PHYSICS WITH H1 AT HERA II

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A sketch is given of the main results obtained with the H1 apparatus at HERA as is a summary of where progress is to be expected as a result of increased HERA luminosity, the measurement of beam charge and polarisation asymmetries, the variation of beam energies, improved systematics and extended kinematic range.

1. The Past

Before the advent of the world's first electron-proton collider HERA, two decades of experiments on deep inelastic lepton-nucleon scattering (DIS) using stationary targets established what is now the conventional picture of nucleon structure: The proton and the neutron contain valence and sea quarks which are dominant at large Bjorken $x > 0.3$ and low $x < 0.05$, respectively. Here, x describes the momentum fraction of the proton carried by the quarks in the infinite momentum frame. In the Quark Parton Model (QPM), the distribution of quarks and anti-quarks in the nucleon is described by momentum density functions, $q(x)$ and $\overline{q}(x)$, which apply universally to elementary fermion interactions. The DIS cross section is largely determined by the proton structure function $F_2 = x \sum e_q^2 (q + \overline{q})$, where e_q are the quark electric charges. The x dependence of the various parton distributions is to be determined from experiment.

DIS was crucial in establishing Quantum Chromodynamics (QCD) as the correct field theory of the strong interactions which describes parton dynamics in terms of the exchange of gluons and includes gluon-gluon interactions due to its non-Abelian character. In QCD, the structure functions are a convolution of calculable coefficient functions with the parton distributions which due to gluon radiation and quark- antiquark pair production depend both on x and Q^2, the square of the four-momentum transferred by the exchanged virtual photon, $W^{\pm}$ or Z boson. The strong coupling constant α_s was found to decrease with Q^2, presumably leading to asymptotically free quarks, i.e. to the restoration of the QPM as a limit of QCD. In inelastic DIS, secondary particles are emitted which allow the parton dynamics in the formation of the final state to be investigated in detail. Polarised eD scattering was instrumental in establishing the electroweak sector of the Standard $SU(2)_L \times U(1) \times SU(3)_c$ Model (SM).

2. HERA and H1

HERA was built in the eighties to carry these investigations much further. The H1 detector [1] is a large, multipurpose device of nearly 4π acceptance, comprising tracking and calorimetric detectors. The range of x and Q^2 accessible is much wider than that available to fixed target experiments. The kinematics is reconstructed both from the scattered electron and from the final state. This results in a superior accuracy for the HERA DIS measurements which need to be precise to reveal the subtleties of strong interactions. Moreover, due to the high collision energy, HERA provides much richer information about the final state than is accessible at fixed target experiments.

During its first phase of operation, between 1992 and 2000, H1 recorded an integrated luminosity of about 110pb^{-1} of e^+p and 15pb^{-1} of e^-p data with both beams unpolarised. In its second phase, termed HERA II, the aim is to record an increased integrated luminosity of about 1 fb^{-1} with longitudinally polarised leptons at highest energies, and also to provide data at lower proton beam energy. The increase of the luminosity is achieved due to better focussing of the beams in the interaction region (IR). Thus superconducting quadrupoles were put close to the ep interaction point and detectors close to the beam had to be modified. Bending the positron beam nearer to H1 caused stronger synchrotron radiation than in HERA I. This and the modified IR caused beam induced backgrounds, mainly from the dynamic interplay of synchrotron radiation with the proton beam, which initially prevented H1 and the other collider experiment, ZEUS, from collecting data. While this article is being written, early 2004, HERA is delivering beams with increasing intensity yet a factor of $2-3$ below the design value. The longitudinal positron polarisation is typically about 40%. It remains a challenge to achieve routine operation at the highest luminosities but the prospects are good.

The H1 detector underwent a major upgrade for HERA II. A new finely segmented inner proportional chamber will improve the vertex trigger capabilities. A dedicated trigger uses central drift chamber hits to reconstruct tracks, e.g. allowing the online identification of charm in photoproduction events. New forward and backward silicon detectors extend the tracking and thus the heavy flavour physics capabilities to larger and to lower x, respectively. A new forward drift chamber system improves tracking at large x and high Q^2. Downstream along the proton beam line, a new Roman pot fibre detector extends the acceptance for diffractive scattering and measures t dependent cross sections. A new Compton polarimeter will measure the beam polarisation with increased precision and for each bunch separately. These and further improvements represent significant investments and form, together with the standard components of the H1 apparatus, calorimeters and chambers, a solid basis for high precision physics and searches at HERA II.

This paper provides a brief account of the results [2] obtained by the H1 Collaboration from the first phase of HERA operation. Subsequently, selected topics are described which are central to physics with HERA II. With much increased luminosity and improved systematics genuine surprises may be encountered. New developments, such as unintegrated parton distributions or parton correlation functions, may well change our view on proton structure in a qualitative way. QCD predicts that instantons exist and that instanton induced cross sections are accessible to DIS experiments at HERA. Given that interactions mediated by two gluon, or Pomeron, exchange have been observed, should odderons exist, i.e. three gluon exchange? The excitement of HERA physics is largely due to the unprecedented richness of Quantum Chromodynamics.

3. Results of the H1 Experiment at HERA

With beam energies of $E_e = 27.5$ GeV and $E_p = 920$ GeV, corresponding to a cms energy squared of $s \simeq 10^5$ GeV^2, HERA allows the regions of very high $Q^2 < s$, and of very small Bjorken $x = Q^2/sy > 10^{-5}$ to be explored in DIS for the first time. Here y is the inelasticity, which in the proton rest frame, corresponds to the relative energy transferred by the exchanged boson. At large Q^2, the standard model predicts that the cross sections for exchanging neutral (γ, Z_0) and charged bosons $(W^{\pm})$ are of similar strength. A major triumph of the electroweak theory and of HERA was that this indeed could be observed by the H1 [2] and ZEUS [3] experiments, see Fig.1. The detailed exploration of weak neutral and charged current scattering at high Q^2 and large x using high statistics and polarised $e^{\pm}$ beams is a central issue for the future HERA programme, as described

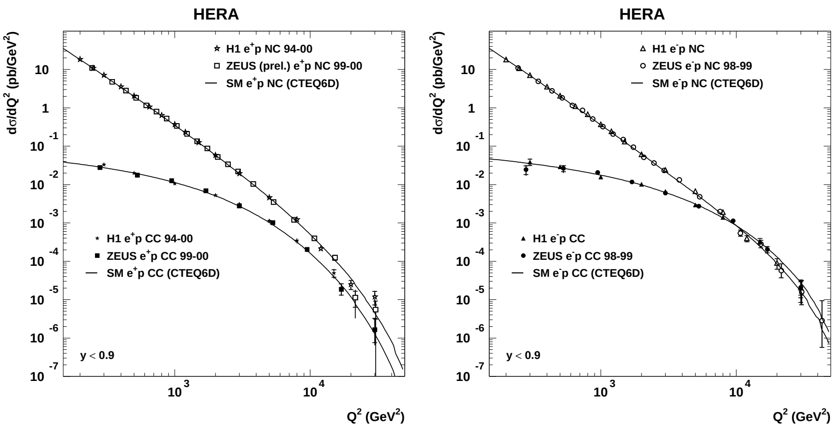

Figure 1. Measurements by H1 and ZEUS of the positron (left) and the electron (right) proton scattering cross sections at large Q^2 in neutral and charged current scattering. The curves represent calculations of the DIS cross section using standard model electroweak couplings and a set of parton distributions determined by the CTEQ Collaboration.

below.

Soon after the start of HERA operation, H1 and ZEUS discovered new features of the strong interactions and of proton structure. A striking observation from the first 1992 data was that the proton structure function $F_2(x, Q^2)$ rises strongly towards low x, at fixed Q^2. This observation was later confirmed with much improved accuracy [2,3], see Fig.2. The rise of F_2 in the DIS region implies that the sea quark density at low x is high while the strong coupling constant, $\alpha_s(Q^2)$, is rather small. This defines a new regime of parton dynamics, the theoretical understanding of which is not complete despite impressive theoretical attempts over the past decades [4]. The x dependence of $F_2(x, Q^2)$ is observed to change [2] at momentum transfers $Q^2 \sim 1\,\mathrm{GeV}^2$, corresponding to a distance of 0.3 fm which is where partonic interactions seem to emerge. As striking as the x dependence, is the strong rise of $F_2(x, Q^2)$ with Q^2 at low, fixed x. In the classic evolution equations of perturbative Quantum Chromodynamics (pQCD), the Q^2 dependence, characterised by the derivative $\partial F_2/\partial \log Q^2$, is related to the gluon density. It was soon realised that, at low $x < 0.01$, the quark contribution to the F_2 scaling violations is small for $Q^2 > 3\,\mathrm{GeV}^2$. Therefore, the measurement of a large derivative $\partial F_2/\partial \log Q^2$, see Fig.2, indicates that the gluon density is large at low x. The experimental investigation of low x physics will be extended at HERA II as part of the effort to establish

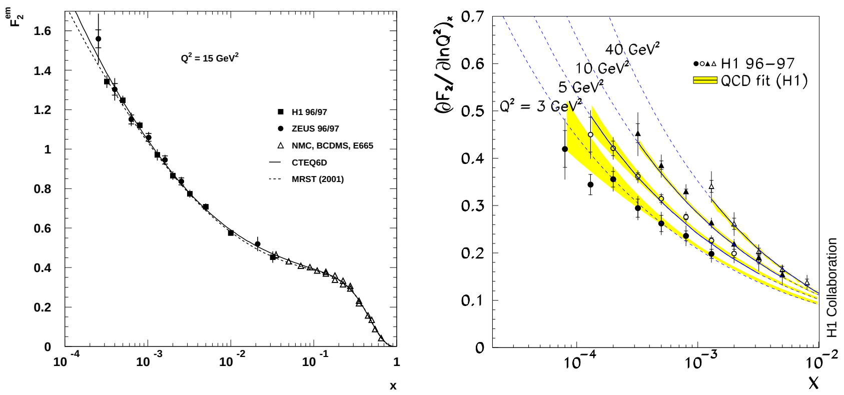

Figure 2. Left: Measurements of the proton structure function $F_2(x, Q^2)$ at medium Q^2 as a function of the proton momentum fraction x carried by the struck quark. HERA has significantly extended the kinematic range of these measurements and discovered a new regime of high sea quark densities. This can be attributed to a large gluon density as can be inferred from the measured scaling violations of $F_2(x, Q^2)$, right. Further improvements of the measurement accuracy and new data are envisaged to accurately determine xg and the strong coupling constant.

the theory of high density parton dynamics.

Low x physics soon turned out to be much richer than one could deduce from the inclusive DIS measurements. A further outstanding result from HERA in the early nineties was the observation [2,3] that in about 10% of all DIS events the proton does not dissociate but remains intact [a]. Since then deep inelastic diffraction has been investigated in much more detail. Diffraction, which may be related to colour confinement occurs, in a simplified view, as a two-gluon exchange which is both a fascinating theoretical problem and may prove to be a means of finding new particles at hadron-hadron colliders as it gives rise to particularly clean events, if both hadrons stay intact.

Because of the high energy available for particle production and since the gluon density is large, HERA is also a laboratory for heavy quark physics allowing the production mechanisms of charm and beauty particles to be studied. This has led to the development of heavy flavour theory [6] in next to leading order (NLO) QCD, as it turned out that much can be learned about parton dynamics from a 20-40% charm event fraction. No consistent view on strong interactions can be obtained, and no reliable extraction of

[a]Note that the elastic $ep \to ep$ scattering cross section decreases like Q^{-12} and is thus negligible in DIS at HERA [5].

$\alpha_s(M_Z^2)$ is possible, without accurately understanding heavy flavour physics at HERA. Heavy quarks may be a clue to finding exotic multiquark bound states [7].

The production of final state particles became a further testing ground for QCD. Going much beyond DIS fixed target final state physics, at HERA jet physics became a central issue. Fig.3 shows, as an example, a recent H1 measurement [2] of the jet production cross section at low $Q^2 < 1\,\mathrm{GeV}^2$, termed the photoproduction region. The cross section, measured as a function of the transverse energy of the jet, is seen to decrease by 7 orders of magnitude, a behaviour which is consistently described by NLO QCD calculations. Jet measurements are used [2] to measure $\alpha_s(M_Z^2)$ and jet shapes are investigated [2] in resummed NLO QCD calculations which also include power corrections.

A most exciting aspect of HERA physics is the search for new interactions and the new particles with which they are associated, such as leptoquarks and squarks. Outstanding events with high mass multi-electrons or with large missing transverse momentum, including flavour changing neutral current events, have been observed by H1 [2]; somewhat more than expected in the Standard Model. At high Q^2 and large x, a rich field of physics has been opened, allowing, for example, the search for quark-substructure [2] and measurements of parton distributions [2] in the valence quark region, at $Q^2 \sim M_Z^2$. The physics at large x and high Q^2 can not be explored thoroughly with the luminosity obtained so far, since the cross section decreases with x as $(1-x)^3$ at large x and, for photon-exchange, with Q^2 as $1/Q^4$. High luminosity will lead to new insight and perhaps discoveries at HERA. In this regard, lepton beam polarisation is an interesting feature, as will be discussed below.

4. The Programme for HERA II

4.1. *High Precision Inclusive DIS*

In QCD, variations are logarithmic, often involving factors of $\ln Q^2/\Lambda^2$ or $\ln 1/x$ where Λ is the scale parameter in QCD. Tests of QCD therefore need to reach a high level of accuracy, typically 1%, if they are to be decisive and if the data are to be of use for predicting cross sections at other machines, such as the LHC or for neutrino astrophysics. An important example in this regard constitutes the measurement of α_s in DIS. The strong coupling $\alpha_s(M_Z^2)$ is the least well known of all the coupling constants, but is of great importance for testing QCD and for the unification pattern of the funda-

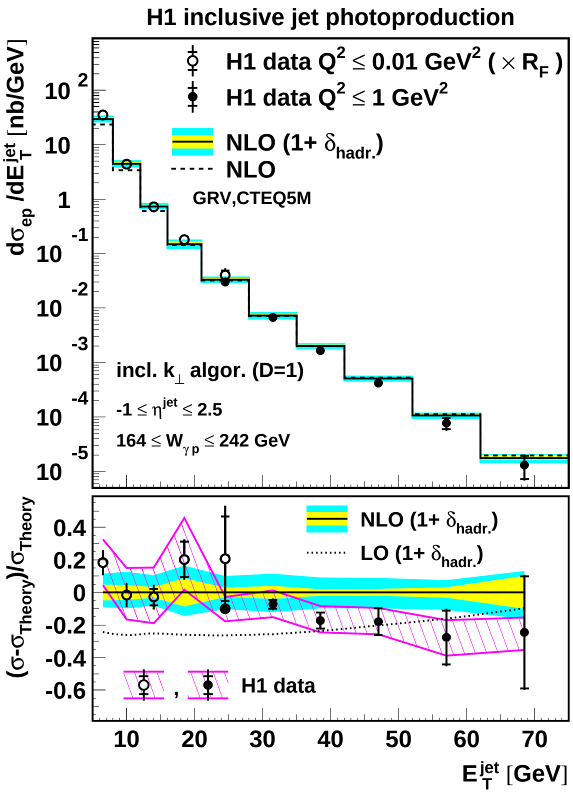

Figure 3. Top: Differential cross section for inclusive jet production as a function of the jet transverse energy. Bottom: relative difference between the data, the LO QCD prediction and the NLO calculation including hadronisation corrections.

mental interactions at extremely high energy. Inclusive deep inelastic scattering is a process particularly well suited to the measurement of α_s because it is calculable to high orders, in perturbation theory, and independent of the non-perturbative corrections that arise in jet and other analyses from final state effects. An accurate measurement of $\alpha_s(M_Z^2)$ in DIS was obtained by H1, the result being $\alpha_s(M_Z^2) = 0.1150 \pm 0.0017(exp) \pm 0.0008(model)$. This measurement is based on a systematic analysis of the BCDMS μp and the H1 ep inclusive cross section data. Contrary to other determinations of $\alpha_s(M_Z^2)$, the correlation of $\alpha_s(M_Z^2)$ with the gluon distribution is resolved, leading to competitive, consistent contributions of the data of both experiments to the final result, see Fig.4. The HERA II programme foresees further progress with this analysis which can be achieved by still improving the measurement of the ep cross section, using low E_p HERA data to access large x, a better understanding of the model uncertainties like the charm mass, possibly the use of data with deuterons [8] and, last but not least, from the calculation of the splitting and coefficient functions in NNLO [9] or their modification [10]. In an *ad hoc* procedure, the variation of the renormalisation scale μ_r^2 between $Q^2/4$ and $4Q^2$ leads in NLO to an estimated uncertainty of about ± 0.005 on $\alpha_s(M_Z^2)$. It is expected that this will be halved using forthcoming NNLO calculations. The prescription of varying μ_r by factors of 1/2 and 2 must be reexamined since the data exclude the possibility of such big variations [2,12].

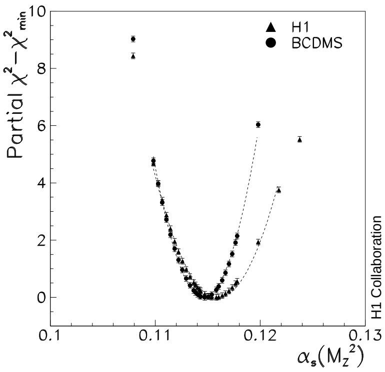

Figure 4. Contributions from the H1 and the BCDMS data to the χ^2 in the minimisation procedure using NLO QCD theory as a function of $\alpha_s(M_Z^2)$.

A further example of the importance of large data samples at HERA regards the flavour decomposition of the partonic contents of the proton. Not much is known about the strange quark and its possible asymmetry $s-\overline{s}$ at high Q^2 and x which may be important to the understanding of the electroweak mixing angle measurements [13]. The problem of the ratio of down and up quark distributions at large x is important for discoveries of high mass particles [b]. HERA II can contribute to this through improved measurements of the neutral and charged current cross sections at very high

[b]As was pointed out recently [8], the H1 detector offers the opportunity of tagging spectator protons in electron-deuteron scattering, thereby removing the binding corrections otherwise necessary in the unfolding of the neutron structure. This allows both the sea quark asymmetry $\overline{u}-\overline{d}$ to be extracted accurately at low x, which is not accessible in ep scattering at HERA II, and the ratio d/u to be measured at large x.

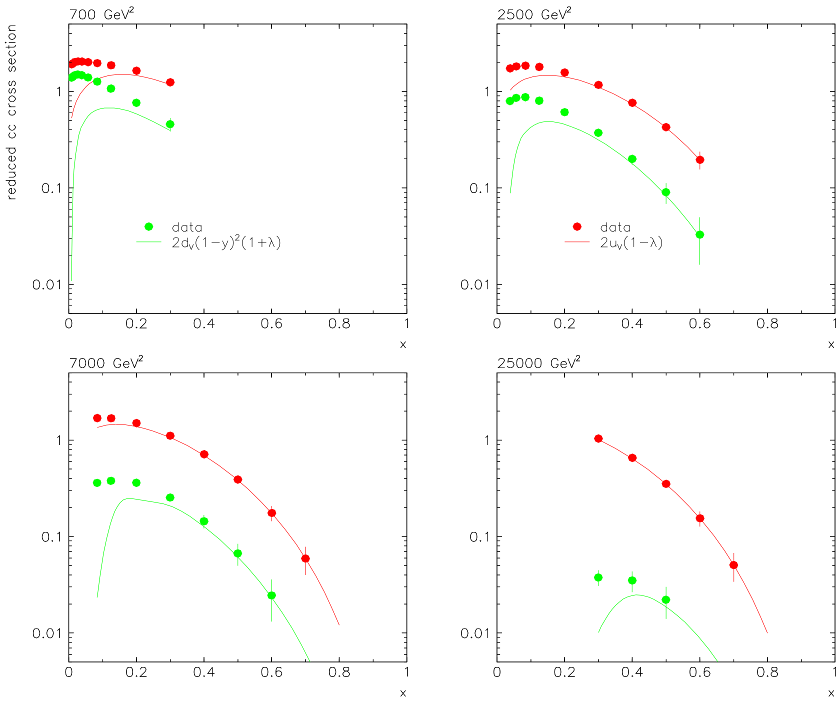

Figure 5. Simulation of charged current measurements with $250\mathrm{pb}^{-1}$ luminosity for 50% polarisation showing statistical errors only for e^+p (grey points) and for e^-p (black points). The curves represent the valence quark contributions to the CC cross sections.

Q^2, see [14] Fig.5.

4.2. *Physics with Polarised $e^{\pm}$ Beams*

4.2.1. *Parity Violation and Valence Quarks*

The increased luminosity and the use of longitudinal lepton polarisation will allow the electroweak structure functions [15] to be measured. For NC interactions, in addition to F_2, this applies to the lepton beam charge asymmetry which essentially determines xG_3, the $\gamma - Z$ interference part of the generalised structure function $\mathbf{xF_3}$. Variation of the lepton beam helicity determines the structure function, $G_2 = 2x\sum e_q v_q(q + \overline{q})$, so far unmeasured, which is the $\gamma - Z$ interference part of the generalised structure function $\mathbf{F_2}$. Here, v_q is the weak vector coupling of the quark q. At high x, $G_2(x, Q^2)$ is proportional to the sum $u_v + d_v$ while $F_2 \propto 4u_v + d_v$. Both G_2 and F_2 will thus provide complementary information on the valence-quark distributions, independent of nuclear binding corrections. A simulated measurement of G_2 was presented in [16]. Unique information on the valence quarks at rather low $x \geq 0.01$ can be obtained from beam charge asymmetry data determining the non-singlet structure function $xG_3 \propto 2u_v + d_v$. Since the underlying asymmetries rise with Q^2, the charge asymmetry is proportional to $1-(1-y)^2$ and the valence quark distributions drop like a power of $(1-x)$, it would be desirable to significantly exceed the current goal of $1\,\mathrm{fb}^{-1}$with the upgraded HERA collider.

4.2.2. *Right Handed Currents*

The determination of the helicity structure in neutrino-nucleon scattering has long been considered an interesting problem. It can finally be solved using polarised lepton beams at HERA, which provides the equivalent of neutrino and antineutrino beams on fixed targets of 54 TeV energy. The charged current scattering cross section is predicted to be $\sigma^{\pm}_{CC}(\lambda) \propto (1 \pm \lambda)$. A departure from this expectation would hint at the existence of right handed currents. The accuracy of this measurement depends mainly on the maximum degree of beam polarisation achievable.

4.2.3. *Generalised Parton Distributions*

Deeply virtual Compton scattering (DVCS), the hard diffractive scattering of the virtual photon off the proton, $ep \to e\gamma p$, interferes with Bethe-Heitler (BH) scattering. The interest in this process arises from the possibility it presents to measure parton correlations, i.e. to measure generalised, or non-diagonal parton distributions [17]. It is in this respect similar to vector meson (VM) production, but avoids the complications due to the VM wave function. Large asymmetries are predicted [18], both in lepton beam charge and polarisation asymmetry measurements, which access the real and the imaginary part of the $BH \cdot DVCS$ interference amplitude, respectively. Improvements in the accuracy of the measurements [2,3], see Fig.6, is likely to shed new light on the partonic structure of the proton and on the nature of the diffractive interaction. Exploitation of this process requires maximum luminosity.

4.3. *Physics with Varied Proton Beam Energy*

Apart from one adjustment of the proton beam energy, from 820 GeV to 920 GeV, HERA has been operated for 11 years at fixed beam energies.

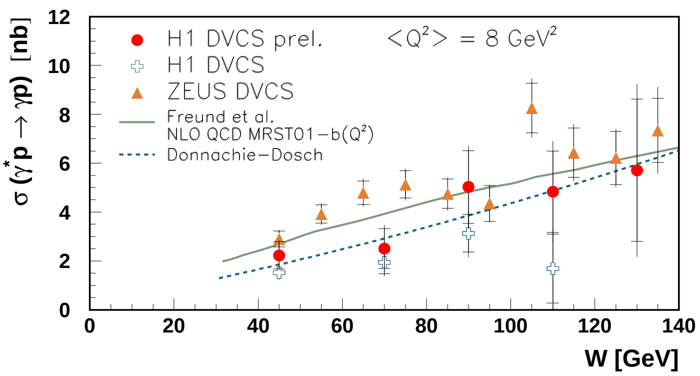

Figure 6. The $\gamma^* p \to \gamma p$ DVCS cross section as a function of W measured by H1 and ZEUS. The data are compared with NLO QCD using a GPD parameterisation (solid curve) and with a Colour Dipole model prediction (dashed curve).

However, there are good reasons to vary the beam energies. Increasing the proton beam energy [c], E_p, is most desirable when searching for new phenomena, since all search limits are set by the available energy, rather than by the luminosity, and given, e.g. in the mass range for new particles, roughly by $M \leq \sqrt{s} = 2\sqrt{E_e E_p} = 318\,\text{GeV}$ at the present energy settings. An increase in proton beam energy involves certain risk, or investment, regarding the quench protection of the proton machine dipole magnets.

Lowering the beam energy up to about half the present values is possible at the expense of reducing the luminosity. It makes possible the extension of the kinematic range for many HERA measurements, such as the total γp and the vector meson cross sections [2]. The study of two further, specific questions requires E_p to be lowered. The first regards the understanding of the gluon density and pQCD at low x. Investigations based on $\partial F_2/\partial \log Q^2$ only can not uniquely pin down the behaviour of $xg(x, Q^2)$ at low x. More generally, an additional constraint is necessary if QCD is to be tested to higher order at low x. This requires an accurate determination of the longitudinal structure function $F_L(x, Q^2)$. Such a measurement [19], accurate to about 5%, can be made with the present H1 apparatus for $Q^2 > 3\,\text{GeV}^2$ in a sequence of runs at low E_p, for example at 460 and 570

[c] The electron beam energy of 27.6 GeV is chosen to achieve maximum lepton beam polarisation. HERA could be operated at somewhat larger E_e depending on the rf. power available.

GeV, with luminosities of about 10 and 5 pb^{-1} .

The second question concerns access to the medium Q^2, large x region with HERA. This is of great interest for a precision measurement of $\alpha_s(M_Z^2)$, for the determination of parton distributions at large x and perhaps also for the search for an intrinsic heavy flavour contribution to proton structure. Since the luminosity is expected to degrade roughly like E_p^2, it is presently not realistic to envisage a luminosity larger than about 30 pb^{-1} . As is demonstrated in Fig.7, such data would be of considerable use in extending the kinematic range of the HERA data and achieving a larger overlap with the data from the BCDMS experiment. These have the peculiar feature of forcing $\alpha_s(M_Z^2)$ in DIS QCD analyses to small values unless the BCDMS high y data are excluded, see [11].

4.4. *Final States, Diffraction and Heavy Flavour*

Final state physics at HERA allows the parton dynamics to be studied in detail. At low x it has been realised that, while collinear factorisation, as is inherent in DGLAP evolution, seems to be able to account for the rise of F_2 towards low x, data on final state production may be better described in k_t factorisation approaches. The phenomenology based on different evolution equations (DGLAP, BFKL, CCFM) applied to data on forward particle production [2] or on azimuthal correlations between dijets [2], for example, promises to yield new insight [4] into parton dynamics at low x. Larger data samples of increased systematic accuracy and extended kinematic range will be extremely valuable in the pursuit of these studies. It is noteworthy that currently a major step is being made in these areas. While previously final state physics, diffraction and heavy flavour were, and will of course continue to be, considered separately, joint studies of all these fields and their interdependence using data of higher luminosity are now being made. This concerns, for example, the investigations of how NLO parton distributions in the pomeron, determined in inclusive diffraction, are applicable to diffractive charm [2] or jet production [2], see Fig.8. The study of diffraction with H1 will be further pursued using an upgraded system of proton tagging spectrometers and high luminosity data permitting the t dependence to be employed.

Jet physics is a major testing ground for QCD. Recently progress was made in describing consistently event shapes in jet production [2] using resummed NLO QCD calculations. With high luminosity, the measurement of $\alpha_s(M_Z^2)$ from jet rates will become more precise and joint analyses of

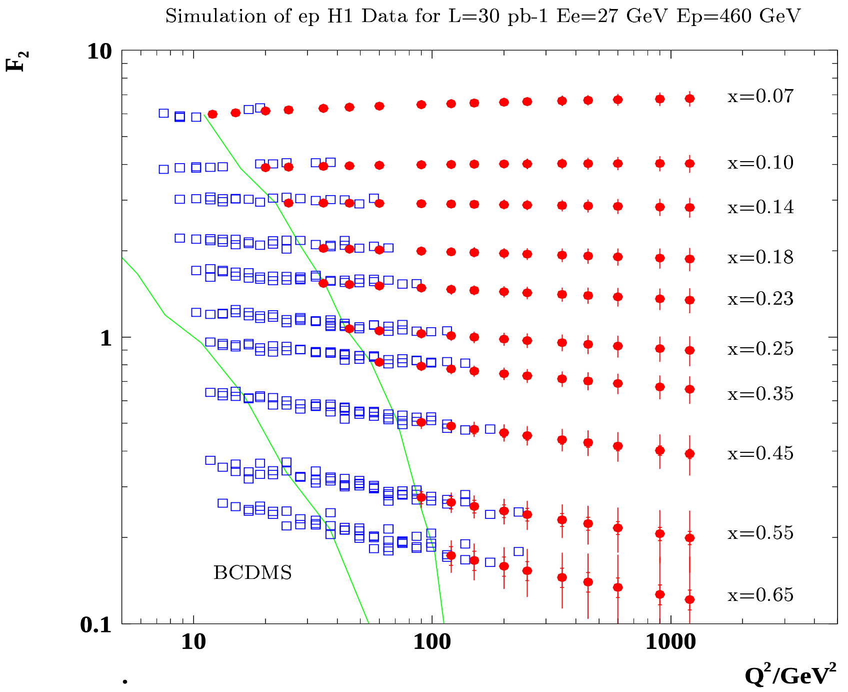

Figure 7. Measurement of the proton structure function $F_2(x, Q^2)$ by the BCDMS Collaboration using 4 different muon beam energies, between 120 GeV and 280 GeV (squares). Simulation of precision low energy run data (points), for $E_p = 460$ GeV, $E_e = 27.6$ GeV and 30 pb^{-1} luminosity, with a full simulation of the systematic accuracy (inner error bars). The lines mark the kinematic range limit $Q^2 = 2ME_\mu xy$ for $y = 0.3$ and 120 GeV and 280 GeV enforced in the H1 QCD fit to the BCDMS data. Precision H1 data from extended low energy running will have substantial overlap with the BCDMS data.

inclusive DIS with jet production may help in the determination of the gluon density at large x, that remains unresolved in DIS. The description of multi-jet final states will be much improved in following the development of parton shower simulation programs at higher orders [20] (MC@NLO).

A consistent theory is necessary to describe charm and beauty production in DIS. Describing correctly the effects that occur close to charm threshold is a nontrivial task in the DGLAP framework which considers the charm quark to be light at high $Q^2 >> m_c^2$. The amount and accuracy of heavy flavour data [21] from HERA I, on charm mesons [2], fragmentation functions [2], J/Ψ production [2] etc., is most remarkable and work is ongoing. Based on the first observations, see Fig. 8, one may well speculate that beauty at HERA II will play the role of charm at HERA I. Accurate beauty data, based on the large transverse momentum of the b-quarks and on their measurable lifetime, corresponding to about 0.5 mm decay lengths, promise to open an important new testing ground for QCD. New reactions like the production of strange quarks in CC scattering will be also studied.

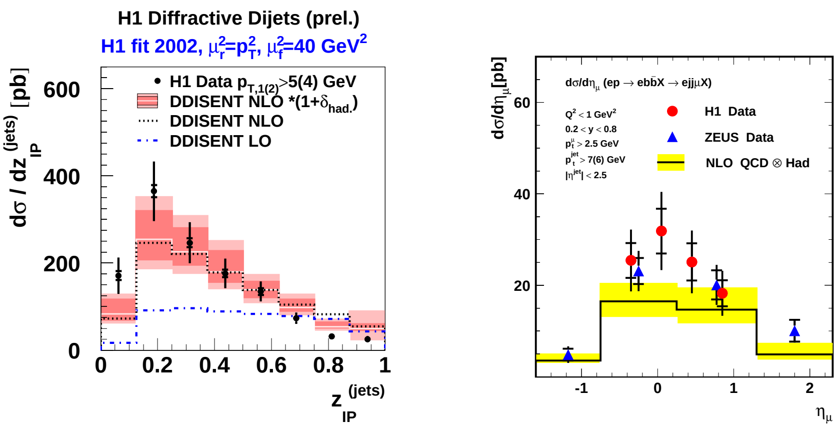

Figure 8. Left: Diffractive dijet production cross section in DIS as a function of the longitudinal momentum fraction of the Pomeron. The data are compared with predictions, within an uncertainty dominated by the renormalisation scale choice, using (N)LO diffractive parton distributions determined from inclusive diffractive H1 data. Right: Measurements of the beauty jet production cross section in photoproduction as a function of the muon rapidity compared with NLO QCD calculations including hadronisation corrections. A considerable increase of the luminosity is required to perform precision measurements of such quantities at HERA II.

4.5. *Searches for Exotic Physics*

Dedicated analyses of the H1 data from HERA I, using about 15 pb^{-1} of e^-p and 110 pb^{-1} of e^+p data, have discovered a few peculiar events of a type or a rate beyond the expectations of the Standard Model. Isolated electrons and muons with large missing transverse momentum, 10 events with $p_t > 25\,\mathrm{GeV}$, are observed and 2.9 ± 0.5 are expected. Furthermore, H1 saw multi-electron production at a rate above the Standard Model expectations. Three $2e$ and three $3e$ events were observed which is to be compared with an expectation of 0.30 ± 0.04 and 0.23 ± 0.04, respectively. Based on a considerable simulation effort, new effects were also searched for *generically* in 28 event classes, e.g. of the type ej or $e\mu\mu$, using electrons, muons, jets and missing energy (neutrinos) to characterise the classes. The preliminary H1 result [2], using all available HERA I data, is shown in Fig.9. It confirms the excesses in the aforementioned channels but no further significant departure from the SM expectation is found. It is obvious that a larger data sample is required to put such generic studies and dedicated searches on a firmer ground and possibly to discover new particles or interactions, a major goal of HERA. If, for example, leptoquarks were to be seen, charge and lepton beam polarisation would enable their spectroscopy to be studied. New ways could be found to further increase the luminosity beyond the HERA II values. Moreover, new, LHC type, magnets could be used to double the proton beam energy [22] if findings at HERA, the TeVatron or the LHC would require ep data in an extended range of energy.

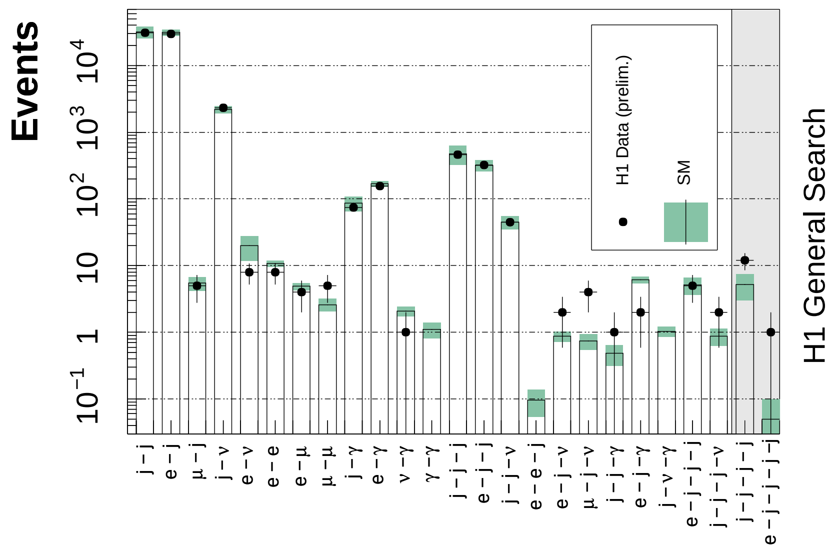

Figure 9. Event yields, measured and calculated in the standard model using various simulation programs, for all event configurations with an expectation larger than 0.1. Four jet simulations are not yet reliable and kept separate in the generic analysis.

5. Future

As was sketched here, the HERA programme is of fundamental importance in its own right. Seen from the perspective of the LHC, which will take particle physics into the TeV energy region, it is becoming clear that the results of HERA are of interest in all areas: high precision measurements will pin down the SM expectations and may be necessary for the determination of the LHC luminosity; high x parton distributions are of crucial importance for the understanding of any state possibly discovered at the LHC; understanding low x and diffractive phenomena appears also to be important for the LHC, because of the significance of the quark and gluon distributions in understanding pp collisions and the possibilities of detecting Higgs production in double diffractive scattering [23]. It is desirable to operate HERA when the LHC runs and new questions may be posed which HERA could answer.

The past and the current programmes have not exhausted HERA's potential. Precision studies of high parton density phenomena near the transition from parton-like to hadron-like behaviour, at $Q^2 \sim 1\,\mathrm{GeV}^2$ and smallest x, the investigation of neutron structure in the range opened up by HERA, the study of nuclear and thus high density gluon structure with high energy electron probes and the exploration of the completely new kinematic region accessible to a polarised eN collider are all scientifically most attractive elements of a programme to which particle physicists will have to return to if the study of QCD and nucleon structure is to be brought to a satisfactory conclusion: they are all topics which HERA allows to be studied uniquely.

Acknowledgments

I would like to thank the organisers of the 2003 Ringberg workshop for the invitation to attend what has been an excellent discussion meeting of physicists interested in deep inelastic scattering at HERA. The H1 results presented here, and those I had no time to discuss, rely on the efforts of a large collaboration of physicists and engineers to whom I want to express my deep gratitude. In particular, I like to thank Allen Caldwell, Tim Greenshaw, Peter Kostka, Tomas Lastovicka, Paul Newman, Carsten Niebuhr, Daniel Pitzl, Vladimir Shekelyan and Ferdinand Willeke for a most faithful and enjoyable collaboration in recent times.

References

1. H1 Collaboration, I. Abt et al., *Nucl. Inst. Meth.* **A386** (1997) 310 and 348.
2. Results of the H1 Collaboration presented here are either published or were submitted to recent conferences, see the H1 paper collection on the web `http://www-h1.desy.de`. For a recent review see P. Newman, hep-ex/0312018 (2003).
3. For results of the ZEUS Collaboration see `http://www-zeus.desy.de` and R. Yoshida, these Proceedings.
4. For reviews see e.g.: The Small-x Collaboration, J. Andersen et al., hep-ph/0312333 (2003) and ref.s cited therein;
   E. Iancu, A. Leonidov and L. McLerran, hep-ph/0202270 (2002).
5. M. Klein and T. Riemann, *Z. Phys.* **C8**, 239 (1981).
6. For a review see W. K. Tung, Proceedings DIS00 Workshop, Liverpool.
7. P. Z. Huang et al., hep-ph/0401191 (2004).
8. H. Abramowicz et al., MPI-PhE/2003/06 (2003);
   T. Alexopoulos et al., DESY/03-194 (2003).
9. S. Moch, J. A. M. Vermaseren and A. Vogt, hep-ph/0309056 (2003).
10. G. Altarelli, R. D. Ball and S. Forte, *Nucl. Phys.* **B674**, 459 (2003) [hep-ph/0306156].
11. H1 Collaboration, C. Adloff et al., *Eur. Phys. J.* **C21**, 33 (2001) [hep-ex/0012053].
12. S. Chekanov *et al.* [ZEUS Collaboration], *Phys. Rev.* **D67**, 012007 (2003) [hep-ex/0208023].
13. S. Kretzer et al., hep-ph/0312322 (2003).
    B. Portheault, Proceedings DIS03 Workshop, to be published.
14. M. Klein, Inv. Talk at HiX2000, Philadelphia, USA, *http://ba323.scitech.temple.edu/hix2000*, unpublished.
15. M. Klein and T. Riemann, *Z. Phys.* **C24**, 151 (1984)
16. M. Klein, *Proceedings of the 9th International Workshop on Deep Inelastic Scattering (DIS 2001)*, Bologna, Italy, April 2001, p.409 (2002)
17. For a review see: M. Diehl, *Phys. Rept.* **388**, 41 (2003) [hep-ph/0307382].
18. A. Freund, *Phys. Rev.* **D68**, 096006 (2003) [hep-ph/0306012].
19. L. A. T. Bauerdick, A. Glazov and M. Klein, hep-ex/9609017 (1996).
20. S. Frixione and B. R. Webber, hep-ph/0309186 (2003).
21. For a recent review see: R. Gerhards, *Nucl. Phys. Proc. Suppl.* **115**, 126 (2003).
22. D. Pitzl, Energy upgrade of HERA, DESY 2003, private communication.
23. A. B. Kaidalov, V. A. Khoze, A. D. Martin and M. G. Ryskin, hep-ph/0311023 (2003).