QUANTUM CHROMODYNAMICS AT HIGH ENERGIES AT HERA

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HERA is the world's only accelerator to study inelastic electron-proton scattering at the energy frontier which uniquely allows the partonic structure of the proton and the theory of strong interactions, QCD, to be deeply explored. A review is given here of recent results from the HERA ep collider experiments H1 and ZEUS and the fixed target eN spin experiment HERMES as was presented to the 32^{nd} Rochester conference at Beijing in summer 2004. The summary comprises new results on the quark and gluon structure of the proton, on the strong coupling constant α_s, on the production of charm and beauty particles and on hard diffractive scattering. New ideas and developments in HERA physics are presented as are the first measurements with the upgraded polarised ep collider.

1 Introduction

QCD is the renormalizable, non-Abelian gauge field theory which describes the strong interaction of coloured quarks and gluons. This year marks the 30^{th} anniversary of the discovery of asymptotic freedom [1]. HERA is the first electron-proton collider of energies $E_e = 27.6\,\mathrm{GeV}$ and $E_p = 920\,\mathrm{GeV}$, equivalent to a fixed target deep inelastic scattering experiment of $54.1\,\mathrm{TeV}$ electron energy, thus allowing proton structure to be deeply explored. HERA has an $e^\pm$ beam with longitudinal polarisation P between -0.5 and $+0.5$ which serves the HERMES experiment operating with stationary targets and which has been utilised in the ongoing second phase of operation (HERA II) to measure polarised charged current scattering at H1 and ZEUS for the first time. This year marks a 20^{th} anniversary of HERA [2]. The subsequent chapters briefly describe physics results on QCD as obtained in recent years at HERA by the collider experiments H1 and ZEUS, and also by HERMES. The experiments have submitted nearly 100 papers to the Beijing conference which are available from the collaboration's webpages [3] and those of the conference. Here emphasis is given to the partonic proton structure, both regarding quarks, light and heavy, and gluons, to diffractive scattering and to new ideas and the most recent results.

2 Quark Structure of the Proton

HERA measures the inelastic scattering of electrons or positrons off protons at four-momentum transfers, Q^2, from very small values, $Q^2 < M_p^2$, a region termed photoproduction, up to very large values approaching the kinematic limit given by the centre of mass energy squared, $s = 4E_eE_p \simeq 10^5\,\mathrm{GeV}^2$. Here M_p is the proton mass. At low Q^2, this reaction is dominated by single-photon exchange between the positron and the proton. Fig.1 shows the H1 and ZEUS measurements [4] of the single differential cross sections, $d\sigma/dQ^2$, in neutral (NC) and charged current (CC) scattering, $ep \rightarrow eX$ and $ep \rightarrow \nu X$, respectively, based on all the $e^\pm p$ data taken in the first period of HERA operation which ended in 2000. As was anticipated 20 years ago, the NC and CC cross sections indeed fall with Q^2 to values which are of similar size when Q^2 is of the order of the masses of the exchanged Z and W bosons, $Q^2 \sim 10^4\,\mathrm{GeV}^2$, mediating the weak interaction. Due to the uncertainty relation, high momentum transfers correspond to probing the proton structure at small distances. From a comparison of the NC measurements presented in Fig. 1 with the standard model expectation, limits on the quark radius are obtained as small as $r = 0.85(1.0) \cdot 10^{-18}\,\mathrm{m}$ from the ZEUS (H1) ex-

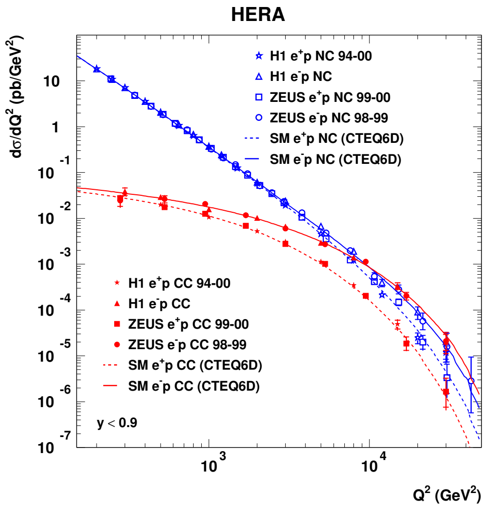

Figure 1. Measurements of the neutral and charged current electron- and positron-proton scattering cross sections as a function of Q^2 by the H1 and ZEUS experiments.

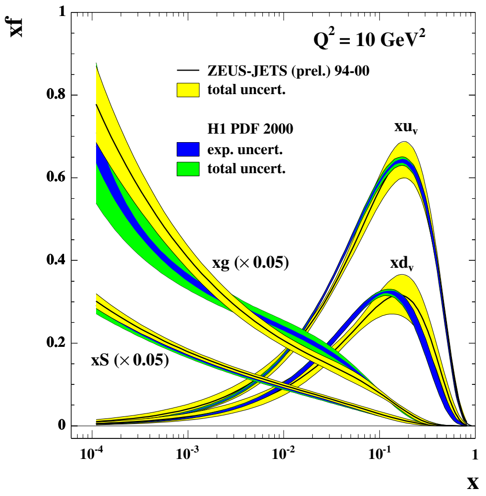

Figure 2. Determinations of the valence, sea and gluon distributions from NLO QCD fits to NC, CC, and to jet data (ZEUS), at $Q^2 = 10$ GeV^2 as a function of Bjorken x, the parton momentum fraction of the proton. The low x region is dominated by the gluon and sea quark distributions while u_v and d_v dominate the valence-quark region at large x.

periment. Hence, quarks are pointlike down to at least 1/1000 of the proton radius.

The collider experiments have measured the full set of NC and CC double differential $e^{\pm}p$ inclusive scattering cross sections which are determined by structure functions and quark momentum distributions in the proton as follows:

$$\sigma^{\pm}_{NC} \sim Y_+ F_2 \mp Y_- \cdot xF_3, \quad (1)$$

$$F_2 \simeq e_u^2 x(U + \overline{U}) + e_d^2 x(D + \overline{D}), \quad (2)$$

$$xF_3 \simeq 2x[a_u e_u(U - \overline{U}) + a_d e_d(D - \overline{D})], \quad (3)$$

$$\sigma^{+}_{CC} \sim x\overline{U} + (1-y)^2 xD, \quad (4)$$

$$\sigma^{-}_{CC} \sim xU + (1-y)^2 x\overline{D}. \quad (5)$$

Here $y = Q^2/sx$ is the inelasticity, $Y_{\pm} = 1 \pm (1-y)^2$, $U = u + c + b$ is the sum of the momentum distributions of the up-type quarks with charge $e_u = 2/3$ and axial vector coupling $a_u = 1/2$ while $D = d + s$ is the sum of the momentum distributions of the down type quarks with charge $e_d = -1/3$, $a_d = -1/2$. Similar relationships hold for the anti-quark distributions $\overline{U}$ and $\overline{D}$. In the kinematic range of HERA, the NC structure function F_2 is dominated by its electromagnetic part, Eq.(2), while xF_3 is dominated by its γZ interference part, Eq.(3), which is a direct measure of the sum $2u_v + d_v$ of the valence up and down quark distributions. The exchange of $W^{\pm}$ bosons in CC $e^{\pm}p$ scattering allows different quark flavour distributions to be accessed and the valence quark distributions to be directly determined, for large $x > 0.3$. NC and CC scattering data as measured by H1 and ZEUS therefore allow the complete set of parton distributions to be unfolded in a single experiment. The results for the valence quark, the gluon and the sea distributions [5] are consistent, see Fig.2, where $S = 2(\overline{U}+\overline{D})$. Residual differences between the parton distribution functions (*pdf*) and their uncertainties reflect different conventions regarding the parameterisations and error treatments. The *pdf s* presented here rely only on H1 or ZEUS data and yet are in agreement with recent fits from the MRST and CTEQ Collaborations which include fixed target DIS, jet and Drell-Yan data. With increased luminosity and range the *pdf* determinations at HERA, including charm and beauty, see below, will become rather precise. Some information on the strange quark distribution can be obtained from strange particle production and charm production in CC.

Polarised structure function measurements derived from double spin asymmetry data provide information on the spin content of the proton. The polarised parton distributions, $\Delta q(x, Q^2)$, are complementary to the unpolarised distributions, $q(x, Q^2)$, because of $q = q^+ + q^-$, with $2F_1 = \sum e_q^2 q$, and $\Delta q = q^+ - q^-$, with $2g_1 = \sum e_q^2 \Delta q$. The notations $q^{+(-)}$ refer to parallel (antiparallel) orientation of the quark and proton spins. HERMES has also measured [6] semi-inclusive polarised eN scattering using p and D gas targets which are internal to the HERA electron beam. Based on a dual RICH, particle identification is achieved for π, K and p in a wide momentum range. The complete set of g_1^p, g_1^d and semi-inclusive asymmetry data determines the polarised up and down quark and anti-quark distributions as well as the polarised strange quark distribution, Δs. Fig.3 represents the first attempt to resolve the flavour composition of the polarised sea. The up (down) quark polarisation is (anti) parallel to the proton spin while all sea quarks carry nearly zero polarisation. This behaviour is well reproduced by recent LO QCD analyses [7,8].

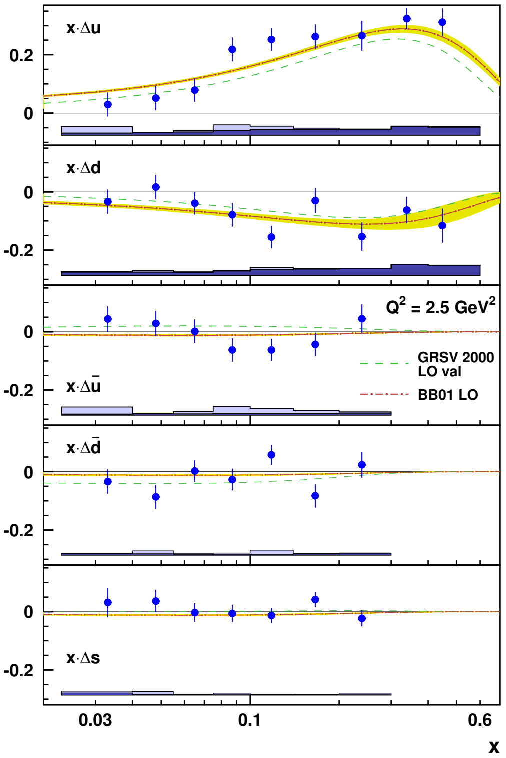

Figure 3. Measurements of polarised quark distributions in the proton by the HERMES Collaboration at HERA unfolded from inclusive and semi-inclusive double spin asymmetries. The curves show LO QCD analyses of polarised data.

3 Strong Coupling Constant and the Gluon Distribution

QCD is most accurately tested in deep inelastic scattering via the scaling violations of the proton structure function $F_2(x, Q^2)$ which can be expressed to leading order as

$$\partial F_2 / \partial \ln Q^2 \propto \alpha_s [P_{qg} \otimes g + P_{qq} \otimes F_2], \quad (6)$$

where P_{qg} and P_{qq} are the appropriate splitting functions. H1 and ZEUS have measured $F_2(x, Q^2)$ in a wide range of x and Q^2, to an accuracy of about 2% in the bulk region of $x \sim 0.001$ and $Q^2 \sim 20$ GeV^2. Roughly,

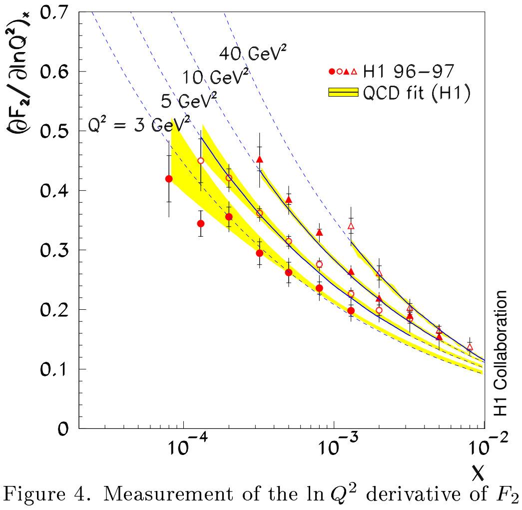

Figure 4. Measurement of the $\ln Q^2$ derivative of F_2 compared with a NLO QCD fit analysis by the H1 Collaboration. The rise towards low x points to a dominantly gluonic proton at low x ("large $\omega = 1/x$") as was anticipated 30 years ago [9].

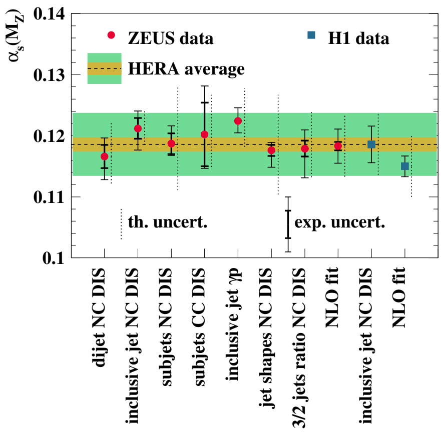

Figure 5. Measurements of the strong coupling constant $\alpha_s(M_Z^2)$ by ZEUS and H1 in inclusive DIS and jet production at HERA to NLO in QCD.

at large x the gluon density is negligible and thus α_s is directly determined by Eq. 6. At small x the gluon contribution dominates and therefore $xg(x, Q^2)$ is determined from the derivative of F_2. This derivative, shown in Fig. 4, constrains the gluon distribution at low x to about 20% accuracy in the DIS region. Both the rise of $\partial F_2/\partial \ln Q^2$ towards low x at fixed Q^2 and the increase of the first derivative with Q^2 at fixed x are well described by NLO QCD.

The strong coupling constant is the least well-measured of the fundamental coupling constants. It thus dominates the uncertainty of extrapolations of the electromagnetic, weak and strong coupling constants to a unification scale near the Planck mass [10]. New α_s data were presented by ZEUS, obtained from the ratio of 3-to-2 jets and in a NLO fit to inclusive DIS and jet data [5]. As can be seen in Fig. 5, the ZEUS and H1 experiments have determined the strong coupling constant $\alpha_s(M_Z^2)$ in a variety of processes [5,11]. To NLO, the averaged result for ZEUS is $0.1209 \pm 0.0015(exp) \pm^{0.0048}_{0.0049}$ (thy) while H1 obtains $0.1160 \pm 0.0016(exp) \pm^{0.0058}_{0.0046}$ (thy). There has been a noticeable difference between the $\alpha_s(M_Z^2)$ values determined with jets, which tend to be large (~ 0.120), and in

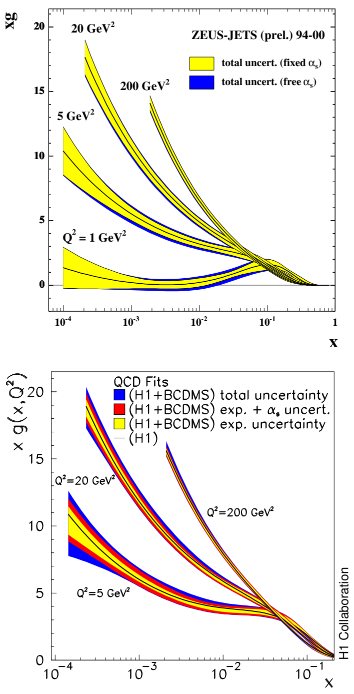

Figure 6. Determinations of the gluon momentum distribution in the proton to NLO by the ZEUS Collaboration (top) and by H1 (bottom).

inclusive DIS, which tend to smaller values (~ 0.115). This behaviour is related to the gluon distribution, in particular to the size of xg at large x. The difference may be due to the effect of the BCDMS structure function data, used in the H1 analysis, which are crucial for a precise measurement of $\alpha_s(M_Z^2)$ and thus should be verified in a future precision experiment, possibly at HERA. The average $\alpha_s(M_Z^2)$ value to NLO from ZEUS and H1 currently is

$$\alpha_s = 0.1186 \pm 0.0011(exp) \pm 0.005(thy). \quad (7)$$

A striking peculiarity of this result is the so-called theoretical error. Its size reflects the *ad hoc* convention that the renormalisation (and factorisation) scale should be varied by factors of 2 and 1/2. This convention is not supported by the data: in both the H1 and the ZEUS QCD analyses, fits are very poor at the extremes of these scale variations and thus the variation prescription is question-

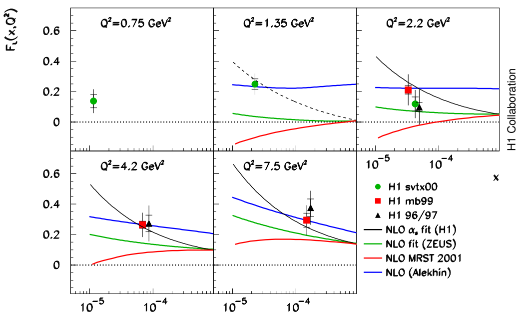

Figure 7. Extraction of the longitudinal structure function $F_L(x,Q^2)$ from inclusive ep scattering cross section data at high $y < 0.9$. The curves represent predictions from recent NLO QCD analyses based essentially on the description of the data on the F_2 scaling violations at low x.

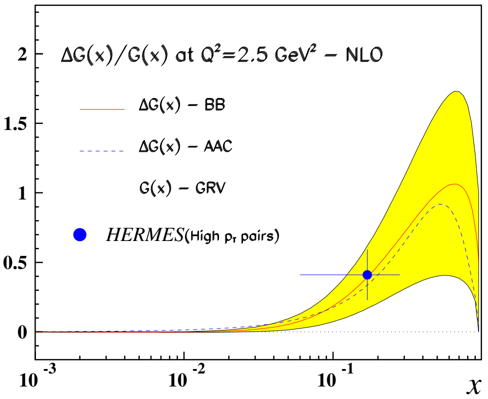

Figure 8. Determinations of the polarised gluon distribution, $\Delta G/G$, in NLO QCD from different spin data analyses. The uncertainty band reflects the total uncertainty for the BB analysis. The data point represents the result as obtained at $p_t^2 = 2.1$ GeV^2 by HERMES from hadron pair production at large p_t, using PYTHIA and setting $x_g = x$.

able. Furthermore, with forthcoming exact NNLO analyses, based on the seminal work of [12], the scale dependence will be reduced. It has been a challenge to further improve the experimental accuracy and to extend the kinematic range of the HERA structure function data using new instrumentation, and by exploiting the overconstrained determination of the event kinematics as well as the high accuracy in tracking and calorimetry of the HERA collider detectors. Theoretical and experimental progress in DIS is therefore expected to pin down $\alpha_s(M_Z^2)$ to an accuracy of better than 0.001. A further significant improvement could be expected with luminous electron-deuteron scattering data from HERA. These would resolve the non-singlet and singlet evolutions and would not require significant nuclear corrections since the spectator proton could be tagged, giving access to accurate electron-neutron scattering data [13]. HERA thus seems to have the potential to measure α_s perhaps almost an order of magnitude more accurately than the current world average.

The ZEUS NLO QCD analysis of inclusive DIS and jet data provides a new determination of α_s and of the gluon momentum distribution in the proton, as shown in Fig. 6 (top). The jet data used are dijet data in direct photoproduction, for $x_\gamma > 0.75$, and also DIS dijet data. The jet data help to constrain xg at medium $x \sim 0.1$. The result is in good agreement with the H1 determination of xg, Fig. 6 (bottom), which uses the fixed flavour number scheme for charm instead of the variable number scheme applied by ZEUS.

It has long been known that, in the transition region from DIS to photoproduction ($Q^2 \simeq M_p^2$), the gluon distribution vanishes at low x and exhibits a valence like shape at larger x, as can be seen in Fig. 6. This leads to the expectation that the longitudinal structure function F_L may be very small or even negative [14] at small Q^2 and x. Data obtained from measurements of the DIS cross section at high y by the H1 Collaboration [15] show that $F_L(x,Q^2)$ is not small, see Fig 7. Increased accuracy and range in x are necessary to determine F_L and thus to get an independent constraint on low x physics and on xg in particular. Such data can be obtained from low energy runs at HERA [16].

The determination of the gluon contribution to the proton's spin is based on the measurement of the Q^2 dependence of $g_1(x,Q^2)$. There are two major problems, however. Firstly, the extraction of g_1 from the mea-

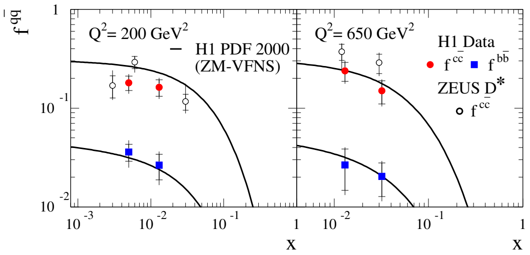

Figure 9. Measured fractional contribution of charm and beauty quarks to the proton structure function F_2 using impact parameter tagging by H1 (solid symbols) and the D^* method for charm by ZEUS (open circles). The curves represent the H1 NLO QCD fit to the inclusive NC and CC cross section H1 data.

sured cross section asymmetries is diluted by the polarisation factor $D(y) \simeq y$. Thus each experiment contributes g_1 data only in a narrow band at large $y = Q^2/sx$ in the x, Q^2 plane determined by the lepton beam energy E_l via $s = 2M_pE_l$. The Q^2 dependence of g_1 can thus be measured only by a combination of a variety of experiments, from HERMES at low Q^2 to SMC at larger Q^2. Secondly, the range in Q^2 of the world's fixed target polarised DIS experiments is limited, and so is the accuracy of ΔG. It is thus obvious that spin physics requires that a polarised *ep* collider be built, with variable beam energies and high luminosity, in order to measure the gluon distribution much better than currently has been possible, Fig. 8, or is envisaged with COMPASS [17] and at RHIC. A collider such as HERA with polarised protons or deuterons or the EIC at Brookhaven would have a fascinating potential to extend the spin measurements towards low x and high Q^2 and to solve the nucleon spin puzzle.

4 Heavy Flavour Production

The dominant heavy flavour production process at low x at HERA is photon-gluon fusion, in which a pair of charm or beauty quarks and antiquarks is produced. These hadronise to form D or B mesons which subsequently

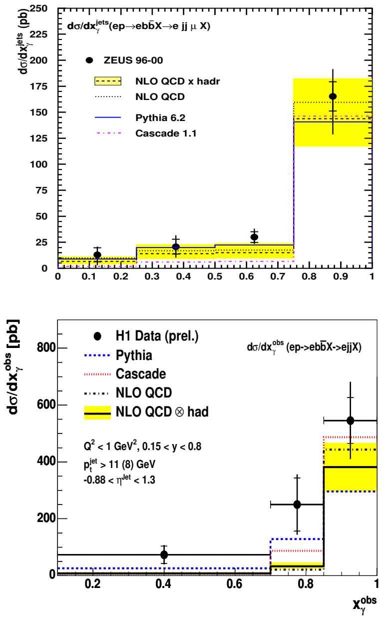

Figure 10. Single differential beauty dijet cross sections as measured by ZEUS (top) and H1 (bottom) compared with different NLO QCD calculations with and disregarding hadronisation effects.

decay. In photoproduction, gluon-gluon fusion leads to hadron-like quark pair production, while the interaction of a heavy quark from the photon with a gluon from the proton leads to c or b excitation. The list of fundamental questions, to which heavy flavour studies contribute, includes the determination of the c and b *pdfs* in the proton and the photon, the study of the mechanism of gluon radiation, of fragmentation and the rôle of heavy quarks in the strong interaction, e.g. whether c or b must be considered heavy or light given extra scales as Q^2 involved.

The experimental techniques have much progressed. Charm has mainly been identified via the production and decay of $D^{*,\pm}$ mesons into $D^o\pi_{slow} \to K\pi\pi_s$. The H1 Collaboration has presented cross sections [18] on charm and beauty production using the central silicon tracker. ZEUS has obtained data with a newly installed silicon vertex detector. Lifetime tagging is becoming a powerful tool for heavy flavour physics at HERA. Fig. 9

shows the contribution of charm and beauty quarks to the proton structure function measured at high Q^2 and medium $x \sim 0.01$. As at lower Q^2 and x, charm is a sizeable (about 20%) fraction of F_2, while the beauty contribution is found to be small (about 2%). These results enabled the first ever measurement of the beauty structure function, F_2^{bb}. The data are well described by the prediction of the NLO QCD analysis of the inclusive NC and CC cross sections which is parameter free for the beauty part and tests the evolution of F_2^{cc} over 2 orders of magnitude in Q^2. The vertex tagged H1 charm data are consistent with the D^* ZEUS data and complement the accurate data being obtained at lower Q^2. With rising Q^2 the charm and beauty structure functions increase and in the "rapidity plateau region" at the LHC, for $x \sim 0.001$ and $Q^2 \geq 10^3\,\mathrm{GeV}^2$, eventually reach values nearly as large as the up and down quark distributions. Their accurate measurement is thus also an important task in view of the LHC data to be taken.

HERA data were presented [19] on inclusive D^* cross sections in DIS, correlations of inclusive charm with charm jet data, on F_2^{cc} and further results. NLO QCD is able to describe the data within theoretical uncertainties which, however, are rather large and may require NNLO calculations for some of the data to become available. Studies of charm fragmentation in photoproduction by ZEUS and in DIS by H1 suggest that charm fragmentation is universal [19]. The complete set of D mesons, D^+, D^o , D_s^+ and D^{*+}, allows the associated production of charm with up, down and strange quarks to be studied which was found to be in good agreement with LEP data.

Remarkable progress was achieved in beauty production. Fig. 10 shows new data from ZEUS (top) and H1 (bottom) on dijet beauty photoproduction as functions of x_γ^{jets} which allows the dominant direct contribution to be distinguished from the re-

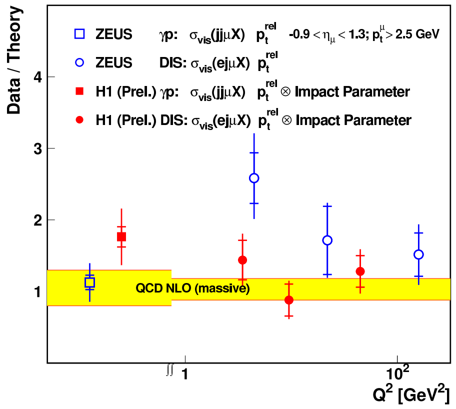

Figure 11. Ratio of measured single jet and dijet beauty cross sections to NLO QCD calculations in photoproduction and in DIS.

solved part. Both collaborations find the resolved cross section to be somewhat higher than the calculation of this process in NLO QCD, including corrections for hadronisation effects. A summary of the HERA beauty results as compared to NLO QCD is presented in Fig. 11 both for photoproduction and in DIS. The new improved data are above but not inconsistent with the theoretical calculations. This result includes data based solely on the large transverse momentum identification of beauty jets and, for H1, in addition using impact parameter tagging in the transverse plane.

5 Diffractive *ep* Scattering

Nearly 20 years ago, a model was formulated [20] in which diffractive deep inelastic scattering can be ascribed to the scattering of virtual photons and Pomerons in an *ep* interaction in which the proton stays intact causing a large 'rapidity gap' between the first produced final state particle and the scattered proton. This process was indeed observed at HERA, for about 10% of the DIS events at low Q^2 and x. A diffractive structure function, $F_2^{D(4)}(t, x_{I\!P}, Q^2, \beta)$, was then introduced which factorises into calculable coefficient functions and the distribution of partons in the diffractive exchange

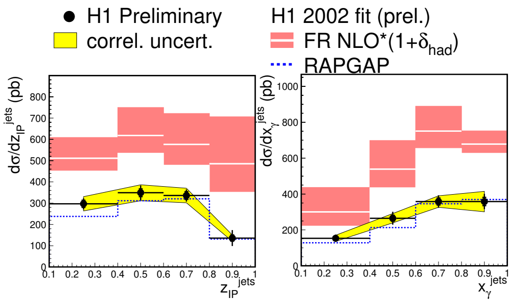

Figure 12. Diffractive dijet production cross sections as functions of z_P, the fractional parton momentum in the hard interaction, and x_γ as measured in photoproduction by H1 compared with NLO QCD, including hadronisation corrections, and with RAPGAP.

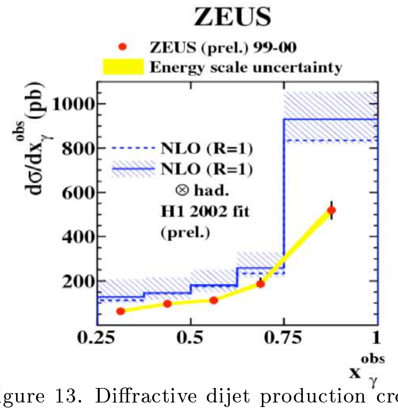

Figure 13. Diffractive dijet production cross section as a function of x_γ measured in photoproduction by ZEUS compared with NLO QCD including hadronisation corrections.

(Pomeron). Here t is the four-momentum transfer to the scattered proton (often integrated over), $x_{I\!P}$ is the fraction of proton's momentum carried by the diffractive exchange and β is the fraction of the Pomeron's momentum carried by its interacting constituent in the parton model. In QCD hard diffraction is often viewed as 2 gluon exchange. Since the gluon distribution rises towards low x, a potential unitarity limit of $\gamma^* p$ scattering may be observable earlier in diffraction than in inclusive ep scattering. At the LHC double diffractive scattering is expected to provide a clean event environment for studying or perhaps the discovery of the Higgs boson or exotic particles.

Diffractive scattering can be identified via the rapidity gap or by tagging the non-dissociated proton in the leading (ZEUS) or forward (H1) proton spectrometers, LPS and FPS, respectively. There is a wealth of HERA data on F_2^D with increasing accuracy and kinematic coverage [21] which are generally consistent between the experiments and between the different tagging methods applied. The hard scattering part of virtual photon-Pomeron scattering may be treated similarly to $\gamma^* p$ scattering which allows NLO diffractive *pdfs* to be determined from the Q^2 evolution and β dependence. A striking result is that about 80% of the momentum of the diffractive exchange is carried by its gluonic component, at $Q^2 = 5$ GeV^2. The evolution of the diffractive parton distributions has now been shown to agree with NLO QCD up to values of Q^2 as large as 1600 GeV^2 where the gluon momentum fraction still is about 70%. Recently, diffraction was observed at HERA in CC scattering [21] at high Q^2 where it contributes 2-3% to the inclusive CC cross section.

The question is being investigated whether the diffractive parton distributions may be universally applied, in particular to pp scattering. The calculation of single diffractive scattering at the Tevatron using the diffractive *pdfs* from H1 was found to overestimate the CDF data [22] by about a factor of 10. Spectator interactions may thus hinder the "pure" diffractive exchange in pp scattering to take place as frequently as naively expected. It is important to verify whether the final state data at HERA can be predicted based on the *pdfs* from inclusive diffractive DIS assuming the factorisation hypothesis to hold. This has been found to be correct [23] in DIS, both with dijet and charm data. In photoproduction, resolved photon interactions may be expected to resemble the configuration studied in pp scattering. In dijet production x_γ is calculated from the hadronic final state which is adequate for a consistent treatment in NLO QCD and direct production dominates for $x_\gamma > 0.75$. It came as a surprise that diffractive dijet production in photoproduction is suppressed [23] relative to predictions assuming factorisation for *all* x_γ by a factor of about 2, i.e. both for the resolved and for the direct part, as has been found by H1 (Fig. 12) and by ZEUS (Fig. 13). The mechanism of diffractive scattering and its treatment in QCD is a field of major interest and growing activity. If, for example, 'absorptive corrections' were to be applied for diffractive contributions, as suggested in [24], the conventional determinations of the gluon and also the quark distributions in the proton would be misleading and so would be their extrapolation to the LHC region.

6 New Ideas and Developments

While the behaviour of partons at larger x and Q^2 at HERA seems to follow the expectations from fixed target DIS experiments and perturbative QCD (DGLAP) evolution, the domain at low Bjorken x is puzzling. HERA provides phase space in x and transverse parton momentum k_t which allows the mechanism of gluon radiation at low x to be studied in detail. In the low x DIS region, the gluon density is high. Also, $\alpha_s \cdot \ln(1/x)$ is large and DGLAP evolution should not be applicable without resummation of the large $\ln(1/x)$ terms. Nevertheless, DGLAP seems to describe the bulk of the inclusive DIS, heavy flavour and diffractive data, with the x shapes of the *pdfs* determined from the low x data. Alternative (BFKL) and complementary (CCFM) prescriptions have been worked out to describe gluon emission. Monte Carlo programs have been written which model k_t ordered (as DISENT/NLOJET), angular ordered (CASCADE) and emission random in k_t (ARIADNE), corresponding to the DGLAP, CCFM and BFKL equations to some extent. A wealth of data has been investigated in order to find deviations from the DGLAP prescription and contribute to the development of low x theory. At the conference, both H1 and ZEUS presented some evidence [25] that DGLAP theory in NLO fails in the description of the emission of jets in the forward, the proton beam, direction at low x and Q^2, for $x_{jet} < x$ (to enhance BFKL effects) and $E_T(jet) \simeq Q^2$ (to suppress DGLAP evolution). Hints for a breakdown of the conventional theory come also from the study of azimuthal correlations [25] between dijets, which at low x and Q^2 seem to be weaker than predicted in NLO DGLAP theory. "Unintegrated", k_t dependent parton distributions are being introduced which may allow a more accurate description of the final state.

An exciting new field is opened with measurements of deeply virtual Compton scattering, $ep \to ep\gamma$ (DVCS) via diffractive exchange. In the transition from the interacting virtual to the emitted real photon, a finite momentum t is transferred which causes the quark interacting with the γ^* to be off shell by an addition of ξ to its momentum fraction x and of $-\xi$ for its interaction with the outgoing photon. This way parton correlation functions can be measured which are related to the angular momentum of the proton [26]. The DVCS process interferes with Bethe-Heitler (BH) scattering. One can thus establish "proton holograms" [27] by measuring the t dependence which allows the transverse dimension of the proton to be mapped. The BH-DVCS interference gives rise to measurable parton scattering amplitudes which depend linearly on generalised parton distributions (*gpd*), such as H and $\widetilde{H}$. In the limit $t = 0$ and $\xi = 0$ these *gpds* are the conventional polarised and unpolarised quark momentum distributions q and Δq, respectively. Recent ZEUS and H1 data [28] show a steep W dependence of the DVCS cross section, which is characteristic for a hard QCD process and is described within first models based on *gpds*. The collider data corre-

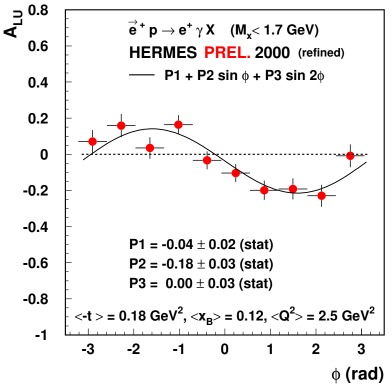

Figure 14. Measurement of the beam spin asymmetry in polarised positron-proton scattering into $e^+\gamma X$ for $M_X < 1.7\,\text{GeV}$.

spond to low x and thus to gluon exchange dominantly. Fig. 14 shows recent HERMES data [28] on a DVCS beam spin asymmetry measured at larger $x \sim 0.1$. This asymmetry is proportional to the imaginary part of the DVCS scattering amplitude modulated by $\sin\Phi$, where Φ is the azimuthal angle between the $e\gamma^*$ scattering plane and the $\gamma^*\gamma$ plane. Further data were presented by HERMES on the beam charge asymmetry measured with proton and also with deuterium targets. With polarised lepton beams of both charges, increased statistics and new instrumentation, the field of DVCS has a great future at HERA which is expected to lead much beyond the conventional partonic picture of proton structure.

7 First Results from HERA II

HERA II is the second phase of HERA operation for which the accelerator was shut down in August 2000 in order to equip the interaction region with strong focussing magnets, placed at about $\pm 2\,\text{m}$ from the vertex position, and to modify and upgrade the collider detectors. The increase in synchrotron radiation due to bending inside the apparatus region in combination with strongly interacting protons caused a dynamic increase of the gas pressure. This prevented efficient data taking until the problem was sufficiently understood and measures could be taken to reduce backgrounds to a tolerable level, by improved pumping, collimation, monitoring and orbit optimisation. Efficient data taking resumed in October 2003. Since then HERA has delivered about 100 pb^{-1} of polarised positron-proton interactions with tuneable polarisations, of about 35% and -40%, with beam currents of up to 50 mA for the e^+ beam and 100 mA for the p beam at specific luminosities exceeding the HERA I values by about a factor of 3.

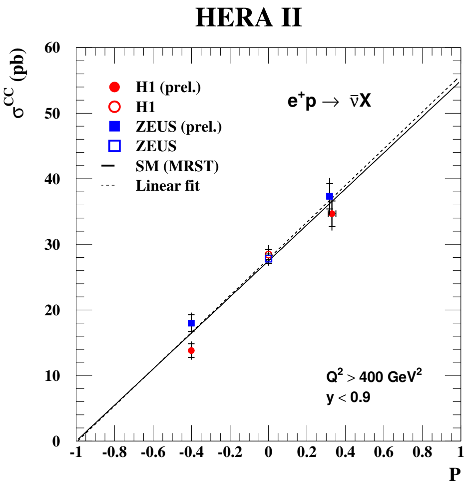

Figure 15. Measurements of the total CC cross section as a function of the positron beam helicity P in e^+p scattering at HERA. The central values, for $P = 0$, correspond to the published HERA I results of ZEUS and H1 while the values with non-zero helicity represent the first preliminary cross section measurements at HERA II. The lines are the expectation from NLO QCD using the MRST01 *pdf* set and a linear fit to determine the cross section at -1 helicity.

Polarised *ep* scattering, with 3 spin rotators and despite disturbing solenoid magnets, has been a major success at HERA which will enable electroweak physics to advance. New polarised NC and CC e^+p scattering data were presented by the collider experiments [29], including data taken shortly before the conference. Fig. 15 shows the total CC scattering cross sections as measured by ZEUS and H1 combining HERA I data ($P = 0$) with polarised HERA II data. The measurements

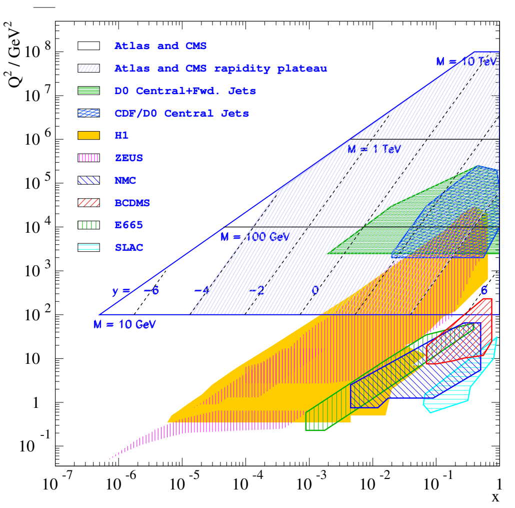

Figure 16. The kinematic plane of DIS fixed target and the HERA collider experiments compared to the kinematics of pp scattering in jet production.

firmly establish the dependence of the CC cross section on the lepton beam polarisation. The e^+p cross section is expected to vanish for $P = -1$ unless right handed weak currents exist. The preliminary, combined result of the cross section measurement extrapolated to $P = -1$ is $0.2 \pm 1.8\,(sta) \pm 1.6\,(sys)$ pb with a χ^2/dof of 5.4/4. The inverse process, $\bar{\nu}N \to \overrightarrow{\mu} X$, was measured before [30].

New data taken at HERA II were also presented by HERMES on single spin asymmetries in π production on a transversely polarised proton target which allow previously unmeasured quark transversity distributions to be accessed [31].

8 Outlook

Currently, HERA physics is being discussed in the context of the LHC [32]. HERA will determine the full set of parton distributions rather accurately, i.e. u_v, d_v, $\overline{u}$, $\overline{d}$, s, c and b, in a kinematic region as close as possible to the LHC, see Fig. 16. This will permit measurements at the LHC to be interpreted and possibly the LHC luminosity to be measured accurately using the *pdf s* and NNLO QCD to describe W and Z production in the rapidity plateau, at $Q^2 \sim 10^4\,\mathrm{GeV}^2$. Precision measurements of $\alpha_s(M_Z^2)$ and of the gluon distribution are expected to shed light on the unification of forces and the interpretation of Higgs production, possibly to be discovered at the LHC. Low x physics, in particular the exact mechanism of parton radiation, needs to be theoretically understood and experimentally better constrained in order to make reliable predictions for the LHC, neutrino astrophysics and to develop high density QCD. Diffraction may play a key role in the study of Higgs production at the LHC and remains so far a field which is not satisfactorily integrated in the QCD picture of the proton.

Physics at HERA is fundamental irrespective of the LHC and it extends beyond the fields which could be mentioned here. It includes further QCD studies presented to the conference [33] and comprises searches for new particles [34,35] at HERA which were not part of this presentation. The potential of HERA to exploit the physics of polarised eN scattering, both with fixed nucleon targets and in colliding mode, is not diminishing but growing as more research is done. New, fundamentally different approaches are being developed for the structure of the proton, in 3 dimensions and polarised. Even when HERA has achieved luminosities of $\sim 1\,\mathrm{fb}^{-1}$ and has changed beam energies its scientific potential will still not have been exhausted [13,36]: it is extremely desirable to complement the HERA ep measurements with neutron structure data and further data at low x and Q^2 with improved precision and range. Electron-nucleus scattering is of great interest for a deeper understanding of nucleon structure, the quark-gluon plasma and further aspects of QCD. HERA is the world's most powerful miscroscope. Its premature termination, foreseen for 2007, is in striking contradiction to its scientific and accelerator [37] potential. HERA could later serve as a proton ring which, combined with the ILC, would restore the mutual benefit of pp, ee and ep scattering at the new, the TeV energy frontier.

Acknowledgments

The results presented here are due to the intense work and the fruitful collaboration of the HERA machine group with and inside the ZEUS, H1 and HERMES Collaborations. I wish to thank all HERA speakers and many more colleagues for help with talk and text, and Claudia Glasman for the α_s compilation. For proper citations I have to refer to the contributed papers and to the proceedings of the workshops on DIS and QCD, Strebske Pleso 2004, and before. I thank the organisers of this conference and for the invitation.

References

1. D. Gross and F. Wilczek, Phys. Rev. Lett. **30** (1973) 1343; Phys. Rev. **D8** (1973) 3633; **D9** (1974) 980; H. Politzer, Phys. Rev. Lett. **30** (1973) 1346; Phys. Rep. **14** (1974) 129.
2. On April 6th 1984, the German Minister of Science, H. Riesenhuber, and the DESY director, V. Soergel, announced at DESY that HERA would be built.
3. HERMES, H1 and ZEUS websites: see http://www.desy.de.
4. S. Schmitt, these proceedings.
5. C. Gwenlan, these proceedings.
6. J. Stewart, these proceedings.
7. M. Glück, E. Reya, M. Stratmann and W. Vogelsang, Phys. Rev. **D63** (2001) 094005.
8. J. Blümlein and H. Böttcher, Nucl. Phys. **B636** (2002) 225.
9. A. DeRujula *et al.*, Phys. Rev. **D10** (1974) 1649.
10. B.C. Allanach *et al.*, Nucl. Phys. Proc. Suppl. **135** (2004) 107 [hep-ph/0407067].
11. A. Everett, these proceedings.
12. S. Moch, J. Vermaseren and A. Vogt, Nucl. Phys. **688** (2004) 101 and **691** (2004) 129.
13. T. Alexopoulos *et al.*, eD Scattering with H1, A Letter of Intent, DESY 03-194.
14. A. Martin, R. Roberts, W. Stirling and R. Thorne, Eur. Phys. J. **C23** (2002) 73.
15. V. Lenderman, these proceedings.
16. M. Klein, in Proceedings of DIS04.
17. I.A. Savin, these proceedings.
18. A. Meyer, these proceedings.
19. J. Loizides, these proceedings.
20. G. Ingelman and P Schlein, Phys. Lett. **B152** (1985) 256.
21. M. Kapishin, these proceedings.
22. T. Affolder *et al.*, CDF Collaboration, Phys. Rev. Lett. **84** (2000) 5043.
23. O. Gutsche, these proceedings.
24. A.D. Martin, M.G. Ryskin and G. Watt, hep-ph/0406225.
25. D. Dobur, these proceedings.
26. X. Ji, Phys. Rev. Lett. **78** (1997) 610.
27. V. Belitzky and D. Müller, Nucl. Phys. **A711** (2002) 118 [hep-ph/0206306].
28. F. Ellinghaus, these proceedings.
29. K. Nagano, these proceedings.
30. M. Jonker *et al.*, CHARM Collaboration, Phys. Lett. **86** (1979) 229.
31. A. Airapetian *et al.* [HERMES Collaboration], Phys. Rev. Lett. in press [hep-ex/0408013 (2004)].
32. see http://www.desy.de/∼heralhc/.
33. J Bracinik, 'Jets', these proceedings; T. Kluge, 'γs', these proceedings; X. Janssen, 'high t', these proceedings; N. Coppola, 'Mesons', these proceedings; H. Lim, 'Baryons', these proceedings; S. Levonian, '$\bar{D}$', these proceedings; Z. Ren, 'Instantons', these proceedings.
34. J. Gayler, '5 Quarks', these proceedings; A. Raval, '5 Quarks', these proceedings.
35. E. Sauvan, 'Leptons', these proceedings; C. Nguyen, 'SUSY', these proceedings; A. Schoening, 'Searches', these proceedings; C. Niebuhr, 'LFV', these proceedings.
36. H. Abramowicz *et al.*, A New Experiment for HERA, MPP-2003-62.
37. F. Willeke and G. Hoffstaetter, Talks at the Workshop on the Future of DIS, Durham 2001, unpublished; http://hep.ph.liv.ac.uk/∼green/HERA3/.