FUTURE OF SMALL-x AND DIFFRACTION AFTER 2006 (EXCEPT LHC)*

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The initial phase of HERA running has produced exciting and fundamental results on the nature of strong interactions. These results are summarized, and the case is made for a new round of precision measurements on low-x and diffractive physics.

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1. Introduction

The HERA accelerator has provided a wealth of results on proton and photon structure, diffractive and exclusive production of different states, jet and particle production, $\alpha_{\rm S}$ measurements, limits on exotic particle production, *etc.* [1]. The most important results to date are the measurement of the steep rise of the structure function F_2 at small-x [2], and the measurement of a large diffractive cross section [3]. These measurements are of fundamental importance and have generated intense activity in trying to understand their physical origin.

A further round of experiments designed with this physics in mind, at the EIC, with HERA-III, or with a combination of TESLA and HERA (THERA) could lead us to a much better understanding of the physics opened up by the HERA data. The possibility of colliding leptons on nuclei, as well as polarized lepton on polarized nucleon (nucleus) would add valuable information beyond standard unpolarized lepton-nucleon scattering. As this workshop makes clear, we are still struggling to find the best approach to understanding the strong interactions. Theoretical breakthroughs are needed, and new measurements could show the way.

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2. Physics goals of HERA colliding beam experiments

The original physics goals for the HERA experiments can be summarized with a few quotes from ZEUS Technical Proposal (March 1986):

- "HERA [is] first and foremost an electron quark collider ...".
- "The measurement of the proton structure functions gives access to three domains of physics: electron and quark substructure; properties of the electroweak current; QCD interactions".

under QCD interactions, we find:

- "Measurements of the quark and gluon structure functions and their logarithmic dependence with Q^2 should allow a precise measurement of the strong interaction parameter, $\alpha_{\rm S}$".
- In addition, we find some comments on the search for exotic particles and photoproduction experiments.

There is no mention at this time of low-x physics or diffraction. Small-x physics, due to kinematics, is small-Q^2 physics, and small Q^2 implies primarily small electron scattering angles. The granularity, acceptance and resolution of the detectors were not optimized in this region. Both H1 and ZEUS upgraded their detectors in this 'rear' direction, with significant improvements in position and energy resolution, and increased kinematic coverage, but a new detector could offer much improved measurements.

Diffractive physics, $eP \to ePX$, requires an outgoing scattered proton. ZEUS and H1 equipped the forward region with proton spectrometers, but these have small acceptances limiting their usefulness for diffractive measurements. In fact, the large diffractive cross section at HERA was discovered by seeing a rapidity gap in the main detectors in the proton direction. A new detector with strong emphasis on diffractive measurements could have great impact on our understanding of this physics.

3. Structure function measurements

An extract of early HERA data is shown in Fig. 1.

The HERA data demonstrated the now well-known rise of F_2 with decreasing x. The rise in F_2 depends strongly on Q^2. An early question was 'how low in Q^2 does this rise persist'? The H1 and ZEUS detectors employed upgrades to address this question. A summary of the the rise of F_2 at small-x is made by fitting F_2 to the form $Ax^{-\lambda_{\rm eff}}$ for $x < 0.01$ for fixed Q^2, and is shown in Fig. 2. The H1 collaboration has shown new results at this conference (presentation by T. Laštovička) in the Q^2 range around

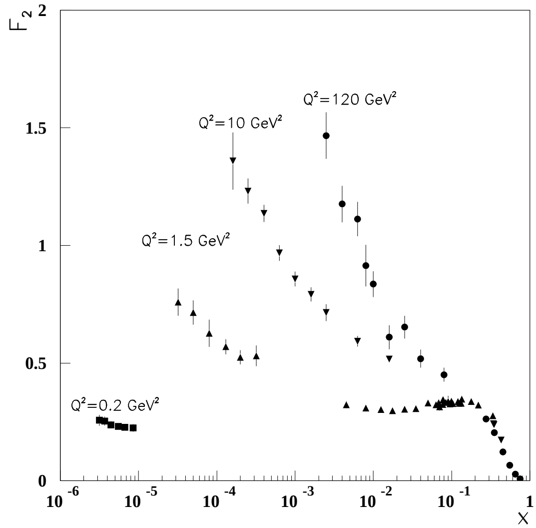

Fig. 1. Some of the early HERA data on the proton structure function F_2.

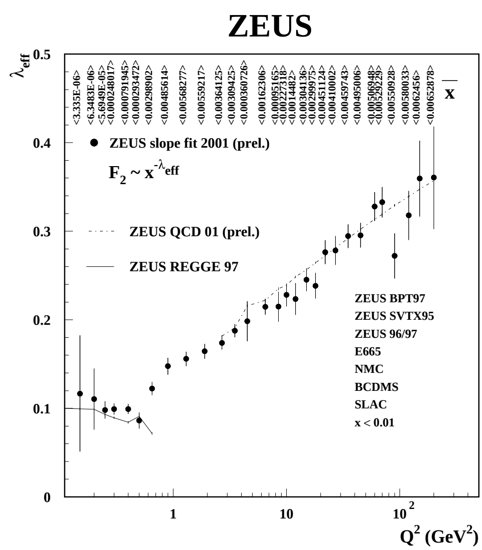

Fig. 2. Effective power of F_2 at small-$1/x$ *versus* Q^2.

1 GeV^2, showing that the behavior of $\lambda_{\text{eff}} \propto \ln Q^2$ extends down to these Q^2 values. These data, in conjunction with the ZEUS BPC/BPT data indicate a transition in λ_{eff} around $Q^2 \approx 0.5$ GeV^2.

An important question raised by the HERA data is whether this transition can be understood within QCD. Note that the region around $Q^2 \approx 1$ GeV^2 is not measured very precisely at HERA, since the main detectors have limited acceptance at this Q^2, and special detectors installed later measure at lower Q^2. Special runs, such as the 'shifted vertex' runs used by H1 help, but typically do not yield the same precision results as standard data.

4. Gluon density

The behavior of F_2 is shown *versus* Q^2 at fixed x in Fig. 3.

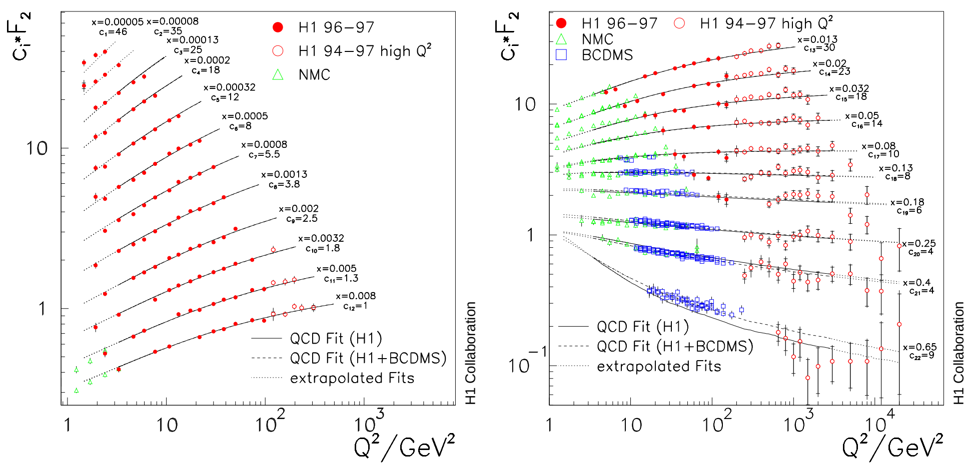

Fig. 3. Proton structure function F_2 plotted *versus* Q^2 at fixed x.

At large-x, the gluon density is small, and $dF_2/d\ln Q^2$ is used to extract α_S. At small-x, scaling violations are dominated by the gluon density, and in LO pQCD, $dF_2/d\ln Q^2 \propto \alpha_S xg(x,Q^2)$. The gluon density from a full NLO DGLAP fit is shown in Fig. 4. At smaller Q^2, it is observed that the fits yield a vanishing NLO gluon density at small-x, while the quark density is still rising. These results are non-intuitive, and may signal the presence of screening or other types of corrections. More precise data from ZEUS were presented at this conference by E. Tassi, showing the contrasting behavior of the gluon and sea densities even more strongly than previous analyses. The ZEUS fits additionally show that F_L has a tendency to become negative at small Q^2 (less than about 1 GeV^2) and small-x, which is of course physically impossible. These results are indications that NLO DGLAP evolution is not sufficient to describe the data in this kinematic regime. Similar conclusions were reached by D. Haidt and the R. Thorne (representing the MRST group) at this workshop.

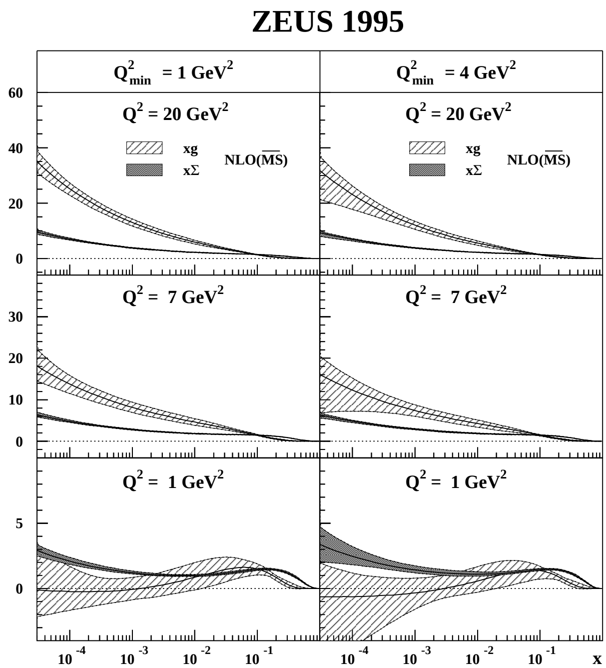

Fig. 4. The gluon and quark momentum densities plotted *versus* x for different Q^2.

Again, precision data around $Q^2 \approx 1$ GeV^2 would be very useful in elucidating the breakdown of DGLAP in this region. Clearly, a precision measurement of $F_{\rm L}$ could play a big role in understanding the behavior of the gluon density and be a fundamental test of our understanding of the strong interactions.

5. Diffraction in DIS

The diffractive events were initially seen in the HERA data as excess events with large rapidity gaps — *i.e.*, events with no hadronic activity in the direction of the proton beam. Events were later analyzed where the outgoing proton was tracked, allowing a measurement of the t-dependence of the diffractive cross section. However, the bulk of the physics results stem from data integrated over t, *e.g.*, as shown in Fig. 5. These data have high precision and yield a wealth of information, but events where the proton has dissociated cannot be clearly separated, and models must be used to perform a subtraction leading to substantial systematic uncertainties.

A striking observation is that the diffractive and DIS cross sections have very similar energy dependences. This is seen in Fig. 6. This is a non-trivial observation which has generated considerable theoretical activity, such as the

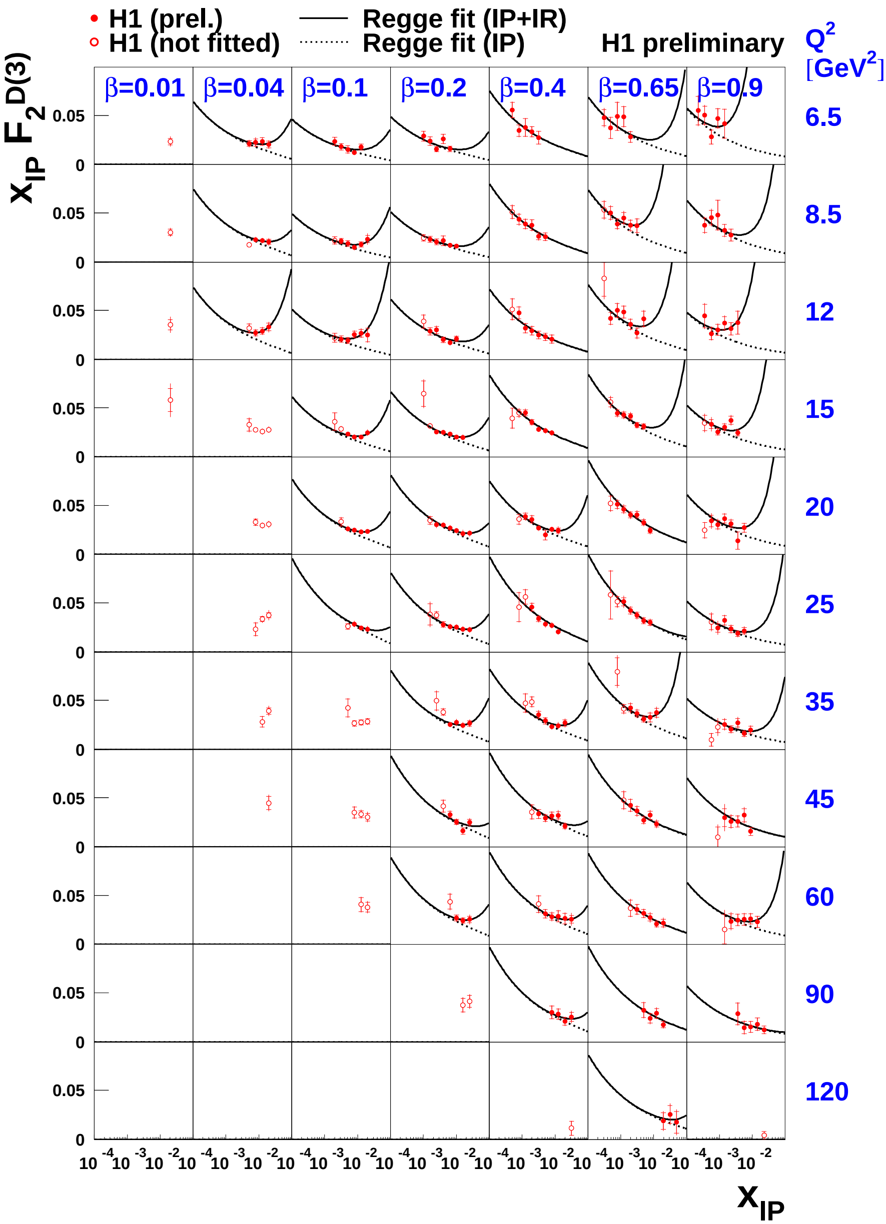

Fig. 5. The diffractive structure function $F_2^{D(3)}$ at HERA.

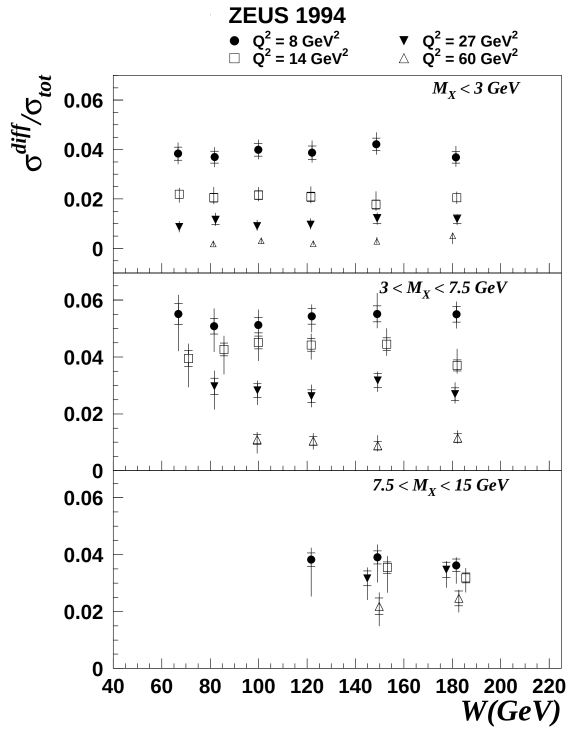

Fig. 6. The ratio of the diffractive to total $\gamma^* P$ cross sections as a function of the $\gamma^* P$ center-of-mass energy for different Q^2 and masses of the diffractive final state.

development of the Golec-Biernat & Wüsthoff model of small-x DIS [4]. A full understanding of diffraction will undoubtedly require the measurement of the full 4-dimensional diffractive cross section, which would require high acceptance forward proton spectrometers.

6. Future options

I have given a brief outline of the main HERA results in small-x physics in the preceding section. Here, I list some of the possible future experiments/accelerators which could yield further insight into the physics questions discussed above.

6.1. EIC

The Electron Ion Collider (EIC) is a facility currently under discussion at BNL [5] for colliding RHIC ions with a future electron beam. Several possibilities are under discussion for the electron beam, with typical electron energies of 3–10 GeV considered. The physically allowed values of $1/x$ and Q^2 are one order of magnitude lower than HERA. However, the EIC would be designed for high luminosity ($10^{33} \rightarrow 10^{34}/\mathrm{s}/\mathrm{cm}^2$). It would also naturally allow scattering on very heavy ions such as gold, and also scattering on longitudinally polarized protons.

Scattering on heavy ions provides a complementary approach to the physics of high parton densities. At HERA, high gluon densities are achieved by probing at very small-x, where the gluon density is rising quickly with decreasing x. On the other hand, an incoming lepton beam would see a large density of partons (in the transverse plane) from overlapping nucleons when crossing a heavy nucleus, at not such small-x. Comparison of the data from these two kinematic regions are expected to provide insight into the behavior of QCD in a novel regime of high densities and small coupling [6]. This data is likely to play a crucial role in understanding the formation of a quark-gluon plasma.

The scattering of polarized electrons on polarized protons will address the issue of the spin content of the proton carried by small-x partons. Here, the high luminosity planned for the EIC will be crucial since spin structure functions are measured as differences of cross sections.

Reference [5] should be consulted for a more complete list of measurements possible at the EIC.

6.2. HERA-III

The first phase of HERA running ended in 2000 and included the discoveries of the rise of the parton densities at small-x and the large diffractive DIS cross sections. HERA is now entering a second phase of running which will bring considerably larger luminosities as well as the possibility of longitudinally polarized leptons for the H1 and ZEUS experiments. This HERA-II phase has as a goal 1 fb^{-1} per experiment distributed among $e^{\pm}_{\mathrm{L,R}}$ as determined by the experiments. This high luminosity and polarization will open up the era of large-x and large Q^2 measurements at HERA, and will allow tests of the electroweak sector of the Standard Model. The HERA-II phase is expected to extend until the end of 2006.

There are many reasons to consider further running of HERA beyond the HERA-II phase. For example, one could consider:

- Electron-deuteron scattering, to study the partonic structure of the neutron at low-x, and to unfold individual parton densities at high-x.
- Precision diffractive and non-diffractive measurements, to study the transition seen in HERA data around 1 GeV^2, to measure longitudinal structure functions and 4-dimensional diffractive cross section. These will severely constrain models and hopefully guide us in our understanding of small-x physics.

- Electron-nucleus scattering, to understand the parton distributions in heavier nuclei, and for another approach to the saturation of parton densities ($A^{1/3}$ increase in parton density at given Q^2).
- Polarized structure function measurements to understand the nature of spin in a nucleon.

These different physics topics would clearly place different constraints on HERA, and would in some cases require the construction of a new detector.

6.3. THERA

One could also consider the scattering of high energy electrons from TESLA with HERA protons. This option has been studied in some detail, and is summarized in the TESLA technical proposal [7]. Separate small-x and high-Q^2 scenarios have been considered. Clearly, this approach would be the most straighforward extension of the small-x physics and could be an exciting successor of the EIC or HERA-III.

7. Conclusions

HERA has generated a very interesting and important discussion on the physics underlying small-x cross sections. At the heart of this discussion is the understanding of what happens in dense systems of virtual particles. These clouds of virtual particles can be probed at HERA with varying resolutions, thus giving a handle to understanding how they are formed. These clouds are universal, in the sense that they exist at the heart of any particle. They therefore represent a fundamental aspect of nature, and certainly warrant deeper study. Possibilities for such future measurements which have been discussed are the Electron–Ion Collider at BNL, and HERA-III and THERA at DESY. These facilities would present largely complementary approaches to the question of the behavior of large parton densities, and should all be considered seriously.

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