ZEUS – A DETECTOR FOR HERA

Proposal 760

Collaborating Institutes by Country

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Introduction.

The 1993 running period provided ZEUS with twenty times as much data as that of 1992. A number of physics analyses on the 1993 data have already been published or accepted for publication and quite a few more will be submitted for publication before the end of 1994. Notable among the physics topics is the measurement of the proton structure function F_2, which has been greatly improved allowing a more detailed study of the interesting low x region. The higher statistics have also allowed studies of the gluon density in the proton; this is seen to rise strongly at low x.

The 1994 running period will end on 31 October, by which time there will be at least a factor five increase in luminosity compared to 1993. The Central Tracking Detector (CTD) has continued to perform well and significant enhancements have been made to the detector readout. Analysis of the 1994 data is in its early stages but will provide interesting results in the coming year.

HERA.

HERA delivered a total luminosity of about 1 pb^{-1} to the experiments in 1993. The performance of HERA has improved in 1994 and the end of data taking, on 31 October 1994, will see the machine having delivered more than 5 pb^{-1}. The factor of five increase over 1993 is in line with that predicted by the HERA machine group based on improvements made. The klystron power is a factor of two higher than in 1993 and the number of colliding bunches has been doubled from 84 to 168, 80% of the design value. Proton beam currents of 52mA at 820 GeV have been achieved and the maximum measured luminosity is within a factor of three of the design value of 1.5 10^{31} $cm^{-2}s^{-1}$. The maximum specific luminosity, higher than the design value, is 5 10^{29} $cm^{-2}s^{-1}mA^{-2}$.

At the start of the 1994 data taking HERA was running with beams of electrons and protons, the electron beam being at a slightly higher energy, 27.52 GeV, than in 1993. The lifetime of the electron beam was low at about three hours, and so, having delivered about 1 pb^{-1} of electron-proton collisions, it was decided to change to positrons. The necessary changes (reversing magnet polarities, etc.) were carried out in the second half of July, and since then positron running has led to lifetimes of about eight hours and improved luminosities.

Longitudinal polarisations of the electron beam of more than 60% have been reached using a pair of spin rotators in HERA – this is the first time that longitudinal polarisation has been achieved in an electron storage ring. However, spin rotators will not be installed in the ZEUS (or H1) experiment regions until the end of 1996 and therefore there will be no physics with longitudinally polarised beams until at least 1997.

The problems with the electron beam lifetime were found to be due to ion sputter vacuum pumps and the only remedy is to replace all such pumps. This will not happen before the 1995/1996 shutdown and so the 1995 running will continue with positrons to maintain good luminosities.

ZEUS data taking and detector.

The ZEUS detector has generally been working well this year even though there was much installation work and modification of hardware, electronics and trigger and readout systems during the 1993/1994 shutdown. The much improved luminosities have meant that all three levels of the trigger have had to be modified significantly. Despite this, the performance of ZEUS is better than in 1993 and nearing the end of the 1994 running we regularly see data taking efficiencies of over 90%. Recently installed detectors (eg. SRTD, FNC, LPS – see below) are beginning to provide interesting data. Approved upgrades covering the small angle and beam pipe regions will allow ZEUS to extend its physics reach to lower Q^2, higher precision and improved study of diffractive physics.

The Central Tracking Detector (CTD) and its associated electronics, trigger and readout, were designed, constructed and commissioned by the UK groups. The CTD is a large volume drift chamber, 2.4m long and 1.7m in diameter, providing charged-particle tracking and momentum analysis over the central region. The CTD trigger and track information is essential for all physics analyses in ZEUS. The UK groups continue to be responsible for all aspects of the operation of the CTD. In the last year a great deal of effort has been devoted to increasing both the speed and the functionality of the CTD data acquisition (DAQ). In the period between the 1993 running and the 1994 running, the speed at which the DAQ can accept first level triggers without unacceptable deadtime has increased from less than 100 Hz to around 450 Hz, and recent work implies that 600 Hz should be readily attainable. Features such as automatic pedestal subtraction and improvements to the pulse timing algorithm in the Flash Analogue to Digital Converter (FADC) system have been introduced. The structure of the CTD run control program has been improved and made more efficient. Stage I of the CTD first level trigger has been commissioned and is used in a variety of physics triggers. The final design for Stage II of the trigger has been completed and prototypes of the remaining boards tested during data taking. Production of the final trigger processor boards has begun and the full system will be operational for 1995 running. The CTD second level trigger has been optimised and largely rewritten to improve speed and functionality. A great deal of work has still to be done to improve the general slow control facilities and the high voltage control of the CTD. The maintenance, understanding and improvement of the CTD electronics and DAQ is a major and long-term effort which is being successfully undertaken by a team from the UK groups.

In the last year significant progress has been made in developing the CTD reconstruction algorithms and improving the understanding of systematic effects in the chamber. The data from the chamber are essential to all physics analyses requiring determination of the position of the primary interaction. The power of the chamber is particularly important in analyses involving the reconstruction of secondary vertices. As an example, Figure 1(a) shows the result of a search for the decay $K^0_S \rightarrow \pi^+ + \pi^-$. A clear peak is visible at the known K^0_S mass. Figure 1(b) shows a typical event in the detector. The secondary vertex at which the K^0_S decays is clearly seen. A second team is energetically pursuing an analysis to improve further the understanding of systematic effects in the chamber. The same team is responsible for ensuring that the quality of the data coming from the CTD is maintained during the running period.

The Transition Radiation Detector (TRD), part of the Forward Tracking Detector (FTD) is primarily a Bonn responsibility, but considerable assistance with this has been provided by the Glasgow group. Successful operation of the TRD in ZEUS has been demonstrated, with signals from both electrons and pions, and with hits positioned correctly on extrapolated tracks. However, shortage of readout electronics has led to the temporary loan of the TRD read-out to the Rear Tracking Detector (RTD), since the RTD is crucial to improving the measurement of the scattered electron at low Q^2.

Although the ZEUS detector is mostly complete and functioning, there are still some components being commissioned and there are further upgrades planned. Most enhancements reflect the need to reduce systematic errors as the amount of data increases, or to improve precision in measurements of energies, positions etc. Another area of interest is the forward and rear low angle region: the very forward region is particularly important for diffractive physics; improving the coverage for electron (positron) measurements at small angles in the rear region allows regions of low Q^2 and hence low x to explored.

The Small-angle Rear Tracking Detector (SRTD) was installed during the 1993/1994 shutdown. This scintillator strip detector placed around the beam pipe is designed to improve electron (positron) position measurement in this important low angle region, and to identify electrons that pre-shower before reaching the calorimeter. It has been taking data during 1994, and the combination of the SRTD and Calorimeter information leads to a dramatic improvement in the electron energy measurement.

A new smaller beam pipe is being designed and will be installed in the 1994/1995 shutdown. This will allow improved coverage at small angles and give less material in front of the calorimeter, thus allowing improved measurements of the scattered electron (positron) at low Q^2. The new beam pipe will also create space in the inner region for a new or additional vertex detector.

In the very forward region the Leading Proton Spectrometer (LPS) detects protons scattered at very small angles and small transverse momenta ($p_T < 1$ GeV/c). Leading protons are expected in a substantial fraction of all neutral and charged current interactions, including low x and elastic and diffractive processes. The ability to tag and measure the leading proton improves the determination of the event kinematics. In 1993 the LPS was partially equipped and data corresponding to a luminosity of 28 nb^{-1} were collected. A resolution in x_L, the fraction of the proton beam energy carried by the forward proton, of 8 10^{-4} was achieved. Studies indicate that requiring a track in the LPS allows a clean and unbiased selection of high x_L events in the whole kinematic range. For the 1994 running the LPS was 80% complete and there is now about 1 pb^{-1} for which the LPS information has been recorded. Analysis of these data is beginning.

The Proton Remnant Tagger (PRT) consists of scintillator 'paddles' surrounding the beam pipe in the forward region at distances of 5m and 24m from the interaction point. This device, which provides energy and time measurements for particles which escape through the forward beam pipe hole of the central detectors, has recently started to be read out. The PRT will help to distinguish events with diffractive dissociation of the proton from elastic scattering.

Another element of the very forward detection system in ZEUS is the Forward Neutron Calorimeter (FNC). A test FNC used in the 1993 running led to the first observation of leading neutrons in *ep* collisions. It was found that about 8% of tagged photoproduction events and of deep inelastic scattering events with $Q^2 > 10$ GeV^2 have leading neutrons with energy greater than 400 GeV. Leading neutrons at HERA are expected to be produced through reggeon or pomeron exchange. An upgraded FNC, was installed in time for the 1994 running and studies of peripheral processes in *ep* collisions are underway. The complete FNC should be available next year.

Other elements of the detector which are still to be completed or commissioned are the forward and rear tracking detectors (F/RTD), calorimeter pre-samplers and the hadron-electron separators (HES). As already mentioned, the RTD is now being read out and will be used for physics; the first data taking with part of the FTD occurred in October 1993. The pre-samplers are layers of segmented scintillator which will be placed in front of the calorimeter modules to detect showering particles and correct for energy loss. A small prototype is currently in position in front of the rear calorimeter; this is being read out. Further modules have been beam-tested during the summer. The rear HES is complete and the forward HES is under construction.

Zarah.

The success of the ZEUS collaboration in carrying out a wide range of analyses and producing an enormous wealth of physics results in the past year has been due in large part to the computing facility known as Zarah. Zarah consists of Silicon Graphics processors with disks and peripherals and was purchased by DESY in the middle of 1993. Zarah has proved essential for UK physicists working on physics analysis, both at DESY and in the UK, as it allows access to the complete 1993 physics sample and a representative sample of Monte Carlo data. All ZEUS event reconstruction is performed centrally at DESY on a dedicated farm of processors provided by DESY. The reconstructed data in mini data summary tape (MDST) format, as used for physics analysis, are then made available on Zarah. The data volumes involved are large: the 1994 MDSTs are expected to occupy 500 Gbyte of storage. The logistics and delays in transporting this data to the UK and ensuring that it is kept up to date would have seriously restricted UK analysis efforts. Due to the increased data volume in 1994 and the increased analysis load Zarah is to be upgraded and the costs borne by the collaborators.

Physics.

The 1993 data have already provided a rich physics output for ZEUS. Many analyses are still ongoing and we expect many more publications in the coming months. The physics accessible with ZEUS at HERA covers a vast range of topics many of which were presented, in preliminary form, at the 1994 International Conference on High Energy Physics (ICHEP) held in Glasgow in August. ZEUS submitted 26 abstracts and papers to ICHEP. Below we mention some of the highlights and areas where UK physicists are heavily involved.

The twenty fold increase in the amount of 1993 deep inelastic scattering (DIS) data compared to those of 1992 allowed a much better determination of the proton structure function F_2 (see Fig.2). Both the statistical and the systematic errors were significantly reduced and the range of the measurement was extended to both higher and lower Q^2 values. Prior to experiments at HERA there were discrepant theoretical predictions of the likely behaviour of the parton densities in the proton at low x. The strong rise of F_2 with decreasing x seen for the first time last year was confirmed with the 1993 data and led to the exclusion of models predicting a flat gluon momentum distribution in the proton. Whether this is evidence of the so-called Lipatov evolution or can be explained by the normal Altarelli-Parisi behaviour is still the subject of argument amongst theoreticians.

The gluon density in the proton is related indirectly to F_2. In leading order, scaling violations at low x are dominated by effects due to the gluon density and hence this density can be extracted from the slope $dF_2/d\ln Q^2$ using approximate solutions of the perturbative QCD evolution equations. This technique has already been applied to the ZEUS data of 1992; it is now being used on the F_2 measurements from the 1993 data together with an alternative method which performs a full next-to-leading order iterative fit to the F_2 data. A large contribution to F_2 from the gluon density is seen at low x.

The increased statistics of the 1993 data have permitted a more detailed study of DIS events with a large rapidity gap (LRG) between the outgoing proton system and the remaining hadronic system. Such diffractive DIS events were first seen by ZEUS in the 1992 data. The proton, or proton system, is not detected though this will be remedied by the new detectors in the forward region (FNC, LPS, PRT). The diffractive DIS process is modeled using the exchange of a colourless object, the pomeron, between the proton and the virtual photon. There are two different models of this process. In one the beam proton emits a pomeron whose constituents take part in a hard scattering process with the virtual photon or its constituents. The other model assumes that the exchanged photon fluctuates into a $q\bar{q}$ pair which interacts with a colourless two-gluon system emitted by the proton. Both these models fit the data reasonably well though a hard, rather than a soft, pomeron quark momentum density is needed in the former in order to reproduce the data. Several fits to the distributions of the hadronic angle and the maximum observed rapidity in the event have been used to extract the fraction of diffractive events in the DIS sample. The fraction is about 10%, the value obtained depending slightly on the model used. The diffractive cross section has also been evaluated. Jet searches have been carried out in the LRG events both in the ep system and in the γ^*p centre of mass system. Production of LRG events with transverse energy greater than 5 GeV in the γ^*p system is saturated by jet production; this hard scattering and jet production support the idea of a partonic structure to the pomeron.

Studies are underway into exclusive vector meson production in DIS. A clear ρ^0 signal is seen in the 1993 data and earlier this year ZEUS presented the first measurement at HERA of the diffractive production cross section for ρ^0 mesons produced by the virtual photoproduction process $\gamma^*p \to \rho^0 p$ in the Q^2 range $(7 - 25\ \mathrm{GeV}^2)$. This cross section is predicted to depend on the gluon density in the proton and so may be useful for extracting this density. The properties of the ρ^0 events have also been studied and compared to diffractive electroproduction calculations based on vector meson dominance models and calculations in perturbative QCD as well as to similar data at lower centre of mass energies. The heavy vector mesons ϕ and J/ψ are also observed in DIS.

HERA offers a large kinematic range for the study of the hadronic final state system in DIS. One particular area of study has been the measurement of the scaled momentum and charged multiplicity distributions in the current region of the Breit frame, i.e. the region of the outgoing struck quark. These can be used to study QCD coherence effects in DIS and to test the universality of quark fragmentation by comparing with e^+e^- data. The growth in the mean charged multiplicity with Q is similar to the growth in e^+e^- experiments with the centre of mass energy and the evolution of the scaled momentum indicates a coherent evolution of the parton shower. The consistency with e^+e^-data affirm the QCD cascade picture.

The gluon content of the proton is the subject of intense theoretical and experimental interest. Several methods have been proposed to measure the gluon density in the proton indirectly via the scaling violations of F_2 (as mentioned above). The production of heavy quarks at HERA is sensitive to the gluon density at first order, and as such represents a direct and sensitive probe of the gluon density. Great progress has been made this year in isolating a signal for J/ψ and D^* meson production.

The J/ψ has been observed via its decay into electron and muon pairs. As an example the invariant mass of the electron pair in the candidate $J/\psi \to e^+e^-$ events is shown in Figure 3. The events found in roughly one tenth of this year's data are shown as the points together with a fit to determine the mass, width and number of events. For comparison the mass peak observed with the full 1993 data is shown as the hatched histogram. A publication is in preparation reporting the cross section measured using the 1993 data. The five fold increase in the luminosity in the 1994 data taking means that we expect to be able to study the events in much finer detail in order to study the gluon density in the proton.

The observation of D^* mesons demonstrates that the experiment is sensitive to the production of open charm. The most sensitive way to search for the production of the D^* is to search for events in which the D^* decays to D^0. The D^0 is observed via its decay to $K\pi$ final states and the D^*, D^0 mass difference $m_{D^*} - m_{D^0}$ is formed. Figure 4 shows a plot of the mass difference in which a clear D^* signal is observed. Once again a paper is in preparation reporting the cross section measured using the 1993 data. The higher luminosity of the 1994 data means that the gluon density may be investigated using this data.

A paper in which the ZEUS group announced the first separation of the direct and resolved processes in hard photoproduction has now been published. This has opened new areas of physics, which are now being followed up. One of the topics in which ZEUS-UK have a particular interest is the identification of heavy flavours in hard photoproduction. Signals from K^0 and Λ particles have been identified in photoproduction events containing high-p_T jets, and these particles are found to be associated largely with the jets. Studies are in progress to measure the direct and resolved components of photoproduction events of this type, which will give new handles on the partonic content of the photon and the proton.

Searches for "exotic" particles have continued. These are particles which are not known to exist, but whose existence is suggested by analogy with the patterns and properties of other particles. The much increased luminosity now available has still given no examples of leptoquarks (decaying into an electron, or ν or μ or τ, and a quark) with standard couplings. This excludes the existence of these particles with masses up to 242 GeV/c^2. Similarly searches, again negative, for excited states of electrons have placed stringent limits on coupling strengths for masses up to 250 GeV/c^2. These searches are not yet limited by background; tighter limits (or else discovery!) will be provided by more data in this and subsequent years running.

Conclusions.

The luminosity of HERA has increased substantially over the last year and can be expected to do so again next year. Further modifications to ZEUS have improved its capabilities for physics, and the reliability of its components has improved as problems are ironed out, leading to improved running efficiency. HERA is a unique facility for studying high energy lepton-quark interactions. The increased data accumulated in this last year (and foreseen for the future) will sharpen the conclusions of analyses begun with earlier data and open further facets of this fundamental physics to experimental study.

Publications.

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Figure Captions.

Fig. 1(a) Invariant mass of a sample of oppositely charged track pairs showing a clear K_s^0 mass peak.

Fig. 1(b) An event containing a K^0 decay in the CTD.

Fig. 2 The proton structure function F_2 as measured by ZEUS for different values of Q^2 as a function of Bjorken x. The error bars on the data are the sum (in quadrature) of the statistical and the systematic errors. The strong rise of F_2 persists up to $Q^2 = 500$ GeV^2. Five different F_2 parametrizations are also shown on top of the data points. ¿From the lower Q^2 points it becomes clear that the lower MRSD$'_0$ curve assuming a flat gluon at low x can be excluded.

Fig. 3 Invariant mass of the e^+e^- pair for $J/\psi \to e^+e^-$ candidates (see text).

Fig. 4 $D^* - D^0$ mass difference (see text).