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What HERA may provide ?

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More than 100 people participated in a discussion session at the DIS08 workshop on the topic *What HERA may provide*. A summary of the discussion with a structured outlook and list of desirable measurements and theory calculations is given.

1 Introduction

The HERA accelerator and the HERA experiments H1, HERMES and ZEUS stopped running in the end of June 2007. This was after 15 years of very successful operation since the first collisions in 1992. A total luminosity of ~ 500 pb^{-1} has been accumulated by each of the collider experiments H1 and ZEUS. During the years the increasingly better understood and upgraded detectors and HERA accelerator have contributed significantly to this success. The physics program remains in full swing and plenty of new results were presented at DIS08 which are approaching the anticipated final precision, fulfilling and exceeding the physics plans and the previsions of the upgrade program.

Most of the analyses presented at DIS08 were still based on the so called HERA I data sample, i.e. data taken until 2000, before the shutdown for the luminosity upgrade. This sample has an integrated luminosity of ~ 100 pb^{-1}, and the four times larger statistics sample from HERA II is still in the process of being analyzed.

Soon the LHC will start operation and will draw the attention of a large fraction of HEP physicists, including many of those that have been working on HERA during the last years. There is however still a lot to learn from the HERA data, much of it will be of extremely high importance also for understanding LHC data, or for making precision measurements with LHC data. So it is worth continuing the analysis and investing the necessary time to complete this job. Hence, it seems to be timely to summarize and structure topics, where analysis of HERA data can contribute significantly to answer general and fundamental questions of QCD. In order to benefit fully from the power of the HERA data some further developments in theory are needed as well, which will be addressed in this note too.

A discussion on future measurements at HERA took place at DIS 08, with more than 100 people attending a specially organized evening session. Many interesting issues were brought up. The clear support from the DESY directorate for fully utilizing the HERA potential encouraged us to prioritize a list of investigations and ideas for what still can or should be done with HERA data. As reflected in this report, questions of factorization and universality emerged as very prominent themes.

This paper is structured as follows: in the second section we discuss the prospects of measurements of parton distribution functions (PDFs), which are the essential input for all calculations and predictions in hadron-initiated processes. We also discuss the theoretical interpretation of such measurements.

When scrutinizing the emerging hadronic final state, issues like universality of hadronization, the color structure of the partonic final state and multi-scale phenomena become important. This is the topic of the third section.

Finally, since HERA is a machine perfectly suited for precision measurements in large areas of QCD, it is an ideal place to test the validity of the present theoretical approaches, and to limit their ranges. For example, deviations from linear evolution equations can be investigated, related to a regime where collective phenomena become dominant. Topics like this are discussed in the fourth section.

We discuss the impact of the measurements on tuning and validation of Monte Carlo event generators in the fifth section and give a conclusion in section 6.

In the final section we give a wish-list of measurements which should be done with HERA data.

Last but not least, one should secure the future. HERA has been the only lepton-proton collider in the world so far, and no construction of a similar machine is presently scheduled. Hence the data and analysis environment of the HERA experiments should be preserved such that it is possible in future to turn to these data for questions and studies, if future physics requires it.

2 Parton distribution functions – the irreducible input to all calculations involving hadron beams

The factorization theorems in QCD allow us to evaluate cross sections from the convolution of corresponding hard scattering matrix elements, which are perturbatively calculable, with parton distribution functions (PDF), which include also non-perturbative physics. Although the factorization theorems are strictly proven only for a very limited number of processes, see for instance [1], their validity always is implicitly assumed when such cross sections are calculated. Different factorization theorems exist, which are applicable to different regions

of phase space:

- **Collinear Factorization**, applicable at large enough Q^2.
  Cross sections are factorized into process-dependent coefficient functions C^a and collinear (integrated over k_t) parton distribution functions at a factorization scale μ_f (e.g. $\mu_f^2 = Q^2$ for the inclusive cross section in deep inelastic scattering):

$$\sigma = \sigma_0 \int \frac{\mathrm{d}z}{z} C^a \left(\frac{x}{z}, \mu_f\right) f_a\left(z, \mu_f\right) \tag{1}$$

- k_t - **Factorization**, applicable at small enough x (high energy factorization).
  Cross sections are k_t–factorized [2–5] into off mass-shell (k_t–dependent) partonic cross sections $\hat{\sigma}(\frac{x}{z}, k_t)$ and k_t–unintegrated parton distribution functions $\mathcal{F}(z, k_t)$:

$$\sigma = \int \frac{dz}{z} \mathrm{d}^2 k_t \, \hat{\sigma}\left(\frac{x}{z}, k_t\right) \mathcal{F}\left(z, k_t\right) \tag{2}$$

The proper and precise determination of the various PDFs is essential, as their uncertainties directly contribute to the uncertainties of the respective cross section calculations.

Besides the determination of the parton distribution functions, the coupling strength $\alpha_s(\mu^2)$ has to be determined. A 4-loop analysis of the non-singlet world data [6] resulted in

$$\alpha_s(M_Z^2) = 0.1141 \begin{array}{l} +0.0020 \\ -0.0022 \end{array} \quad . \tag{3}$$

The complete statistics of HERA shall be analyzed in a corresponding singlet analysis, from which a further improvement of the error of $\alpha_s(M_Z^2)$ and improved error contours of the sea-quark and gluon distributions are expected. This analysis can be carried out at 3–loop order. Since the charm-quark contributions are large in the small-x region, the corresponding Wilson coefficients have to be calculated to the same level [7–9]. Only if universal PDFs and α_s are measured and obtained can the whole factorization program be used in practice. Therefore the most precise measurements of these quantities relates to very fundamental questions of our theoretical understanding. Precision charged current (CC) and neutral current (NC) cross-sections at high Q^2 also provide constraints on the electroweak couplings of the light quarks.

To extract the different PDFs, cross section measurements need to be performed for various processes. The most precise of these measurements are obtained for the inclusive total cross sections. In semi-inclusive measurements (like jet, charm or diffractive cross sections), which require tagging of one or more particles in the final state, only parts of the phase space are experimentally accessible. Charmed - or diffractive structure functions, F_2^c or F_2^D, can only be obtained after extrapolation from the visible to the total (partially invisible) phase space, which requires assumptions and thereby introduces an additional model dependence and systematic uncertainty. For example, in the case of charm production, large model uncertainties enter through the extrapolation from the visible cross section of D^* production in DIS to the total charm production cross section [10]. Measurements based on the impact parameter have much smaller extrapolation uncertainties [11].

Therefore, aiming for minimal model dependence, emphasis has to be put on the measurement of mostly visible cross sections. In addition, in order to further reduce the uncertainties

in the measurements and thus of the extracted PDFs, efforts have already been started to combine the measurements of H1 and ZEUS. This requires a detailed agreement concerning the kinematic ranges and accessible phase space. The combination of the inclusive cross section measurements [12] of H1 and ZEUS, based on part of the HERA I data, is already leading to a very good precision. A combination of inclusive cross sections with measurements of heavy quarks and jets [13] can be used to further constrain the gluon distribution function and α_s. Also for the inclusive diffractive cross section a much better precision can be achieved from a combination of the measurements from H1 and ZEUS, which has already started.

Strategies to extract the most precise PDFs to be used at the LHC, and questions on how to use future LHC data to further constrain the PDFs are discussed in the PDF4LHC [14] forum.

From these measurements the PDFs can be determined, either in the collinear and/or the k_t-factorization approach. The combined measurements constrain much better the PDFs, especially the low x gluon density [15]. This new parameterization (HERAPDF) will be made available in LHAPDF. An issue which is still open is whether the proton contains an intrinsic charm component. In order to verify and potentially quantify this experimentally, extra efforts to tag charm in the very forward proton region would be needed.

However to fully appreciate the impact of highly precise measurements, further theoretical progress is required in the following issues:

- collinear factorization
  - inclusive cross sections and structure functions at three loop order in α_s
  - heavy quark cross sections: transition from the massive to the massless approach
  - discontinuities when going beyond NLO in collinear factorization
  - higher order calculations for semi-inclusive cross sections (i.e. jet cross section at NNLO)
- k_t-factorization
  - NLO calculations
  - unintegrated PDFs also for medium and large x
- usage of PDFs in Monte Carlo event generators (PDF4MC)

Activities in these areas have started, but are not fully completed yet.

3 Universality of the hadronic final state

The hadronic final state in ep collisions is much more complicated than in e^+e^- annihilation, due to the presence of the colored proton remnant.

Although it implicitly has been assumed for all theoretical predictions up to date, the universality of parton-jet correlations at perturbative scales has never systematically been investigated in processes where more than one jet is produced. This correlation depends on the color structure of the final state, therefore the so-called underlying event, which includes everything except the lowest-order process, might play a significant role. In addition, in the soft and non-perturbative regime the universality of hadronization and the parameters of the phenomenological hadronization model still waits to be verified in detail.

3.1 Color structure of final state

The color flow between the partons of the hard process with the proton-remnant is responsible for the production of the hadrons in the phase space region between the hard scattering and the remnant. In diffractive events, the color flow from the proton to the hard scattering is broken, in a simple model realized by the exchange of two gluons which neutralize each other's color. Single parton exchange (non-diffractive) and double parton exchange are only two extreme cases. Multi-parton exchanges, which are not in a color singlet state, are also possible and can increase the hadron multiplicity, since each of them will radiate further partons, possibly modified by interference effects. Multiparton interactions have been studied with jets in photoproduction [16–18] and there are indications for interesting effects in DIS [19].

In general, everything except for the lowest order process under investigation contributes to the so-called underlying event (UE). The UE includes contributions from initial and final state parton showers, as well as hadronization but also multi-parton exchanges including diffraction. Thus the study of the UE turns out to be as important and interesting for the basics of QCD as the hard perturbative processes itself are.

Measurements of the transverse hadronic energy flow can be used to test the

- universality of the color connection between hard partons
- universality of the color connection between hard partons and proton-remnants

The application of hard scattering QCD collinear factorization [20] to the leading Q^2 component of diffractive DIS ($ep \to eXp$) leads to a concept of 'diffractive parton distribution functions' (DPDFs), describing interactions which produce a leading final state proton with a particular four-momentum. Several authors have recently analyzed diffractive DIS data and extracted DPDFs [21–23]. Many tests of the factorization properties of diffractive DIS have been made by comparing predictions based on these DPDFs with observables from the diffractive hadronic final state, such as jet and heavy quark cross sections.

Testing the factorization properties of diffraction and improving on the precision of the DPDFs remains a major theme in diffraction at HERA, with the diffractive longitudinal structure function F_L^D a notable new observable which may provide an interesting test of the large gluon density. However, perhaps the most important remaining work to be done centers around understanding the manner in which diffractive factorization can be broken. There are two main themes, which are briefly discussed below.

As expected [20], diffractive factorization breaks down spectacularly when DPDFs from HERA are applied to diffractive $p\bar{p}$ interactions at the Tevatron [24]. However, with the introduction of a 'rapidity gap survival probability' factor to account for secondary interactions between the beam remnants [25, 26], a good description has been recovered. There remains much to be learned about gap destruction and survival, which together with the HERA DPDFs are the two essential ingredients for predicting the phenomenology of diffraction at the LHC. HERA may still contribute here through the study of the onset of gap destruction events in resolved photoproduction.

A factorization - breaking effect which is present even in diffractive DIS arises due to the presence of perturbatively calculable configurations from Q^2-suppressed non-leading twist $q\bar{q}$ fluctuations of longitudinally polarized photons [27]. Although $q\bar{q}$ dipole scattering is not the dominant feature of inclusive diffraction at HERA, it gives rise to a good description

of vector meson production, which have a large component arising from longitudinally polarized photons and are suppressed with increasing Q^2. Completing the program of study of exclusive processes will lead to a better understanding of the scattering of $q\bar{q}$ pairs from the proton. Non-factorizing longitudinal $q\bar{q}$ contributions also play a significant role in the inclusive cross section at large momentum fractions $z_{I\!P}$ [22, 28], which must be better understood in order to decrease the large DPDF uncertainties in that region. This is essential for LHC preparations, as high $z_{I\!P}$ inclusive processes are the dominant background to central exclusive processes such as diffractive Higgs production. Among other possibilities, a comprehensive search for exclusive contributions to diffractive dijet production is urgently needed.

3.2 Universality of parton-jet relations

The hard perturbative process in e^+e^-, ep, pp collisions can be studied either by tagging the produced heavy objects (typically quarks in ep collisions) or by measuring jets, which originate from hard partons produced in the hard process. The jets are reconstructed from the observed hadrons. The precise definition of a jet, i.e. which hadrons and how they are combined into a jet depends on the jet algorithm and its resolution scale [29]. It has been a long-standing issue that jet algorithms need to be infrared- and collinear-safe (i.e. the result must not change when a soft or collinear particle is added). Much progress has been made recently in providing also infrared- and collinear-safe definitions of cone-type jet algorithms [30]. In all jet algorithms decisions are made on how many and which particles are clustered into a jet, and thus are potentially affected by the contribution from particles which do not belong to or originate from the hard perturbative process under consideration.

With a proper jet definition, the measured jet cross-sections can be compared with theoretical predictions calculated at fixed order at parton level or supplemented with parton showers (resummation) and hadronization. Similarly to the PDFs, the parton shower resummation is assumed to be universal. However, no explicit factorization theorem exists, which is applicable to the parton showers (although some steps in this direction have been made [31]), and thus experimental tests are vital.

Processes with one or two jets can provide experimental tests of

- universality of parton-jet correlation
- universality of soft gluon resummation
- universality and importance of small x resummation

New and additional measurements are needed for a precise investigation of the parton-jet to hadron-jet relation for multi-jet events; especially the influence of multiparton interactions needs to be understood.

In the context of high energy factorization and the BFKL approach, forward jets well separated in rapidity from the outgoing lepton in DIS [32, 33] are sensitive to next-to-leading order effects in the gluon Green's function, which have proved to be very important. In particular, the azimuthal angle correlations increase when higher order corrections are introduced (opposite to what is expected in a fixed order calculation) for a fixed value of x, while the jet and the electron become more de-correlated as we increase the center-of-mass energy. Such investigations are important for the description of Mueller-Navelet jets at the

LHC, and contribute to the production of high-multiplicity events [34], where differences to the standard approaches [35] could be observed.

3.3 Universality of hadronization

Most of the parameters needed to describe the transition from on-shell or almost on-shell partons to observable hadrons have been precisely determined at e^+e^- colliders, especially at LEP. However, the structure of the final state of events in $e^+e^- \to hadrons$ is different from that in $ep \to e' + hadrons$ and even more so from that in $pp \to hadrons$. There are hints from HERA measurements that there are some differences of hadronization in those process. For example, the K/π ratio in ep-collisions seems to be different from that obtained in e^+e^--annihilation events [36]. It is therefore crucial to investigate the universality of hadronization — the factorization of the soft and the perturbative region.

A comparison of fragmentation parameters obtained at HERA with those from LEP will clarify the question of universality of hadronization. The measurements from HERA are important, as they allow us to understand the transition from e^+e^- to hadron colliders and they may be necessary for a precise modeling of the hadronic final state at LHC.

Fragmentation functions are among the simplest quantities to describe the hadronization process in QCD. Measurements at HERA of *identified* inclusive hadron production would provide a strong impact to global fits. Furthermore, the p_T spectrum and azimuthal distribution of the produced hadron provides insight into the intricacies of the dynamics and can be interpreted within a powerful theoretical formalism [37].

D-meson production at HERA is fairly well described by NLO calculations treating charm as massive and employing a fragmentation function. Measurements of distributions in x_{Bj}, pseudorapidity, p_T etc, have been performed by both H1 and ZEUS collaborations. The dominant uncertainty in the NLO description is due to the value of the charm (pole) mass, and a parameter in a charm fragmentation function (e.g. Peterson, or Kartvelishvili). For a given choice of PDF set and hadronization fraction $f(c \to D_i)$, the value of these universal parameters can be determined in a correlated fit. A first good attempt yielding promising results can be found [38].

More measurements are needed for a precise determination of fragmentation and hadronization parameters. With these measurements a detailed comparison of hadronization parameters and fragmentation functions with those obtained in e^+e^- at LEP can be performed, and for the first time a systematic test of the universality of hadronization can be achieved.

4 Deviations from expectations in linear QCD evolution equations

Most of the topics discussed in the previous sections are related to single-parton exchange processes and to linear evolution equations, i.e. DGLAP, BFKL and CCFM. The latter describe a regime which is normally classified as a dilute region, where the density of partons can be large, but still small enough such that they do not significantly interact with each other. However, when the density of partons becomes larger, they can shadow or start to overlap and thus interact with each other. This is the regime of a dense system, where non-linear evolution equations are relevant, the oldest example of which is the GLR-MQ equation [2,39]. Hints at the onset of a dense region come from the observation of diffractive events at HERA and their interpretation in terms of the dipole picture. A strong signal for the onset of a dense region (or black disk limit) are the measured diffractive gluon PDFs,

which indicate [40] that for $x \sim 10^{-4}$ and $Q^2 \sim 4$ GeV^2 the probability of diffraction in gluon induced processes reaches $\sim 40\%$ which is close to the black disk limit of 50%. Now, the theoretical understanding of the dense region has received much support from measurements at RHIC, and new evolution equations (like the Balitsky-Kovchegov equation [41, 42] (BK)), which include non-linear terms, are available. However, the BK equation is derived for a large nucleus and only approximately applicable to *ep* and *pp*.

Although saturation is theoretically well motivated, a clear, clean and indisputable experimental signature for it is still missing. To decide if and where nonlinear dynamical effects become important at HERA is difficult, especially since some signatures of saturation can be mimicked approximately within the linear DGLAP or BFKL descriptions.

However, the k_t-dependence of the unintegrated PDF as a function of x could provide important information. In a linear scenario (BFKL) the parton density (for fixed k_t) is expected to increase with deceasing x, while in the case of saturation this density will first increase, then flatten for smaller and smaller x and will eventually decrease. As a function of k_t the parton density is expected to decrease for k_t below the saturation scale and the x-dependence of the saturation scale can thus be studied directly. High-precision data in a wide kinematic region for dedicated observables will certainly help.

On the theoretical side progress is needed in

- the calculation of the evolution of unintegrated PDFs in the presence of saturation
- the factorization and factorization breaking in the presence of saturation
- the calculation of the change of the leading pion spectrum expected due to the onset of the saturation regime compared to the factorization prediction

Besides investigations on saturation, the range of validity of the linear evolution equations is not yet fully understood:

- in the moderate Q^2 region contributions from higher twist effects (multi-parton exchange processes) are expected. However they are suppressed by additional powers of $1/Q^2$ and therefore typically have only a small effect. At small x this contribution is increased by large $\log(1/x)$ terms. A systematic investigation of the higher-twist region would require measurements at the same Q^2 but with x varying over a larger range than available up to now. This can be achieved with F_2 measurements recorded at lower center-of-mass energies.
- in the large x region a breakdown of the collinear factorization ansatz is expected due to the transverse momentum as well as energy momentum conservation as advocated in [43].

The program to investigate non-linear effects at HERA further and to constrain the validity of linear evolution equations is essential for any proper interpretation of small-x effects at LHC. HERA is the only place where these effects can systematically be studied in a clean and controllable environment, i.e. where precision measurements are possible. The results of such a program will have direct impact on measurements at RHIC but even more at LHC, where deviations from linear dynamics (saturation and multi-parton interactions) are expected even for high p_t processes [44].

5 Tuning and validation of MC event generators and models at HERA for future colliders

With precision measurements, as described in the previous sections, different models and calculations can be systematically scrutinized. In many cases it will be possible to find parameter settings which describe specific sets of measurements very well, while failing for different sets of observables, making different parameter settings unavoidable. Such a situation is not at all satisfactory, as it indicates deficits in our understanding of the underlying physics.

Since many of the calculations are also applied and used at different colliders (most prominently the LHC), the investigation of the range of validity of various models is essential for their success. For a detailed investigation all measurements from HERA, but also from other collider experiments, need to be available in a computer-readable form, which automatically includes all necessary cuts and reconstruction algorithms. Such frames exist in form of HZTOOL and its successor RIVET [45].

For the major Monte Carlo event generators, which are applicable for ep as well as for pp, such as ARIADNE [46], CASCADE [47], HERWIG [48] and PYTHIA [49], a number of tunable parameters can be obtained from the measurements described here. These investigations should include:

- parton showers
  - tuning of hadronization parameters
  - tuning and validation of parton shower resummation; validity range of collinear and k_t factorized parton showers
  - significance of angular ordered parton showers
  - significance of LL or NLL parton showers
- parton distribution functions for MC event generators
  - LO or NLO PDFs
  - determination of dedicated PDFs for MCs (PDF4MC)
  - unintegrated PDFs

It could also happen that some parameters are not uniquely tunable to describe all the measurements. Such a situation indicates the incompleteness and inconsistency of the ansatz used and would be of general interest. HERA with its QCD precision measurements may well be the only place for a long time where such a global validation of the different models can be done in an environment with a hadron beam and a controllable probe. In a global validation also measurements from $p\bar{p}$, pp and e^+e^- have to be included.

6 Wish-list for measurements

In the following we list the measurements which are needed in our view to complete the program outlined above.

6.1 Parton Distribution Functions

A summary of cross section measurements relevant for the determination of the proton PDFs is given in Tabs. 1 and 2. The measurements described here are either already done or are to be completed with the full statistics of HERA II. The inclusive cross section measurements can be used to determine integrated as well as unintegrated PDFs. Using the full statistics will be important for measurements of the visible cross sections, especially for multi-jets and heavy flavor tags. The determination of unintegrated PDFs is complemented by measurements of semi-inclusive cross sections like charm or jet cross sections. Measurements of $\Delta\phi$ and p_t correlations can further constrain the k_t–dependence of the unintegrated PDFs (Tab. 2). A extended kinematic range to smaller Q^2 and smaller p_t as well as more differential data as a function of p_t and the dijet mass would be desirable, requiring new measurements.

neutral current (NC) (inclusive)	
$F_2^{\gamma/Z}(x,Q^2)$ $(e^\pm + p \to e^\pm + X)$	α_s, sea quarks,gluon
$F_L^{\gamma/Z}(x,Q^2)$ $(e^\pm + p \to e^\pm + X)$	α_s, gluon
$F_2^{\gamma/Z}(x,Q^2)$ $(e^\pm + p \to e^\pm + X)$ at large Q^2	d/u at large x
$xF_3^{\gamma/Z}(x,Q^2)$ $(e^\pm + p \to e^\pm + X)$	$q - \bar{q}$
$\sigma_{vis}^{K^*}(x,Q^2)$ $(e^\pm + p \to e^\pm + K^* + X)$	strange-quark
$\sigma_{vis}^{D^*}(x,Q^2)$ $(e^\pm + p \to e^\pm + D^* + X)$	charm-quark, α_s, gluon
$\sigma_{vis}^{jets}(x,Q^2)$ $(e^\pm + p \to e^\pm +$ n-jets $+ X)$	α_s, gluon
charged current (CC)	
$F_2(x,Q^2)$ $(e^- + p \to \bar{\nu} + X)$	$u + c$, $\bar{d} + \bar{s}$
$F_2(x,Q^2)$ $(e^+ + p \to \nu + X)$	$d + s$, $\bar{u} + \bar{c}$
neutral current (NC) (diffractive)	
$F_2^{D(3)}(x,Q^2,x_{I\!P})$ $(e^\pm + p \to e^\pm + X + p)$	diffractive quarks, gluon

Table 1: Summary of measurements relevant for the determination of the parton distribution functions. The right column indicates which quantities can be constrained by the measurements.

charm in DIS	
$\frac{d^2\sigma(ep\to e' D^*+X)}{dx\, dQ^2}$, $\frac{d\sigma(ep\to e' D^*+jet+X)}{dp_t^{D^*,jet}}$	$\int dk_t\ \mathcal{A}(x,k_t,\mu)$
charm and/or jets in DIS	
$\frac{d\sigma(ep\to e' D^*+jet+X)}{d\Delta\phi_{12}^{D^*,jet}}$, $\frac{d^2\sigma(ep\to e' D^*+jet+X)}{d\Delta\phi_{12}^{D^*,jet} d\Delta\eta_{12}^{D^*,jet}}$	$\int dx\ \mathcal{A}(x,k_t,\mu)$
$\frac{d^2\sigma(ep\to e' D^*(jet)+jet+X)}{d\Delta\phi_{12}^{D^*,jet} dx}$	$\mathcal{A}(x,k_t,\mu)$
$\frac{d^2\sigma(ep\to e' D^*(jet)+jet+jet+X)}{d\Delta\phi_{12}^{D^*,jet} dx}$, $\frac{d^2\sigma(ep\to e' D^*(jet)+jet+jet+X)}{d\Delta\phi_{13}^{D^*,jet} dx}$	$\mathcal{A}(x,k_t,\mu)$

Table 2: Summary of measurements relevant for the determination of the unintegrated PDFs $\mathcal{A}(x,k_t,\mu)$. The indices label the jets (D^*) ordered in p_t. The right column indicates which part of the unintegrated PDF can be constraint by the measurement.

The photoproduction of muon pairs [50] is largely induced by quark-antiquark annihilation and is therefore directly sensitive to the quark distributions in the real photon, which were up to now measured only in e^+e^- collisions from the photon structure function F_2^γ. A measurement at HERA could probe a different flavor combination than the one appearing in F_2^γ, thereby yielding a measurement of the flavor structure of the quark content of the photon. Such a measurement would have important implications for predicting photon-proton cross sections at the LHC, and photon-photon cross sections at a future linear collider. A new measurement of F_2^γ would complete the structure function measurement at HERA.

6.2 Color structure of the final state

The color structure of the hadronic final state can be investigated with measurements of transverse energy flow and charged particle spectra over the widest possible phase space:

- Universality of the color connection between partons from the hard process (new measurements)

  ◦ The energy flow between the jets depends on the color connection of the hard partons. In diffraction, 3-jet events should show the same string-effect as in e^+e^--annihilation into three jets, whereas in non-diffractive events the particle flow between the jets is expected to be different. A new measurement in the same phase space region of diffractive and non-diffractive events needs to be performed.

  ◦ The energy flow between the jets is also influenced by contributions of multi-parton exchanges. Thus a comparison of 2- and 3-jet measurements in photoproduction with those at large Q^2 in the same phase space region will show the importance of multi-parton interactions in DIS. In the photoproduction region, a comparison between direct photon enhanced and resolved photon enhanced regions for the same jet phase space is also sensitive to multi-parton exchanges.

- Universality of the color connection between partons from the hard process and the proton-remnant (new measurements in extended phase space)

  ◦ In non-diffractive events the transverse energy E_T and the hadron multiplicity in the forward region does not decrease as expected from collinear factorization [51]. Measurements of E_T and hadron multiplicity as a function of η, x and Q^2 are not well described by theoretical predictions [51–53].

  ◦ In diffraction the formation of a rapidity gap is directly related to the color structure of the exchange. Rescattering effects between the remnants may destroy the rapidity gap. This is directly related to the observation of factorization breaking in diffractive di-jet production in the low-Q^2 region [54]. A systematic study of factorization breaking using diffractive di-jets in photoproduction and DIS as a function of the diffractive variables $x_{I\!P}$, β and Q^2 are indispensable. The understanding of rescattering effects is essential for central exclusive Higgs boson production at the LHC.

  ◦ New measurements (also in diffraction) of energy flow, hadron multiplicity but also jets especially close to the rapidity gap are needed. If the diffractive exchange emerges from the proton due to processes which take place at non-perturbative scales (and thus, if diffraction can be incorporated into the starting condition of the usual PDFs), then the rate of jets with large transverse momenta (forward jets) close to the rapidity gap should be small. However, if the diffractive exchange contains a hard perturbative component, the cross section of diffractive forward jets should be sizable.

  ◦ The measurement of transverse energy E_T and hadron multiplicity in the forward region will be an important ingredient for any uniform description of non-diffractive, diffractive and multi-parton interaction events as provided by the AGK cutting rules. Such a new measurement would require further investigations on tracking in the forward region.

6.3 Universality of parton-jet relations

The universality of the correlation between parton and jets (at parton or hadron level) can be investigated with processes which have one or two jets. The following, partially new, analyzes would be useful:

- correlation between hard partons and jets at parton level

  ◦ The correlation can be investigated by measurements of the di-jet production cross section as a function of the di-jet mass m_{ij}, thereby avoiding to compare directly the transverse energy and rapidity of the jet with those of the parton jet in the calculation.

  ◦ The correlation as a function of the jet p_t as well as the influence of the underlying event can be quantified by jet production cross section measurements from lowest possible $p_t \sim 1$ GeV to high p_t. The influence of soft and collinear radiation can be studied with measurements as a function of the jet resolution parameter and as a function of the jet algorithm (inclusive k_t, anti-k_t, SiSCone, etc.). In addition, energy flows inside the jets or the jet profiles could shed light on this effect.

◦ Measurements of $\Delta p_t = |p_{t;1} - p_{t;2}|$ or $\sum p_t = p_{t;1} + p_{t;2}$ for di-jets, with $p_{t;1,2}$ being the transverse momentum of the jets, as a function of p_t^{jet}, η^{jet}, Q^2 and x are extremely important as they give direct access to higher-order contributions.

- universality of soft gluon resummation
  The probability to have two jets exactly back-to-back in the $\gamma^* p$ center-of-mass should vanish since gluon radiation from the initial and final state destroys the LO back-to-back configuration. This so-called Sudakov effect also plays an important role for the p_t-spectrum of W/Z production as well as the p_t distribution for the Higgs boson in hadron-hadron collisions.
  The effect of soft gluon radiation can be investigated by di-jet measurements as a function of $\Delta\phi$, as a function of the di-jet mass and of Q^2, ranging from photoproduction to high Q^2. In the region of $\Delta\phi \sim 180^o$ contributions from soft gluon resummation can be studied.

- importance of small x resummation
  At large enough energies or small enough x the suppression of higher-order contributions (due to higher orders in α_s) is compensated by logarithms of $1/x$, thus the jet (or leading particle) cross section increases with $p_t^2 \sim Q^2$. At small values of x also the transverse energy and the particle multiplicity become larger than expected from pure hadronization. Small x resummation can play an important role for the p_t-spectrum of W/Z production as well as the p_t distribution for the Higgs as pointed out in [55]. The small x resummation can be studied by the forward jet cross section associated with jets or heavy quarks in the central region.

  ◦ Important information on parton radiation can be obtained by a measurement of the transverse energy flow as a function of η in events with a forward jet.

  ◦ The measurement of the DIS di-jet cross section in the region of $\Delta\phi < 120^o$ is sensitive to contributions beyond $2 \to 3$-processes and thus can signal effects of all order resummation. The transverse energy flow and particle multiplicity in DIS di-jet events as a function of $\Delta\phi$ and jet p_t is important.

  ◦ The measurement of forward jet production with $p_t^2 \sim Q^2$ can provide essential information on small x resummation. The forward jet needs to be at smallest possible angle w.r.t. proton beam axis. The cross section as a function of the angle ϕ between the scattered electron and the forward jet, as a function of the rapidity separation between both, and as a function of the jet p_t is essential.

The relation between partons (or jets at parton level) and jets at hadron level can be investigated with the following new measurements:

- the inclusive single jet production cross section as a function of the jet resolution parameter R, as well as the differential jet cross section as a function of x, Q^2, transverse momentum p_t^{jet} and η^{jet}.

- the investigation of the above cross sections for different jet algorithms and a comparison with theoretical predictions at parton level and with those after parton showering and hadronization.

- measurement of multi-jet production cross sections as a function of N_{jet} in photoproduction and DIS as a probe for the relevance of higher-order contributions. This measurement could be repeated using the full HERA II statistics.

- measurement of differential multi-jet cross sections in photoproduction and DIS for an investigation of higher-order contributions. Correlations between the jets in ϕ and p_t should allow one to separate multi-parton interactions from multi-jet production coming from a single interaction (similar to what was done in [56]).

- measurement of particle multiplicity and energy flow in multi-jet events. Underlying event contributions and multi-chain processes will show an increasing activity away in η and ϕ from the hard process.

- measurements of jet cross sections with equal and with very different transverse momenta for an investigation of multi-scale processes.

6.4 Universality of hadronization

The effect of hadronization in general is difficult to separate from soft parton radiation. Energy flow, charged and neutral particle multiplicities can be used to determine general properties of hadronization, requiring new investigations:

- particle multiplicity and transverse energy distributions, differential in x, Q^2 as well as in η and ϕ. This would also potentially provide insights into the role of small x dynamics (BFKL), multiparton radiation (higher order contributions and parton showers) as well as multiple-parton interactions.

- particle multiplicity, energy and p_t spectra in the forward region: this would help to fix the fragmentation of the proton-remnant. Natural questions to ask include: Does the proton remnant fragmentation depend on x or Q^2? What is the intrinsic k_t of quarks and gluons in the proton? HERA data could help to answer such questions.

The following measurements (using full statistics and extended phase space) are needed for a precise determination of fragmentation and hadronization parameters:

- measurements of charm fragmentation functions and at the same time the charm (pole) mass as a function of x, Q^2, p_t and $\hat{s}$

- measurement of non-strange meson (π) and baryon (p, n) and strange meson and baryon production (hyperons) as a function of x, Q^2, η, ϕ and p_t and correlations between them, needed in particular for the determination of light and strange hadron fragmentation functions

- quark and gluon jet fragmentation: measurement of leading and subleading particles in jets to allow a separation of quark and gluon jets.

- measurement of proton and anti-proton production in the forward region (proton-fragmentation region)

6.5 Deviations from expectations in linear QCD

Deviations from linear QCD might be seen in inclusive measurements but the best observables are semi-inclusive measurements. The following measurements using the full statistics could show effects of non-linear QCD:

- k_t-dependence of the unintegrated PDF for different values of x with the transverse momentum of a di-jet pair, a heavy-quark pair or a $J/\psi + g$ system.
- the energy dependence of the ratio F_2^D/F_2 of diffractive and inclusive structure functions.
- geometric scaling of the inclusive structure function$F_2 - F_2^c$ (with the charm contribution subtracted)

6.6 Proposals for additional measurements

Here we present proposal for measurements in addition to the program outlined above.

6.6.1 Intrinsic Heavy Quarks at HERA [57]

As emphasized by the CTEQ group [58], there are indications that the structure functions used to model charm and bottom quarks in the proton at large x_{bj} have been strongly underestimated, since they ignore the intrinsic heavy quark fluctuations of hadron wave-functions. The probability for Fock states of a light hadron such as the proton to have an extra heavy quark pair decreases as $1/m_Q^2$ in non-Abelian gauge theory [59,60]. The intrinsic Fock state probability is maximized at minimal off-shellness; *i.e.*, when the constituents have minimal invariant mass and equal rapidity. Thus the heaviest constituents have the highest momentum fractions and the highest x_i. Intrinsic charm thus predicts that the charm structure function has support at large x_{bj} in excess of DGLAP extrapolations [61]; this is in agreement with the EMC measurements [62].

The SELEX [63] discovery of ccd and ccu double-charm baryons at large x_F reinforces other signals for the presence of heavy quarks at large momentum fractions in hadronic wave-functions, which is a novel feature of intrinsic heavy quark Fock states. This has strong consequences for the production of heavy hadrons, heavy quarkonia, and even the Higgs at the LHC. Intrinsic charm and bottom leads to substantial rates for heavy hadron production at high x_F [64], as well as anomalous nuclear effects. The heavy quark distributions in the proton at large x are perhaps the most important uncertainties in hadron structure; the uncertainties in $c(x, Q^2)$ also causes confusion when one uses charm production to tag gluon distributions.

Although HERA measurements of charm and bottom cross sections in deep inelastic ep scattering are normally restricted by kinematics and rate to small x_{bj}, there is some chance of seeing excess $\gamma^* p \to cX$ events at high Q^2 and x.

In addition, other hard scattering reactions may allow access the intrinsic component of heavy quark distributions at large x at HERA:

- Study the hard photoproduction process $\gamma p \to cX$ where the charm jet is produced at large p_T. The dominant subprocess is $\gamma c \to cg$, where a gluon jet recoils against the charm quark trigger.

- Look for open or hidden charm production at high x_F in the proton fragmentation region in normal high Q^2 deep inelastic events, possibly using the existing forward silicon detectors. In this case one looks at fast charm produced from the excitation of the $|uudc\bar{c}>$ Fock state of the proton.

- Use $ep \to e'\gamma cX$ to effectively lower the electron energy; this would require tagging a forward photon along the electron direction.

6.6.2 Exclusive Processes [65]

- The extraction of the bare $3I\!P$ vertex
  The triple-Pomeron vertex is an important ingredient for the physics of diffraction [66, 67]. In order to determine the value of the bare (unscreened) vertex, the triple-Pomeron interaction should be measured in a process where the rescattering effects are suppressed. Such a process is proton dissociation in the inelastic diffractive J/ψ photo (or electro-) production. Unfortunately, the existing HERA data are fragmentary and no results on the distribution over the mass M of the system Y accompanying J/ψ are available. We need better statistics of inelastic diffractive J/ψ events. The inelastic diffractive Υ events are of a special interest, but are limited by the recorded statistics. It is crucially important to have the data with an explicit measurement of the proton dissociation mass spectrum-spectrum in order to perform the full triple-Regge analysis which will allow to separate the $I\!P I\!P I\!P$ term from the other tripple-Regge contributions.

- More precise measurements of exclusive Υ photoproduction
  Exclusive Υ photoproduction allows to probe the generalized unintegrated gluon distribution in a kinematical region which is close to the expected one in central exclusive production of the Higgs boson at the LHC [68]. Currently, the uncertainties caused by the lack of knowledge of the gluon distribution at low x and small scales are sizable, and better statistics of exclusive Υ event will allow to constrain the expectations for the central exclusive production of new physics events at the LHC. Also exclusive γp collisions at the LHC could be directly used.

- Measurement of the ratio R of diffractive and inclusive di-jet photoproduction.
  It was suggested in [69] that a good way to study the effects of factorization breaking in diffractive di-jet photoproduction is to measure the ratio R of the diffractive process to the corresponding inclusive production process. In this ratio many theoretical and some experimental uncertainties can cancel. It will be very interesting to have the results on R as a function of Q^2 in order to observe variation of absorptive effects.

  Further studies of the E_T dependence of the screening effects in diffractive di-jet photoproduction are very important. It is expected (for instance [70]) that with decreasing of the jet E_T the screening effects become stronger. This is because at lower E_T the role of the large size diffractive component with larger absorptive cross section becomes more pronounced. The new H1 and ZEUS data seem to indicate such behavior but more data are urgently needed.

6.6.3 *Semi exclusive diffraction [71]*

- Hard Pomeron trajectory
  One of the important issues of the hard Pomeron dynamics is the t-dependence of the hard Pomeron trajectory. It has been measured at HERA for small t in the exclusive electro (photo) production of onium states. To study it at large t it is necessary to use rapidity gap events at large t: $\gamma(\gamma^*) + p \to VM + gap\, X$. A number of such analyses were performed at HERA. However, practically in all cases M_X^2/W^2 was kept constant. It turns out that in this case sensitivity to $\alpha_{I\!P}(t)$ is very low as the energy dependence is mostly given by x dependence of the gluon density in the target [72]. It is necessary to perform analyses of the energy dependence of the process for the fixed upper limit on M_X. In this case sensitivity to $\alpha_{I\!P}(t)$ will be maximal.

- Improving knowledge of the transverse distribution of small x partons
  Knowledge of transverse distribution of gluons and quarks (which is a Fourier transform of the t-dependence of gluon and quark GPDs measured in exclusive DVCS and DIS vector meson production) is crucial for a realistic modeling of the geometry of the pp collisions at the LHC. One needs to determine more precisely the difference between the t-slopes of DVCS, electro and photo production of J/ψ and measure the slope of the Υ photoproduction.

- Gluon fluctuations in the nucleon
  It was demonstrated in [73] that the ratio

$$R(W, Q^2, M_X) = \frac{\frac{d\sigma(\gamma^* + p \to VM + M_X)(t=0)}{dt}}{\frac{d\sigma(\gamma^* + p \to VM + p)(t=0)}{dt}}$$

  measures the variance of the fluctuations of the gluon density in the nucleon for a given x. A slow Q^2, x dependence of this ratio is predicted. Hence a systematic experimental study of this ratio will provide an important new information about structure of the nucleon and will allow a better modeling of the pp collisions at LHC.

- Novel two $\to$ three processes
  There exists a number of novel DIS processes which were not studied so far which are sensitive to the generalized PDFs (GPDs) in the nucleons and large t GPDs in the nucleon. One example [74] is the process which maybe feasible for detection at HERA is the process $\gamma^* + p \to VM + gap + \pi^+ + n$ where a pion is produced with $x_F \leq 0.1, p_t \geq 1.5$ GeV/c corresponding to relatively small rapidities and the neutron hits the neutron calorimeter and has $x_F \geq 0.9, p_t \leq 0.1$ GeV/c. The transverse momenta of the VM and pions are nearly balanced in this kinematics and selection of large t for the process (color transparency) and low p_t for the neutron lead to a suppression of the final state interaction. This process is expected to be reasonably enhanced for large t since it has a much weaker t dependence than the $\gamma^* + N \to VM + N$ process (a factor $\propto 1/t^2$) due to a weaker large t dependence pion GPD as compared to the nucleon GPD.

6.6.4 *Observation of the Odderon at HERA*

Odderon exchange has never been observed in experiment, even though it is an essential prediction of QCD.

The asymmetry in either the fractional energy distribution or the angular distribution of charm versus anti-charm jets produced in high energy diffractive photoproduction

$$\gamma^* p \to c\bar{c}p$$

is sensitive to the interference of the Odderon ($C = -$) and Pomeron ($C = +$) exchange amplitudes in QCD [75]. This asymmetry has been estimated to be of the order 15% using an Odderon coupling to the proton which saturates constraints from proton-proton vs. proton-antiproton elastic scattering.

Measurements of this asymmetry at HERA could provide firm experimental evidence for the presence of Odderon exchange.

7 Conclusion

HERA was and is still the only place where precision measurements in QCD in a controlled environment with an electron probe and a hadron beam are performed. The vast amount of data collected at the HERA II collider with excellently understood detectors is still in the process of being analyzed.

Many fundamental questions of QCD, such as the universality of the PDFs for different processes, hadronic final state and hadronization universality can be addressed with HERA data. The answers to these questions are extremely interesting on their own, but even more so, this will be necessary ingredients for many potential discoveries at the LHC and elsewhere.

It has been discussed in this note that the HERA physics program is still extremely rich, full of potentially very important measurement in many different areas of QCD. We tried to structure the topics and to focus on the most fundamental questions such as universality and factorization.

We believe that much progress can be achieved in theses fields in the next few years, and we look forward to many exciting and challenging new results.

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