Deep Inelastic Scattering - Status and Future

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Abstract

Deep inelastic lepton-nucleon scattering (DIS) is briefly characterised in its historical role in establishing the standard model of the electroweak and strong interactions. Key results are presented which are being obtained with the world's highest energy DIS experiments performed at HERA. Prospects are discussed for the future of DIS and experimentation with electron-proton beams approaching the TeV scale of energy in the next decade(s).

Key words:
lepton-nucleon scattering, QCD, strong interaction, proton structure
PACS:

1. DIS - a historical perspective

While the pp machine LHC is being built and the e^+e^- machine ILC is being prepared for a construction decision in 2009 there is so far no supported project for realising an ep machine at the TeV energy scale. Since, moreover, the present energy frontier electron-proton collider HERA has been scheduled to be terminated in 2007, with increasing necessity [1] discussions are being and are to be pursued about the status and the future of the physics of electron-proton or deep inelastic scattering (DIS).

In the past four decades, both at the 10 GeV and the 100 GeV energy scales, hadron-hadron, electron-positron and lepton-proton scattering experiments have been pursued simultaneously. This has been very important for particle physics. With these complementary types of experiments, crucial discoveries were made which established the now *standard* $SU(2)_L \times U(1) \times SU(3)_c$ model as the appropriate gauge field theory at the Fermi energy scale, comprising the weak, the electromagnetic and the strong interactions, respectively.

In 1968 in electron-proton scattering at SLAC partons were first 'observed'. In the seventies, at $\sqrt{s} \sim 10$ GeV, the Quark Parton Model (QPM) was established with seminal measurements in deep inelastic lepton-nucleon experiments (quark spin, scaling and scaling violations, respectively) and in e^+e^- scattering experiments ($R =$

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[1] The situation of particle physics is becoming rather dramatic with the recently announced terminations of the TeVatron operation at Fermilab and of (Super)Babar at SLAC which implies that accelerator based particle physics in Europe and the US soon will be confined to the LHC. Despite its likely far reaching programme the LHC cannot replace a diverse particle physics landscape. SLAC, Fermilab and DESY, will lose their accelerator home base in the next few years. High energy physics is in a challenging transition phase in which its current, fundamental programmes are not completed and its dreams far from their realisation.

$\sigma(e^+e^- \rightarrow hh)/\sigma(e^+e^- \rightarrow \mu\mu)$). About thirty years ago the J/Ψ resonance, open charm and neutral weak currents were found. The decisive confirmation of the $SU(2)_L \times U(1)$ weak isospin structure was due to a polarised ep experiment at very small momentum transfer. The distorted momentum balance in the nucleon and the logarithmic dependence of the strong coupling constant α_s on the momentum scale involved, complemented by the observation of trijet events due to gluon bremsstrahlung in $e^+e^- \rightarrow q\bar{q}$ reactions in 1979, were supportive of QCD as the appropriate colour field gauge theory of the strong interaction. This exciting period of particle physics culminated in the discovery, at the S$p\overline{p}$S collider, of the $W^\pm$ and Z bosons mediating the charged and neutral current weak interactions.

In the past decades a new energy scale of $\sqrt{s} \sim 100\,\text{GeV}$ was reached with the e^+e^- collider LEP, the pp collider Tevatron and HERA, the first ep collider ever built. Three fundamental results were obtained at these three machines: the number of light neutrinos was measured to be 3, the bottom and top quarks were observed, restoring lepton-quark symmetry after the τ neutrino had been found, and the quarks were measured to be pointlike down to $10^{-18}\,\text{m}$, i.e. 1/1000 of the proton radius, respectively. The high precision measurements at LEP (top quark mass prediction from radiative electroweak corrections) and HERA (determination of quark and gluon densities in inclusive and perhaps in diffractive scattering) are essential in interpreting Tevaton data. HERA discovered the rise of sea quark and gluon momentum densities towards low x thereby confirming 'one of the most dramatic predictions' (Wilczek) of QCD. Major contributions are being made to the development of QCD which turns out to be a theory much richer and deeper than the celebration of asymptotic freedom may hint to. All three colliders hoped and planned to find exotic physics at the (Fermi) scale of a few hundreds of GeV and all failed so far, searches at the Tevatron and HERA being further pursued with increasing luminosity. Peculiar events with isolated leptons and large missing transverse momentum with a frequency beyond expectation are observed by the H1 experiment at HERA (1).

The present summary of the status and future of deep inelastic scattering was delivered at a symposium dedicated to the memory and the 100 year's anniversary of P.A. Cerenkov, who, at the age of 80 already, with great enthusiasm directed physicists of the Physics Institute of the Academy of Sciences (FIAN) at Moscow to join the H1 experiment, one of the two large scale collider experiments at HERA, to which the FIAN has been making major contributions. The talk summarised here was delivered in June 2004, and it was accompanied by a detailed account (2) of QCD at HERA with emphasis on hard diffraction and final state physics which are thus not covered in this report. References can only be given here to reviews and talks (3).

2. Physics at HERA

HERA collides electrons or positrons of 27.6 GeV energy off protons of 920 GeV energy allowing inelastic ep scattering at a cms energy of $\sqrt{s} = 319\,\text{GeV}$ to be studied. HERA is thus equivalent to a 54 TeV lepton accelerator, i.e. the H1 and ZEUS experiments operate at about 200 times higher cms energy than the largest energy muon-nucleon experiments at CERN. The kinematic range accessed in deep inelastic scattering experiments is thus much extended towards higher momentum transfers squared, Q^2, and much lower Bjorken-x, Fig. 1, i.e. towards smaller fractions of proton momentum carried by the struck parton. It has been a great challenge at HERA to achieve high enough luminosity to explore the physics up to the kinematic boundaries.

Compared to fixed target experiments, the collider experiments have the additional advantage of reconstructing the kinematics in a redundant way: the simultaneous measurement of the angles and energies of both the scattered electron and the hadronic final state overconstrains the reconstruction of Q^2 and x for each event. This reduces the systematic uncertainties of the inclusive cross section measurements. Moreover, the extension of the phase space and the large, nearly 4π acceptance of the collider detectors allow for a uniquely detailed and accurate measurement of the final state

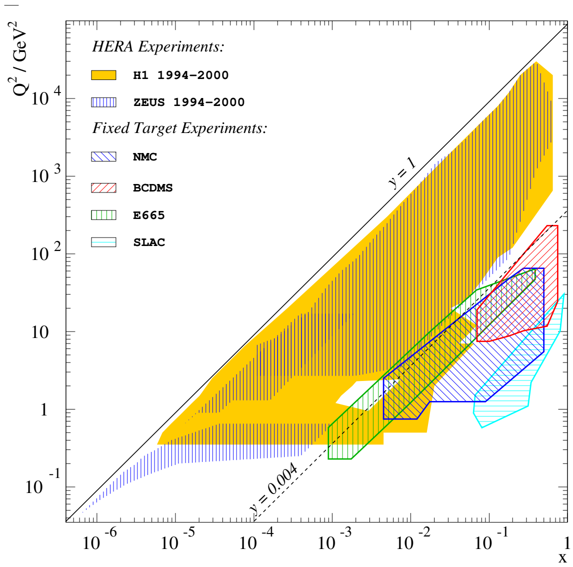

Fig. 1. Kinematic regions in Bjorken x and momentum transfers Q^2 covered by fixed target lepton-proton experiments and the extension by the H1 and ZEUS experiments at HERA.

properties, such as heavy quark production, jets and diffractive scattering. Thus HERA has been an ideal laboratory for the study of the partonic structure of the proton and the dynamics of strong and weak partonic interactions as described in QCD and the electroweak standard model.

HERA delivered its first data in 1992 and is now operating in a second phase, with stronger focussing near the ep interaction regions, to increase the luminosity, and, with rotators around H1 and ZEUS, to utilise the longitudinal electron beam polarisation for studies of electroweak physics in the spacelike interaction region. Subsequently a few highlights of deep inelastic scattering at HERA are introduced. For a recent more detailed review see (1).

2.1. *Light Quark Distributions*

The classic measurement in deep inelastic scattering regards the inclusive scattering cross section which in most of the kinematic range is determined by the proton structure function $F_2(x, Q^2)$. In the Quark-Parton Model (QPM) and in QCD, in the so-called DIS renormalisation scheme, F_2 directly measures the quark momentum density given by the sum over all flavours, $F_2 = x \sum e_q^2(q + \bar{q})$, where e_q are the fractional electric charges of up-type quarks (u, c, t), $e_u = 2/3$, and down-type quarks (d, s, b), $e_d = -1/3$. The first measurement of F_2 in the inelastic region made at SLAC in 1968, for $x \sim 0.2$, revealed Bjorken scaling, i.e. the independence of F_2 of Q^2, which was subsequently found to be broken in all but the originally accessed range of x. The measurement of a logarithmic dependence of F_2 on Q^2 was pivotal in establishing QCD as the correct, perturbative field theory of strong interactions which, in the asymptotically free limit, contains the QPM. A series of precise deep inelastic fixed target experiments using electron, muon and neutrino beams measured the up and down quark distributions rather accurately, at typical Q^2 values of $20\,\mathrm{GeV}^2$, including their valence and sea quark components. A conventional assumption has been, for u and d quarks, that sea and anti-quark distributions are equal and, for the heavier quarks, s, c, .., that quarks and anti-quarks have the same distributions. It has not been tested whether $u_{sea} = \bar{u}$ or $d_{sea} = \bar{d}$ and there are indications for $s \neq \bar{s}$ and $\bar{u} \neq \bar{d}$ which hint to non-perturbative effects in the nucleon structure.

HERA is the ideal machine to determine the complete set of quark distributions in the truly DIS region, in a wide range of Q^2 from $5\,\mathrm{GeV}^2$ up to $50000\,\mathrm{GeV}^2$. It extends the kinematic range to very low x, down to $x \simeq 10^{-4}$, and also to very large momentum transfers accessing thereby also the valence-quark region, $x > 0.2$. At large Q^2 values both Z and W exchange are measured. This permits different quark flavours to be disentangled for $x > 0.01$ because the interference between photon and Z boson exchange amplitudes and the weak charged currents depend differently on the up and down quark distributions than F_2 from pure photon exchange. As a result, fits to the neutral and charged current HERA data, performed to NLO in QCD independently by H1 (4) and by ZEUS (5), lead to determinations of the gluon, the sea and the valence quark distributions as is illustrated in Fig. 2. A striking observation from this and previous results has been the dominance of the sea quarks and gluons at low x, discussed be-

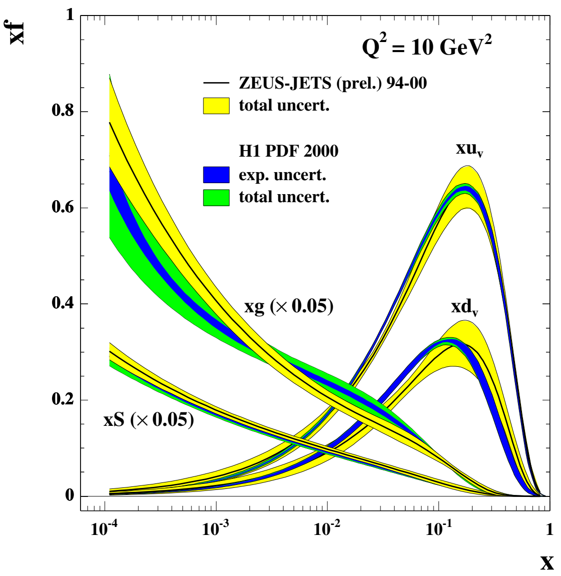

Fig. 2. Determinations of the gluon, sea and valence quark distributions in NLO QCD fits to the H1 and ZEUS data. Here the sea is defined as $S = 2(\bar{U} + \bar{D})$ with $U = u + c + b$ and $D = d + s$.

low. The determinations of the valence quarks by H1 and ZEUS are consistent but further effort is needed to improve the data accuracy at high x, by increasing the luminosity and by reducing the calibration uncertainty of the calorimeters, and also to straighten technical aspects of the fitting procedures regarding the parameterisations and systematic error treatment. The goal of this ongoing part of HERA physics is to determine the light and also the heavy quark distributions to NNLO QCD to maximum possible accuracy as is required to understand proton's structure [2] and to pin down new physics effects at the LHC.

2.2. *Heavy Quark Distributions*

A completely new field of the physics of parton distributions has been opened at HERA with the observation of sizeable fractions of events related to charm ($\sim 20\%$) and beauty ($\sim 2\%$) production. Based on the observation of large samples of events with $D^* \to D^0\pi_{slow} \to K\pi\pi_s$ decays, the deep inelastic charm production cross section, related to the charm structure function, $F_2^c = x\sum e_c^2(c + \bar{c})$, has been measured in a wide range of x, between 0.0001 and 0.1, and Q^2, between a few GeV^2 and a few 1000 GeV^2. Recently the first measurement of F_2^b became available based on the characteristic signatures of high relative transverse momentum of beauty decay muons and of the lifetime of B particles measured in H1's Silicon strip detector around the interaction region. These measurements 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, $Q^2 > m_c^2, m_b^2$, the heavy quarks appear light and behave as ordinary constituent partons with momentum distributions, $c(x, Q^2)$ and $b(x, Q^2)$, inside the proton. With the photon-gluon fusion process one has found an independent measure for the gluon density in the proton at very low x. Much can be learned in heavy flavour studies at HERA about fragmentation, hadronisation and also about exotic particle production as related for example to pentaquarks which may exist. Beauty physics is yet in its infancy at HERA as it relies on the increase of luminosity and further Silicon detectors recently installed.

2.3. *The strong coupling constant α_s*

The strong coupling constant is much worse determined than the fine structure, the Fermi and even the gravitation constant. The question of whether these coupling constants reach a common limit at a unification scale of about 10^{19} GeV as well as the precision tests of QCD demand a much improved measurement of α_s. Deep inelastic scattering has been a classic process to measure the strong coupling constant because it is theoretically well defined, i.e. there exists an operator product expansion due to light cone dominance of the structure functions The current measure-

[2] Note that fixed target neutrino scattering is becoming more and more accurate. The Minerva project (6) promises to measure the complete set of CC structure functions at lower Q^2 with high precision.

ments of α_s at HERA, Fig. 3, have reached an experimental accuracy of about 1% based on inclusive and jet cross section measurements, the average for $\alpha_s(M_Z^2)$ extracted using NLO QCD being $0.1186 \pm 0.0011(exp) \pm 0.005(thy)$. There are a variety of improvements still possible for higher accuracy of the HERA data due to higher statistics, refined calibration methods and cross calibration and averaging of H1 and ZEUS measurements. Data with deuterons would yield a further improvement by disentangling the singlet and non-singlet evolution parts. HERA thus has the potential to determine α_s to a precision much better than 1%. This requires a substantial reduction in the theoretical uncertainty by carefully examining the limits of applicability of DGLAP QCD, performing the analysis in NNLO (7) and reconsidering the true freedom of variations of the renormalisation scale. An important aspect of this programme regards the role of the BCDMS data: these are most precise at large x and medium Q^2 but themselves yield a very small value of $\alpha_s \sim 0.10$. Whether this is indeed correct or due to the limited redundancy of the BCDMS cross section measurement, which solely relied on the scattered muon kinematics, requires to be verified. A new fixed target precision measurement, as envisaged with COMPASS, and a high statistics low energy run at HERA would be necessary to improve the dynamic range which is worth such an effort given the importance of knowing the true value of $\alpha_s(M_Z)$. The prospects to measure α_s at the LHC are meager.

2.4. *Physics at High Parton Densities at Low x*

The observations at HERA of the rise of the structure function $F_2(x, Q^2)$ and of its derivative $\partial \ln F_2 / \partial \ln Q^2$ towards low x imply that the sea quark distribution and the gluon distribution, respectively, increase dramatically at low x where the valence quarks carry no momentum anymore, see Fig. 2. At low x apparently the proton structure is driven by gluons and the formation of quark-antiquark pairs. While the proton charge is determined by the valence quarks, the kinetic and potential energy of gluons determines its mass. Understanding quark-gluon dynamics is thus a key to the mass of the universe. An accurate knowledge of the gluon distribution [3], in a wide range of x, is necessary to understand Higgs production at the LHC since the gluon-gluon fusion to the Higgs particle is the heavily dominant process in the expected range of Higgs masses from about 100 GeV to almost 1000 GeV. The question as to whether gluons contribute sizeably to proton spin is being investigated but is unresolved as yet because of the

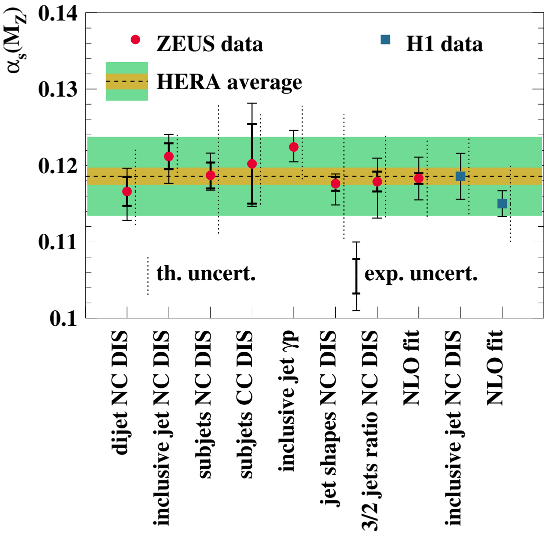

Fig. 3. Measurements of α_s in NLO pQCD by the ZEUS and the H1 Collaborations at HERA. The theoretical uncertainty is determined following the *ad hoc* convention of varying the renormalisation and factorisation scales by a factor of 1/4 to 4. The recent use of jets (5) to NLO has much improved the accuracy to determine the strong coupling constant at HERA and reduced the uncertainty for the gluon distribution in the medium x range, $x \sim 0.1$.

[3] Note that the gluon distribution is not directly observable, it depends on the theoretical framework used. There are arguments (8) that the diffractive part of the inclusive scattering cross section causes shadowing corrections which are to be subtracted prior to analysing DIS data. This in turn changes the gluon distribution significantly (9) and hence predictions one hopes to be able to firmly make for the LHC.

limited Q^2 span of polarised fixed target experiments.

There are a number of questions being studied related to low x physics. Low x physics may differ fundamentally from the classic Bjorken limit region of deep inelastic scattering. The growth of the gluon distribution needs to be tamed and finally a maximum phase space density for a given proton radius should be reached (10). If gluon recombination becomes indeed dominant, the evolution of the parton dynamics is expected to be non-linear. In the Regge limit the BFKL equation may hold and, analogeously to condensed matter physics, classic effective theories are applied (11). By modifying the splitting functions (12) of the DGLAP evolution equations one is rescuing these incorporating small x logarithms. Different parton evolution at low x leads to modified correlations between hadrons and jets. Recent measurements (1) of jets in the forward direction, in a kinematic range where DGLAP evolution is suppressed and BFKL evolution enhanced, and of azimuthal dijet correlations hint to difficulties of DGLAP evolution to represent the full dynamics at low x. It is to be noted that these developments were not foreseen when HERA started to operate and represent an exciting extension of QCD.

A crucial test for QCD at NLO yet to be performed at HERA is the measurement of the longitudinal structure function F_L at low x. This is possible with running at reduced beam energies. This measurement represents a genuine test of QCD at high orders. Since both the derivative of F_2 and F_L access the same gluon distribution but with different splitting functions their direct comparison represents a decisive test of the universality of the gluon distribution and whether DGLAP QCD is able to provide a consistent description of both measurements or needs to be modified. Moreover, the gluon distribution at low x and Q^2 is not well constrained and thus parton distribution fits appear possible which describe equally well F_2 but with inconsistent gluon distributions. The measurements of F_L and of the $\ln Q^2$ derivative of F_2 require the highest attainable accuracy, to better than 1% for the inclusive cross section, and thus can represent a true highlight of physics and instrumentation at HERA.

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

Recently spin rotators were installed next to the collider experiments. Lepton beam helicity and charge variations allow new questions in DIS to be studied, as high luminosity becomes available. With the first polarised e^+p data both H1 and ZEUS have observed the beam helicity dependence of the weak charged current interaction to be compatible with linear, in agreement with the standard model (1). Further measurements will follow regarding the violation of parity in the weak neutral current interaction at high Q^2, i.e. small distances, and the thorough test of the electroweak interaction in DIS, complementary to LEP both regarding the space-like character of the interaction and the specific quantities extracted such as the light quark weak neutral current couplings.

A new field of research is the physics of deeply virtual compton scattering (DVCS), $ep \rightarrow ep\gamma$, (13). Here a parton in the proton absorbs the virtual photon, emits a real photon and the proton ground state is restored. As in this process a momentum t is transferred to the outgoing photon the virtual partons, gluons at low x (characteristic for DVCS at collider experiments) or quarks at larger x (as studied in the fixed target experiment HERMES at HERA), carry different fractions of the intial proton momentum. The DVCS process thus measures generalised parton distributions which depend on two momentum fractions x and ξ, as well as on Q^2 and t. The DVCS process interferes with Bethe-Heitler scattering. This allows parton scattering amplitudes to be measured, instead of cross sections in the classic DIS concept. This interference has been viewed as a possibility to establish holograms of nucleons in leptoproduction experiments (14). Experimentally as much as phenomenologically this field is new and developing rather rapidly with the first measurements being performed at HERA, including the fixed target experiment HERMES (15), and elsewhere. The measurement of charge and helicity asymmetries allows different types of parton distributions to be accessed which may be related via the 'Ji sum rule' to the unmeasured angular momentum contribution to the spin of the proton.

3. Future *ep* Colliders

3.1. *HERA III*

The current high luminosity phase of HERA is scheduled to end in 2007. The accelerator will then be turned off because its injector will be used to build a 3^{rd} generation synchrotron light source in the PETRA tunnel at DESY. This unfortunate decision implies that the *ep* physics programme as originally planned will not be completed. Moreover, it disregards the unique physics potential of HERA extending far beyond luminous electron-proton scattering. It hence ignores the insight into the proton's structure and QCD that would lead to and the high investments which HERA represents.

The programme proposed recently (16) for a subsequent phase of operation, termed HERA III, has three main components:

i) The precision measurement of the transition from deep inelastic scattering to soft hadron collisions. In the infinite momentum frame DIS probes the partonic structure of the proton, down to distances of 0.001 fm at HERA. In the proton rest-frame, however, one may view this process as proceeding by the photon splitting into a colour dipole of variable size $2/Q$ which interacts with the proton at an energy of $W^2 \simeq sy = Q^2/x$ which for $Q^2 = 1\,\mathrm{GeV}^2$ is as large as about $10000\,\mathrm{GeV}^2$. The distance at which the splitting occurs, the coherence length (Gribov) is large because of $L \propto 1/x$. Thus low x, by variation of Q^2, is sensitive to the transition from soft to hard physics, which occurs at $Q^2 \simeq 1\,\mathrm{GeV}^2$ equivalent to a distance of 0.3 fm. Investigation of this phenomenon has to include the study of the two virtual photon polarisation states. This programme, at high accuracy, has not been pursued yet because the HERA II phase has been dedicated to maximising the luminosity by introducing focusing magnets very close to the interaction regions of H1 and ZEUS which removed acceptance to that region, $Q^2 < 5\,\mathrm{GeV}^2$.

ii) The measurement of electron-nucleus collisions. Prior to HERA every DIS charged lepton scattering experiment used deuterons to study the neutron structure and the partonic content. HERA has discovered the rise of $F_2 \propto 4\bar{u} + \bar{d}$ towards low x. There are non-perturbative models, like the chiral quark soliton model, which predict up and down anti-quarks not to be equal. While this has been indeed confirmed at larger $x \sim 0.1$ common wisdom assumes $(\bar{d} - \bar{u}) \rightarrow 0$ at low x but may yet be wrong. It is necessary to measure this in order to understand nucleon structure at low x and to be able to predict the high energy, low x cross sections at the LHC (up to the rapidity plateau) and in astroparticle physics (superhigh energy neutrino scattering off isoscalar targets). The *ed* programme at HERA would be fascinating and more powerful than at fixed target experiments since, by tagging the spectator proton, *en* scattering could be measured nearly free of Fermi motion corrections and, moreover, a diffractive programme would be pursued on p, n and d which also would allow the shadowing corrections to be determined for the first time. Extending this programme to heavier nuclei would determine nuclear parton distributions, as is required for ALICE at the LHC and for RHIC, and it would search for the predicted black body limit of DIS, with $F_2 \rightarrow Q^2/\ln(\delta/x)$ and a diffractive scattering component of up to 50%. Moreover, since the gluon density is amplified in nuclei as $A^{-1/3}$, one would exceed the unitarity limit $\sim Q^2/\alpha_s$ and be able to study saturation phenomena which in *ep* scattering are not uniquely seen at HERA. The eN programme focussed on low x is a low luminosity programme and would constitute a natural complement to the HERA *ep* programme.

iii) The study of the structure of polarised nucleons. The HERA proton beam may be polarised. This would allow measurements of double spin asymmetries to be pursued at HERA. For spin physics that would make a huge difference as compared to fixed target experiments which usually suffer from a narrow kinematic phase space and non-perturbative effects. Asymmetries at large Q^2, as in CC scattering, are large while spin effects at low x, such as the A_1 asymmetry, which determines the polarised gluon density in the proton, are proportional to x and are thus small. Consequently, HERA spin physics would require high luminosities, of the order of $1\,\mathrm{fb}^{-1}$, to be available. Polarisation of deuterons may be easier to obtain because of the reduced anomalous magnetic moment which implies that less resonances are to be crossed as compared to the polarised proton case.

The HERA III programme would require to build a new injector for protons. A new detector was proposed to be built for low x physics and the H1 detector was proposed to be kept and upgraded. The fixed cost for making HERA an eN accelerator complex would be much lower than the investment HERA represents. Apart from the spin programme only low luminosity is required. This for the low x and the eA physics one could operate the machine for only a small fraction of time reducing the cost of its operation in electricity and manpower. With external contributions from the international community HERA III could still be realised. This would not start before 2010 since time is required to build a new 40 GeV proton synchrotron in a new tunnel.

3.2. *eRHIC and ELIC*

At Brookhaven, the eRHIC project (17) is designed to provide high luminosity electron-nucleon interactions at the RHIC ion collider complemented by a ring, or perhaps linear, electron and positron accelerator. The design energies are $E_e = 10\,\mathrm{GeV}$ and $E_p = 250\,\mathrm{GeV}$, i.e. $\sqrt{s} = 100\,\mathrm{GeV}$ which is three times less than HERA. This loss in energy is expected to be partially compensated by an increase in luminosity. HERA, after its luminosity upgrade is reaching peak luminosities of up to $5 \cdot 10^{31} cm^{-2} s^{-1}$. The eRHIC design (17) is expected to lead to higher luminosity than HERA, of up to $10^{33} cm^{-2} s^{-1}$, in dedicated mode, and of $4.4 \cdot 10^{32} cm^{-2} s^{-1}$ with ion collisions at two further interaction points. At JLAB a plan is being developed (18) for an "Electron Light Ion Collider" of energies between 3-7 GeV for electrons and 30-150 GeV for nucleons. By using energy recovering techniques a design is made with luminosities of up to $8 \cdot 10^{34} cm^{-2} s^{-1}$.

The physics programme at eRHIC/ELIC is very similar to the HERA III physics programme sketched above. These machines are complementary as HERAIII has much higher energy while the others are designed to have much higher luminosity, which is an advantage for spin physics and high x but of no particular relevance for low x physics. If precision QCD were more highly prioritised, both lower and the higher energy programmes would be completely realised as were several DIS experiments performed in the past. Testing QCD is to a large extent demanding high precision in a large kinematic range. Several independent experiments have often been required for measurements to be correct. As much as HERA III profits from HERA to exist, eRHIC would be an add on to the existing RHIC machine complex. The plan for eRHIC (19) is to have first collisions in 2013/2014. The ELIC project (18) is in an R+D phase regarding the possibility to achieve high bunch currents, beam polarisations and using energy recovery before a time schedule can possibly be made.

4. Towards DIS physics at the TeV Scale

Today much of the world's particle physics attention is devoted and focused to the Large Hadron Collider (LHC), a 7 TeV proton ring collider which leads to typical parton-parton cms energies of $\sqrt{s} \simeq 2xE_p \sim 2\,\mathrm{TeV}$ with a maximum of 14 TeV. There are theoretical predictions which let us hope for the discovery of the Higgs particle which explains the masses at the elementary fermion level while the colour force, QCD, generates the baryonic matter of the universe Genuine unification of the fundamental forces within perhaps supersymmetric theories may be found. The LHC is thus the greatest adventure of modern particle physics as a genuine discovery machine with the potential of finding phenomena beyond the current theoretical expectation. If there is nothing new occuring, theoretical dogma will need to be revised and the LHC will be a machine to study QCD at high scales.

The LHC should be accompanied by a linear collider at high energies in order to be able to study the physics at the TeV scale, perhaps the spectrum of SUSY particles, in a rather clean environment. Much effort has been spent following the legacy of Bjoern Wiik in order to develop the technology and design of what is now called the International Linear Collider (ILC). In the current version this is a two-arm 250 to 500 GeV superconducting machine corresponding to a cms energy of up to 1 TeV. Given the cost of the ILC and current plans, it is obvious that the detailed parameters of the ILC will not be decided prior to the LHC finding new physics for which the ILC is suited. Thus the energy of the linear collider will be an open issue until then. This also implies that there is a decade with essentially only the LHC as the only high energy accelerator base for particle physics unless decisions regarding HERA and/or the TeVatron are revised.

On the time scale of the LHC and the ILC the physics of DIS needs to conquer the TeV scale. It is obvious from the past development of particle physics, sketched in the introduction, that lepton-nucleon experiments at the energy frontier have been of very high importance for particle physics. The physics of DIS at the TeV scale is extremely rich. It has been summarised in a series of studies on a LEP $\times$ LHC *ep* machine (20) and more recently on THERA (21), a HERA $\times$ TESLA *ep* option of the cold linear collider. Since the cross section falls rapidly with Q^2, luminosities of the order of a fb^{-1} or more are required to study the smallest distance region accessed by the new accelerators. In case leptoquarks are discovered at the LHC a polarised $e^{\pm}$ proton machine is ideally suited to study their spectroscopy. At energies as large as 1 TeV or beyond in DIS, major questions regarding low x physics (regarding parton distributions and the saturation of the rise of the gluon distribution, the nature of diffraction and the heavy quark structure of the photon, for example) can be studied much deeper than at HERA, and with low luminosity. At high Q^2 new effects such as parton substructure at 10^{-19} m may be discovered and investigated.

The next generation of colliders is not cheaper than the previous one, and huge efforts are needed to realize any of these steps. An *ep* machine is most economically realised combined with the ILC electron or the LHC proton beams. It thus is cost effective, in particular if one used the HERA, or the Tevatron, proton ring magnets together with the ILC. The physics of DIS at the TeV energy scale may thus be realised as a 500 $\times$ 1000 GeV^2 ILCp or a 70 $\times$ 7000 GeV^2 eLHC complex. A symmetric machine requires an extended detector in the e beam direction to measure scattered electron at low x. An asymmetric machine requires special detection efforts for the forward going hadronic final state to access the region of large x. Detectors for an *ep* collider do not pose extraordinary difficulties, see (20; 21) and Fig.4. With the precision measurements of proton structure and the potential for new physics, deep inelastic scattering will remain a unique and necessary part of particle physics. Not to pursue this field further would be a terrific mistake and irrevocable loss for our attempt to reveal the secrets of nature.

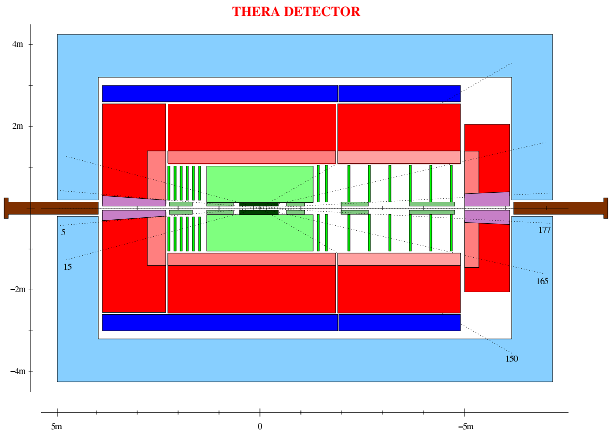

Fig. 4. Sketch of a detector for experimentation at THERA, a *ep* machine of 500 $\times$ 1000 GeV^2 of energy. The right part of the detector is designed for low x physics. It is removeable for operation at maximum luminosity with focusing magnets placed close to the *ep* interaction region. In the THERA design annual luminosities of several hundreds of pb^{-1} were estimated to be achieveable.

5. Summary

Deep inelastic scattering has made enormous progress over the past decades, in particular due to HERA and the collider experiments H1 and ZEUS. The physics at HERA is by far not exploited and vital elements of QCD need to be developed further. This already led to completely unforeseen developments, such as low x physics, hard diffraction and generalised parton distributions. With high luminosity and further improved accuracy HERA may still radically change our view of the smallest structure and find new phenomena beyond the Standard Model. Non-perturbative QCD effects, the sea asymmetry at low x, instantons, odderons, pentaquarks, or the transition from the soft to the DIS region are yet to be explored.

HERA is expected to be closed in 2007. Its programme can not be completed by then and its scientific potential will not have been explored. This would represent a failure to fully exploit an investment of about 1 Billion Euro and of a huge experience accumulated in the past. This loss is not balanced, neither by the vision for the ILC nor by the use of HERA's injector ring PETRA for synchrotron radiation research.

The TeV scale may open the chapter of Higgs physics and may discover supersymmetry, i.e a rich new spectrum of particles. Likely it will be different. In any case an *ep* collider at the TeV energy scale is necessary to further develop QCD, to complement new physics searches at the LHC and the ILC thus maintaining the symbiosis of *pp*, e^+e^- and *ep* experiments which over the last 4 decades established the Standard Model. That will be overcome by a more profound theory which has to include QCD. Until the TeV scale is really reached there is a decade of time in which many fundamental questions ought to be solved and new ones will be posed.

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References

[1] For a review and references see: M. Klein, "Quantum Chromodynamics at High Energies at HERA", Inv. Talk. at ICHEP, Beijing 2004, Proceedings, to appear.

[2] T. Greenshaw, Radiation in QCD - Results from HERA, http://www.x4u.lebedev.ru/che2004/

[3] For an overview over the rich field of DIS, see recent proceedings of the annual workshop series on deep inelastic scattering, DIS03 St. Petersburg, DIS04 Strebske Pleso and DIS05 Madison.

[4] C. Adloff, H1 Collaboration, Eur. Phys. J. **C30** (2003) 1.

[5] S. Chekanov et al., ZEUS Collaboration, DESY 05-050 (2005), submitted to Eur. Phys. J.

[6] J. Morfin, The Minerva Project, http://www.pas.rochester.edu/ ksmcf/minerva/Jorge-PAC03.pdf.

[7] S. Moch, J. Vermaseren and A. Vogt, Nucl. Phys. **688** (2004) 101 and **691** (2004) 129.

[8] S. Brodsky et al., Phys.Rev. **D65** (2002) 114025.

[9] A. Martin, M. Ryskin, G. Watt, Eur.Phys.J. **C37** (2004) 285.

[10] A.H. Mueller, Nucl. Phys. B (Proc. Suppl.) **18C** (1990) 125.

[11] E. Iancu and L. McLerran, Phys.Lett. **B510** (2001) 145.

[12] G. Altarelli, R. Ball and S. Forte, Nucl.Phys.Proc.Suppl.135 (2004) 163.

[13] For a review see M. Diehl, Phys. Rep. **388** (2003) 41.

[14] A.V. Belitsky and D. Müller, hep-ph/0206306.
For a review see: A.V. Belitsky and A.V. Radyushkin, hep-ph/0504030.

[15] A. Airapetian et al., Phys. Rev. Lett. 87 (2001) 182001

[16] T. Alexopoulos *et al.*, eD Scattering with H1, A Letter of Intent, DESY 03-194;
H. Abramowicz *et al.*, A New Experiment for HERA, MPP-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/.

[17] eRHIC homepage, http://www.phenix.bnl.gov/WWW/publish/abhay/

[18] R. Ent, Report to NSAC Subcommittee, BNL, June 2004, http://nsac2004.bnl.gov/pres/ent.pdf.

[19] R. Milner, Report to Barnes Committee, June 2004, eRHIC web page (17).

[20] J. Feltesse and R. Rückl, Talks at the LHC Workshop, Aachen 1990, CERN 90-10 (1990), Proceedings Vol.1 p.219, 229, eds. C. Jarlskog and D. Rein.

[21] The THERA Book, *ep* Scatering at $\sqrt{s} \sim$ 1 TeV, DESY 01-123F, eds. U. Katz, M. Klein, A. Levy and S. Schlenstedt.