EPJ manuscript No.
(will be inserted by the editor)

Physics at HERA

Max Klein

DESY D - 15 738 Zeuthen Platanenallee 6 klein@ifh.de

Received: date / Revised version: date

Abstract. A brief review is given of the physics at HERA with emphasis on what it means for the LHC.

PACS. 14.65-q 14.70.Dj 12.38.-t

1 Introduction

Kinematics and Reconstruction

HERA is the world's only lepton-proton collider. It operates at beam energies of 27.6 GeV for polarised electrons or positrons and of 920 GeV for protons. The centre-of-mass energy $\sqrt{s}$ is 319 GeV, as determined from $s = 4E_eE_p$. HERA thus is equivalent to a 54 TeV fixed target lepton scattering machine. Therefore it reaches very high negative momentum transfers squared, $Q^2 < 10^5\,\mathrm{GeV}^2$, i.e. it resolves spatial distances as small as 10^{-18} m. From the neutral current inclusive cross section measurements, $\sigma_{NC}(ep \rightarrow eX)$, quark substructure limits have been set to 1/1000 of the proton radius by the two collider experiments H1 [1] and ZEUS [2]. Compared to previous fixed target lepton scattering experiments, the Q^2 range of deep inelastic scattering (DIS) has been extended with HERA by more than two orders of magnitude, see Fig.1. Due to the very high energy a new kinematic region of very low Bjorken x has been explored, down to $x \simeq 10^{-5}$, for $Q^2 \simeq 1\,\mathrm{GeV}^2$.

HERA physics is precision physics. The scattering kinematics is reconstructed from the angles (θ_e, θ_h) and energies $(E'_e,\ E_h)$ of both the scattered electron (e) and the hadronic (h) final state. The uncertainties currently reached are: $0.3 - 1\%$ for the electron energy scale, $0.2 - 1$ mrad for the electron scattering angle, 1% for the hadronic energy scale and $1 - 2$ mrad for the scattering angle of the struck quark as reconstructed from the final state particles. The electron energy calibration uses the "double angle method" by reconstructing E'_e from θ_e and θ_h and the fact that in a large part of the kinematic region, at larger x and medium Q^2, the scattered electron energy has to agree with the known electron beam energy ("kinematic peak method"). The hadronic energy scale can be determined accurately from the transverse momentum balance of the neutral current (NC) events. The polar angle measurement profits from redundant tracking based on Silicon detectors, drift and proportional chambers. The luminosity is measured from the Bethe-Heitler scattering process,

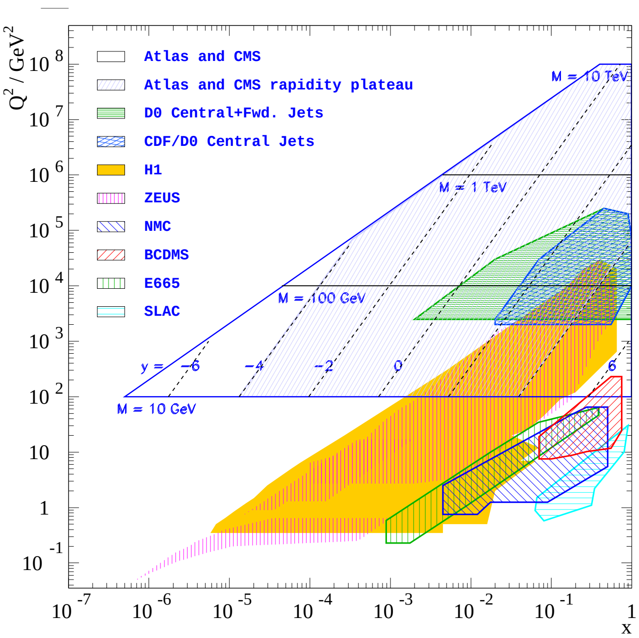

Fig. 1. Kinematic range of momentum transfers squared Q^2 and Bjorken x covered by deep inelastic fixed target experiments and by HERA and the equivalent kinematic ranges of the TeVatron and the LHC pp collider experiments.

$ep \rightarrow ep\gamma$, to within an accuracy of about 1%. Therefore the accuracy of inclusive cross section measurements reaches a few % extending with increased luminosity to larger Q^2. Both H1 and ZEUS are highly efficient apparatus of nearly 4π acceptance. This allows the complete final state to be reconstructed, apart from losses close to the beam pipe, in p and in e beam direction. Calorimeters and fibre detectors placed in forward direction, upstream the proton beam, allow charge exchange processes with forward going neutrons and colour less ("pomeron") exchange processes with forward going protons to be tagged, respectively. HERA physics thus extends much beyond the classic inclusive NC measurements: by including inverse charged current processes $(ep \rightarrow \nu X)$, heavy flavour production, often lifetime tagged, final state physics to study parton radiation and diffractive physics. Operating at the current energy frontier, H1 and ZEUS have been searching for new physics beyond the standard model.

1.1 Low x, high x and the LHC - Outline

The observation of the rise of the quark distributions, as determined from the proton structure function $F_2(x,Q^2) = x\sum_q (q+\overline{q})$, towards low x at fixed Q^2 came unexpected. Soon after, the derivate $\partial F_2/\partial \ln Q^2$ was observed to rise as well towards low x. This implies a rise of the gluon distribution $xg(x,Q^2)$ which dynamically causes a large sea quark density. Low x physics thus is devoted to the exploration of a high density, gluon dominated dynamic system of partons. The low x region, as can be seen in Figure 1, corresponds to the forward acceptance region at the LHC with a rapidity range of η between -1 and -5 depending on the mass of the produced system. Low x physics is an exciting field as it regards a new state in which the density of partons is high but the strong coupling constant small [3]. At very high density, saturation effects are predicted to set in, when gluon recombination $gg \to g$ becomes dominant [4], which restores unitarity. Signs for saturation may have been seen at HERA [5]. Low x physics is intimately related also to neutrino astrophysics at very high energies [6]. Ongoing developments of low x physics are presented in Section 1.

The region of larger x corresponds to the central, the rapidity plateau region at the LHC. In this region of x, the parton densities are not large at HERA. The Q^2 evolution from the DIS fixed target experiment region to HERA has been proven to follow the DGLAP approximation of perturbative QCD, in which partons are radiated collinearly and strongly ordered in transverse momentum. One thus expects that the parton distribution functions (*pdf*'s) measured at HERA can be evolved to the kinematic region of the LHC experiments [1]. The second part of this talk comprises the results and prospects of determining the possibly full set of parton distributions, of up, down and heavy quarks, from the H1 and ZEUS data. Besides perhaps determining the parton luminosity at the LHC, this programme, performed at higher order pQCD, would be a most reliable basis for discriminating new phenomena from ordinary parton radiation background.

While forward physics and the physics in the rapidity plateau region at the LHC have clear relations to the low and medium x regions at HERA, respectively, there are many more subjects being investigated at HERA which possibly are relevant for the LHC and for developing a consistent view on high energy deep inelastic scattering. The third section thus briefly describes some recent developments and directions of HERA physics.

[1] The extrapolation from HERA to the LHC is yet over nearly three orders of magnitude. New physics, however, as due to new strongly interacting particles [7] may alter the parton distributions at large Q^2.

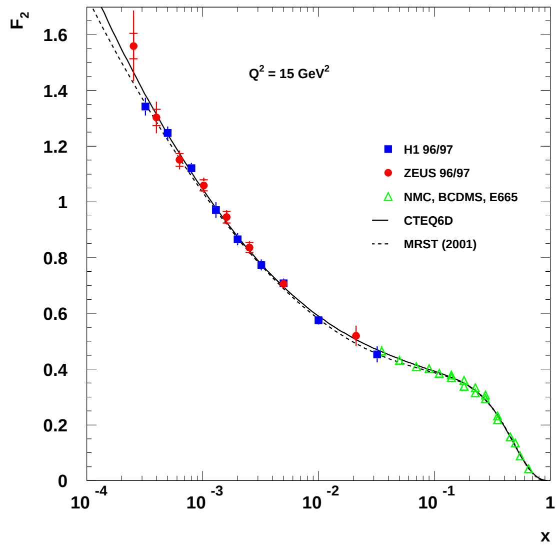

Fig. 2. Accurate data have been obtained at HERA in the measurement of the proton structure function $F_2(x,Q^2)$ which is observed to rise towards low x. The range covered by the F_2 data is from $10^-6 - 0.5$ in x and from $0.1 - 30000\,\text{GeV}^2$ in Q^2.

Within the framework of a still ongoing workshop [9] the relations of the physics and experimentation at HERA and at the LHC are being intensively studied in working groups on parton density functions, multi-jet final states, heavy quarks, diffraction and issues and tools for simulation. Naturally, these relations are wider and deeper than can possibly be demonstrated in this brief summary.

2 Low x Physics

The rise of the sea quarks towards low x

Already from the first small data set, the proton structure function $F_2(x,Q^2)$ was observed to rise towards low x. This observation has subsequently been verified with much improved precision, see Figure 2. Currently F_2 is measured to an accuracy of up to 2% in the bulk region of the data, for x approximately between 10^{-4} and 10^{-2}, and for Q^2 between 5 and 50 GeV^2. The data of H1 and ZEUS agree rather well and they match also well to the fixed target data. At low x the structure function F_2 rises approximately like $x^{-\lambda}$. The Q^2 dependence of λ is logarithmic, $\lambda \simeq 0.05 \ln Q^2/\Lambda^2$ ($\Lambda \simeq 0.3\,\text{GeV}$) [1] but flattens at Q^2 near to $1\,\text{GeV}^2$. In this region, corresponding to dimensions of 0.3 fm, the transition from a partonic to soft behaviour seems to occur: here λ approaches the value, of about 0.08, determined in soft hadron reactions using Regge theory.

The proton structure function measures at low x only one specific combination of up and down quarks, $F_2 \simeq 2x(4\overline{u}+\overline{d})/9$, neglecting for illustration the strange s and

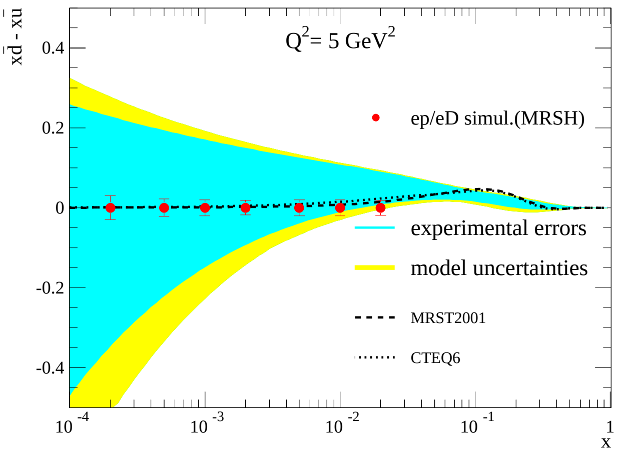

Fig. 3. Simulation of the difference of sea quarks, here assumed to be zero at low x based on additional $20\,\mathrm{pb}^{-1}$ of electron-deuteron data at HERA. The error band represents the uncertainty of the H1 NLO QCD fit to the H1 ep and the BCDMS μp and μd data without the constraint $\overline{d} = \overline{u}$ at low x. The dashed curves represent calculations by MRST and CTEQ which for $x \simeq 0.1$ account for the sea asymmetry measured in Drell Yan fixed target scattering

the heavy c, b quark contributions. Any QCD analysis directed to a determination of the parton distributions inside the proton assumes that $\overline{u} = \overline{d}$ at low x. This, however, is a very strong assumption, as is illustrated in Figure 3, which can be verified in electron-deuteron scattering at HERA. Measurements of ed would also disentangle the singlet and non-singlet evolution in pQCD at low x, where it is a particular issue [10], and improve the accuracy of the measurement of the strong coupling constant α_s by about a factor of two. Deuteron scattering at HERA would be much more accurate than at fixed target experiments because, by tagging the spectator proton with high resolution, one could reconstruct the electron-neutron scattering kinematics essentially free of nuclear corrections. Furthermore, shadowing effects could be related to and likely controlled [11] with diffractive scattering data. Unfortunately there has been no time allocated to pursue such an experimental programme at HERA [12] although this means a significant loss of insight to nucleon structure and a substantial reduction of the predictive power of the HERA data for the LHC.

The Gluon Distribution

A central role for predicting physics at the LHC plays the gluon momentum distribution in the proton. High transverse momentum jets at the LHC, the rate of which is predicted to be 6 orders of magnitude higher than the pair production of squarks, are predominantly due to gluon-gluon interactions, i.e. $gg \rightarrow qq$. The production of the Higgs decaying into two photons or into a bottom quark pair is as well due to gluon-gluon interactions. An accurate determination of $xg(x, Q^2)$ is of crucial importance for the LHC, as are hadronisation effects and simulations, see e.g. [13]. The current accuracy of the gluon distribution achieved at HERA is illustrated in Figure 4. Improvements on the gluon distribution are still expected [14] from a variety of measures: in the whole x range by an improved measurement accuracy, from typically 3% to 1% in the bulk region ($x \sim 10^{-3}$ and $Q^2 \sim 30\,\mathrm{GeV}^2$) and from 10% to a few % at large x; from HERA jet data at $x \sim 0.05$, mostly di-jets in photoproduction; and at small $x \sim 5 \cdot 10^{-4}$ from a measurement [2] of $F_L(x, Q^2)$. The Q^2 evolution of valence quarks is a non-singlet evolution and thus not sensitive to the gluon distribution. Therefore, in the region of $x > 0.3$, where xg becomes very small, DIS constrains the gluon distribution essentially only via the momentum sum rule. This may explain the large differences observed at large x of otherwise rather compatible parton distribution fits. Further work is needed and improvements are expected to come with averaging the HERA data, see below, and critically assessing the fit assumptions regarding the error treatment and parameter choices.

Parton Radiation

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 *pdf*'s determined from the low x data. PYTHIA and HERWIG simulation programs are successfully used which are based on the DGLAP radiation mechanism. 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 dedicated working group within the HERA-LHC workshop deals with simulation programs and techniques [15].

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. Recent analyses of H1 and ZEUS suggest that DGLAP theory in NLO may fail 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

[2] This requires to run HERA at lowered proton beam energy. Such a measurement is of crucial importantance for testing the whole consistency of QCD to high orders perturbation theory in the region of large parton densities. As this is written, detector and machine studies are being done to prepare a possible low energy run of a few months duration in 2007.

DGLAP evolution). Hints for a breakdown of the conventional theory come also from the study of azimuthal correlations between dijets, which at low x and Q^2 seem to be weaker than predicted in NLO DGLAP theory. Firm interpretations of these observations are subject to the uncertainties connected with yet higher order pQCD contributions and with effects of the resolved photon structure. "Unintegrated", k_t dependent parton distributions are being introduced [16] which may allow a more accurate description of the final state as they incorporate transverse momentum kinematic effects in their definition.

Hard Diffraction

The observation of hard diffraction at HERA, characterised by a gap of activity in forward region, along the proton beam direction, came unexpected. Since then a wealth of measurements has been performed by both H1 and ZEUS, in which this process is tagged by the rapidity gap or the leading proton in Roman pot detectors. Much of the discussion in the HERA-LHC workshop has been devoted to both to the interpretation of the results and the measurement techniques, having in mind the Roman pot installations from 17 m to perhaps 420 m at the LHC, and the TOTEM experiment in particular. For diffractive ep scattering, a factorization theorem has been proven which allows diffractive structure functions and parton distributions to be introduced, which quantify the density of partons in the exchanged particle, the "Pomeron".

At the LHC the key interest is perhaps the double diffractive production of the Higgs particle which supposedly occurs in a clean environment. The reaction $pp \to pHp$ is proportional to the product of unintegrated gluon distributions which are related to the gluon distribution as $\int^{\mu^2} d^2k_t^2/k_t^2 f(x, k_t^2) = xg(x, \mu^2)$. A possibility used, e.g. in the description of J/Ψ production, to determine the unintegrated distribution consists in a differentiation of xg. This requires to measure the (integrated) gluon distribution much more accurately than hitherto, see above. Strictly speaking, the cross section is described by an unintegrated gluon distribution, a function $f(x, x', k_t^2, t)$ which is skewed since $x \simeq M_H^2/s \sim 10^{-2}$ and $x' \simeq k_t^2/s << x$, see [17]. Such generalised parton distributions could be accessed with deeply virtual Compton scattering (DVCS, $ep \to ep\gamma$) and vector meson measurements at HERA. The t dependence is characterised by the shrinkage effect $f \propto x^{-\alpha'(t)}$. Exclusive Higgs production at the LHC is related to the gap survival probability which is being studied at HERA by comparing resolved virtual photon-Pomeron scattering to theory with unsuppressed gap probability, with actually a surprising result: suppression is not only observed for the resolved part but as well for the direct part of the $\gamma^* IP$ interaction, by a factor of two in the whole accessible range of x_γ.

Diffraction is a basic phenomenon possibly related to confinement. Diffraction, saturation and multiple parton interactions, i.e. remnant-remnant interactions which lead to the "underlying event", are intimately connected [19]. The development of the QCD of hard diffraction is a fundamental task in its own. At HERA many processes are studied, more and more relating diffraction to charm and jet production, but as well improving the accuracy and consistency of the inclusive data, mostly in NC but recently also in CC reactions. In view of the LHC, HERA has the challenging tasks to measure precisely the gluon distribution, to determine the diffractive parton distributions, study the gap suppression and constrain the models for unintegrated and generalised parton distributions. Regarding DVCS, first cross section data have been published. With the availability of polarised positron and electron data of high luminosity, beam charge and beam spin asymmetries become measurable, not only at HERMES[3] but as well at low x at H1 and ZEUS. Further progress is expected from tagged and thus 4 fold differential diffractive data and from a measurement of the longitudinal diffractive structure function F_L^D when HERA will be operated at low proton beam energies. At the LHC diffraction will not be easy to measure. Rapidity gap detection may require dedicated data taking at reduced luminosities of $\sim 4 \cdot 10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, and the installation of Roman pots in the cold will be a challenge. Techniques acquired at HERA are for sure of help, from theory to cold bypass and Roman pot technology.

3 Physics at the Rapidity Plateau

Parton Distributions

The measurement of the parton distributions in DIS enables a prediction of the cross sections of the production of the weak bosons, W and Z, from the fusion of two quarks, at the LHC. The weak boson production has been proposed to be used to determine the pp luminosity [8], assuming the rate measurements and the cross section prediction could be accurate to the level of a few per cent. An accurate determination of the different quark and antiquark momentum distributions at HERA will thus be very important for such a precision to be reliably achieved.

The HERA 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:

$$\sigma_{NC}^{\pm} \sim Y_+ F_2 \mp Y_- xF_3, \tag{1}$$

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

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

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

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

[3] HERMES is the fixed target eN experiment at HERA. Measurements are focused on the longitudinal and transverse spin structure of the proton. For measurements in the coming years, a detector will be installed to tag the recoiling proton in DVCS interactions, and the physics will be focused to investigate generalised parton distributions at larger x [20].

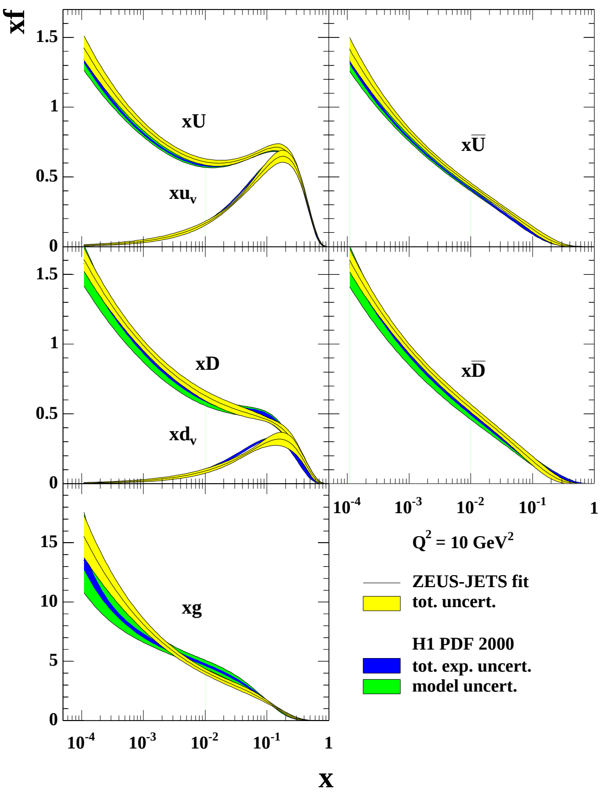

Fig. 4. Determinations of the quark and gluon distributions from NLO QCD fits to NC, CC, and to jet data (ZEUS), at $Q^2 = 10$ GeV^2 as a function of Bjorken x. The differences $U - \overline{U}$ and $D - \overline{D}$ are used to determine the valence quark distributions u_v and d_v, which dominate at large x.

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). The structure function xF_3 is a direct measure of the sum $2u_v + d_v$ of the valence up and down quark distributions, unless there is an asymmetry between anti-quarks and sea quarks [4]. 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. Results for the determinations of the quark and the gluon distributions [2] are consistent, see Fig.4. Residual differences between the parton distribution functions and their uncertainties reflect different conventions regarding the parameterisations and error treatments and hint to subtle effects in the data. The *pdfs* presented here rely only on H1 or ZEUS data. They are in agreement with recent fits from the MRST and CTEQ Collaborations, which include fixed target DIS, jet and Drell-Yan data. Analyses based on HERA data only have the advantage of being systematically coherent: global fits often use *ad hoc* χ^2 definitions in order to compensate for apparent inconsistencies in the world's data sets. With increased luminosity and range the *pdf* determinations at HERA, including charm and beauty, will become rather precise. This is expected to reduce the spread of the extrapolated cross sections, which, for example, for $pp \to HW$ is as large as 20% [21]. Thus predictions for the LHC require still much more data and analysis work to become reliable at the few per cent level. Theoretical questions regard for example the validity of the DGLAP approximation used towards low x (do partons have to be "conservative"? [22]) and the effect of soft gluon resummation [23]. QCD is a subtle theory and requires extreme care and high knowledge to be fully developed and practically useful.

[4] Indications for such an asymmetry have been discussed in the strange sea, in connection with the NuTeV $\sin^2\theta$ anomaly [18].

Strong Coupling Constant and Jets

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 [24]. The average $\alpha_s(M_Z^2)$ value to NLO from ZEUS and H1 as determined in inclusive DIS and in jet production currently is

$$\alpha_s = 0.1186 \pm 0.0011\,(exp) \pm 0.005(thy). \qquad (6)$$

Here the first uncertainty comprising all experimental and model dependent effects is already smaller than the current world average error. 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 inclusive NLO QCD analyses, fits are very poor at the extremes of these scale variations and thus the variation prescription is questionable. With forthcoming exact NNLO analyses the scale dependence will be further reduced but the arbitrariness of the scale choice remains to be resolved.

Jets at HERA are measured at scales of the order of 10 GeV, while ATLAS and CMS will focus on much higher energies. Jets at lower scales at the LHC will be measured in the forward region by the LHCb experiment [19]. At HERA jets are studied in DIS and photoproduction, used not only to measure α_s , as from the three-to-two jet ratio, but as well to study parton correlations, event shapes and alike.

Beauty and Charm Quark Distributions

Heavy flavour physics is an important, still much developing part of HERA physics. Initial measurements of the charm structure function $F_2^{c\overline{c}}(x, Q^2)$ have measured the charm quark contribution to the sea quark density at low x to be about 20%. This and further measurements of charm and beauty production at HERA are stimulating much theoretical activity in describing heavy flavour production near and above threshold within QCD. While near threshold one thinks of heavy quarks being produced in the fusion of the interacting photon with a gluon from a proton made of u, d and s quarks, much above threshold, $Q^2 > m_Q^2$, the heavy quarks $Q = c, b$ appear light and behave as ordinary constituent partons with momentum distributions, $c(x, Q^2)$ and $b(x, Q^2)$, inside the proton.

Charm production at HERA is usually tagged using the reaction $D^* \rightarrow D^0\pi_{slow} \rightarrow K\pi\pi_s$ and the $\Delta M = M(K\pi\pi) - M(K\pi)$ technique. Beauty production mostly has been observed in events with enlarged transverse momentum of muons with respect to jets. Both H1 and ZEUS have observed an excess of beauty production in the reaction $ep \rightarrow ejet\mu X$ with respect to NLO QCD predictions for large muon rapidities $\eta \sim 1$. Measurements of vector mesons and of quark-antiquark correlations involving charm and beauty quarks are being performed to constrain theory and understand parton dynamics, e.g. the fusion $\gamma^* g \rightarrow Q\overline{Q}$, which provides independent information on the gluon distribution.

Recently, the first measurements of $F_2^{b\overline{b}}$ and of $F_2^{c\overline{c}}$ became available based on the characteristic signature of the long lifetime of D and B particles, as measured in H1's central Silicon strip detector. Both H1 and ZEUS have extended their Silicon detector systems and upgraded the forward tracking. The inclusive, lifetime based measurements of heavy flavour production promise the charm and beauty densities in the proton to be accurately measured. In the kinematic range of the LHC, both charm and beauty quarks acquire a flavour democratic share of proton's momentum. The beauty contribution to the total Z production at the LHC amounts to about 5%. It thus needs to be measured at HERA with an accuracy of 10-20% in order not to dominate the Z cross section prediction which one hopes to determine at the per cent level of accuracy. The b quarks will play an extensive role at the LHC, in the investigations of parton dynamics as in the searches for new physics, as for example in the gluon-gluon Higgs production, $gg \rightarrow bH\overline{b}$ or $gb \rightarrow Hb$. Some information on the strange quark distribution can be obtained from strange (Φ) particle production and charm production in charged current scattering (e.g. $W^+s \rightarrow c$) and be confronted with the common assumption $xs = 2x(\overline{U} + \overline{D})$ at the initial Q^2.

HERA is the ideal place to measure the heavy quark densities accurately. Since beauty at HERA contributes only about a per cent of F_2, this requires high luminosity, which is being collected.

4 Recent Developments in HERA Physics

Beyond the developments which are briefly presented below, there are further very interesting results and ideas, for example i) deeply virtual Compton scattering, a process which allows parton correlations to be measured for the first time, ii) detailed studies of correlations, e.g. between heavy quarks, or between diffraction and heavy quark production, iii) the puzzling observations of pentaquark states involving strange but also charm quarks, and many others. It is difficult to ascribe to all these developments a definite or even practical value for better understanding physics at the LHC. However, surely only a consistent picture of the standard model and parton dynamics in particular may allow firm extrapolations to be made to the LHC.

Electroweak Physics

With the proton structure becoming better determined and the luminosity increasing, $e^{\pm}p$ NC and CC scattering data from HERA can be used to perform interesting tests of the standard electroweak theory in the spacelike region. A recent first analysis [25], which treated the parton distribution and the electroweak parameters in a common NLO QCD and $SU(2)_L$x$U(1)$ fit, has determined the light quark axial and vector couplings to the Z_0. Using data in the region of high Q^2, this analysis resolves sign ambiguities inherent in LEP data at resonance. Results have also been obtained for the measurement of the propagator mass in CC scattering, for the top mass from radiative corrections and of $\sin^2\theta$. All results are consistent with the standard model. The accuracy will be much enhanced when the full set of polarised electron and positron data will become available and analysed.

Combination of Cross Sections

Within the framework of the HERA LHC workshop a method has been put forward to average the cross section data prior to analyzing them in QCD fits [26]. This procedure has the attractive feature of cross calibrating the H1 and ZEUS measurements and of reducing the limiting effects of both statistical and systematic nature. Thus new data sets will become available, which may be used in subsequent analyses and in predicting cross sections for the LHC. This method requires the input of large and analysed data sets, and it will require to return to the individual analyses with the aim of averaging results. By exploiting the systematics correlations, the approach goes beyond a simple statistical average and beyond fitting the data prior to averaging them. The benefit of this method has been investigated [14], but quite some studies on the data and the method are still ahead.

Searches for Physics Beyond the Standard Model

HERA, as the TeVatron, is a machine operating at the energy frontier. Thus a strong effort is made to search for physics beyond the Standard Model [27]. Competetive limits have been set, for example in searches for contact interactions, leptoquarks, extra dimensions or supersymmetric particles, which in *ep* may be singly produced as is allowed in R parity violating SUSY theories. An intriguing peculiarity are events in which the final state contains an isolated lepton, large missing transverse momentum and a hadronic system with a large transverse energy, which by the H1 Collaboration are regularly observed in e^+p scattering, at an excess rate of 3.4 standard deviations from 158 pb^{-1} of integrated luminosity. The data still to be taken are expected to shed further light on this observation, which currently is the largest deviation from the standard model observed at large scales at HERA.

5 Concluding Remarks

The HERA collider experiments are still taking data of high luminosity and with polarised lepton beams. From these data new insight is expected on the dynamics of parton interactions. Many results which are being obtained can be predicted to become more accurate. For example, the gluon distribution at low x will be reexamined at NNLO QCD with more accurate data and with new data on jet production and on the longitudinal structure function. Refined analyses of heavy quark production, jet production and diffraction, and of data combining these characteristics are still being performed. New concepts as DVCS and unintegrated parton distributions are at their infancy and will develop further. It thus will take time to explore *ep* HERA physics fully. While the accuracy of the HERA data will still be increased, the first LHC data are expected to become available. This will much strengthen the fruitful interaction of the communities. One would wish HERA a longer lifetime than is currently foreseen for its physics is fundamental and complementary to the LHC.

Acknowledgment It has been a good tradition that HERA physics is being presented at the HCP conference as are TeVatron results at DIS Workshops. I would like to thank the organisers for the invitation and the realisation of such a stimulating meeting.

References

1. For results of the H1 experiment at HERA see: http://www.h1-desy.de
2. For results of the ZEUS experiment at HERA see: http://www.zeus-desy.de
3. sometimes called Colour Glass Condensate, for a review see E. Iancu, A. Leonidov and L. McLerran, hep-ph/0202270.
4. L. Gribov, E. Levin and M. Ryskin Phys. Rep. **100**, (1983) 1.
5. J. Bartels, Eur. Phys. J. **C 43** (2005), 3.
6. see for example M. Glück, S. Kretzer and E. Reya, Astropart. Phys. **11** (1999), 327 [astro-ph/9809273].
7. E. Berger et al., Phys. Rev. **D71** (2005), 014007 [hep-ph/0406143]
8. M. Dittmar, F. Pauss and D. Zuercher, Phys. Rev. **D56** (1997), 7284 [hep-ex/9705004].
9. HERA and the LHC, “A workshop on the implications of HERA for LHC physics”, http://www.desy.de/ heralhc, A first round of meetings has been finished and Proceedings will appear in 2006. The workshop participants have agreed to meet anually to discuss the progress and exchange information between the HERA and the LHC communities.
10. S. Forte, private communication.
11. M. Strikhman, private communication.
12. T. Alexopoulos *et al.*, eD Scattering with H1, A Letter of Intent, DESY 03-194;
H. Abramowicz *et al.*, A New Experiment for HERA, MPI-2003-62;
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/.
13. G. Corcella and S. Moretti, Phys. Lett. B **590** (2004), 249 [hep-ph/0402146] and in [9].
14. M. Cooper Sarkar, in [9].
15. V. Lenderman, Summary Talk March 2005, in [9].
16. G. Watt, A. Martin and M. Ryskin, Eur. Phys. J. **C 31** (2003), 73 [hep-ph/0306169];
J. Collins and X. Zu, JHEP **03** (2005), 059 [hep-ph/0411332].
17. M. Diehl, Summary Talk March 2005, in [9].
18. F. Olness *et al.*, Eur. Phys. J. C **40** (2005), 145 [hep-ph/0312323].
19. L. Loennblad, Summary Talk March 2005, in [9].
20. For results of the HERMES experiment at HERA see: http://www.hermes-desy.de
21. S. Forte, Summary Talk March 2005, in [9].
22. R. Thorne, in [9].
23. L. Magnea, in [9]
24. B.C. Allanach *et al.*, Nucl. Phys. Proc. Suppl. **135** (2004) 107 [hep-ph/0407067].
25. H1 Collaboration, A. Aktas et al., Phys. Lett. **B** in print [hep-ex/0507080].
26. A. Glazov, Summary Talk March 2005, in [9].
27. M. Kuze and Y. Sirois, Prog. Part. Nucl. Phys. **50** (2003), 1 [Erratum-ibid. **53** (2004), 583] [hep-ex/0211048].