FUTURE DEEP INELASTIC SCATTERING WITH HERA AND THERA

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A brief summary is given of the prospects for precision structure function physics at HERA, and of the THERA project for *ep* scattering in the TeV range of energy.

1 Introduction

HERA, in its initial years of operation, has discovered the rise of the proton structure function $F_2(x, Q^2)$ towards low Bjorken x and observed sizeable contributions of charm quarks and of hard diffraction to the inclusive deep inelastic scattering (DIS) cross section. It explored the transition from photoproduction to DIS, the structure of the photon and the final state, determined a high gluon density, xg, at low x, the strong coupling constant, $\alpha_s(M_Z^2)$, with 1.5% experimental precision, and it verified electroweak unification by the similar sizes of the neutral current (NC) and charged current (CC) DIS cross sections at high four momentum transfers squared, $Q^2 \simeq M_Z^2$.

Based on data of about $100\,\mathrm{pb}^{-1}$ integrated luminosity, new analyses are being made improving previous results and extending the kinematic coverage. At the end of 2001 a new, second phase of HERA is expected to yield a tenfold increase of luminosity for each experiment [1,2] within about 5 years. Beam energy variations and lepton beam polarisation open unique opportunities for DIS precision physics with HERA. With the possible acceleration of deuterons, of heavier nuclei and of nucleon polarisation the strong interaction research programme of HERA leads much beyond the $1\,\mathrm{fb}^{-1}$ runs approved.

The extension of the kinematic range by raising the lepton beam energy from below 30 up to 800 GeV with TESLA opens a window for discovering parton saturation at low x and new phenomena at the highest $Q^2 \leq 10^6$ GeV^2. THERA [3], as the complement of pp scattering with the LHC and e^+e^- scattering with TESLA in the TeV energy range, will solve a number of fundamental problems raised with HERA, and is likely to pose new questions.

This summary was given in the structure function session of the DIS01 conference. Thus prospects for diffraction, final states and searches, though related, are not covered here but a few highlights are presented of inclusive future DIS physics at HERA. Finally the THERA project is briefly summarised.

2 Precision Measurement of $\alpha_s(M_Z^2)$ in Inclusive DIS

The strong interaction coupling constant is known much less accurately than either the Fermi constant or the electroweak mixing angle, yet is equally important with regard to the unification of the particle interactions. The experimental uncertainty of the recent $\alpha_s(M_Z^2)$ measurement[4] based on H1 and BCDMS data, $\delta\alpha_s = 0.0017$, is about equal to the error of the world average value. Further improvements of $\delta\alpha_s$ with HERA can be achieved with improved determinations of the energy scales and efficiencies using much increased statistics. The BCDMS data favour a rather low value of $\alpha_s(M_Z^2)$. It is important to remeasure the DIS cross section at large x and $Q^2 < 100$ GeV^2 and precisely determine α_s with HERA data alone. This is possible with minimum proton beam energy, $E_p^{min} \simeq 300$ GeV, extending the large x range, at fixed Q^2, by a factor of $920/E_p^{min}$. The accurate inclusive DIS data permit the correlation of α_s and the gluon distribution, xg, to be resolved [4], i.e. to determine $\alpha_s(M_Z^2)$ independently of external constraints on the high x behaviour of the gluon distribution. This is different to determinations of α_s with DIS jet data assuming xg to be known. Future α_s measurements with HERA [5] may lead to an experimental $\alpha_s(M_Z^2)$ uncertainty of about 0.0010 which, due to the extended kinematic range and accurate CC measurements at high x and large $Q^2 \sim M_W^2$, may be improved with THERA to about 0.0004. This precision requires pQCD to be applied beyond NLO [6].

3 The Longitudinal Structure Function $F_L(x, Q^2)$

The accurate measurement of $F_L(x, Q^2)$ at low Q^2 is necessary for understanding the low x high parton density region discovered at HERA which can not be unambiguously interpreted with F_2 data alone. Extracting F_L, however, is an experimental challenge since F_L causes only a small correction at high inelasticity y to the reduced DIS cross section, $\sigma_r = F_2 - y^2 F_L/[1 + (1-y)^2]$. Since $y \simeq 1 - E_e'/E_e$ at large y and low Q^2 it is required to measure σ_r at small scattered electron energies E_e'. Recent measurements [4,7] of F_L by H1 are based on a σ_r measurement accuracy of about 7% at highest $y < 0.89$, and on assumptions about the behaviour of F_2 at lowest x. High statistics runs, with luminosities O(10)pb^{-1} at a series of E_p values, will allow the x dependence of $F_L(x, Q^2)$ to be measured. The energy dependence of the photoproduction background and precision tracking in front of high resolution calorimetry should permit this dominating source of uncertainty to be controlled a few times more accurately than hitherto. Thus one may measure the cross section at high y to 2-3%, i.e. F_L to 5-10% accuracy as a function of x.

4 Heavy Flavour Structure Functions

High luminosity, Silicon tracking, extended sensitivity and improved accuracy, e.g. of F_2^c to better than 10%, promise charm and beauty DIS physics to become a central field for precision tests of QCD. Forward and backward Silicon trackers, now installed, extend the kinematic range of F_2^c measurements [8] towards larger x, where intrinsic charm may be seen, and lower x, respectively. The beauty structure function F_2^b, amounting to a few % of F_2^c, may be measured for the first time helping to resolve the puzzle of an anomalously large hadronic b cross section. Moreover, the strange quark distribution may be accessed in CC measurements with sensitivity to $W^{+(-)}g$ fusion into $s\overline{c}(\overline{s}c)$.

5 Charged and Neutral Currents at High Q^2

The charged current cross section, $\sigma_{CC}^{\pm}$, is bound to vanish with lepton polarisation $\lambda \rightarrow \pm 1$ unless right handed charged currents exist. A test of this prediction requires a series of data to be taken in the widest possible range of λ with a total luminosity of about 100pb^{-1}. NC and CC precision data at high Q^2 permit competetive searches for new physics.

The measurement of $\sigma_{CC}^{+}/\sigma_{CC}^{-}$ with high luminosity, in particular for e^+p since d_v is small and $\sigma_{CC}^{+} \rightarrow (1-y)^2 d_v$, determines the d/u valence quark ratio for large $x \leq 0.7$, independently of nuclear uncertainties. Accurate data for d_v/u_v may be obtained from the neutral current, parity violating asymmetry $A^{\pm}$ which in the HERA Q^2 range is given by [9]

$$A^{\pm} = \frac{\sigma_{NC}^{\pm}(\lambda) - \sigma_{NC}^{\pm}(-\lambda)}{\sigma_{NC}^{\pm}(\lambda) + \sigma_{NC}^{\pm}(-\lambda)} \simeq \mp \lambda \kappa_z a_e \frac{G_2}{F_2} \rightarrow \pm \lambda \kappa_z \frac{1 + d_v/u_v}{4 + d_v/u_v} \tag{1}$$

for $x \rightarrow 1$. Here $\kappa_z \sim 10^{-4}/Q^2[\text{ GeV}^2]$ defines the strength of the γZ interference, $a_e = -1/2$ is the axial charge of the electron and $G_2 = F_2^{\gamma Z} = 2x \sum e_q v_q (q + \overline{q})$. The vector couplings are given by the weak isospin charges and the electric charges, $v_q = I_{3,q}^L - 2e_q \sin^2\theta$. With $\sin^2\theta \simeq 1/4$ one has $e_u v_u = e_d v_d = 1/9$, and thus $G_2 \simeq 2/9 \cdot x \sum (q + \overline{q})$ is a singlet structure function. Simulated data extending up to $Q^2 = 30.000$ GeV^2 reveal that G_2 may well be measured at high x, see Figure 1. Information on the valence quark behaviour extending into the sea quark range, $x > 0.005$, will be obtained from high luminosity charge asymmetry measurements [10] determining at large y the interference structure function $xG_3 = xF_3^{\gamma Z} = 2x \sum e_q a_q (q - \overline{q}) = x(2u_v + d_v)/3$. The inclusive cross section measurement for $x \rightarrow 1$ is extremely challenging as $\delta\sigma_r/\sigma_r \rightarrow 1/(1-x)$, yet will be much easier at HERA than with fixed target experiments due to the overconstrained kinematics.

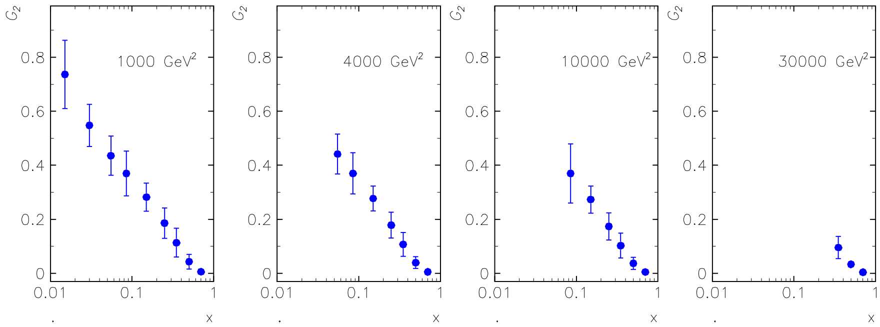

Figure 1. Simulated statistical accuracy of the interference structure function G_2, derived from the parity violating cross section asymmetry with inclusive, same charge *ep* scattering data of opposite polarisation, assuming $\lambda = 0.5$ and a luminosity of $200\,\mathrm{pb}^{-1}$ for each polarisation setting. The $A^{\pm}$ asymmetry is large and changes of polarity during data taking will considerably reduce its systematic uncertainty.

6 Deuterons and eA Scattering at HERA

Electron deuteron scattering at HERA allows quark distributions such as *s*-*c* to be unfolded [10], the d/u ratio to be constrained, the nonsinglet and singlet Q^2 evolutions in QCD fits to be separated, F_2^n and F_L^n to be measured at low x, the sea quark asymmetry $(\overline{u} - \overline{d})$ and the Gottfried sum rule to be constrained and shadowing effects to be studied. Due to its small anomalous magnetic moment, polarisation of deuterons in HERA is easier than that of protons and may be realised without Siberian snakes in the p ring [11]. Polarised *ed* scattering may determine the gluon contribution to the proton spin at low x and lead to a wealth of new information with complete final state reconstruction in a much extended kinematic range compared to fixed target polarisation experiments. The *ed* programme at HERA is thus of prime importance and most exciting if combined with tagging the spectator nucleon.

The nucleus is a laboratory for the study of deconfinement, the origin of multiparticle production and parton saturation. The ratio F_2^A/F_2^d is of interest for understanding the QCD evolution of nuclear parton densities [12] and for the evaluation of the A dependence of shadowing. Shadowing effects are related to diffraction which could contribute a much enhanced part of the inclusive DIS cross section [13]. The gluon density is predicted to be enhanced by a factor $A^{1/3}$ which may be used to study gluon saturation and possibly find the colour glass condensate state of matter [14]. Nuclei at HERA may be accelerated [15] with a new LINAC and electron cooling is required for $A > 12$.

7 THERA - Physics and Facility

THERA [3] may use polarised leptons, $e^{\pm}(\lambda)$, from TESLA scattered off protons or nuclei accelerated in the HERA proton ring. With energies of $E_e = 250 - 800\,\mathrm{GeV}$ and $E_p = 300 - 1000\,\mathrm{GeV}$, THERA reaches c.m.s. energies of 1 TeV and beyond, which compares well with a $250 - 400\,\mathrm{GeV}$ e^+e^- collider and with the LHC. Thus there exists a cost effective opportunity to study ee, pp and ep collisions in the new, TeV range of energies. In the past this triple coexistence has been vital for understanding lepton and parton interactions, in establishing the standard model of electroweak and strong interactions and for searches for new physics.

Extension of the DIS low x range with THERA to $x > 10^{-6}$ is crucial in order to study non-linear gluon interaction effects as the unitarity limit approaches. This will lead to the development of QCD for high density matter, and constrain the rates measured at the LHC as well as astrophysics, in which high energy neutrinos from AGN's or GRB's occur at x values as low as 10^{-8}.

Due to the increase of cross sections and coverage, THERA is an ideal laboratory for heavy flavour physics making use of a transverse vertex extension of only $20\,\mu m$. This may not only lead to precision measurements of F_2^c, but clarify the role of beauty and of intrinsic heavy flavour in the proton. High statistics NC and CC measurements determine the strange and charm quark densities at large x and high $Q^2 \simeq 10^4$ GeV^2.

Forward jet production observed at THERA close to the proton beam direction will reveal the mechanism of gluon emission at low x beyond the k_t ordered conventional prescription and may establish the existence of hot spots [16] of partons in the proton proving the "Thomson model" of continuously distributed partons in the proton to be wrong. The gluon structure of the photon may be resolved 100 years after Einstein.

If new particles exist with masses up to 1 TeV, their properties can be studied under well controlled conditions. An impressive example is leptoquark spectroscopy because of the ability to prescribe the incoming lepton charge and polarisation state as well as using the measurement of the angular distribution of the scattered lepton.

TESLA, with its standing wave type cavities, allows both arms to be used for lepton acceleration towards the proton ring. Its $\sim$300 ns bunch separation and the HERA proton bunch separation of presently 96 ns can be adapted. A superconducting linear collider is thus to be preferred over a warm NLC. Designs of the interaction region [3,17], for E_e/E_p ratios between 1/4 and 1, lead to estimated annual luminosities between 40 and 250 pb^{-1} using cooling and dynamic focussing ideas to reduce the proton beam phase space.

A THERA detector [3] may be located in the West area of HERA, on the site at DESY. Its central and forward dimensions are determined by the HERA proton beam energy and thus resemble H1 or ZEUS. A long defocussing quadrupole separates the beams by orbit. The absence of upstream synchrotron radiation allows the beam pipe radius to be made small ($\simeq 2\,\mathrm{cm}$) which confines the dedicated low x backward detector to a length of $5-10$ m. While the rather symmetric E_e/E_p energy ratio thus represents a solvable challenge for kinematics reconstruction at low x, it is of much advantage at high Q^2 since the whole final state is scattered rather centrally into the detector. This allows focusing magnets to be placed close to the interaction point in a high Q^2, large luminosity phase of experimentation at THERA.

The physics opportunities connected with HERA, its high luminosity, deuterons, nucleon polarisation, heavy nuclei, and its use for the THERA ep, $\overrightarrow{e}\,\overrightarrow{p}$, γN and eA programme, are unique and exciting. They will be missed if HERA is switched off prior to the understanding of nucleon structure.

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