HERA-3*

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A brief review is given on the physics potential of HERA beyond the presently approved programme. Questions of particular interest include QCD in a regime of weak coupling and high partonic densities achieved in eA collisions and spin physics with polarized colliding beams. Those two distinct programmes can be naturally merged and even substantiated by using polarized and unpolarized deuterons at the starting phase of the HERA-3 run. Basic machine implications and detector requirements are also discussed.

1. INTRODUCTION

HERA, an electron-proton facility at DESY, serves two collider and two fixed target experiments. H1 and ZEUS explore high centre of mass energy up to 318 GeV to investigate a structure of the proton at smallest achivable dimensions $\mathcal{O}(10^{-18}\mathrm{m})$. HERMES focuses on spin physics using 27.6 GeV polarized lepton beam with $\langle P_b \rangle \approx 55\%$ and different polarized targets. HERA-B studies charm and beauty sector of the Standard Model by utilizing 920 GeV proton beam interacting with internal wire target.

First running period, so called HERA-1, was completed in year 2000 and has delivered 120 pb^{-1} per collider experiment. Presently, after the luminosity upgrade, data taking has started at HERA-2 with the aim being to collect polarized $\vec{e}p$ scattering data of 1 fb^{-1}. To fully exploit the potential of this unique facility it is proposed to extend its running for another five years available between HERA-2 and TESLA [1] – a major future international HEP project. This third running period, termed here HERA-3, would provide yet deeper insight into fundamental QCD questions, which is not possible in present HERA configuration.

2. QCD PHYSICS AT HERA-1 AND PROSPECTS FOR HERA-2

Before discussing the future of lepton-nucleon scattering let see what did we learn at HERA and where will we be by the year 2006/7, the end of the HERA-2 data taking period. In this context we focus on QCD aspects and the structure of the nucleons.

Low x physics and related to that diffractive DIS constitute a major impact of HERA data on QCD in its high energy limit ($x \propto Q^2/s$). The discovery of the strong rise of the proton structure function F_2 at low x has triggered a discussion about when and how

*Contribution to the Proceedings of QCD-N'02 Workshop, Ferrara, Italy, 3-6 April 2002 this steep rise should slow down due to parton saturation. Fig 1a shows that NLO QCD using linear DGLAP evolution equations is able to describe inclusive DIS data in whole x range down to very low Q^2, $\mathcal{O}(2\mathrm{GeV}^2)$. This suggests the saturation regime is not yet reached at HERA.

Still, since the low-x behavior is governed by gluons one may hope first to see a sign of saturation in diffraction whose cross section is proportional to the gluon density squared: $\sigma_{diff} \propto |xg(x)|^2$. Indeed, by comparing the energy rise of the inclusive and diffractive DIS cross sections, parametrised as $\sigma_{tot}(\gamma^* p) \sim W^{2\lambda(Q^2)}$ and $\sigma_{diff}(\gamma^* p) \sim W^{4\lambda(Q^2)}$ respectively, one can see some systematic shift between the two (Fig. 1b). The error bars for diffractive points are still large, and one of the tasks for HERA-2 is to improve precision of F_2^D measurement and to quantify this so far only qualitative statement.

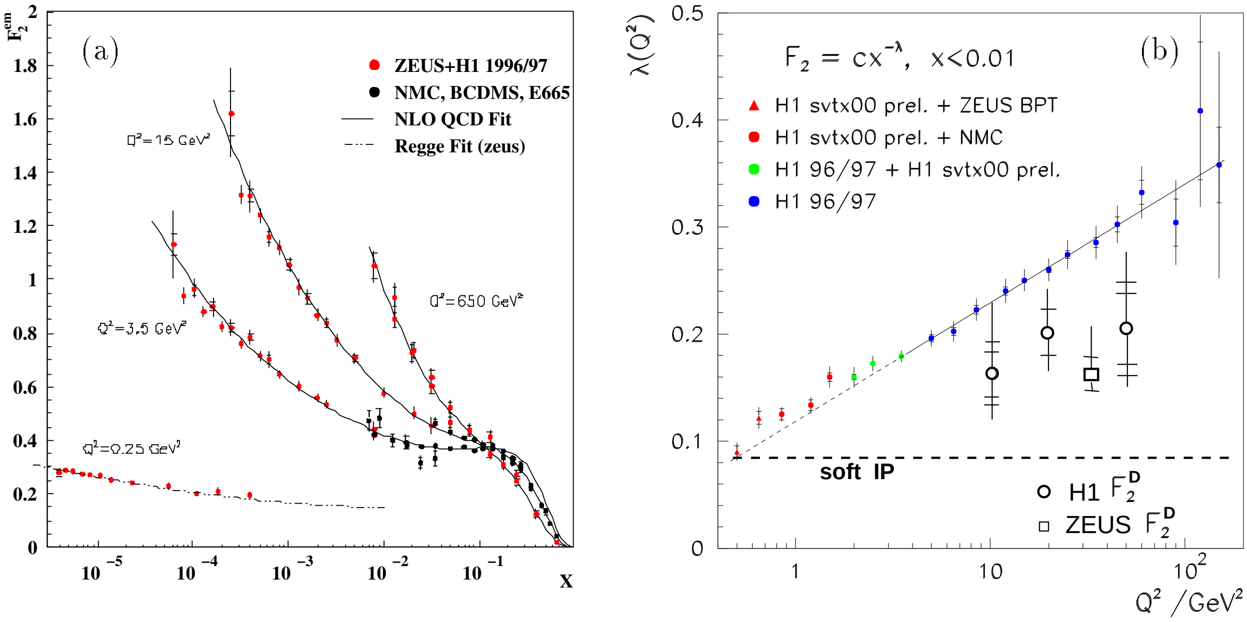

Figure 1. a) Proton structure function at low x and different Q^2; b) The low x behavior of the proton structure function in inclusive and diffractive DIS.

To summarize, there is a controversy about parton saturation at HERA, both between theorists and experimentalists. It is believed that the saturation scale [2,3], $Q^2_{sat} = \alpha_s N_c \frac{dN_g}{dy} / \pi R^2$, is too small in HERA-ep. One needs conditions when linear DGLAP evolution equations break down unambiguously and the parton shadowing effects (or the processes of gluon recombination) become apparent yet in perturbative domain ($Q^2_{sat} \gg \Lambda^2_{QCD}$, $\alpha_s(Q^2_{sat}) \ll 1$). In order to achieve this, gluon density should somehow be magnified. It is possible either by increasing energy, $xg(x,Q^2) \sim s^{\lambda(Q^2)}$ (THERA [4] option), or by using nuclear target instead of protons, $xg_A(x) \sim A^{1/3} xg_p(x)$ (HERA-3, EIC [5]). As an example, eCa^{40} scattering at HERA-3 would be equivalent in terms of gluon density to $1.8\mathrm{TeV}(e) \times 0.9\mathrm{TeV}(p)$ collider.

Another important aspect of QCD is the spin structure of the nucleon. How do the partons conspire to ensure the total spin of the nucleon is 1/2? As quarks cannot account for the total nucleon spin (the fact known since 1988 as "spin crisis") it is important to measure other components: gluon polarization ΔG and orbital angular momenta $L_{q,g}$. In that respect first determination of ΔG by HERMES shown in Fig. 2a is one of the highlights of HERA-1, in spite of its limited precision. Anticipated quality of $\Delta G/G$ extraction by the end of HERA-2 in different fixed target experiments is illustrated in Fig. 2b.

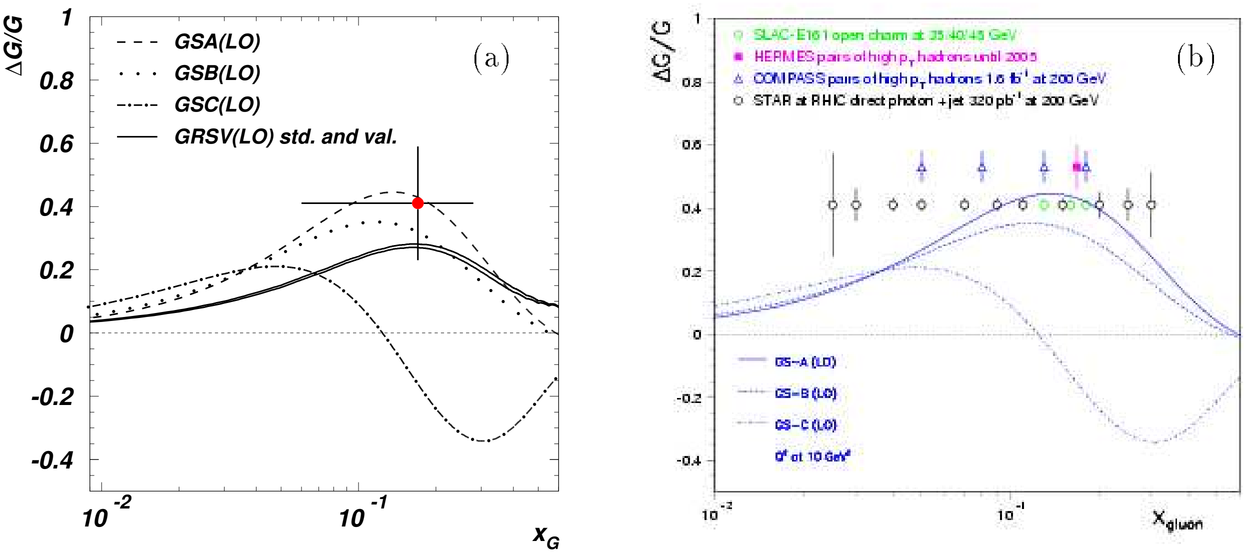

Figure 2. a) Gluon polarization as extracted by HERMES from photoproduction of high p_t hadrons [6]. b) Projected precision of the gluon polarization extraction in different experiments, by the end of HERA-2 [7].

There are however two intrinsic problems with ΔG measurement at fixed target: a) majority of gluons are concentrated below accessible x range and b) strong model dependence of the result, as higher scales are necessary for the reliable extraction of gluon polarization. Additional advantage of higher energies is that several methods can be used to measure ΔG: from scaling violation of $g_1(x, Q^2)$, from dijet events and - statistics permitting - from heavy quarks ($\gamma g \to c\bar{c}$). This motivates the use of the collider mode for such kind of measurements.

3. HERA-3 OPTIONS

Two main possibilities for HERA-3 have been investigated at previous workshops: lepton-nuclei collisions [8] and physics with polarized colliding beams [9]. They were recently summarized in [10]. It has been shown that electron-deuteron scattering appears to be a natural next step following the ep running. It is not only a first part of eA

programme, but also enables F_2^n measurements, which is important on its own. Moreover, due to the small anomalous magnetic moment of the deuteron the polarization is much easier to achieve with deuteron beam than with protons [11]. Hence this option can unify "spin" and "nuclear" physics communities at HERA-3.

3.1. Physics subjects

To summarize, the physics objective for HERA-3 is to shed more light on the partonic structure of the neutron, on the nucleon spin decomposition (especially at low x and at high Q^2 domains) and on the problem of gluon saturation and confinement. In particular, is so called Colour Glass Condensate [3] indeed a new form of matter in high energy limit of QCD?

Key measurements in high energy eA collisions include the ratio $\sigma_{diff}/\sigma_{tot}$, which is predicted to approach the black body limit of 1/2 for large A. A-dependence of the vector meson production, $\sigma_{VM}(x, A)$, is expected to change the behavior from colour transparency ($\sim A^{4/3}$) to colour opacity ($\sim A^{0.4}$) with decreasing x. Inclusive structure function should violate DGLAP: $F_2 \sim Q^2 \ln(x_0/x)$. These measurements at HERA-3 will also be valuable to understand more complicated heavy ion collisions and could be important for LHC.

For polarized beams one would measure g_1 at low x where it is essentially unknown. Structure function g_5 can be for the first time determined from charged current asymmetries. DVCS will give access to the off-diagonal parton distributions at low x. It is important to stress that the study of spin phenomena in this new kinematic domain will be enhanced by the comprehensive reconstruction of the final state possible in colliding beam experiments.

3.2. Machine Aspects

Typical measurements listed in previous subsection put definite requirements on the machine parameters. In case of polarized beams scattering most essential are high luminosity, $\mathcal{L} \approx 500$ pb^{-1}, and beam polarization. This is because one typically measures very small asymmetries at low x, or low cross sections at high Q^2. In case of proton beam one would need spin rotators, flattening snakes and at least four Siberian snakes to maintain polarization. Hence deuteron option looks very attractive, as there is good hope to use transverse RF dipoles to rotate and stabilize longitudinal polarization [11] and thus to avoid complicated Siberian snake scheme. An open question is a high quality source of polarized deuterons.

In contrast, expected effects and measured cross sections are large in eA collisions. Hence moderate luminosity is sufficient: $\mathcal{L} \cdot A \approx 10$ pb^{-1}/ion. Low beam divergence is appreciated to minimize the p_t smearing for elastically scattered and spectator nucleons. Most complicated ingredient for this programme is electron cooling, which is required for $A > 4$ nuclei in order to keep an acceptable life time of the ion beam. Another interesting question which deserves additional studies is a possibility to fill and circulate different A bunches simultaneously. This would reduce systematics in all measured A-dependencies drastically.

In Fig. 3 HERA is compared to other facilities and in particular to the EIC [5]. The two projects are complementary both in the covered phase space and in the planned commissioning time. Although the EIC is superior in terms of anticipated luminosity it

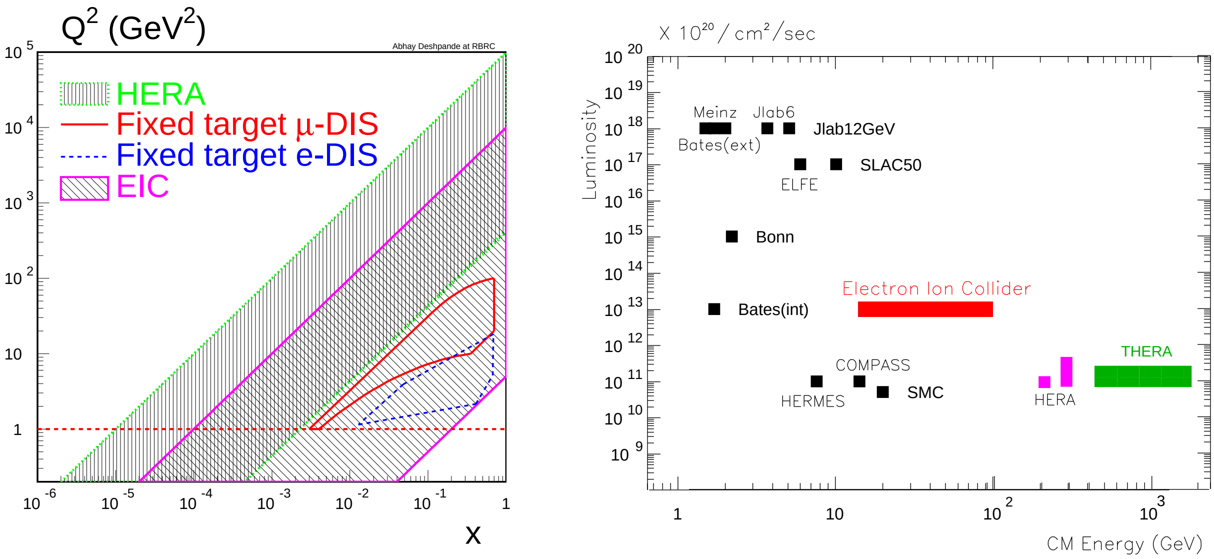

Figure 3. Comparison of the existing and proposed eA and polarized $\vec{e}\vec{N}$ experiments. Two entries for HERA correspond to eA and ep configurations respectively.

can use earlier HERA-3 results to tune its physics programme.

3.3. Detector Requirements

Several options are possible of the experimental setup at HERA-3:

- Retain existing setup: two colliding and one fixed target experiment (H1, ZEUS, HERMES). This in addition would allow to continue fixed target spin programme at HERA.

- Only one general purpose collider detector. This helps saving resources and concentrating efforts, and is also simpler for the machine tuning and stability.

- Two collider detectors optimized for different physics: low x oriented – high acceptance, p/n-tagging capabilities, small beam divergence, and spin physics oriented – high $\mathcal{L}$, polarization, large statistics (stronger focusing, no beam-line detectors).

Current evaluations show that main components of the present H1 and ZEUS detectors could be reused for HERA-3. Some modifications in central tracking and electronics may be necessary. For eA programme an essential requirement is an efficient nucleon tagging capability. To study coherent diffraction $eA \to eAX$ large acceptance H1 VFPS stations [12] at $z = 220$m from interaction region can be used. The existing Forward Neutron Calorimeter [13] at $z = 107$m is important to distinguish central and peripheral eA collisions by the number of detected wounded and evaporated neutrons. Finally, to select $en + p_s$ events in eD scattering a proton tagger with good t resolution (to distinguish spectators from elastically scattered protons) has to be built and installed at around $z = 90$m.

4. CONCLUSIONS

HERA is so far a unique lN collider and its potential must be fully exploited. It is clear that even with high precision HERA-2 data a number of fundamental questions in QCD will remain open. HERA-3 can provide new information for at least three items of prime importance:

- What is the partonic structure of the neutron at low x and at large Q^2, x ?
- What is the origin of confinement, and how can QCD describe a regime of high parton density and weak coupling where cross sections ought to saturate?
- What is spin structure of the nucleon, especially at low x?

Since most of the infrastructure and the apparatus are in place such a programme can be realized with relatively moderate investments in three steps: eD, $\vec{e}\vec{D}$, $eA(A = O^{16}, Ca^{40})$ collisions. The project is complementary to the planned future EIC facility and may provide additional valuable information for the latter.

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