A NEW ROUND OF EXPERIMENTS FOR HERA

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A new round of experimentation with the HERA accelerator is discussed.

1 Introduction

QCD is the most complex of the known forces operating in the microworld. Myriad effects are seen in condensed matter physics resulting from simple non-relativistic quantum mechanical interactions between electrons. Imagine the possibilities resulting from strong interactions of large numbers of gluons and quarks. Further studies are bound to reveal new and exciting results which will challenge our existing paradigms.

QCD is fundamental to the understanding of our universe. As everyone knows, the bulk of the mass of the universe arises via the strong interactions - nearly massless quarks become massive baryons and mesons in the QCD potential. One can therefore speculate on deep connections between gravity and QCD. What is clear is that we need to understand the strong force at short and long distance scales. We believe we can make predictions for strong interaction effects at small distance scales where the coupling is weak. Can we do this at high energies ? Data from HERA on forward jet production already show weaknesses in our ability to make accurate calculations. As the distance scale increases, the strong interactions increase dramatically in strength, radiation is suppressed, and confinement sets in. How this comes about is not well understood, but HERA data clearly show this transition, e.g. in the change of the energy dependence of the total cross section around $Q^2 = 0.5$ GeV^2. Studying this transition from a partonic to a hadronic behavior of matter is of the highest importance, and would be a highlight of further HERA running.

The goal of further experimentation at HERA would be to follow up on the interesting effects already seen at HERA:

- disappearing gluons at small Q^2;
- transition from partonic to hadronic behavior of cross sections;
- forward particle (jet) production and disagreement with NLO DGLAP calculations;
- energy dependence of diffractive cross sections,

with new and/or improved detectors, and make new measurements which will qualitatively change our understanding:

- the longitudinal structure function, F_L;
- a full program of electron-ion collisions;
- scattering on polarized hadronic beams.

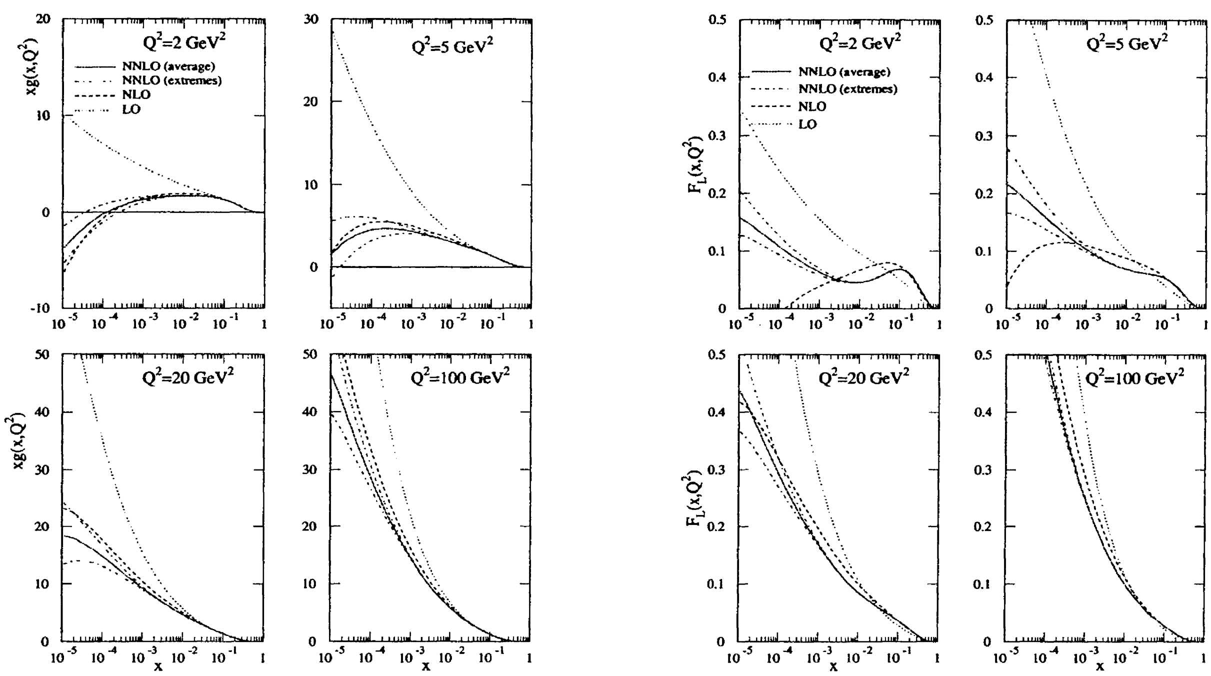


Figure 1: Solution of the DGLAP evolution equation for gluons (left) at different orders of perturbative expansion and the corresponding expectations for F_L (right), as a function of x for fixed Q^2 [3].

Two letters of intent were submitted to the DESY PRC in May 2003 to pursue this program [1, 2]. The first letter of intent focuses on measuring eD interactions with an improved H1 detector, while the second letter of intent proposes a new detector optimized to study the physics mentioned above. The LoI's will be described in more detail below.

It should be pointed out that the research program discussed in the LoI's cannot be carried out with the ongoing HERA running (HERA II). This program is intended to study high Q^2 physics with maximum luminosity, and is made possible by the insertion of accelerator elements near the interaction points, thereby limiting access to the small-x physics.

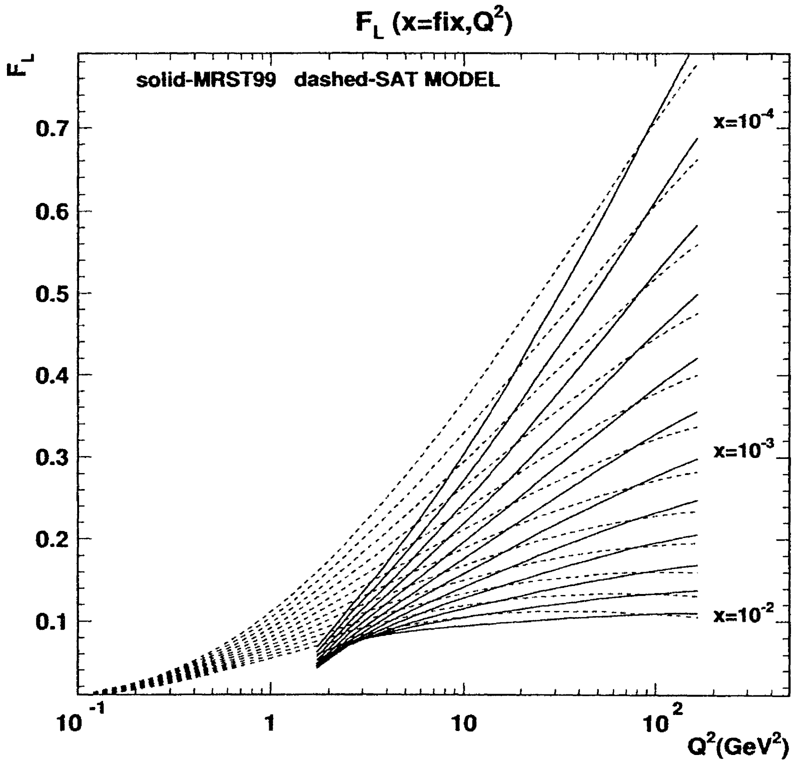


Figure 2: Comparison of the expectations for the Q^2 dependence at fixed x of F_L in the DGLAP approach (MRST99) and the saturation dipole model.

2 HERA III Physics Program

The proposed program goes by the name HERA III. The main research topics discussed in the LoI's are outlined here.

2.1 Precision Structure Function Measurements

It is proposed to measure the F_2, F_2^D, F_L, F_L^D structure functions in the range $0.1 < Q^2 < 100$ GeV^2. The gluon densities extracted at HERA show non-intuitive behavior, such as the tendency to go negative at small x (see Fig. 1). While this is not necessarily a breakdown of the calculational machinery, the fact that these gluon densities also result in negative going predictions for F_L clearly shows a break down in our understanding. More precise measurements of F_2, and measurements of F_L at small x will directly test our understanding of the gluon density. The measurement of F_L will also be a strong test of the popular dipole model [4], which makes significantly different predictions than current NLO DGLAP calculation (see Fig. 2).

Due to the lack of theoretical constraints, many parameters are needed to describe the shape of the parton densities. Many assumptions are required in order to limit the number of parameters below about 30. Once these assumptions are relaxed, the uncertainty on the extracted parton densities get much larger. One example is the assumption that $\bar{u} = \bar{d}$ at small x. The effect of removing this constraint is shown in Fig. 3. It is clear that more observables are required to experimentally constrain the parton densities. One such observable is F_L, which will provide a strong constraint on the gluon density at small-x. Running HERA in eD mode would give the information necessary to separate u and d quark distributions.

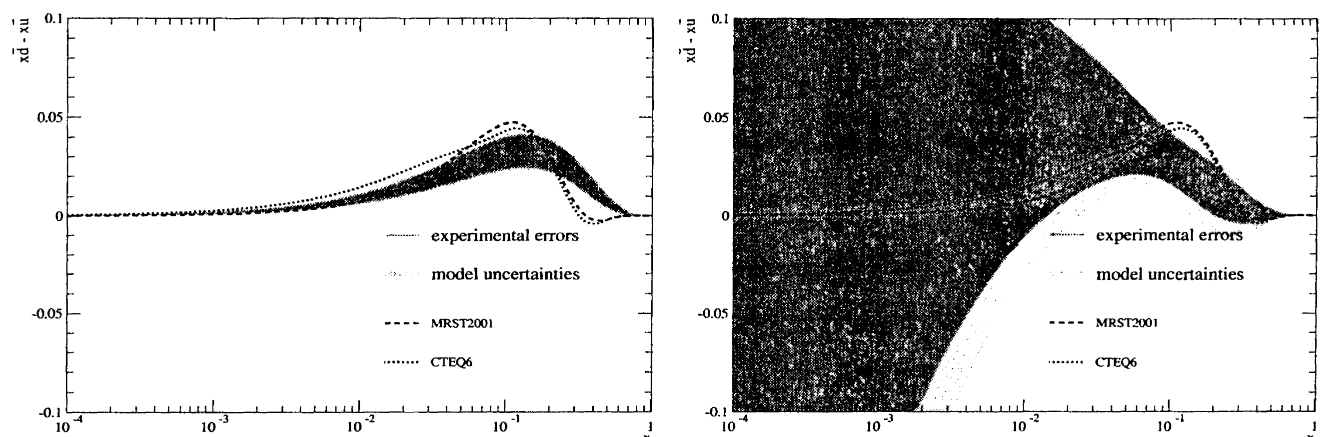


Figure 3: The sea quark difference at $Q^2 = 4$ GeV^2, as determined in a NLO QCD analysis [5]. Left: the constraint $\bar{u} = \bar{d}$ for $x \to 0$ is imposed. Right: the constraint is not imposed.

The structure function F_2 shows a particularly interesting x-dependence near $Q^2 = 0.5$ GeV^2, as shown in Fig. 4. Below this Q^2, the x-dependence is consistent with the energy dependence of hadron-hadron total cross sections, while above this Q^2 the energy dependence becomes significantly steeper. This transition signals a different physics mechanism at work (presumably hadronic degrees of freedom versus partonic degrees of freedom). A new experiment would focus on precision measurements with full acceptance in this Q^2 region.

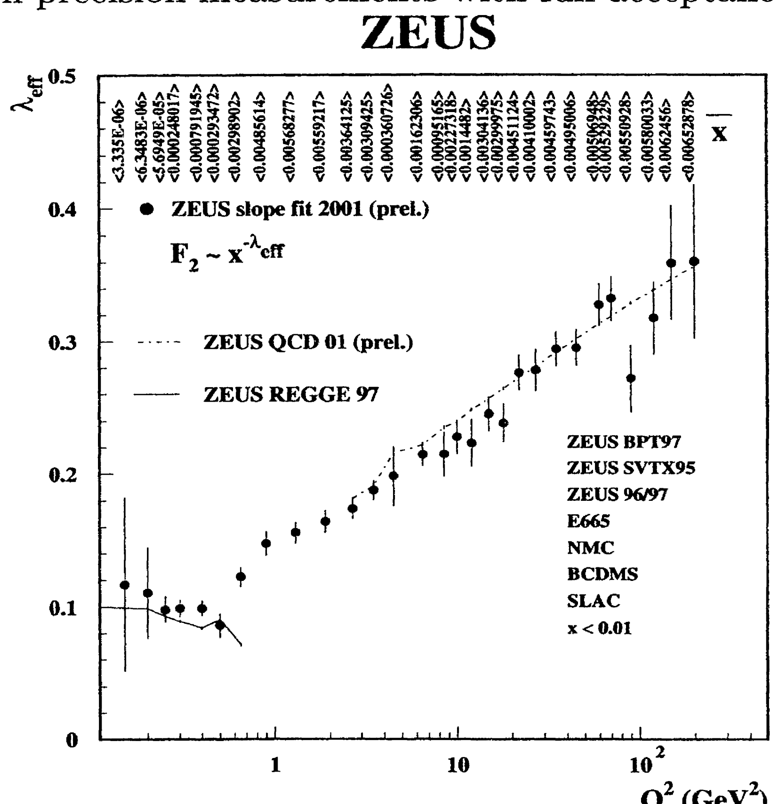


Figure 4: The logarithmic derivative $\lambda_{eff} = \partial F_2/\partial lnx$ as a function of Q^2.

2.2 Exclusive Processes

Exclusive processes allow for a very detailed study of eP interactions. Two additional variables are introduced (4-momentum transfer at the proton vertex and mass of the final state), which allow a many-fold differential study. In the proton rest frame, we can think of the electron emitting a photon far upstream of the interaction point. The photon probes the proton with a transverse resolution which scales as $\hbar c/Q$, and at impact parameter $\sim \hbar c/\sqrt{|t|}$, where t is the square of the 4-momentum transferred at the proton vertex. At small x, the photon interactions are really dipole-proton interactions, with the lifetime of the dipole fluctuation given by $1/2xM_P$. The dipole converts into a vector meson or real photon (DVCS process) after the interaction. The wavefunction of the produced state constrains the dipole configurations which can take part in the scattering. The extra variables measured in exclusive reactions allow a much more detailed mapping of the hadronically interacting matter. An example of the information which may be extracted is given in Fig. 5, where the dipole-proton scattering amplitude is shown as a function of impact parameter. These processes will allow a 3-dimensional mapping of proton structure.

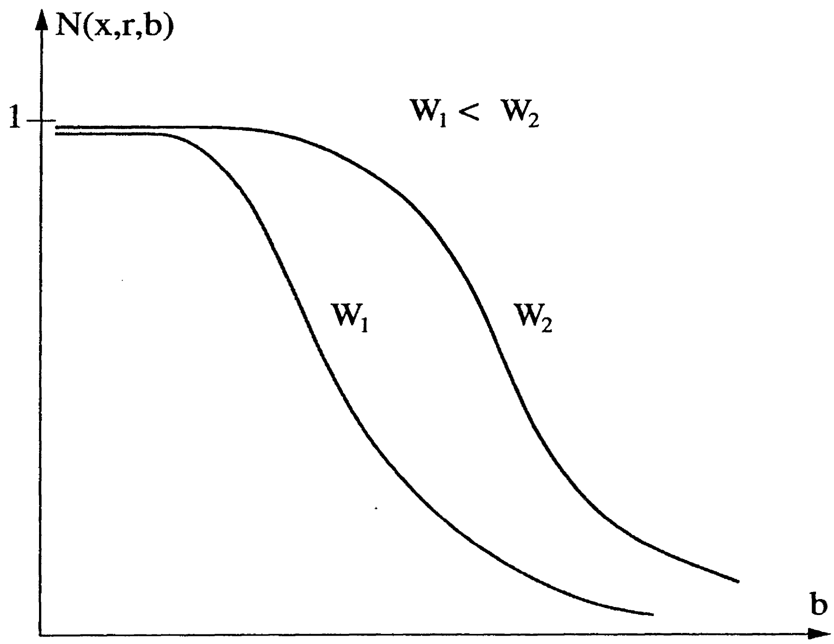


Figure 5: Expectations for the dipole-proton amplitude, $N(x,r,b)$ as a function of impact parameter, b, for different photon-proton energies, W.

2.3 Forward Jet Production

The HERA I results indicate that NLO DGLAP alone is not enough to describe forward jet production. Figure 6 shows the differences predicted [6] in different calculations for different ranges of pseudorapidity, η. It is clear that extending the rapidity coverage of the detectors would greatly enhance the sensitivity.

This applies not just to jet production, but also to particle production. In particular, heavy quark production at high rapidities is a very interesting research topic.

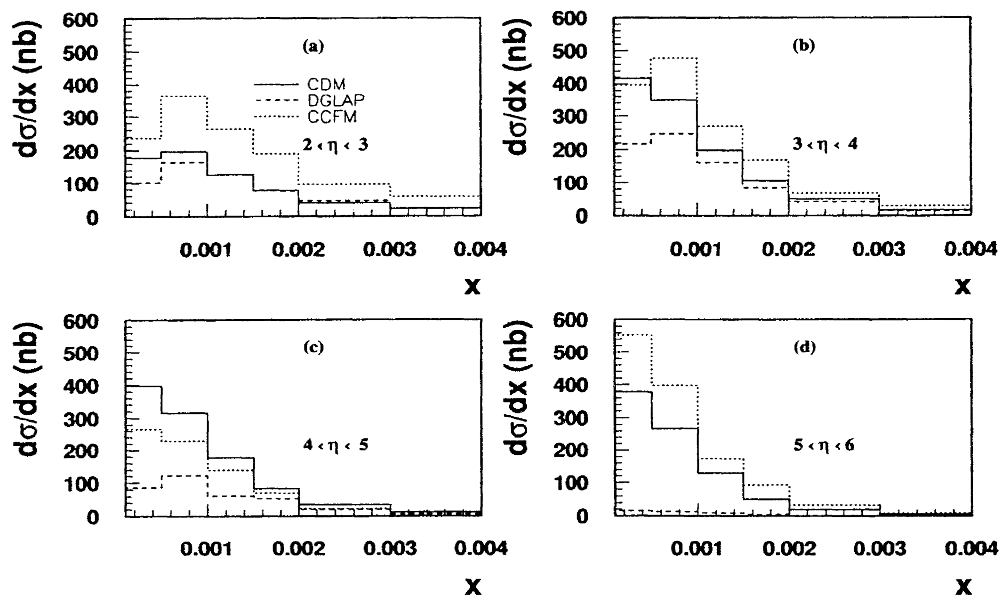


Figure 6: Forward-jet cross section as a function of x obtained from the CDM (Ariadne), DGLAP (Lepto) and CCFM (Cascade) models. The cross sections are shown in different rapidity intervals.

2.4 Precision eA Measurements

Replacing protons with nuclei is widely expected to enhance the striking effects observed at HERA. For example, it is expected that the diffractive cross section will approach 50 % of the total cross section, the maximally allowed value. The black-body limit of QCD will be reached, and new states of matter, such as the color-glass-condensate [7], can be studied. The main argument leading to such conclusions can be stated as follows. The dipole fluctuation from the virtual photon typically lives for distances much larger than the nuclear size at small-x. It is therefore sensitive to all the hadronic matter along a line through the nucleus, whose length scales as $A^{1/3}$. For large nuclei, the extra path length through nuclear matter can lead to saturation of cross sections. The interesting measurements for eA scattering are the same as those for eP scattering - structure function measurements, diffractive cross sections, and exclusive reactions.

2.5 Spin

It is not understood how the intrinsic angular momentum of hadrons is built up from the constituents. This flagrant hole in our understanding of subatomic physics demands an explanation. Colliding polarized electrons with polarized protons at HERA would allow the study of the angular momentum carried by small-x partons, and would open a new line of attack on this fundamental problem.

3 H1 Detector Upgrade

The H1 LoI [1] focuses initially on eD scattering, and discusses a second phase which focuses on the forward and backward region. For the first phase, a new spectrometer would be added to measure protons exiting with approximately half the deuteron beam energy. For the second phase, upgrades in the electron direction (new silicon based tracking, a new small-angle calorimeter) and proton direction (instrumented beamline, new forward calorimeters) are envisaged.

As examples of what could be achieved with an eD program of moderate luminosity, the $\bar{d} - \bar{u}$ measurement at small-x and the ratio of valence quark densities, d_v/u_v, were studied. The results are given in Fig. 7. It is clear that the isospin symmetry of the sea can be extremely well tested, and the valence d/u ratio well constrained.

4 A New Detector for HERA

The H1 and ZEUS detectors were optimized for high Q^2 physics, and as such the detectors are optimal for the HERA II program which is now getting under way. For the small-x physics which has been the highlight of HERA so far, and which would be the physics goal of a HERA III program, a new type of detector concentrating on the forward directions is needed. A new detector designed with this physics in mind is sketched in Fig. 8. The main idea is to build a

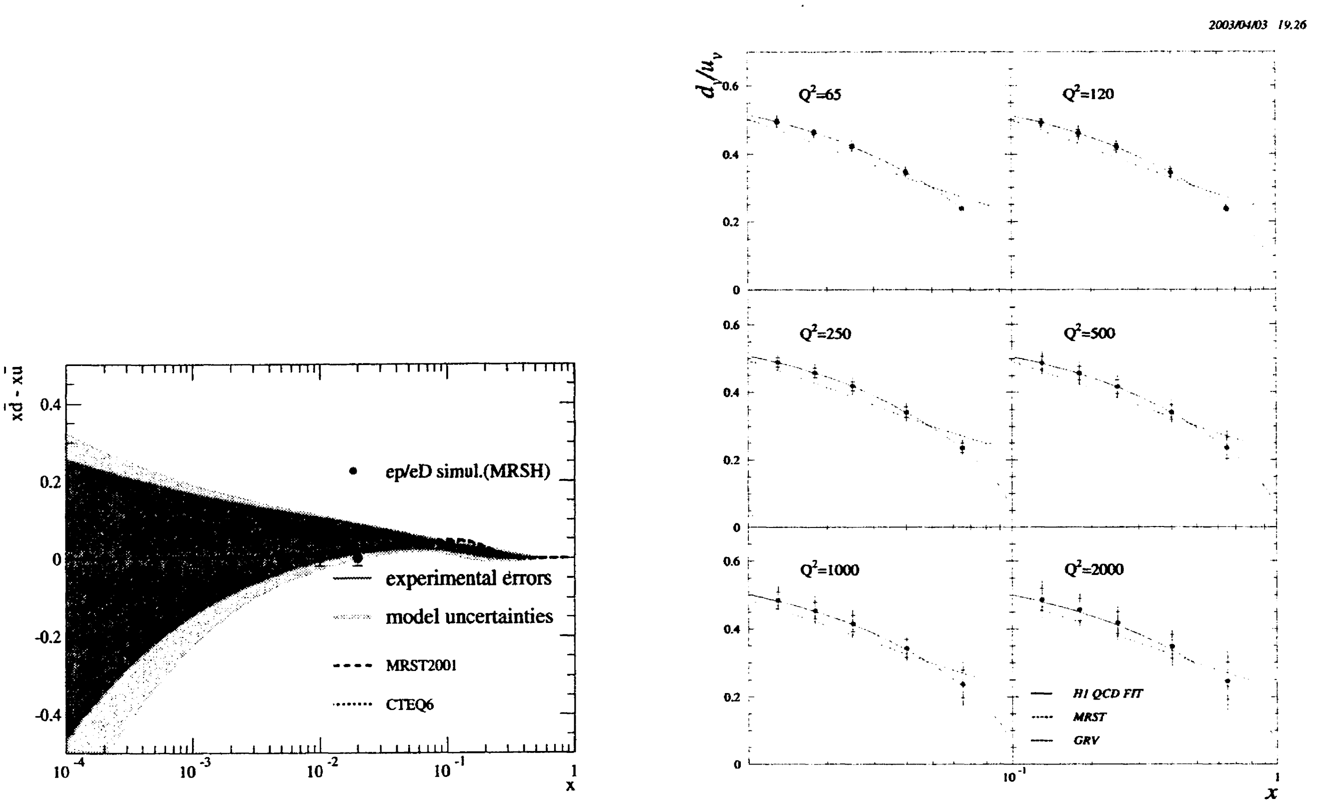


Figure 7: Left: simulation of the difference $\bar{d} - \bar{u}$ using 40 pb^{-1} of eP and 20 pb^{-1} of eD data. The error bar represents the quadratic sum of the statistical and systematic errors. Right: simulation of the measurement of the ratio d_v/u_v with H1 assuming 50 pb^{-1} luminosity for eP and for eD scattering.

compact detector with tracking and central electromagnetic calorimetry inside a magnetic dipole field. Calorimetric end walls are located outside the dipole. The tracking focuses on forward and backward tracks, while the calorimetry focuses on e/π separation and the central electron and photon measurements. The magnetic field extends from ± 4.5 m, and points along the vertical direction. There are 28 tracking planes located along the length of the magnet capable of producing a 3-D coordinate. The barrel calorimeter has an inner radius of 40 cm, and is confined to a tube of 60 cm. The dipole magnet has an inner radius of 80 cm.

In addition to the detector components shown in the figure, additional detectors located further upstream in the proton and electron directions would also be included. These detectors would be used to tag proton dissociation and initial state radiation, as well as be helpful for luminosity measurements.

The acceptance of the detector for the scattered electron and for forward particles in shown in Fig. 9. Here acceptance is defined as at least three silicon

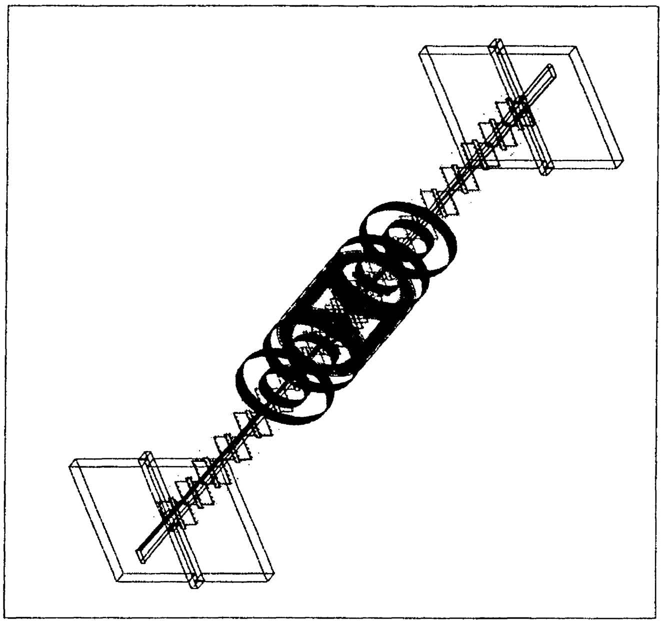
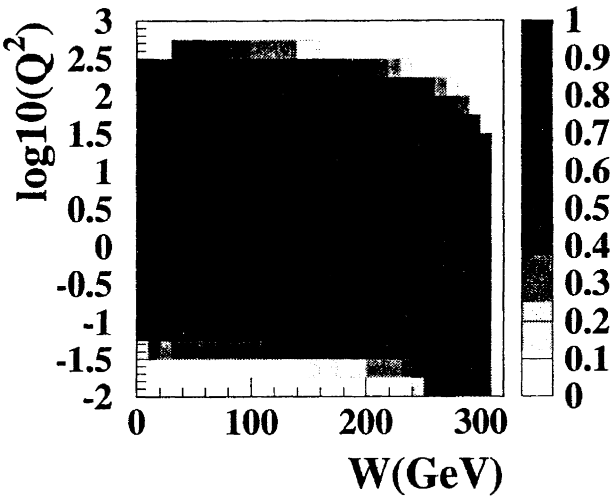


Figure 8: Schematic overview of the detector components within ±6 m of the interaction point. The silicon planes are visible along the beamline. The calorimeter system consists of a central barrel, two catcher rings on each side, and end walls. The calorimeters are all electromagnetic calorimeters, except for the end wall in the proton direction, which also includes a hadronic calorimeter. The dipole magnet enclosing the silicon detectors, central barrel and catcher rings is not shown.

planes crossed. As is clear from the plots, full acceptance is achieved in the transition region near $Q^2 = 0.5$ GeV^2, and the acceptance for forward tracks and jets is vastly increased over what is currently achieved by H1 and ZEUS.

A full GEANT simulation of the detector was performed, including realistic material estimates for the silicon detectors and supports. The EM calorimeters were assumed to be made of Tungsten and silicon, while the forward hadron calorimeter was simulated as the ZEUS FCAL. Momentum and energy resolutions were studied, as was the e/π separation achieved. As an example of the performance of this new detector, the range and precision of a possible F_L measurement was estimated. For this, three beam energies were assumed ($E_P = 460, 690, 920$ GeV). The x range over which a 10 % measurement would be possible is shown in Fig. 10. The required luminosity for this measurement is given in the figure. At the higher Q^2 values, larger Q^2 intervals would be used to allow for reasonable statistical precision with luminosities of order 100 pb^{-1}.

The performance of the detector was also studied for many other physics



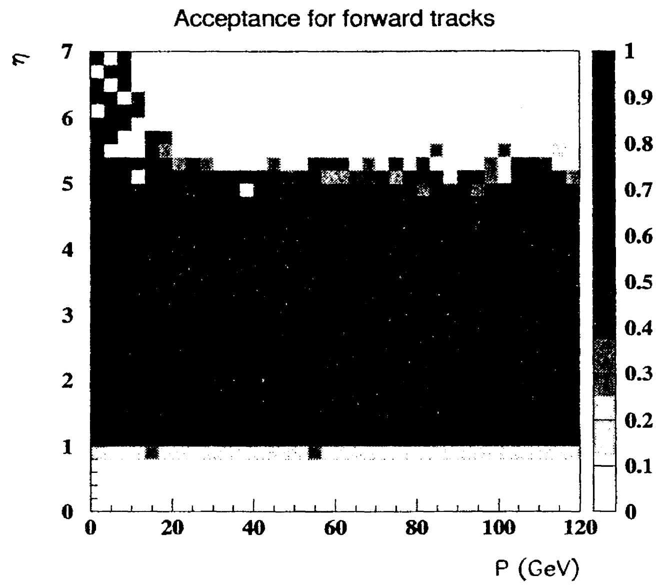


Figure 9: Left: acceptance of the tracking system for the scattered electron vs. W and Q^2 for 3 planes crossed. Right: the acceptance of the tracking system in the proton direction in terms of momentum and pseudorapidity.

processes, as described in the LoI. It is clear from these studies that a detector optimized for forward physics would yield a vast quantity of exciting new results.

5 Conclusions

HERA is a unique facility. With experiments dedicated to strong interaction physics studies, substantial progress can be made in understanding QCD on different distance scales. This is clearly of fundamental importance, as QCD is at the heart of matter. There is a distinct possibility that a paradigm shift in our conception of nature would result as a consequence of the studies outlined here.

In addition to the fundamental nature of the measurements described above, there are many additional benefits which would be derived from carrying out the program. For example, the parton densities extracted are required for high energy particle, astroparticle and nuclear experiments.

The proposed experiments are of moderate scale compared with the LHC or the Linear Collider efforts, and would offer an attractive alternative to the

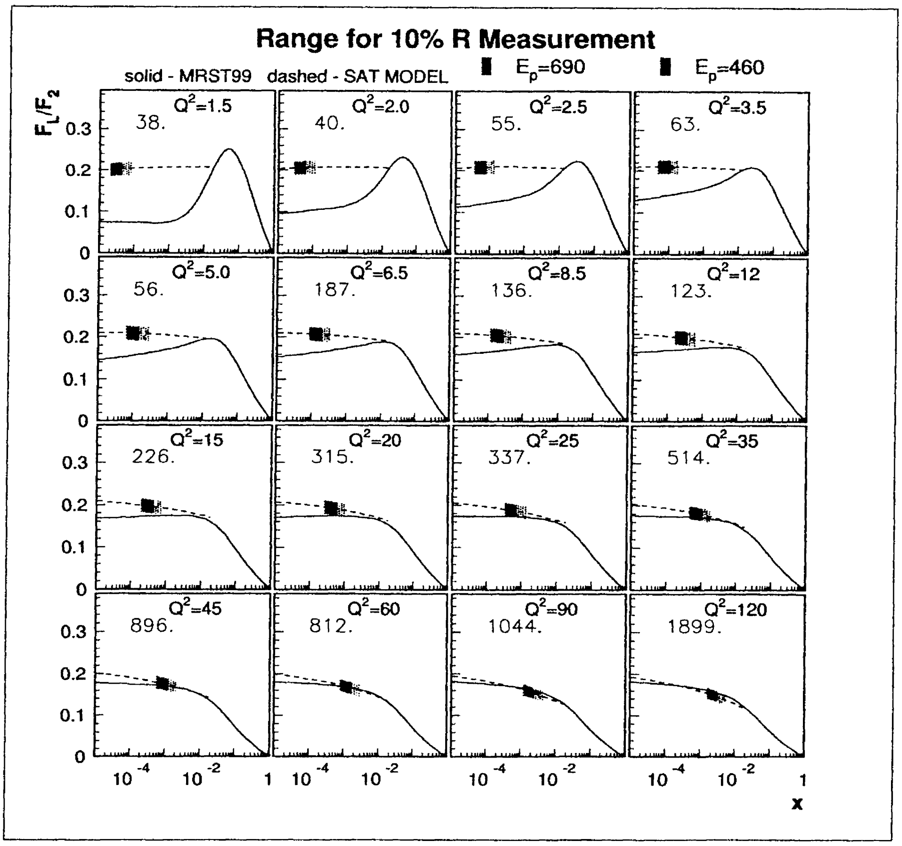


Figure 10: The x-range where 10 % or better measurements of F_L are possible is shown as the shaded band. The required luminosity is given in each bin in the upper left corner in units of pb^{-1}.

very large collaborations involved in those efforts. Additionally, the HERA accelerator is an existing facility which still has substantial physics potential. The manpower and financial expenditures already invested in HERA should be exploited fully.

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