October 1998.

During the planned running time of 5 years an integrated radiation dose of up to 3 kGy can be expected. The radiation-tolerant HELIX analogue chip has been chosen to readout the silicon detectors.

The UK groups are responsible for three key areas of the MVD project commensurate with our existing expertise:

- *Installation of the detector inside the CTD*

  The expert and detailed knowledge of the CTD exists only within the UK groups making this a natural area for our involvement. The MVD installation is made complicated by the redesign of the HERA interaction region requiring the detector to be installed together with the central section of the beampipe. The ZEUS-UK groups are providing engineering and design effort and will oversee the manufacture of the necessary installation equipment as well as the on-site installation. The close collaboration between HERA machine physicists and UK engineers necessary for the success of the project continues.

- *Alignment of the MVD wrt the CTD*

  To exploit the excellent intrinsic position resolution of the silicon detectors, they must be accurately aligned both with respect to each other and the CTD. To achieve this, precise position measurements will be made at several stages during the assembly process, after installation and periodically during running. The ZEUS-UK groups are providing intellectual input to develop the survey and to define the alignment measurements in close collaboration with those institutes at which the detectors will be assembled. For global alignment purposes we are building an electro-optical alignment system to monitor the MVD position as a function of time with respect to the CTD. The UK groups are also developing the software from which the final alignment parameters will ultimately be derived.

- *Clock and control electronics*

  The Clock and Control system provides interfaces between the ZEUS global first level (GFLT) trigger, the run control system, the analogue to digital converter (ADC) crates and the HELIX readout chips. Having designed and constructed the ZEUS CTD timing controller system and being responsible for continuing R&D work on clock and control systems for other experiments, the ZEUS-UK groups are ideally placed to contribute to this vital part of the MVD project. Physically, the clock and control system will be divided into two parts. The 'Masterbox' will sit in the off-detector electronics 'rucksack', along with the GFLT, the ADC crates and the run control system. It will communicate with a 'HELIX interface' which will fan out signals to the HELIX chips and will be positioned closer to the detector in space which is available in the ZEUS cryotower. The functionality of the clock and control system has been specified and a prototype system is foreseen for Autumn 1998.

5 Physics results

ZEUS-UK physicists are involved in a broad range of physics analyses. Very roughly Bristol, IC and Oxford are involved in structure functions and high Q^2 activities, while Glasgow and UCL cover photoproduction. Glasgow and RAL are also involved in studies of the hadronic final state in DIS.

5.1 Proton structure

UK groups continue to play a major role in ZEUS measurements of the proton structure functions from deep inelastic scattering (DIS) at HERA. In addition to the topics discussed below, UK groups are involved in the measurement of F_2 from the full 1996/7 data sample and in a study of DIS events with initial state radiation (ISR). The latter effectively allows the centre-of-mass energy to be varied and with enough data could lead to a measurement of the longitudinal structure function F_L.

5.1.1 F_2 and the gluon momentum density

The HERA 1994 data sample was the first with enough statistics to give precision measurements of F_2 [3]. These data together with shifted vertex data (which enables scattered beam electrons to be measured in the main detector at small angles and hence small Q^2) and ISR events [4] give ZEUS F_2 data in the range $1.5 - 5000\,\mathrm{GeV}^2$ and $3.5 \times 10^{-5} < x < 0.5$. Below a Q^2 of about $100\,\mathrm{GeV}^2$ the precision of the data is systematics limited. The range and precision of the HERA F_2 data are now making a significant impact on MRS and CTEQ global fits to determine parton distributions. This is particularly true of the gluon momentum distribution. To understand how well the parton distributions are measured, it is necessary to take experimental systematic errors into account. This has been studied for the gluon by ZEUS using the large 1994 sample (with fixed target data at large x) as input to next to leading order (NLO) QCD fits [5]. The rapid increase in F_2 at small x is driven by a rapid increase in the gluon density through the coupling of gluons to the $q\bar{q}$ sea. The gluon density is now rather well determined at small x as can be seen from Fig. 3. In the HERA kinematic region, although F_2 is well described by conventional DGLAP evolution in Q^2, there is still a lot of argument about whether one can or should expect to see manifestations of large $\ln(1/x)$ terms beyond DGLAP [6]. Since both approaches have adjustable parameters it is possible to get acceptable fits to F_2 in both cases. However, the different models do give different predictions for other observables, such as F_L or F_2^{charm}, which is why it is so important to measure them precisely.

5.1.2 F_2^{charm}

Charm contributes as much as 30% of F_2 at HERA, largely through the 'boson-gluon fusion (BGF)' mechanism. Events with charmed particles in the final state have been tagged by the identification of D or D^* decays using the excellent charged particle tracking provided by the ZEUS CTD. As Fig. 4 shows, the $D^* - D$ mass difference gives a particularly clean signal, but statistics are limited by the $D^* \to K\pi\pi$ branching ratio of only 2.6%. A major source of systematic error in the measurement of F_2^{charm} is the extrapolation of the measured D^* production cross-section to the full phase space in rapidity and p_T. Preliminary results [7] for ZEUS 1995 F_2^{charm} are shown in Fig. 5, together with published HERA 1994 values [8] and a NLO calculation which shows the uncertainty from the charm quark mass [9]. The importance of accurate F_2^{charm} data for distinguishing QCD models at small x has just been mentioned, in addition because of the BGF mechanism, such data also offer the prospect of a fairly direct determination of the gluon density. Measurement of charm production is also potentially of great importance in discriminating among models of diffractive DIS [10]. Significantly improved charm tagging is one of the main motivations behind the ZEUS MVD project.

5.1.3 F_2 at low Q^2 and $\sigma_{tot}(\gamma^* p)$

HERA offers many opportunities to study the transition from 'soft' to 'hard' physics by varying appropriate scales. One of the most interesting to date is F_2 itself – partly because the description by perturbative QCD seems to work to lower values of Q^2 than conventionally expected. To complete measurements in the range from low Q^2 to real photoproduction ZEUS installed a small tungsten- scintillator calorimeter next to the rear electron beam pipe. The data [11] span the range $0.11 < Q^2 < 0.65\,\mathrm{GeV}^2$ and are shown in Fig. 6. The figure also shows other ZEUS and H1 data and a number of models. Using the relation, valid at small x,

$$\sigma_{tot}^{\gamma^* p}(W^2, Q^2) \approx \frac{4\pi^2\alpha}{Q^2} F_2(x, Q^2) \tag{1}$$

one may also consider the data as a total cross-section. Since $W^2 \approx Q^2/x$ where W is the $\gamma^* p$ CM energy, behaviour at small x is equivalent to large W^2. Many models have been proposed to describe the transition region. Two were available before the data and provide in a sense opposite paradigms. The Donnachie-Landshoff model [12] (curve DL on the figure) is based on Regge theory with the exponents determining the large W^2 behaviour fixed from hadron-hadron data. The other is the NLO QCD parameterisation of Glück et al (GRV(94) curve), which has a very low starting scale in Q^2. Neither describe the data in all details but it is clear that there is a transition in the region of $Q^2 \sim 0.65 - 1.34\,\mathrm{GeV}^2$ from the Regge like behaviour of the real photoproduction cross-section to the 'safely' deep inelastic behaviour above $3\,\mathrm{GeV}^2$. The other models try to combine aspects of both the DL and GRV approaches and have been fit to all or part of the data shown in the figure. The ZEUS data have been vital in furthering the phenomenological understanding of the transition region.

5.2 Photoproduction

The large flux of almost real photons in ep interactions at HERA has opened up a wide range of photoproduction studies. In particular jet production at HERA provides a unique laboratory with which to investigate perturbative and semi-hard QCD and the structure of the photon. Such studies complement very well similar ones undertaken at $p\bar{p}$ and e^+e^- colliders.

5.2.1 Jets and Photon Structure.

Dijet angular distributions and cross-sections from 1994 data were published in 1996[14, 15] and 1997 and preliminary results from 1995 and 1996 data have been presented. An extensive program of measuring in many kinematic regions and with different jet finders is continuing, along with intensive efforts to improve the theoretical predictions in conjunction with theorists [16].

At high transverse energies (E_T^{jet}), these results can be understood in terms of NLO QCD and will lead eventually to direct constraints on photon and proton structure. At lower E_T^{jet}, there are large disagreements between the data and perturbative QCD expectations. These results touch on the transition between soft and hard physics.

Jet cross-section results have also been extended to higher photon virtualities (Q^2), where the hadronic nature of the photon is expected to be suppressed. Fig.7 shows the ratio of resolved[1] to direct photoproduction as a function of photon virtuality. Again, this is an important area in which to test and extend our understanding of strong interaction physics.

As part of the studies for the 'Future physics at HERA' workshop, the potential of dijet studies using polarised protons has been investigated [17]. The results indicate that there are good possibilities for studying the polarised parton distributions of the photon with such techniques.

5.2.2 Multijet Photoproduction.

It is anticipated that the integrated luminosity delivered by HERA will exceed 1 fb^{-1} by the year 2005. ZEUS is thus expected to collect a large sample of events with multiple high transverse energy jets. Another workshop contribution [18] explored the sensitivity of these events to the fundamental QCD property of colour coherence. In addition the analysis of such events will test the theory of QCD where higher order effects and extensions beyond fixed order perturbative calculations are expected to become necessary. Already in the 1996 data sample about 2000 events which contain three high transverse energy jets with a three-jet invariant mass in excess of 50 GeV^2 have been observed. Results from the study of this event sample and its comparison with QCD predictions of order $\mathcal{O}(\alpha\alpha_s^2)$ will be published later this year.

5.2.3 Rapidity Gaps between Jets in Photoproduction.

In 1994 ZEUS published the observation of an excess of events with a large rapidity gap between jets over what would be expected from non-diffractive processes [19]. This can be interpreted as a signal for diffraction taking place within the regime of perturbative QCD and studying this process will help unravel the overlap between QCD and Regge phenomenology. The excess has been confirmed in the 1995 data and analysis of the later samples continues. As demonstrated in the HERA workshop [20], this is a topic which should benefit greatly from the installation of the ZEUS forward plug calorimeter [21].

[1] That is when a $\gamma \to q\bar{q}$ fluctuation takes place before the hard interaction

5.2.4 Charm Production in Jets.

Measurements of inclusive D^* cross-sections in photoproduction at HERA show an excess over various theoretical expectations [22]. The mass of the charm quark places it close to the boundary between hard and soft physics, and hence the treatment of charm in perturbative calculations is an interesting and controversial topic which promises to teach us a great deal about the nature of QCD.

Tagging charm inside jets provides extra information about the kinematics and dynamics of charm production. A first interesting question is whether there are charm quarks 'inside' the photon in same way as there are light quarks. This has a strong influence on the size of the charm production cross-section. If jets are reconstructed, the fraction (x_γ^{OBS}) of the photon's momentum which enters into the hard process can be measured and the effect of charm inside the photon would be expected to show up as an increase in the cross-section at low x_γ^{OBS}. Fig.8 shows the x_γ^{OBS} distribution, as presented in 1997 summer conferences, where each event has at least one jet containing a charm quark, as tagged by the $D^{*\pm} \to D^0\pi_s^\pm$, $D^0 \to K^\mp\pi^\pm$ decay mode. The MC expectations for direct and resolved contributions are shown. Clearly some resolved contribution is required. A publication of these data is currently in preparation. Further studies using semi-leptonic tags and eventually the MVD should thoroughly unravel the nature of charm photoproduction, and allow the investigation of instrinic charm in the photon [23].

5.2.5 Prompt Photons.

Events have been studied at ZEUS containing a high E_T "prompt" photon. Since the photon is radiated directly from a quark which participates in the primary QCD scatter and does not suffer hadronisation, we have here a means of studying a variety of classes of QCD process in a relatively clean way. Fig. 9 from the first observation of prompt photon events made at HERA [24], shows the distribution of x_γ in events containing a prompt photon and a balancing jet, where x_γ is the fraction of the incoming photon's momentum that contributes to the outgoing high E_T photon. The peak near $x_\gamma = 1$ corresponds to the "direct Compton" process $\gamma q \to \gamma q$. We intend to study further processes of this kind, both in photoproduction and DIS, as increased statistics become available.

5.2.6 Inclusive studies in photoproduced jets

The properties of charged particles and neutral K^0 mesons in photoproduced jets have been investigated [25]. The fragmentation function for particle species X is defined here as $D(z) = \frac{1}{N_{jet}}\frac{dN(X)}{dz}$ where N_{jet} is the number of jets in the event and $z = E(X)/E(jet)$. This definition of z is close to that used in e^+e^- annihilation. $D(z)$ for charged particles is shown in Fig. 10 and that for K^0 in Fig. 11. There is an apparent deficit of K^0 mesons compared with expectations at low z, and in resolved photoproduction processes. This may be associated with an inadequate description of the colour flow or multi-parton interactions, and further studies are needed. However at high z in direct processes the features of the fragmentation are similar to those in e^+e^- annihilation and $p\bar{p}$ collisions, confirming the idea of universal parton fragmentation.

5.2.7 Study of ρ^0 Photoproduction at HERA.

A measurement of $\gamma p \to \rho^0 X$ has been performed using the ZEUS Leading Proton Spectrometer (LPS) [26] which detects protons scattered at very small angles. Both quasi-elastic ρ-production as well as the process where the proton dissociates into a low mass state, have been measured. The slope of the t distribution is found to be much shallower when the proton dissociates than when it does not. An extraction of the spin density matrix elements shows consistency with s-channel helicity conservation. These measurements also allow an extraction, within the Söding approach, of the πp cross-section at 50 GeV of $\sigma_{\pi p} = 31 \pm 2(\mathrm{stat}) \pm 3(\mathrm{syst})$ mb, with an additional model dependent uncertainty of 15%. This result is consistent with the predictions of fits to πp data based on the "soft" pomeron approach.

5.3 QCD and DIS hadronic final states

5.3.1 Fragmentation functions

The observation of scaling violations in structure functions measured in neutral current DIS helped to establish Quantum Chromodynamics (QCD) as the theory of strong interactions and has led to measurements of the strong coupling constant, α_s. Similar scaling violations are predicted in the fragmentation functions of quarks and gluons which represent the probability for a parton to fragment into a particular hadron carrying a fraction of the parton's energy. If the fragmentation functions are combined with the cross-sections for the inclusive production of each parton type in the given physical process, predictions can be made for scaling violations in the scaled momentum spectra of final state hadrons [27]. These scaling violations allow a measurement of α_s and such studies have been performed at LEP [28, 29] by incorporating lower energy PETRA data.

A natural and theoretically preferred frame in which to study the dynamics of the hadronic final state in DIS is the Breit frame [30]. In this frame the exchanged virtual boson is purely space-like with 3-momentum $\mathbf{q} = (0, 0, -Q)$, the incident quark carries momentum $Q/2$ in the positive Z-direction, and the outgoing struck quark carries Q/2 in the negative Z-direction. A final state particle has momentum p^B in this frame, and is assigned to the current region if p_Z^B is negative, and to the target frame if p_Z^B is positive. The advantage of this frame lies in the maximal separation of the outgoing parton from radiation associated with the incoming parton and the proton remnant, thus providing the optimal environment for the study of its fragmentation.

In the analysis inclusive charged particle distributions of x_p in the current region of the Breit frame are measured, where the scaled momentum x_p is defined as $\frac{2p_B}{Q}$ with p_B the momentum of a track measured in the Breit frame and $Q/2$ the maximum possible momentum[2]. The scaled momentum distributions are studied as a function of Q and x, in the range $6 \times 10^{-4} < x < 5 \times 10^{-2}$ and $10 < Q^2 < 1280\,\mathrm{GeV}^2$. Thus the evolution of fragmentation functions can be observed within a single experiment over a wide range of Q.

In Fig. 12 the ZEUS data are compared at $Q^2 = s_{e^+e^-}$ to e^+e^- data [31] divided by two to account for the production of both a q and $\bar{q}$. In the Q^2 range shown there is good agreement between the current region of the Breit frame in DIS and the e^+e^-

[2]Ignoring effects due to the intrinsic k_T of the quark within the proton

experiments. When ZEUS data are compared with the lower energy SPEAR [32] data ($\sqrt{s} = 5.2, 6.5$ GeV, not shown) discrepancies begin to show up. The turnover observed in the ZEUS data at low x_p and low Q^2, Fig. 12, can be attributed to processes not present in e^+e^- (e.g. scattering off a sea quark and/or boson gluon fusion) depopulating the current region [33]. In particular, the boson-gluon fusion diagram, which dominates at low-x, provides a significant cross-section for large mass radiation [34], thus producing this depopulation.

Our results can be compared with NLO QCD calculations, as implemented in CYCLOPS [35], of the charged particle inclusive distributions in the restricted region $Q^2 > 80$ GeV^2 and $x_p > 0.1$, where the theoretical uncertainties are small and unaffected by the hadron mass effects which are not included in the fragmentation function [36]. This comparison is shown in Fig. 13. The NLO calculation combines a full next-to-leading order matrix element with the MRSA$'$ parton densities (with $\Lambda_{\rm QCD} = 230$ MeV) and NLO fragmentation functions derived by Binnewies et al. from fits to e^+e^- data [37]. The data and the NLO calculations are in good agreement, supporting the idea of universality of quark fragmentation.

5.3.2 Forward transverse energy flow

There are two types of parton evolution equations, the DGLAP [38] equations describe the evolution with $\ln(Q^2)$, whereas the BFKL [39] that in $\ln(1/x)$. The DGLAP evolution prescribes a strong ordering in the transverse momentum of the emitted gluons whereas the BFKL does not. As a consequence one expects that the average number of emitted gluons and the average transverse momentum is larger in the BFKL approach. This should manifest itself in the hadronic final state.

A measurement of the transverse energy (E_T^*) flow as a function of the pseudorapidity η^* in the $\gamma^* p$ cms is presented in a wide range of Q^2 and W. For fixed values of Q^2 and W the E_T^* flow distributions are almost flat in η^* at a level of 2 GeV/(unit of η^*), except for $Q^2 \gtrsim 40$ GeV^2 where the distribution rises towards the photon fragmentation region ($\eta^* \sim 2 - 2.5$) (Fig. 14). The comparison of the data with new model calculations [40], which consider parton branching processes and hadronisation, show that a firm conclusion about the parton dynamics cannot be drawn from the E_T^* flow measurements alone because of the large influence of the hadronisation and the theoretical uncertainties which remain to be understood.

5.4 High Q^2 and high E_T physics

UK physicists have long played a leading role in studies of high Q^2 and high E_T physics at HERA. With increasing luminosity this experience is having a significant impact on ZEUS analyses in this area.

5.4.1 NC and CC DIS Cross Section measurements at high Q^2.

The collider experiments at HERA provide a unique opportunity to study proton structure at high Q^2 using a charged lepton probe. Whilst both neutrino and antineutrino beams have been used to study charged and neutral current phenomena, a comparison of the CC cross sections of positively and negatively charged leptons has never been undertaken, and the comparison of the charge dependence of the NC cross sections has only been possible at low Q^2 where the contribution of the Z^0 is negligible. We have shown that comparison of the present positron-proton data set with an electron-proton data set of a similar size, which we expect to collect over the next two years, will provide significant information on the electroweak sector of the Standard Model.

The interest in the CC and NC cross sections at high Q^2 increased following the publication of an excess [2] of events at high x and high y ($x > 0.55$ and $y > 0.25$). In a sample which included data from 1994 until approximately two thirds of the way through the 1997 run, five events were observed for a Standard Model expectation of 1.51 ± 0.13. The possibility that this excess may be due to physics not described by the Standard Model is a strong additional motivation to make precise cross-section measurements at high Q^2.

Realising such potential requires a long term effort to understand the data thoroughly, building on knowledge accumulated over many years and using consistent techniques for electron and positron runs to maximise the accuracy of comparisons between data from different years. To achieve this a coherent effort amongst the UK institutes is well underway. CC cross-sections have already been measured using data from 1995-96, Fig. 15 shows $\frac{d^2\sigma}{dxdQ^2}$ as a function of x in four Q^2 bins. This analysis this will soon be extended to include 1997 data. A measurement of the complete high Q^2 NC data from 1994-97 is also nearing completion.

5.4.2 High P_T leptons.

A search for events with high P_T electrons together with missing P_T has been used to measure the W production cross-section in ep collisions. A preliminary result is: $0.9^{+1.1}_{-0.8}(stat) \pm 0.4(sys)$ pb and can be compared to the Standard Model prediction of 0.9 ± 0.5 pb. The uncertainty of the measurement will soon be reduced with the completion of an analysis of events with high P_T muons. The electron analysis alone has enabled 95 % confidence limits of $\Delta\kappa < 4.7$ ($\lambda = 0$) and $|\lambda| < 8.7$ ($\Delta\kappa = 0$) to be placed on the anomalous couplings at the $WW\gamma$ vertex. W production is also the most serious background to many searches for physics beyond the Standard Model, in particular both R_P conserving and certain R_P violating SUSY processes. Fig.16 shows a candidate $W \to e\nu$ event from 1997. The positron with high P_T of 48 ± 2 GeV has a large angle of acoplanarity with respect to the jet, resulting in a transverse mass for the event of 79 ± 3 GeV.

6 Future plans and resources requested

During the present long shutdown, the HERA electron ring integrated vacuum pumps are being replaced to cure a limitation on electron beam lifetimes. It is expected that physics running will begin at the start of August 1998 and will be devoted to high energy electron-proton (27.5 on 820 Gev) running. If successful this mode of operation will continue through 1999 with the intention of accumulating a total e^-p luminosity comparable to the large e^+p luminosity already collected. When combined, these data will allow a first quantitative look at HERA electroweak physics. Other studies, such as high E_T processes, will also benefit from the general increase in data. Physics relying on measurements in the forward (proton) direction, such as diffraction, will be improved by the presence of the recently-installed forward plug-calorimeter.

The maintenance of the quality of the data from the CTD will remain a priority for ZEUS-UK groups. Over the next two years we will complete our parts of the ZEUS MVD project so that it is ready for installation in the long shutdown 1999/2000.

In order to fulfil these tasks, and to continue to be able to capitalise on past UK investment in the ZEUS experiment, we request that the PPESP maintain support for ZEUS-UK over the next two years at not less than the level submitted to the Director Particle Physics CLRC at the end of last year. The request for FY98/99 is £68k for Maintenance and Operations, £316k for Travel and LTA and £115k as the ZEUS-UK contribution to general ZEUS running costs. (This last sum is reviewed, justified and approved at twice yearly meetings of the representatives of the ZEUS funding agencies.) The projected evolution of these various sums suggests that the total annual request will be broadly similar for the rest of ZEUS, modulo sensitivity to the DM/pound exchange rate. We note, however, that the comprehensive "CTD-2005" review may uncover the need for extra expenditure.

The above numbers do not include the £130k already approved by the PPESP specifically for the MVD project. The final payments from this money will fall in FY00/01.

It is also absolutely essential that we are able to make occasional call upon those RAL and university engineers who retain a collective memory of aspects of the CTD not available elsewhere.

Looking further ahead, we note that after the HERA upgrade the collider is expected to run until at least 2005 and that ZEUS-UK groups will continue to be vigorously involved in the exploitation of the rich harvest of physics made possible by high luminosity and polarisation.

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Appendices

A ZEUS Journal Publications

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1. A.T. Doyle, *Diffraction at HERA: an experimental perspective*, J. Phys. G 22 (1996) 797.
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6. P. Bussey, B. Levtchenko and A. Shumilin, p574
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7. J.M. Butterworth, L. Feld, M. Klasen and G. Kramer, p554
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9. R. Cashmore, E. Elsen, B.A. Kniehl, H.Spiesberger, p129
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11. A.Lebedev, L.Sinclair, E.Strickland, J.Vazdik, p560
Colour Coherence in Photon Induced Reactions.
12. V.A. Noyes, p190
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B Conference Talks

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32. N.A. Pavel *Hadronic final states in deep inelastic scattering at HERA.* Topical workshop on "The irresistible rise of the Standard Model", San Miniato, 1997.

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C UK Theses

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1. D. Bailey (Oxford,1996) *The performance of the ZEUS CTD z-by-timing system and a study of charm production at HERA.*

2. V.L. Harris (IC,1996) *Studies in the Breit frame at HERA.*

3. B.H.Y. Hung (IC,1996) J/ψ *meson production in positron proton collisions at HERA.*

4. M.L. Utley (Glasgow,1996) *A first study of the structure of the virtual photon at HERA.*

5. A.F. Whitfield (IC,1996) *A measurement of vector meson production in ep collisions with the ZEUS detector at HERA.*

6. T. Yip (Oxford,1996) *Inelastic* J/ψ *photoproduction in electron-proton collisions at HERA.*

7. S. Campbell-Robson, (Bristol,1997) *A study of charm production in deep inelastic scattering in* e^+p *collisions.*

8. A.S. Cassidy, (Bristol,1997) *Optimising the Central Tracking Detector Readout at ZEUS and Measuring the longitudinal structure function at HERA.*

9. J.D. McFall, (Oxford,1997) *The performance of the ZEUS first level tracking trigger and a study of diffractive* D^* *production in deep inelastic scattering at HERA.*

10. A. Quadt (Oxford,1997) *Measurement and QCD analysis of the proton structure function* F_2 *from the 1994 HERA data using the ZEUS detector.*

11. R.L. Saunders (UCL,1997) *A Measurement of Dijet Photoproduction at HERA using the ZEUS detector.*

12. J.R. Tickner, (Oxford,1997) *Proton structure functions at low* Q^2

13. A. Vorvolakos (IC,1997) *Artificial neural network methods in high energy physics and their application to the identification of quark and gluon jets in electron-proton collisions.*

14. A.S. Wilson (Glasgow,1997) *A study of neutral kaons and charged particles in photoproduced jets at HERA.*

D ZEUS UK Collaboration

Academic staff, RAs and post-doctoral fellows, students in post 1/3/98.

Bristol University D.S. Bailey, O. Barret[1], W. N. Cottingham, B. Foster, R. Hall-Wilton[1], G. P. Heath, H. F. Heath, J.D. McFall, D. Piccioni[1], D. Roff[1], J. Scott[1], R. J. Tapper

Glasgow University J. T. Bromley[1], N. H. Brook, P. J. Bussey, A. T. Doyle, S. W. Lee[1], N. Macdonald[1], D. H. Saxon, L. E. Sinclair, I. O. Skillicorn, E. J. Strickland[1], R. Waugh[1]

Imperial College London T. C. Bacon, I. Butterworth, J. E. Cole[1], G. Howell[1], K. R. Long, D. B. Miller, A. Prinias, J. K. Sedgbeer, D. Sideris[1], A. Tapper[1], R. Walker

Oxford University H. E. Blaikley[1], R. J. Cashmore, A. M. Cooper-Sarkar, R. C. E. Devenish, J. K. Edmonds[1], J. Grosse-Knetter, N. Harnew, C. Nath[1], V. A. Noyes, A. Quadt, O. Ruske[1], R. Walczak, D. S. Waters[1]

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

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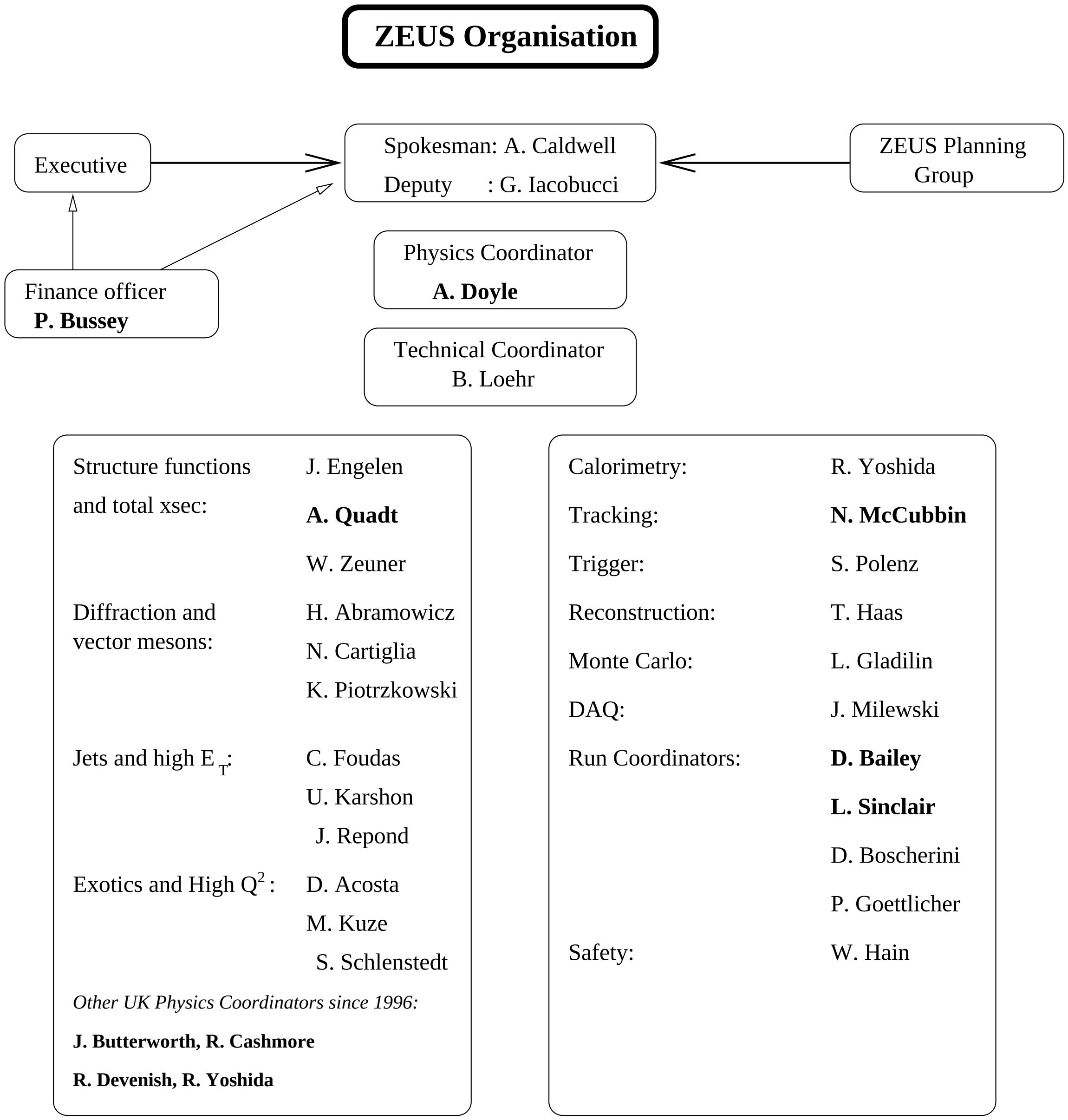
UCL: T. J. Fraser, M. Postranecky, I. A. Vine, D. A. Hayes
Oxford: P. D. Gronbech, G. Harris, I. McArthur, P. Shield, C. Sutton, S. Topp-Jorgensen
RAL: M. Allenby, D. J. Ballard, I. Church, S. B. Galagadhera, M. D. Gibson, J. Hartley, R. Hatley, K. P. Hatton, P. A. Hawthorne, A. C. Hopgood, M. D. Jeffs, S. Madani Bozorg, R. Matson, M. C. Morrissey, C. Moss, B. T. Payne, S. P. H. Quinton, R. L. Thompson

[1]Graduate Student

E ZEUS Organisation



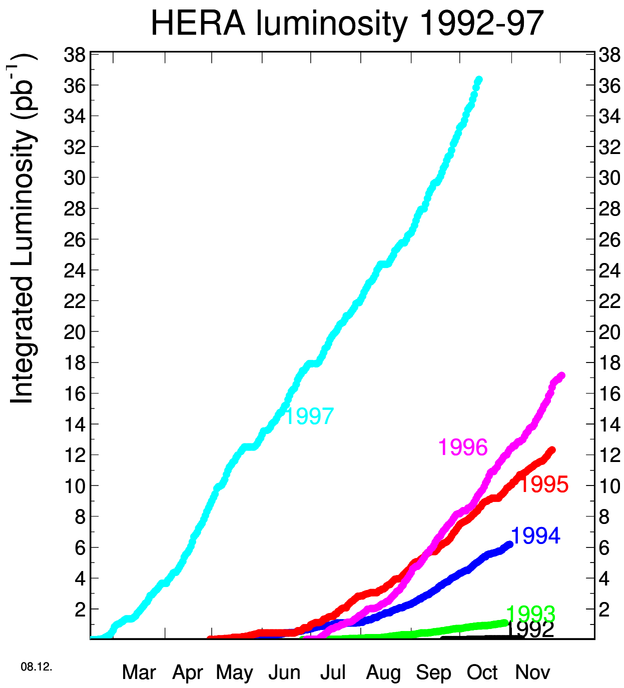


Figure 1: Luminosity delivered by HERA to the ZEUS experiment as a function of time between 1992 and 1997.

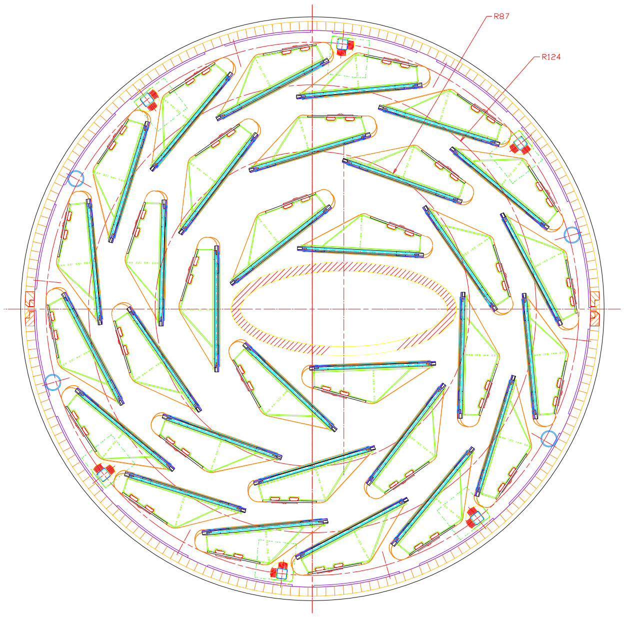


Figure 2: Cross-section of the barrel MVD detector showing the arrangement of detectors in two cylindrical outer and middle layers and the inner layer around the elliptical carbon-fibre beampipe.

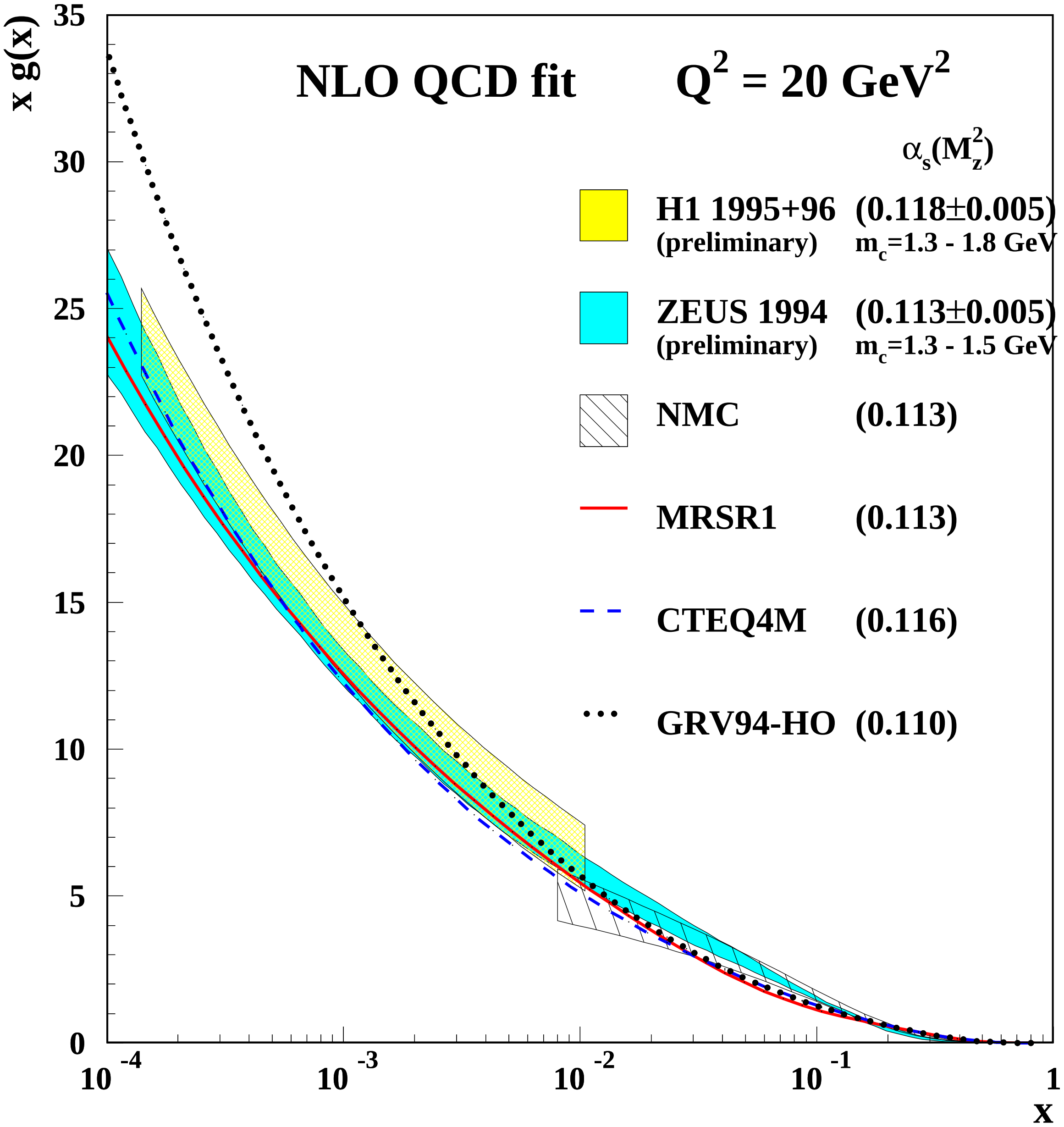


Figure 3: The gluon momentum density extracted from a NLO fit to scaling violations in ZEUS 1994 F_2 data, together with other determinations.

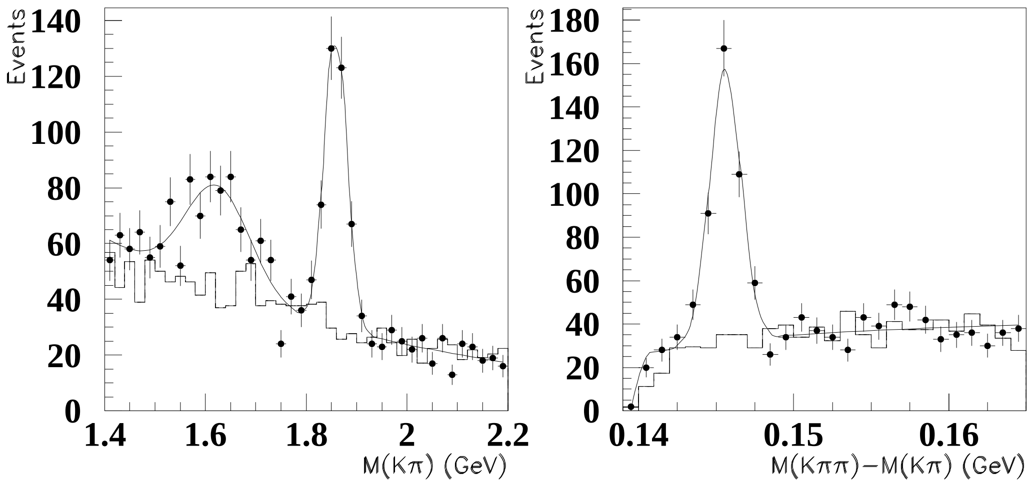


Figure 4: The $D^* - D$ mass difference in ZEUS DIS e^+p events.

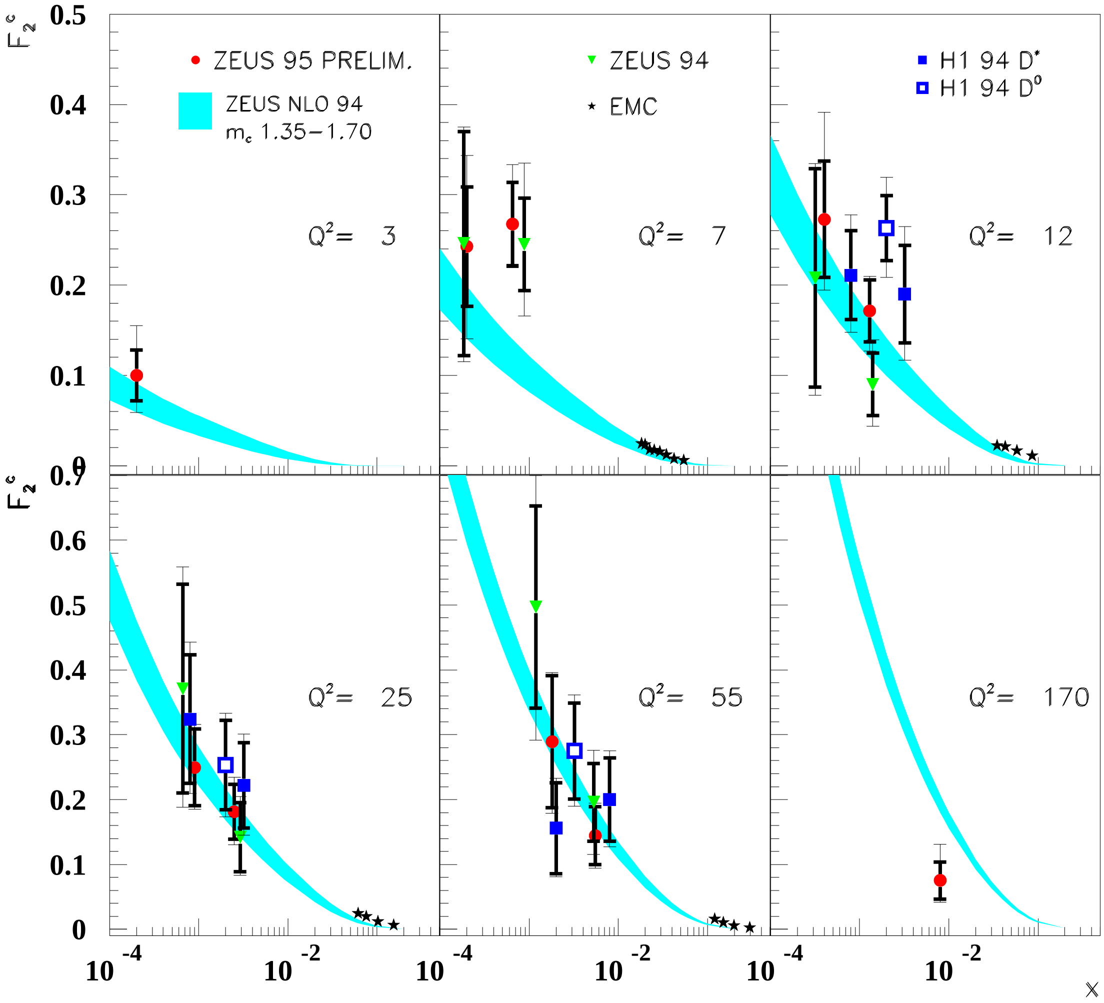


Figure 5: F_2^{charm} for preliminary ZEUS 1995 data, together with earlier H1 and ZEUS data. The shaded band is from a NLO calculation of Harris et al. and shows the uncertainty from the charm quark mass.

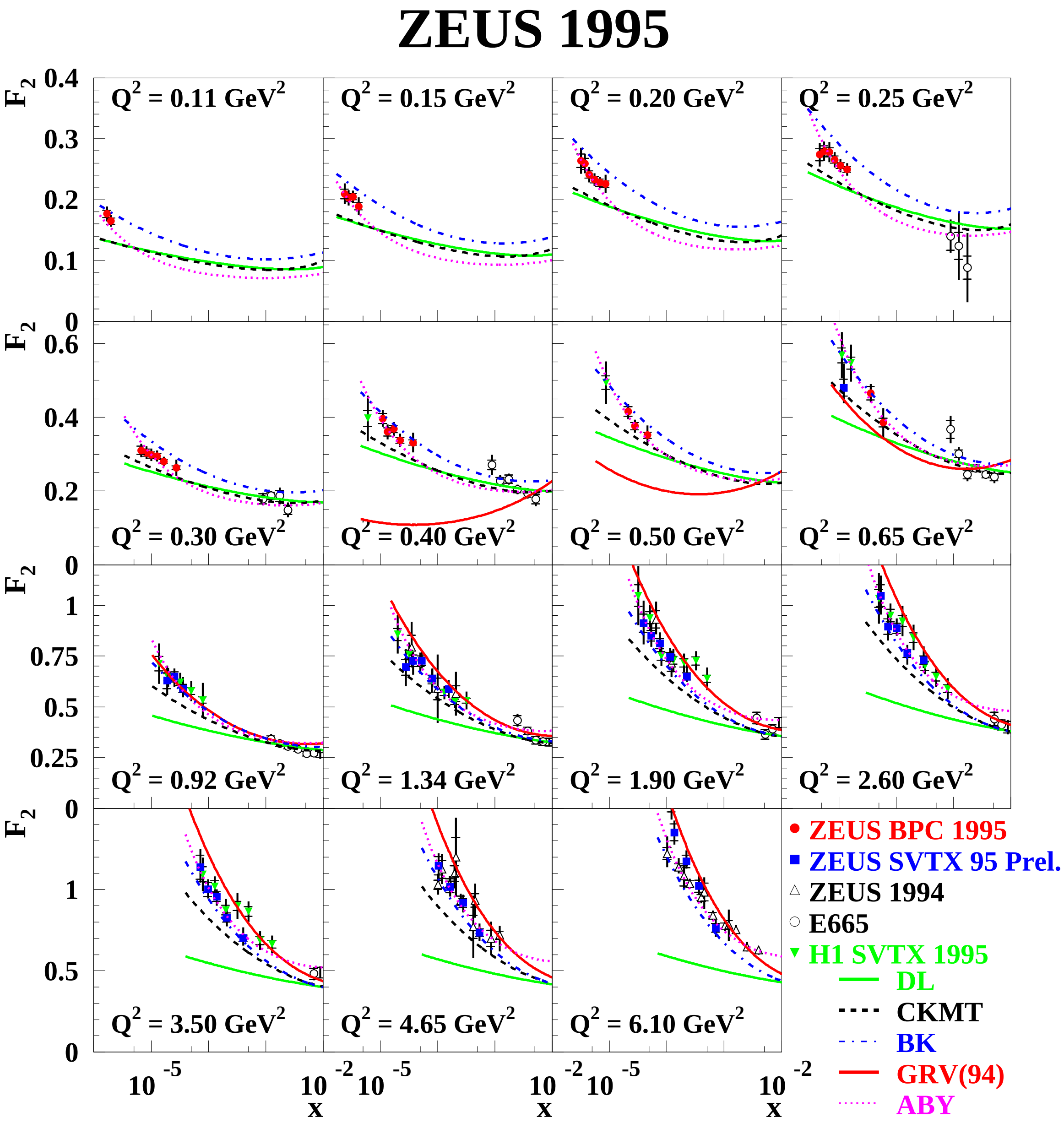


Figure 6: F_2 data at low Q^2 from ZEUS using the beam pipe calorimeter and shifted vertex data, together with data from H1 and various models.

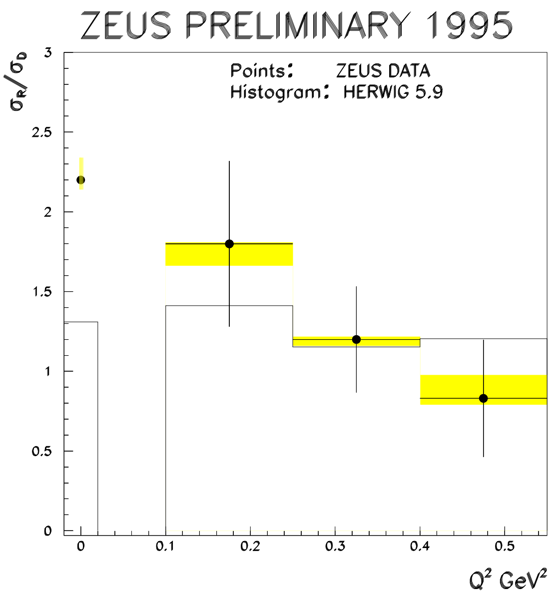


Figure 7: The ratio of 'resolved' ($x_\gamma^{OBS} < 0.75$) to direct ($x_\gamma^{OBS} \geq 0.75$) dijet photoproduction as a function of photon virtuality. The data are corrected to the final state particle level, and the prediction of HERWIG is also shown, using a parton distribution for the photon which has no suppression as the photon virtuality increases. The data exhibit a decreasing fraction of resolved photon events as photon virtuality increases, which is not seen in the MC.

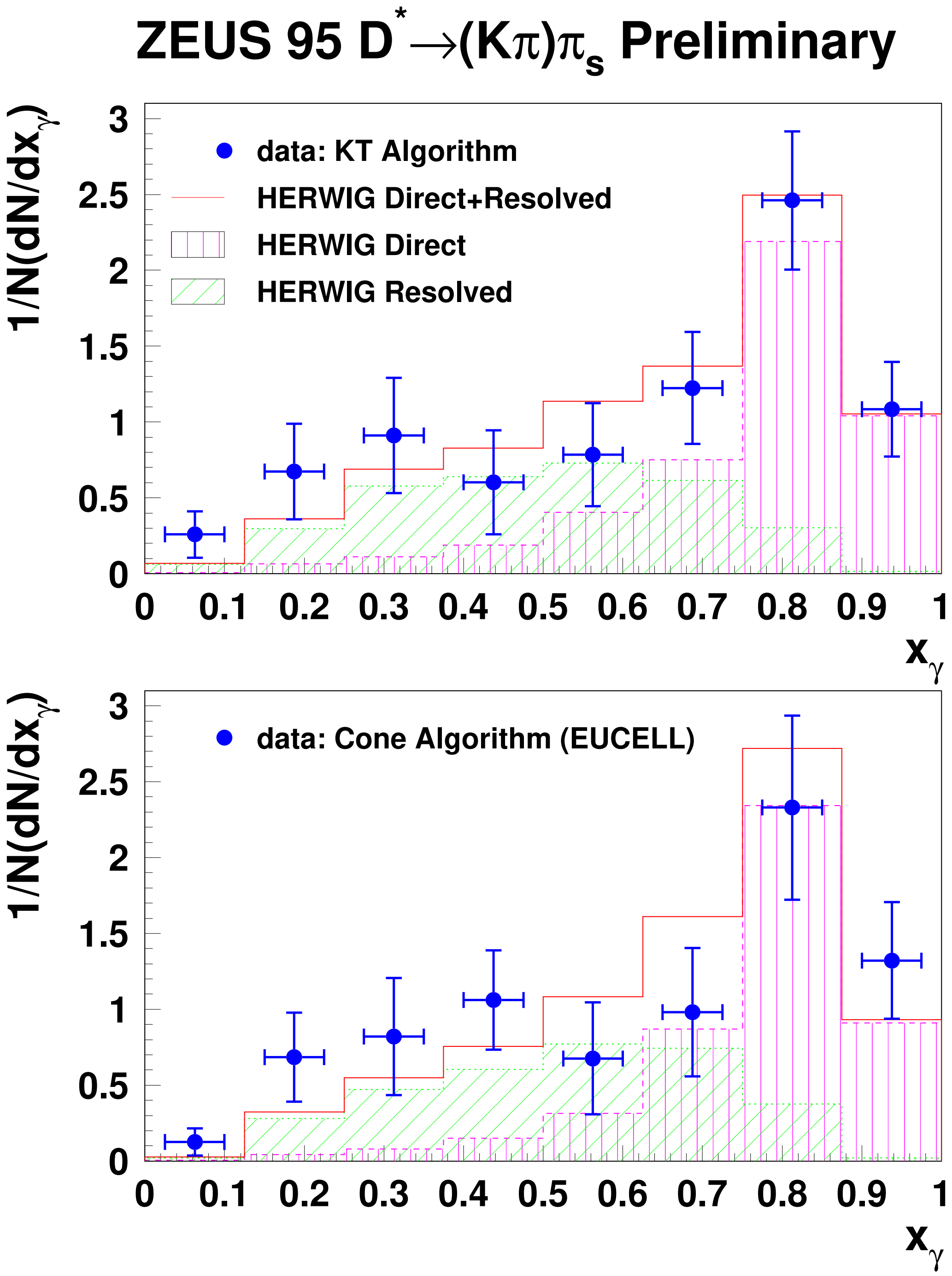


Figure 8: The fraction, x_{γ}^{OBS}, of the photon's momentum entering into the two highest E_T^{jet} jets, where at least one of the jets contains a D^*. The data are not corrected for detector efficiency and resolution, but are compared to MC events which have been passed through a full simulation of the detector. The MC is normalised to the number of events in the data. The comparison indicates that both resolved and direct MC contributions are needed to describe the data. This result is shown to hold for two different jet algorithms (a cone algorithm and the K_T cluster algorithm).

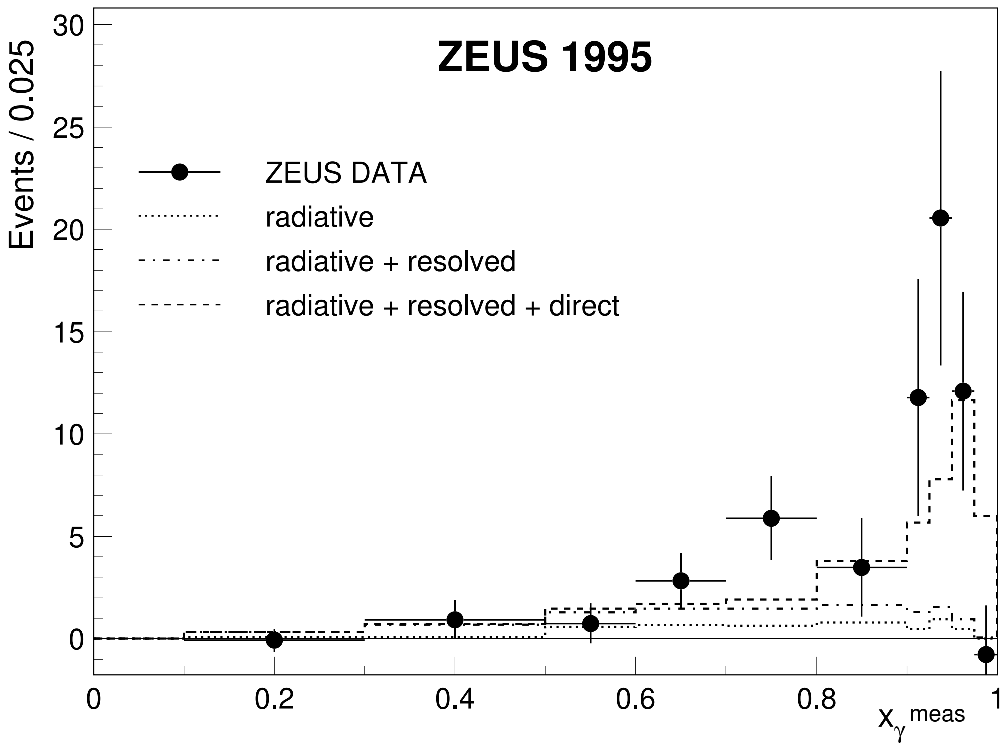


Figure 9: Measured distribution of x_γ in photoproduced events containing a prompt photon and a balancing jet.

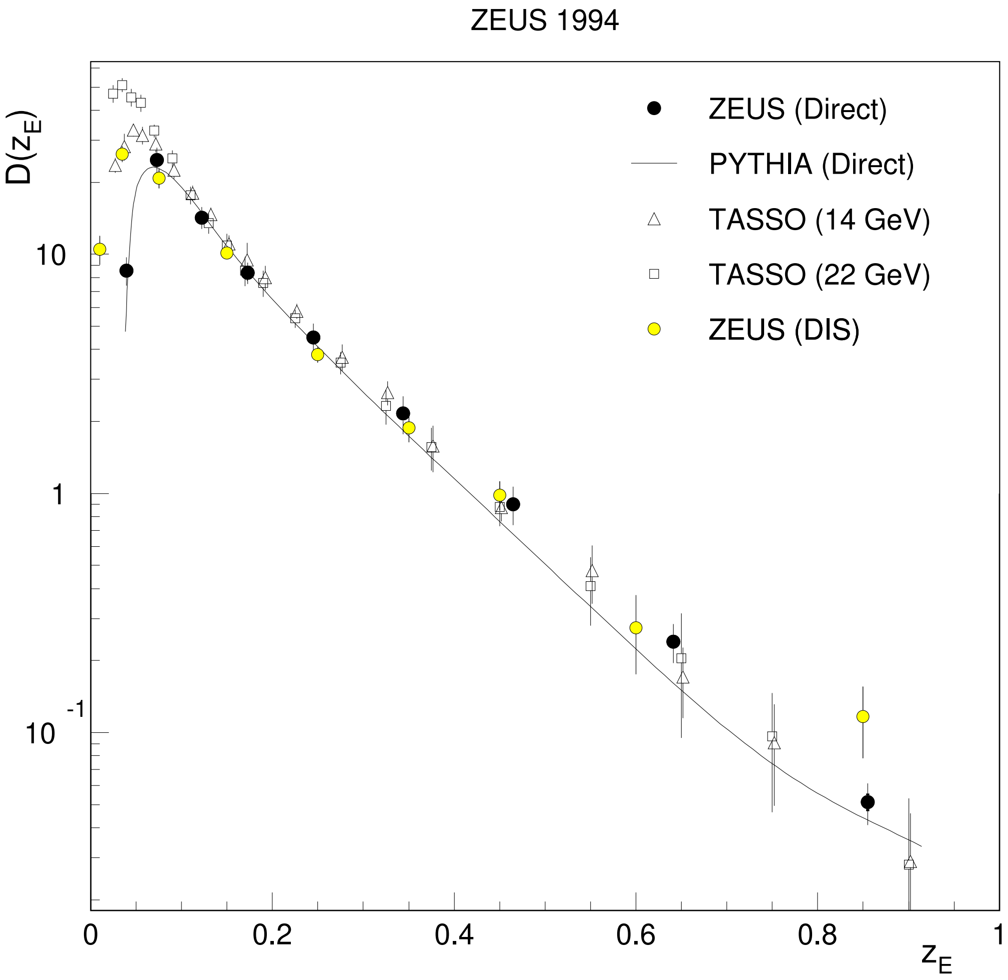


Figure 10: Charged hadron fragmentation function from high p_T jets in photoproduction at HERA as a function of z_E.

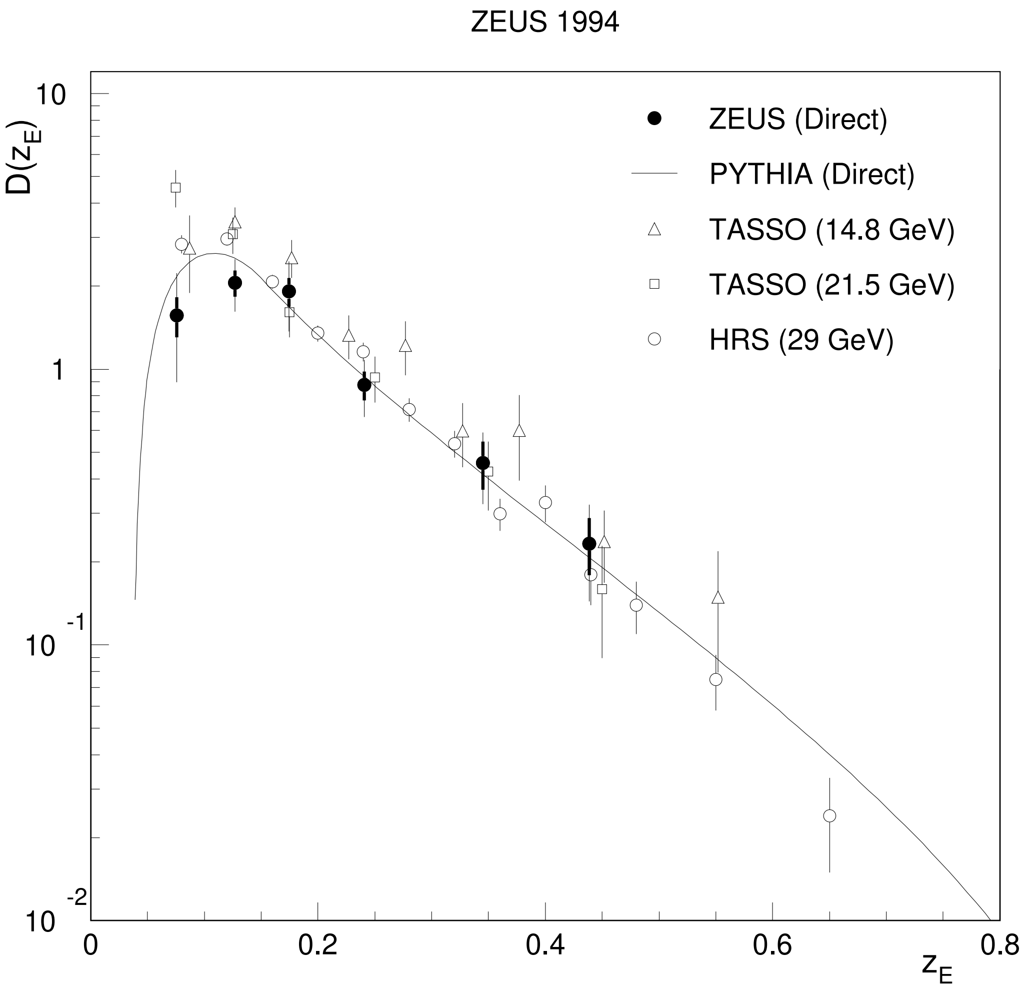


Figure 11: K^0 fragmentation function from high p_T jets in photoproduction at HERA as a function of z_E.

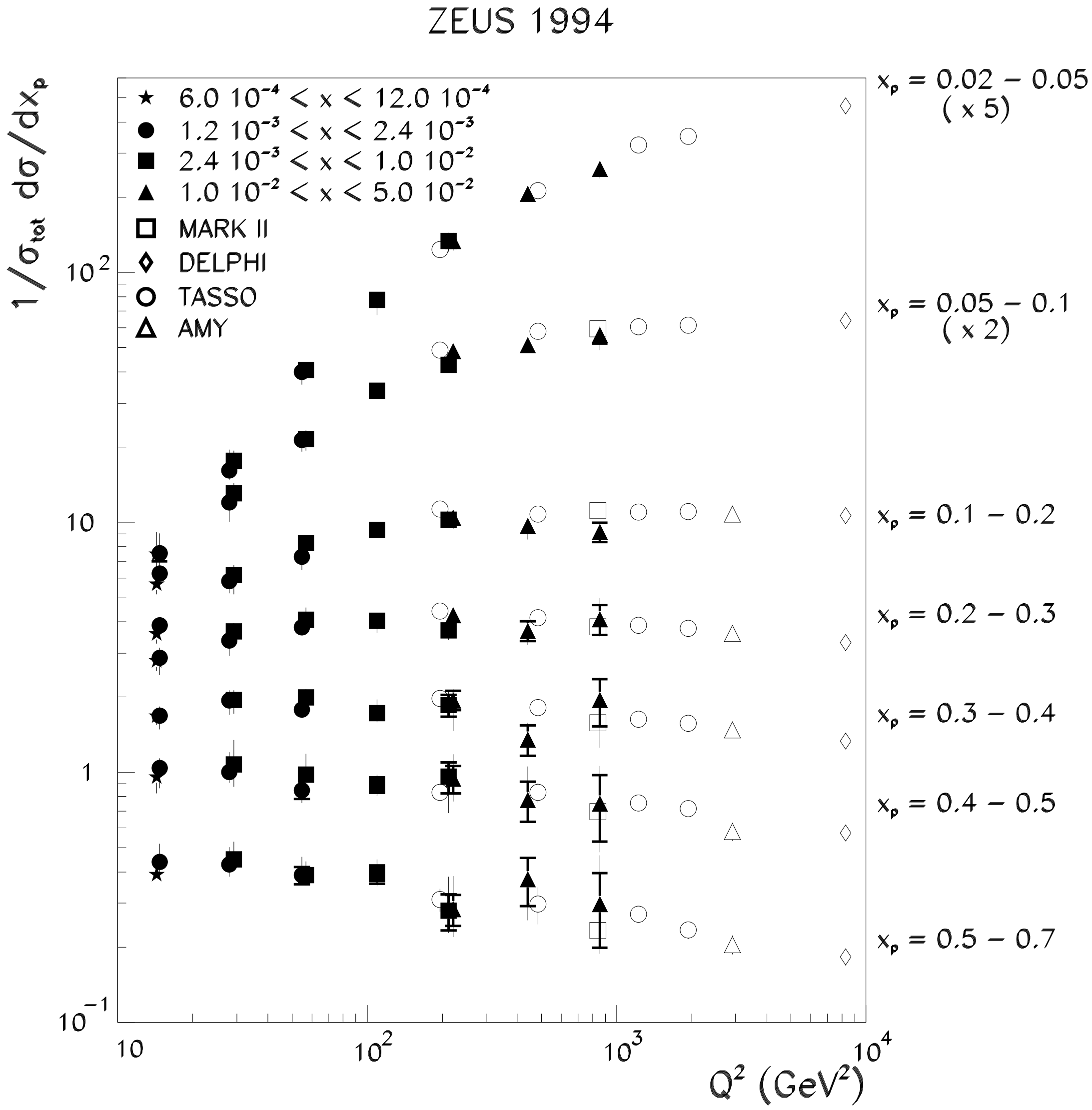


Figure 12: The inclusive charged particle distribution, $1/\sigma_{tot}\ d\sigma/dx_p$, in the current fragmentation region of the Breit frame. The filled data points are from ZEUS. The full errors are statistical and systematic combined in quadrature. The thick lines denote the statistical error. The open points represent data from e^+e^- experiments divided by two to account for q and $\bar{q}$ production (also corrected for contributions from K^0_S and Λ.)

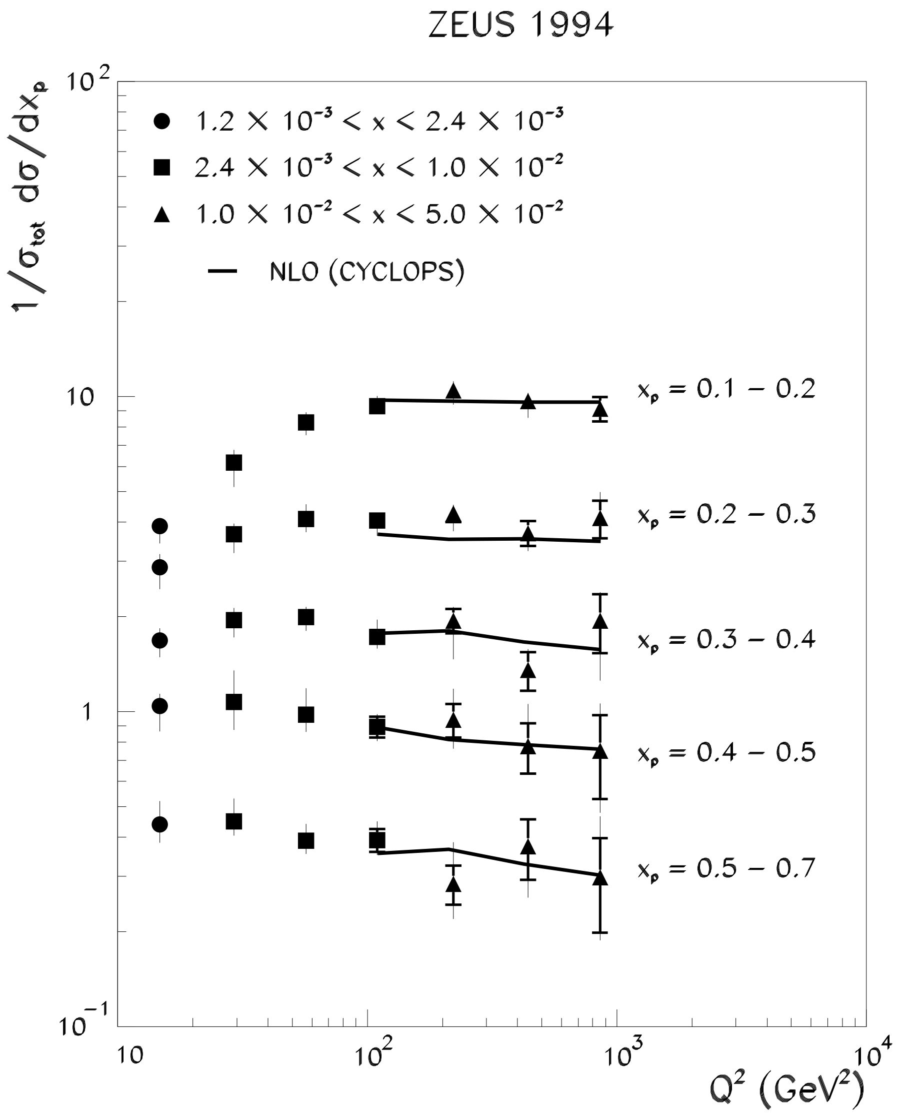


Figure 13: The inclusive charged particle distribution, $1/\sigma_{tot}\ d\sigma/dx_p$, in the current fragmentation region of the Breit frame compared to the NLO calculation, CYCLOPS [35]. For clarity of presentation, only the higher x bin is shown in each Q^2 interval.

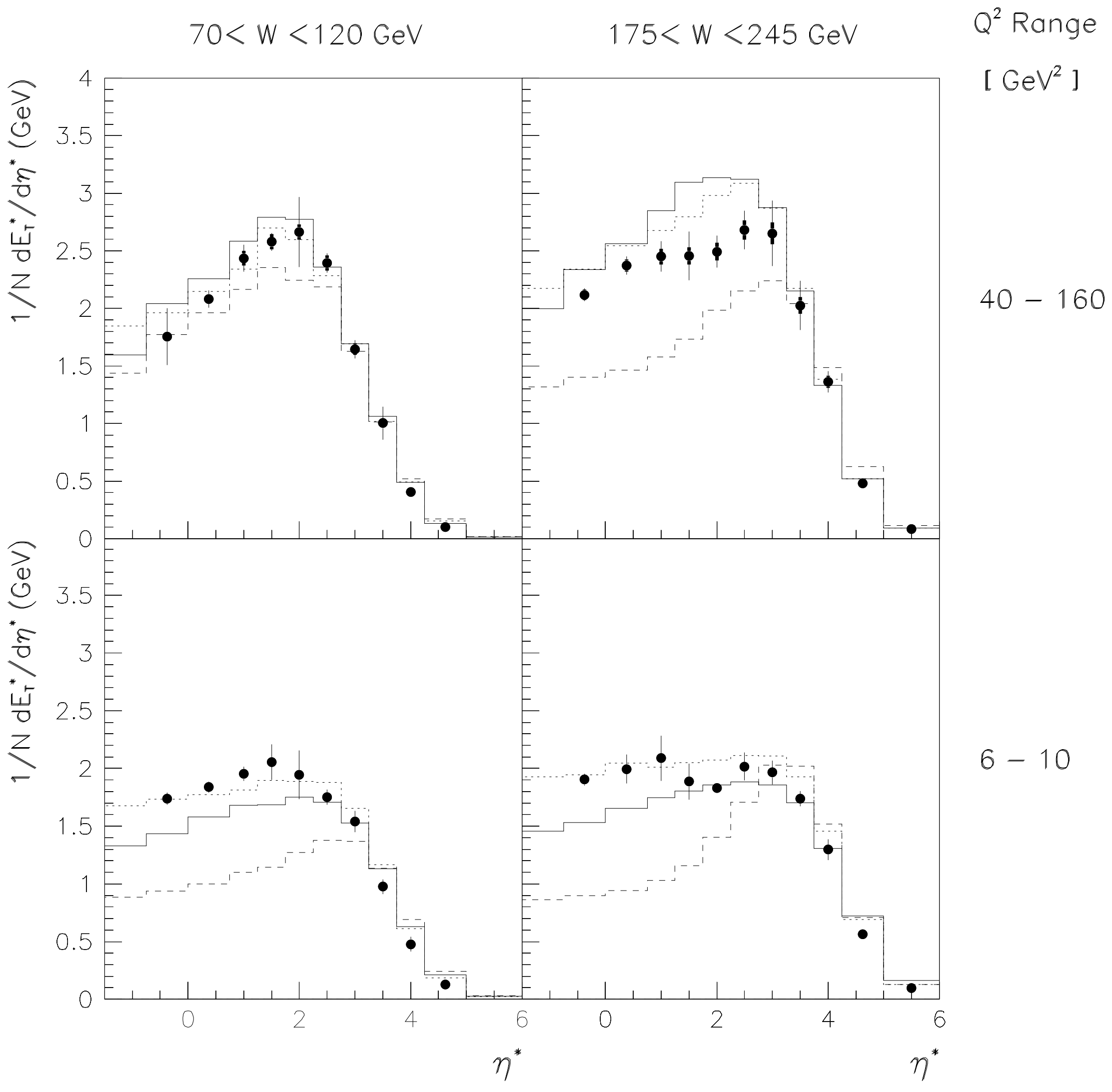


Figure 14: Transverse energy flow (E_T^*) distribution as a function in the $\gamma^* p$ c.m.s., shown in some selected Q^2 and W bins. The photon direction is towards positive pseudorapidities (η^*). The prediction of the old MEPS (Lepto 6.1) (dashed) the new MEPS (Lepto 6.5) (full) and recent CDM (Ariadne 4.8) (dotted) model calculation is shown.

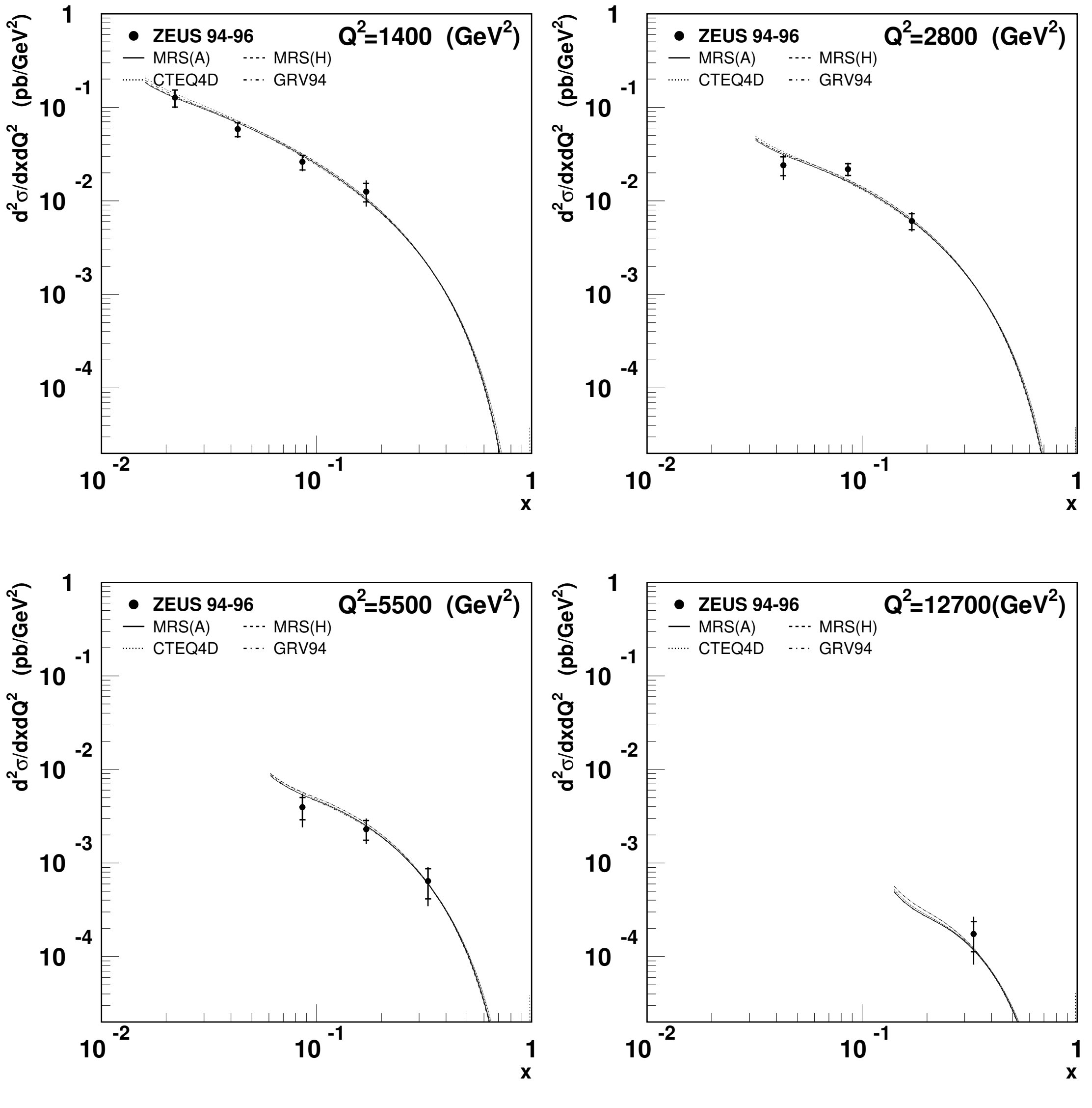


Figure 15: The cross-section $\frac{d^2\sigma}{dxdQ^2}$ for CC DIS at HERA. The data is shown for 4 values of Q^2 as a function of x together with calculated cross-section from four recent parton density functions. Statistical and systematic errors are also indicated.

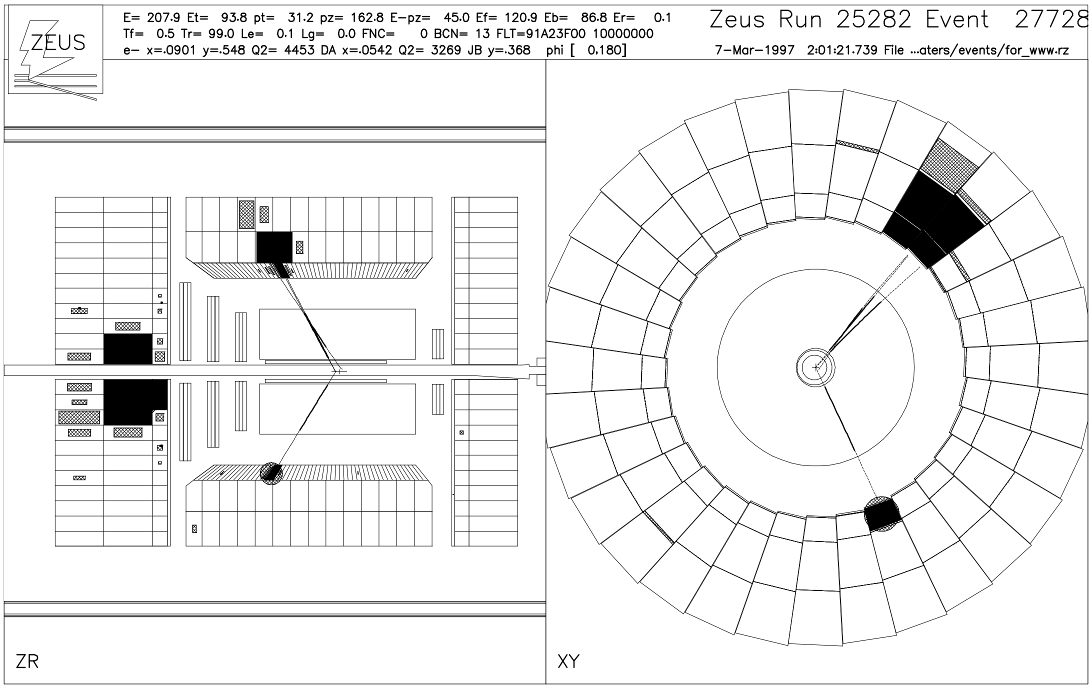


Figure 16: A candidate $W \to e\nu$ event taken during 1997 running. A scattered positron is visible in the BCAL (middle lower section of ZR plot) at a large angle with respect to the jet. The transverse mass for the event is 79 GeV.