Diffractive Hard Scattering
Summary Report of the Working Group

H. Abramowicz[a], J. Bartels[b], L. Frankfurt[ac], H. Jung[d]

[a] Raymond and Beverly Sackler Faculty of Exact Sciences
School of Physics and Astronomy
Tel-Aviv University, 69978 Tel-Aviv, Israel
[b] University Hamburg, FRG
[c] St.Petersburg Nuclear Physics Institute, Gatchina, Russia
[d] CEA, DSM/DAPNIA, CE - Saclay, Gif-sur-Yvette, France
(now at Physics Department, University of Lund, Lund, Sweden)

Abstract: This report discusses the role of hard diffractive scattering in probing new QCD phenomena expected at HERA. Within this framework it summarizes the contributions made to this workshop which cover both theoretical investigations and experimental feasibility studies.

1 Importance of Hard Diffractive Phenomena

Diffractive processes in deep inelastic scattering (DIS) of leptons with protons at small x and large Q^2 offer a unique opportunity to probe the QCD color dynamics in the intermediate region between asymptotic freedom and confinement. The very presence of a large fraction of diffractive like events at high Q^2 is a signal for the interplay of hard and soft QCD phenomena. In the language of color dynamics two effects are expected to play an important role, color transparency (color screening) for systems consisting of quarks and gluons contained within a small size configuration and color opacity for large size configurations. The interactions of small size configurations lead to reactions dominated by hard processes with a cross section rising with energy while the interaction of large size configurations is dominated by soft processes. The ability to separate clearly these two regimes is essential for testing QCD both at a quantitative and qualitative level. In particular the following issues can be addressed:

- The dynamics of compact systems, color transparency and perturbative color opacity. The appearance of a new class of hard diffractive processes calculable in QCD is expected, $\gamma^* + p \to X + p$, where X is a longitudinally polarized vector meson or a system consisting of two high p_T jets. If confirmed experimentally, this would lead to a direct determination of the gluon distribution in the proton as well as the distribution of bare quarks within the vector meson.

- QCD predictions for the high momentum behavior of wave functions of hadrons consisting of light quarks and QCD physics of heavy quarkonia. In this respect the big advantage of hard diffractive processes is that they have large cross sections and provide a variety of new information.
- Violation of DGLAP evolution equation. Theoretical estimates suggest that the increase of parton densities at small x will slow down and that this effect can be observed at HERA in hard diffractive processes, in the measurements of the proton structure functions at moderate Q^2, as well as in the measurements of the structure functions of nuclei.
- Semi-classical approximation to high energy interactions. In the limit of strong color fields which are typical in the HERA kinematical regime, new developments and tests of the semi-classical approach are possible.

Let us repeat that, in order to test and improve our understanding of QCD, it is important to separate small and large size configurations in the diffractive final state. The two regions are described by quite different dynamical mechanisms. On the other hand, the diffractive structure function is an inclusive quantity which contains an integral over the final state configuration. From a theoretical point of view, therefore, this structure function is more difficult than some of the individual final states. This is why in this report the inclusive diffractive structure function can be discussed only after having analysed the small and large size final state configurations. This is quite in contrast to the experimental point of view: inclusive measurements of the diffractive cross section are easier to perform than the measurement of final states e.g. the hard di - jet events.

The outline of the report is the following. The second section gives a glossary and notation. The third section is devoted to the introduction of the theoretical framework which allows to understand the role of hard diffractive processes in testing the mechanism of high energy interactions in perturbative QCD and beyond. The experimental prospects for measuring the properties of the suggested large rapidity gap processes are then discussed in section 4. Section 5 outlines the expected theoretical implications and their significance for understanding the role of QCD in high energy processes.

2 Glossary and Notation

In the course of the presentation we will use a customary notation for variables used in describing deep inelastic and diffractive phenomena. For convenience we define them once for all in this section.

In the process (the momentum vectors are given in brackets):

$$e(l) + p(p) \to e'(l') + X + p'(p')$$

the center of mass energy squared is given by: $s = (l + p)^2$. The center of mass energy squared of the hadronic system is given by:

$$W^2 = (q + p)^2 = -Q^2 + 2pq + m_p^2 = Q^2\left(\frac{1}{x} - 1\right) + m_p^2 \ ,$$

with $q = (q_0, \vec{q})$ and $Q^2 = -q^2$ being the 4 - momentum of the virtual photon. The Bjorken variable x is given by:

$$x = \frac{Q^2}{2pq} \ ,$$

with p being the 4 - momentum of the incoming proton.

For the description of the diffractive interactions we use X to denote the final state corresponding to the photon dissociation. If also the proton dissociates we denote its state by Y to indicate that it is still separated from the state X. The kinematical variables are given in the following. The square of the momentum transfer at the proton vertex,

$$t = (p - p')^2 \ ,$$

where p' is the 4-momentum of the outgoing proton. In the more general case of proton dissociation p' should be replaced by the 4-momentum of the outgoing system Y.

The fraction of the proton momentum carried by the Pomeron is:

$$x_{I\!P} = \frac{(p - p') \cdot q}{p \cdot q} = \frac{M_X^2 + Q^2 - t}{W^2 + Q^2 - m_p^2} \ ,$$

where M_X is the invariant mass of the hadronic system produced as the outcome of photon dissociation, and m_p stands for the proton mass. For large Q^2 and W^2 the influence of t and m_p on $x_{I\!P}$ is negligible. It should be noted that the subscript $I\!P$ may not always be adequate, although it still make sense to talk about the fraction of proton momentum in the interaction. This is particularly true for models where there is no object such as a Pomeron.

In analogy to x we define β as the Bjorken variable related to the Pomeron,

$$\beta = \frac{Q^2}{2(p - p') \cdot q} = \frac{x}{x_{I\!P}} = \frac{Q^2}{Q^2 + M_X^2 - t} \ .$$

Here again t is only included for completeness.

In the splitting of the photon into a $q\bar{q}$ we will denote by z the fraction of the photon momentum carried by one of the quarks of the pair, and by k_t their transverse momentum relative to the photon direction. The transverse momenta of jets in the final state are denoted by p_T.

3 Theoretical framework

This section reviews the theoretical ideas discussed during this workshop pertaining to the hard diffractive scattering and its potential in clarifying and exploring the properties of QCD. It is not meant to be a complete review of all the phenomenological activities developing very dynamically in this area of research. Its main purpose is to outline the fundamentals of QCD that can potentially be probed in diffractive processes.

3.1 Classification of high energy processes

In order to understand the issue of the interplay of hard and soft physics in high energy processes it is fruitful to classify them according to the number of involved scales [1].

Soft QCD - Physics of the Pomeron: Soft hadron collisions are usually considered as processes with one scale ≈ 1 fm. At high energy these processes have been successfully described by Pomeron [2, 3] exchange or by Pomeron cuts as advocated since the sixties and seventies [4] (for a review see [5]). The basic feature of this class of processes is the Pomeron pole factorization, by which we mean that at high enough energy the energy dependence of any hadronic cross section should be given by a universal Pomeron trajectory. With a universal Pomeron the ratio of single to double diffractive cross sections is independent of the projectile [6, 7]. This universal trajectory of the Pomeron described by $\alpha(t) = \alpha_0 + \alpha' t$ with $\alpha_0 = 1.08$ and $\alpha' = 0.25$ GeV^{-2} [8] gives a reasonable phenomenological description of the energy dependence of cross sections. The universal energy dependence of cross sections is also natural in the semi-classical approximation of [9] to quantum field theory.

Hard QCD evolution: The second class consists of hard processes which are determined by two or more different scales involved in the interaction. Deep inelastic lepton scattering off protons as well as all hard diffractive processes belong to this class. The hard scale is supplied by the virtuality of the photon or jets and the soft scale on the proton side is determined by its size of ≈ 1 fm.

In order to be able to use perturbative QCD, it is important to prove that the short distance physics factories from the soft one. For the total cross section and for special hard diffractive processes this is achieved using the factorization theorem in QCD which leads to the DGLAP equations describing the evolution from the large Q^2 scale to the scale of soft QCD processes. The soft physics (and in particular the soft Pomeron) then enters the boundary conditions to these equations.

The characteristic feature of two scale processes is the violation of the Pomeron pole factorization. In hard processes at high energies one may observe different energy dependences for different external particles and that the energy dependence may change as Q^2 changes. Thus to avoid confusion the word Pomeron will be used in this report for the soft QCD processes described by a universal trajectory, as it has been originally suggested.

BFKL evolution In its original form the BFKL equation is derived assuming a small but fixed value of the strong coupling constant. The scale of α_s is that of the external particle, e.g. for onium-onium scattering the scale is defined by the heavy quark of the onium state. The BFKL approximation therefore applies to processes with one large momentum scale. At HERA, a clean test of BFKL would be provided by the measurement of high-p_T forward jets, with $p_T^2 \approx Q^2$, in low-x deep inelastic scattering, as suggested by A.Mueller [10].

Whether the BFKL can be used for predicting the x dependence of the gluon structure function at small x is a topic of heated debate: the structure functions have not only the scale Q^2, but, through the initial conditions, also contain the hadronic momentum scale, and therefore do not provide a clean BFKL application. In deep inelastic diffractive scattering, a promising place to look for the BFKL Pomeron is semi-inclusive diffractive vector production $\gamma^* + p \to V + X$ with a large momentum transfer t.

Color transparency and Perturbative Color Opacity: Color transparency is a phenomenon which describes within QCD the interaction of a small size color neutral parton configuration with a hadronic target. The essence of color transparency is expressed in the formula [11, 12, 13] which follows from the factorization theorem for hard processes in QCD.

$$\sigma_T^{q\bar{q}} = 2\alpha_s \pi^2 b^2 \frac{1}{N_c} Tr \left(\frac{F^2}{8}\right) xG_T(x, 9/b^2), \tag{1}$$

where b is the transverse separation between the $q\bar{q}$ system, F^2 is the Casimir operator of the SU(3) color group and G_T stands for the gluon distribution in the target.

The name derives from the fact that high energy processes are dominated by gluon exchanges and that the cross section for a small configuration is proportional to its size in the impact parameter space (color screening). The decrease of the cross section with decreasing size is partly compensated by the known increase of the gluon density. At fixed size b the cross section increases with increasing energy. At very high energy, when the number of gluons becomes very large, the interaction cross section also becomes large and that leads naturally to perturbative color opacity. Both phenomena are particularly relevant for photon induced high energy interactions as the photon fluctuates into a $q\bar{q}$ pair and most of these fluctuations lead to a small size, large relative k_t quark pair where the partons screen each other. An important consequence of color transparency is that in the region of its applicability initial and final state interactions are suppressed. Color transparency and perturbative color opacity phenomena can be used to probe the diffusion of a small size configuration into a normal hadron size. This diffusion is characteristic for quantum field theory phenomena and is one of the sources of leading twist nuclear shadowing at small x. At sufficiently small x the impact parameter unitarity condition and perturbative color opacity put dynamical limit on the region of applicability of existing pQCD methods to hard processes. In this respect color transparency and color opacity are new phenomena, on top of perturbative QCD.

A few more words might be in place about the BFKL approximation in the diffractive structure function. It is immediately clear that the use of BFKL approximation across the rapidity gap faces the same problem as for the gluon structure function, i.e. it has two scales: the hadronic scale at the coupling to the proton, the other scale characterizing the diffractive system at the other end of the Pomeron. In addition, this latter scale is not necessarily the same as the photon virtuality Q^2. It rather depends upon details of the final state of the diffractive system. As for the diffractive structure function, it has recently [14] been observed that, as a result of its built-in diffusion mechanism, the BFKL itself pushes this upper scale into the infrared region, i.e. into a region of phase space where non-leading corrections to the BFKL approximation are expected to be large.

Beyond these more subtle difficulties in the application of the BFKL approximation to multi-scale processes it is also not clear whether in diffractive dissociation at HERA there is enough phase space available for building up the power-law behavior expected from the BFKL equation. Namely, in order to achieve a multi-Regge type regime in which the BFKL approximation is valid, i.e. where only small correlations between the subsequent parton emissions exist, the rapidity interval available for radiation has to be large. Let us estimate the effective order of terms containing $\ln 1/x$ within the kinematics of HERA. The interval in rapidity covered by HERA is $\Delta y = \ln 1/x + \ln Q/m \sim 12$. A typical correlation length in rapidity space between particles in multi-particle interactions has been measured to be of the order of 2 to 3 units in rapidity. Thus the photon and proton fragmentation regions will occupy typically about 5 units of rapidity. In the multi-Regge kinematics the rapidity interval between adjacent partons should be greater than the typical correlation length. Thus assuming a rapidity separation of 3 units, the BFKL ladder at HERA may contain not more than 2 to 3 steps. In the DGLAP evolution or within the multi-peripheral pQCD kinematics the ladder can be somewhat longer. It is thus not clear whether there is enough phase space available at HERA for building up the power-law behavior expected from the BFKL equation. To unambiguously observe the BFKL asymptotics it is necessary to find a trigger which ensures only one hard scale. Such a kinematical condition will prevent the impact parameter space evolution to larger sizes and will facilitate the search for the behavior predicted by the BFKL approximation (see above).

In reality, the distinction between these four types of physics is not always clear. For example the spatial size of known hadrons varies from the proton having a radius of ≈ 0.8 fm to the Υ whose radius is ≈ 0.1 fm. Thus the J/ψ or Υ scattering of a proton belongs, in a wide kinematical range, to the second class of processes [15]. However, with the increase of the energy of these interactions (i.e. in the Regge limit) the soft regime would dominate in most of the rapidity space as a result of diffusion from the large scale provided by the mass of the heavy vector mesons to the scale of soft QCD processes.

3.2 The physical picture underlying LRG events

The interest generated by the observation in DIS of a significant proportion of events with large rapidity gaps (LRG) in the hadronic final state is easy to understand within the pQCD wisdom. In perturbative QCD [16, 17] the probability for a gap to occur is $P_{gap} \sim \exp(-\Delta y \omega)$, where Δy is the length of the gap in units of rapidity and

$$\omega = N_c \int_{Q_0^2}^{Q_{max}^2} \frac{\alpha_s(k_t^2)}{k_t^2 \pi} dk_t^2 \,, \tag{2}$$

where $N_c = 3$. At low Q_{max}^2 ω is of the order of unity and it increases with Q^2. Of course the lower limit of integration is sensitive to non-perturbative physics and thus in practice the numerical value of ω is uncertain. However one expects an exponential suppression of large rapidity gaps and this fact is reproduced in the MC generators for DIS events. In the Lund Model the confinement forces produce quark-antiquark pairs which fill the rapidity gap [18].

This apparent contradiction stimulated interest in the role of non-perturbative "color re-arrangement" QCD effects in the final states. Models [19, 20] have been suggested where LRG events arise as the result of non-perturbative random soft color interactions between the ejected parton and proton remnants (hard radiation is accounted for using pQCD methods). Within these models the ratio of cross section for diffraction in DIS to the total cross section is expected to weakly decrease with increasing Q^2. The decrease of this ratio with Q^2 seems to be a model independent prediction of QCD since as Q^2 is increased at fixed x, the radiation region will expand to fill up the whole phase space and LRG events will be suppressed. The model of [20, 21, 22], in which the perturbative phase of radiation is described by the DGLAP evolution is capable of describing the gross features of the data on diffraction in DIS. However QCD radiation in terms of a BFKL type approach has been found to lead to much larger radiation [23]. It seems that the probability of gap survival in the production of high p_T dijets separated by a large rapidity gap can provide an effective testing ground for these ideas. Such processes have been observed by ZEUS [24], CDF [25] and D0 [26].

It is of interest to consider the deep inelastic processes at small x in the reference frame where the proton is at rest, a relatively new idea in QCD. In fact, this approach is closer to the theoretical ideas formulated in 1970's for generalizing the then more familiar model of vector meson dominance to the parton model. In principle, the target rest frame description is equivalent to the Breit frame description of Feynman in which the photon has no structure. The difference in the interpretation reflects the fact that the time interval is not Lorentz invariant. Obviously it is only the space-time interval which is Lorentz invariant. However the QCD formulae for the hard diffractive processes clearly reveal the equivalence between both approaches.

In DIS, in the proton rest frame, the virtual photon fluctuates into a quark-antiquark pair at distances $l_c = 1/2m_p x$ upstream from the proton (of mass m_p). A formation or interaction length can be measured when the cross section depends on the masses of the interacting particles [27]. The existence of a large interaction length in DIS has been established by Ioffe [28, 29] based on the decrease of the total cross section with Q^2. Theoretically such an interaction length is a basic property of the parton model- 'ladder diagrams' which dominate the pQCD regime. At fixed x when Q^2 increases pQCD cascades tend to be relevant for most of the phase space of the final state. In this case the interaction length is a measure of the spatial distances occupied by perturbative QCD in DIS.

In the HERA energy range "macroscopic" interaction lengths of up to 1000 fm can be reached, while fixed target experiments reach at most $l_c \sim 10$ fm; in other words, in the HERA kinematics, it is a quark-antiquark pair rather than a photon that interacts with the proton. This knowledge has deep implications for the existence of coherent phenomena in DIS at low x [30] and is the reason why from now on the interaction length will be called coherence length.

Semi-classical calculations of the space-time evolution of a $q\bar{q}$ pair created with size $1/Q^2$ at the origin show that the transverse size b of the $q\bar{q}$ pair upon arrival on the target is $b^2 \approx 1/k_t^2$ [31, 32, 33] where k_t is the transverse momentum of the quarks from the photon. Thus DIS at small x probes the interaction of different quark configurations in the photon wave function with the target. This observation helps to establish the equivalence between the parton model and the proton rest frame description which is in essence the "aligned jet model" (AJM) [31, 32, 33] for DIS. In the AJM the large k_t, $q\bar{q}$ configurations of the virtual photon are inactive and the interaction occurs predominantly through $q\bar{q}$ pairs with small relative k_t, with one of the constituents carrying practically the whole of the projectile momentum. This assumption is necessary to reconcile Bjorken scaling with the laboratory frame description and to avoid the Gribov unitarity limit [34] saying that $\sigma(\gamma^* N)$ would be independent of Q^2 or even increase as $\ln Q^2$, if all quark-gluon configurations were to interact with the same cross section.

These quark-antiquark pairs with large transverse separation, resulting from an asymmetric sharing of the photon momentum generate a strong color field and behave essentially like hadrons. Thus both the parton model and the AJM naturally predict a large leading twist cross section for diffraction in DIS - similar to that observed in soft hadronic interactions.

The modeling of diffraction with the AJM approach [35] has been implemented in the NIKZAK generator [36] and gives a fair agreement with the data. LRG events can also be reasonably well described in terms of diffractive interactions as given by a phenomenological Pomeron exchange. The basic idea is that the Pomeron has a parton content which can be probed in hard scattering processes [37]. This approach is realized in Monte Carlo generators such as POMPYT [38] and RAPGAP [39]. We want to stress that the contribution of naive AJM- configurations of quarks having transverse momenta $k_t \ll \sqrt{Q^2}$ is suppressed in QCD by Sudakov type form factor. This suppression is compensated to a large extent by bremsstrahlung. Thus within QCD the number of jets in the photon fragmentation region should increase with increasing Q^2 [40].

The $q\bar{q}$ configurations with sufficiently small transverse separation in space, i.e. with large relative transverse momenta, interact with a hadronic target, T, with a small cross section given by eq. (1). The presence of the gluon density in eq.(1) $G_T(x, 9/b^2)$ shows another distinctive property of the dynamics of small objects - small objects interact with small cross section which however increase fastly with energy due to the evolution of partons in the target. The presence of the gluon structure function $G_T(x, 9/b^2)$ distinguishes eq.(1) (derived in QCD) from a similar equation suggested within the constituent quark model of hadrons for quarks interacting through two gluon exchange [41, 42, 43].

For the small $q\bar{q}$ configurations diffractive scattering is driven by two gluon exchange. It is important to consider the suppression of gluon radiation from the pair of exchanged gluons. The issue is the coherence in the radiation from a color neutral system when the color charges are almost at the same impact parameter. In this case radiation of gluons with small transverse momenta is known to be suppressed [44, 45] since such a gluon can not resolve a colorless object. Radiation of gluons with large transverse momenta is suppressed by the smallness of the coupling constant. This reasoning is directly applicable to hard diffractive processes initiated by small size $q\bar{q}$ pairs where the exchange of a colorless pair of a hard and a relatively soft gluon can be calculated in QCD. These processes are still of a leading twist type because QCD factorization theorem is modified for processes with diffractive final states [46]. The smallness of the relative impact parameters is the property of QCD evolution. The amplitude of processes with large rapidity gap is generally suppressed due to the fact that all color exchanges have to be at the same impact parameter.

To summarize the following scenario emerges for the energy dependence of hard diffractive scattering. In the soft QCD regime, the parton model predicts the usual Pomeron type behavior somewhat modified by Q^2 evolution. In QCD, in contrast to the parton model, the contribution of $q\bar{q}$ pairs with small relative distances b, (large relative momenta k_t) is only suppressed by α_s/k_t^2 but their interaction cross section increases quickly at small x. Thus, due to the presence of the so called anomalous photon contribution, $\sigma_{\gamma^* N}$ may increase faster with W^2 as compared to cross sections for hadron collisions since the probability of small configurations in the wave function of a hadron is significantly smaller than in the photon wave function. This physics is naturally incorporated in the models for the production of $q\bar{q}$ pairs from a gluon field [40, 47]. Calculation of these diagrams leads to a reasonable interpolation formulae between soft and hard QCD. For the small transverse momenta configuration this approach is more or less equivalent to the AJM. At large transverse quark momenta these diagrams lead to high p_T dijet production calculable in QCD. The smooth matching of the contributions of these two types of physics predicts the violation of universality of the intercept and of the slope of the "effective Pomeron". At large β, small diffractive masses, the result may become closer to that characteristic for the pQCD regime [30, 48].

Finally, a few words should be said about the possibility of observing deviations, in the cross section given by eq.(1) at small x, from the DGLAP evolution equations (often referred to as " saturation effects"). There is very little doubt that the DGLAP-predicted small x behavior of the gluon distribution cannot be correct for arbitrarily small x; similarly, also the BFKL approximation needs larger and larger corrections when x becomes very small. Qualitatively we expect these corrections to tame the increase at small x. The observation and theoretical understanding of such unitarization effects is widely considered to be one of the main challenges of low x physics. Empirically we know that the rate of the increase of the gluon structure function at small x changes with the transverse size of the $q\bar{q}$ pair: for small b^2 we observe a stronger increase and, most likely, will have to go to smaller x before we can see the onset of corrections, whereas for larger sizes of the $q\bar{q}$ system we move into the regime of the non-perturbative (soft) Pomeron with very strong corrections already at not so small x. Hard diffractive scattering, which, at fixed small x, allows to probe different ranges of b^2, therefore offers the exciting possibility of observing the onset of deviations from DGLAP evolution. Compared to F_2, these corrections should become visible already at larger values of x, i.e. at HERA hard diffractive scattering may be the most promising way of addressing this fundamental issue!

3.3 How to distinguish between Soft and Hard Diffractive Processes

Let us now highlight the features that can differentiate between soft and hard QCD diffractive processes. For simplicity let us parameterize the elastic or diffractive cross section for $\gamma^{(*)}p$ in the form

$$\frac{d\sigma}{dt} \propto W^{4n} \exp\left(B_o\, t + 2\alpha'_{I\!P}\, t \ln \frac{W^2}{s_o}\right) , \tag{3}$$

where as usual W is the c.m. energy of the $\gamma^{(*)}p$ collision and t the momentum transfer at the proton vertex.

Energy dependence of the cross sections: The analysis of soft processes shows that n is universal, determined to be $n \approx 0.08$ and $\alpha' \approx 0.25 GeV^{-2}$ [8]. These observations can be interpreted either as evidence for the exchange of a Pomeron with small re-scattering effects [49, 50] or by saying that the observed behavior is a combination of a Pomeron with $n \geq 0.2$ and big re-scattering effects [51, 52]. In the latter case the effective W dependence is expected to vary from process to process.

For the hard diffractive processes we have $d\sigma/dt \approx [xG_p(x, Q^2_{eff}]^2$ where Q^2_{eff} depends on the process (for a discussion see [53, 12, 54]). For the vector meson production $Q^2_{eff} = Q^2\langle b^2_L\rangle/\langle b^2_V\rangle \ll Q^2$ [55], for diffractive dijet production $Q^2_{eff} = p^2_T/(1-\beta) \geq p^2_T$ [56, 57, 58] (for the same process within the constituent quark model of the nucleon see also [59]). The quantity $\langle b^2_V\rangle$ is the effective size of the $q\bar{q}$ pairs in the diffractive production of vector meson V while $\langle b^2_L\rangle$ is the effective size of $q\bar{q}$ pairs in the total cross section for the longitudinally polarized photon. Thus cross sections of hard diffractive processes should increase with W considerably faster than the soft ones with a scale dependent power as dictated by the QCD evolution equations. Hard diffractive physics corresponds to the limit when both $\ln Q^2$ and $\ln(1/x)$ increase at the same time. At fixed Q^2 and M^2_X (Pomeron type kinematics) and at sufficiently small x the energy dependence of cross section should be again dominated by soft QCD.

The BFKL approximation predicts an even faster increase with energy of the cross sections for the hard diffractive processes, but taking into account energy conservation and coherent effects in radiation tends to diminish n [60, 61, 62, 63].

Higher twist hard processes should be specially enhanced in the diffractive production of states with masses $Q^2 \gg M_X^2$ and in the processes initiated by longitudinally polarized photons.

t dependence of the cross sections: The energy dependence of the slope B of the t distribution $\sim \exp(Bt)$ and its universality is a sensitive probe of soft and hard QCD [30, 64]. When soft QCD phenomena dominate B is expected to increase with energy $B_{\text{soft}} = B_o + 2\alpha'_{\mathbb{P}} \ln(W^2/s_o)$, where $\alpha'_{\mathbb{P}}$ is the slope of the vacuum pole as given above. Within the HERA kinematical range the slope should change typically by 2 units if indeed soft QCD dominates. [65]

In the hard QCD regime one expects $\alpha' \approx 1/Q^2$ and $s_o \approx Q^2$. Also the value of B_o should be significantly smaller for hard diffractive processes compared to the soft ones. For ρ meson photo-production the measured value is $B \sim 10$ GeV^{-2} [66] and is well understood in terms of vector dominance model and the similarity between ρN and πN scattering. For hard diffractive processes B should be significantly smaller since the scale of the t dependence at the hard vertex is given by Q^2. At small x it should be practically independent of W, $B = B_o$, and the same for all hard diffractive processes [30]. This seems to be not far from the current data on diffractive electro-production of ρ, ϕ and in particular J/ψ mesons [67]. A unsolved question concerns the kinematical region where Pomeron regime is restored in the limit of $x \to 0$ and large but fixed Q^2 . The signature of this regime is a value for $\alpha'_{\mathbb{P}}$ which should be the same as in the soft hadron interactions.

Diffractive production of light quarks by transversely polarized photon is beyond the control of hard QCD, and therefore its theoretical description is model dependent at present. One of the ways to investigate the interplay of hard and soft QCD in such processes is to observe a difference in the behavior of reactions initiated by transversely polarized photons as compared to those initiated by longitudinally polarized photons: a larger value of the slope of the t dependence and its noticeable energy dependence. Another feature of the soft diffractive processes is the presence of maxima and minima in the t dependence of the differential cross section which are due to the interference between the impulse approximation and the re-scattering terms. For the hard diffractive processes the re-scattering term should be suppressed. Thus for hard diffractive processes such structures in the differential cross section should disappear with increasing Q^2.

The phenomena discussed above can also be used to investigate the onset of deviations from the DGLAP equation. Near the unitarity limit two phenomena are expected, a slowing down of the increase of the parton densities with decreasing x and a fast increase with energy of the t slope (significantly faster than for the soft regime) and its growth with t.

Diffractive charm production: Diffractive charm production may appear as an effective probe of the hardness of the interaction processes [36, 58, 59, 68, 69, 70, 71]. If diffraction is dominated by hard QCD and the masses of the quarks can be neglected, the fraction of diffractive charm production is given by the ratio of the squares of the quark electric charges: $e_c^2/\sum e_i^2 = 0.4$. If soft QCD dominates in diffraction, for example by the exchange of two soft non-perturbative gluons [68] or via boson gluon fusion with a gluon coming from a non-perturbative partonic Pomeron a la Ingelman - Schlein [37], the production of charm is expected to be smaller. An estimate of charm production can be obtained assuming a universal structure of the Pomeron. For a typical transverse momentum of a quark in the soft QCD regime of ~ 0.4 GeV and a bare mass of the c quark of $m_c = 1.2$ GeV, the ratio $F^D_{2\,charm}/F^D_2$ is proportional to $(4/9 \cdot k_t^2/m_c^2)/(6/9 + 4/9 \cdot k_t^2/m_c^2) \approx 0.07$. A larger yield can be obtained if the structure of the parton ladder relevant for the process depends on the channel. In reality the expected yield of charm should be larger since QCD evolution leads to diffractive production of high p_T jets which should be enriched by charmed particles [36, 58, 59, 68, 69, 70] The first experimental indications are that charm production at HERA [72] is not small. Thus the absolute value, the energy and t dependence of diffractive charm production are sensitive probes of interplay of soft and hard QCD.

Azimuthal distribution: Hard physics should manifest itself in very specific azimuthal distributions for the process $e + p- > e + q\bar{q} + p$ [73, 74, 75]. The azimuthal distribution in exclusive two jet production will be different for boson gluon fusion than for a two gluon exchange mechanism. Thus the study of azimuthal distributions should help in differentiating between hard and soft diffractive physics.

Thus we conclude that the competition between soft and hard QCD requires attention in the comparison between results of different groups and of different measurements of the same group. This is because in the different kinematical ranges different physics may dominate.

3.4 Semi-classical approach to diffractive processes

In [69] a semi-classical approach to diffraction is proposed in which the proton is treated like a classical background field. Working in the proton's rest frame, the contributions of different configurations of the $q\bar{q}$ pair in the virtual photon to diffractive and inclusive structure functions are calculated. A physical picture emerges that is very similar to Bjorken's aligned-jet model. As the very fast partons of the pair pass through the proton they interact, essentially elastically, with its color field, which is treated as a classical background field. This leads to non-abelian eikonal factors in their wave-functions which allow the possibility of diffractive scattering. Leading twist diffraction is dominated by the configuration in which one of the partons in the pair carries most of the momentum of the photon and a large transverse distance develops between the partons by the time they arrive at the proton. Unlike the inclusive cross section, it has no logarithmic enhancement at large Q^2. The approach has a few features similar to the more phenomenological model advocated in [19], in which diffractive events are kinematically dominated by single gluon exchange and non-perturbative soft color interactions allow the formation a color singlet final state.

In [76] the model is expanded to include an additional gluon in the final state. Leading twist diffractive processes appear when at least one of the partons has a small transverse momentum and carries a small fraction of the longitudinal momentum of the proton. The other two partons may have large transverse momentum, i.e. they stay close together as they move through the proton, acting effectively as one parton. This high k_T jet configuration produces the only leading twist contribution to F_L^D at this order (which is constant) and $\ln Q^2$ enhancement of F_2^D. This signals that F_2^D also has leading twist contribution from the configuration in which the transverse momenta of the partons interacting with the target transverse momenta are small. Phenomenologically one expects the ratio F_2^D/F_2 to decrease like $1/\ln Q^2$. There should be fewer jets in F_2^D, since they appear only at order α_s, than in F_2 where they appear at leading order. In F_L^D the leading twist diffraction appears at order α_s which will be dominated by jets.

3.5 Hard diffractive processes calculable in QCD

It has been understood recently that hard diffractive processes, in particular elastic electroproduction of vector mesons by longitudinally polarized photons at large Q^2, $\gamma^* + p \to V + p$, and high p_T dijet production, $\gamma^* + p \to q(p_T)\bar{q}(-p_T) + p$, are calculable in QCD. Although these processes are higher twist effects, QCD factorization theorem justifies factorization of the hard blob from the soft blob [77]. The large interaction length at low x justifies the use of completeness of hadron states produced in the intermediate step and as the outcome, the calculation of the cross sections for the hard diffractive processes in terms of quarks and gluons. Therefore, as for the deep inelastic processes, the scattering amplitude can be expressed by the distribution of the gluons in the nucleon and in case of vector mesons by the bare quarks inside the vector meson.

A feature particular to these new hard processes is that as a result of energy-momentum conservation the fractions of proton momentum carried by the exchanged partons are not equal [53, 46, 30, 78] leading to non-diagonal parton distribution. At sufficiently small x within the leading $\alpha_s \ln x$ approximation of QCD the non-diagonal gluon distribution tends to the diagonal one [79]. However this result could be valid even beyond this approximation since it is the property of both multi-Pomeron [79] and multi-peripheral kinematics. Within the leading $\alpha_s \ln Q^2$ approximation the difference between diagonal and non-diagonal distributions, at sufficiently small x, is calculable in pQCD because as a result of QCD evolution, in the non-perturbative distribution, only partons with large fraction of the proton momentum are important. The radiation from asymmetric gluons is a small correction since the gluons are effectively at the same impact parameter. This is a particular case of Gribov's theorem [44] which states that, as a result of gauge invariance radiation of vector particles with small p_T in high energy processes is predominantly from large distances and insensitive to the interior structure of amplitude. For a colorless exchange only gluons with large p_T can be radiated but this radiation is suppressed by the smallness of the coupling constant. Thus there is a definite possibility to measure the same gluon distribution in different hard diffractive processes.

The investigation of these processes will provide a novel information on the hadron structure and on the space-time development of QCD processes at high energies. They offer the possibility to measure parton distributions in hadrons in a new way, to establish the three-dimensional distribution of color in hadrons as opposed to the one-dimensional one from the leading twist phenomena and to check the predictions of QCD for the asymptotic behavior of the light-cone wave functions of hadrons. This field is rather young, but progress in the theory and in the experiment is rather fast.

The processes of this type which have been considered at this workshop are diffractive vector meson production by longitudinally polarized photons, diffractive production of two high p_T jets, and large t diffractive J/ψ production.

One of the striking experimental observations at HERA is the qualitative difference in the energy dependence of diffractive photo-production of J/ψ meson as compared to electro-production of ρ meson. This fact is in line with the significant high momentum tail of the wave function of J/ψ which follows from realistic models of charmonium. As a result, in the processes determined by the first power of charmonium wave function, color in the $c\bar{c}$ pair is strongly localized. This explains the precocious applicability of pQCD to the diffractive photo-production of J/ψ [55]. This process is an effective probe of relativistic effects in the charmonium wave function. The fact that such effects are large has been known long ago from the calculation of QCD radiative corrections to the decay of J/ψ into leptons.

Other processes which have been considered are diffractive production of masses $M^2 \ll Q^2$ [30, 80] and diffractive open charm production [68, 71, 58]. Both belong to a class of processes where special care has to be taken for the contribution of the transversely polarized virtual photon. The theoretical description of diffractive processes initiated by transversely polarized photons is model dependent [81, 80]. This is because the contribution of soft physics is not suppressed for such processes up to extremely large Q^2 where it becomes suppressed by Sudakov type form factors.

The pQCD calculation of diffractive reactions initiated by longitudinally polarized photons can in principle be applied to a more general case of low mass hadronic final states. However the presence of crossed diagrams (4 gluon exchange) leads to the end-point, non-perturbative QCD contribution which may spoil the predictive power of the calculation unless it is restricted to the region of exclusive states with $(1-\beta) \leq \mu^2/Q^2$ where μ is a Q^2 independent hadronic scale. This is not an issue for vector meson production as the end-point contribution is suppressed by the the decrease of the wave function of vector mesons as $\sim z(1-z)$ or faster [30, 79].

3.6 Color transparency phenomenon and possible signatures

Not unexpectedly the low x physics and hard diffraction in particular indicate the importance of color dynamics in QCD. It seems that certain aspects of hard diffraction are easier to understand in the language of color dynamics than in the quark-parton language. The important starting point is to view the deep inelastic scattering in the rest frame of the proton. As explained earlier, in this frame the photon fluctuates into a $q\bar{q}$ pair long before reaching the target. The interaction of this photon with the target depends on the initial configuration of the $q\bar{q}$. In order to achieve scaling a la Bjorken, one has to assume that certain configurations, those in which the pair of quarks have a large relative k_T are inactive [31, 32, 33] (this is the assumption of the AJM).

In QCD the pseudo-neutrality of the large k_t configurations is explained by the fact that they occupy a small transverse area in which color is screened. It turns out that the interaction cross section of such a small size configuration is not zero but proportional to the square of the transverse distance between the partons and the gluon density in the target (see formula 1). Thus the QCD corrections to scaling find a natural explanation. Since the interaction cross section for a small size object is small this leads to the notion of color transparency (CT). CT in QCD is the consequence of color screening and asymptotic freedom.

In low x processes (large coherence length) CT is expected when Q^2 is large and its role will increase with increasing Q^2. Albeit even at large fixed Q^2 when x decreases CT may disappear. Due to QCD evolution the number of gluons increases with decreasing x and even for an interaction of a small object the cross section may become very large and reach the unitarity bound. Thus the regime of color transparency will lead to perturbative color opacity. A way to enhance the role of CT is either to go to very large Q^2 or to select photons with longitudinal polarization for which the $q\bar{q}$ tends to have a large relative k_t. Note that the picture which emerges in this language of color optics is very consistent with the one forged on ideas of the QCD improved quark-parton model.

CT leads naturally to the appearance of hard diffractive processes where a color neutral small objects traverses the target without disturbing it too much and reappears either as a small mass diffractive final state (a vector meson in particular) or as a two jet configuration. The fact that these interactions can be described as due to two perturbative gluon exchange without form factor suppression requires further theoretical insight as explained in one of the previous sections.

One the consequence of CT is that the process of re-scattering of a small object within a target should be suppressed and thus in general initial and final state interactions should be suppressed in a wide range of high energy interactions (see discussion and references in [82]). This striking prediction of QCD can be hardly understood in terms of pre-QCD ideas. This is why CT phenomena are at present searched for at all high energy accelerators. Another important role of CT is that it will allow to probe the onset of saturation expected at very low x.

One of the recent experimental confirmations of ideas leading to CT phenomenon is the observation by H1 and ZEUS of a fast increase of cross sections of hard diffractive ρ, ϕ, ψ meson production with decreasing x [79]. The slope of the t distribution is also found to be smaller compared to photo-production data. The E665 experiment at FNAL has found some evidence for color transparency [83] in the ρ meson production. However, the data have low statistics, cover a rather restricted range of x and Q^2 and cannot reliably separate events without hadron production.

In the context of vector meson production a direct consequence of CT would be the disappearance at large Q^2 of maxima and minima in the t distribution which for soft processes are due to the interference between the impulse approximation and the re-scattering terms.

The suppression of initial and final state interactions should be observed also in the diffractive processes in DIS off the proton. This is because at small x the initial and final state interactions of the small size $q\bar{q}$ pair with proton remnants should be suppressed by an additional power of the size of the quark-gluon configuration b^2. But there are no firm conclusions to be drawn as yet.

A generic example of a process in which CT can be tested is the production of jets separated by a large rapidity gap in photo-production. A real or virtual photon contains with a significant probability an unresolved photon defined as a small size quark-gluon configuration where color is well screened (anomalous contribution to the photon structure function and direct contribution to the photo-production cross section). Hence CT should be important in any process induced by the contribution of the unresolved photon. If CT is a viable phenomenon the probability of survival of large rapidity gaps between jets is expected to be higher for jet production initiated by the unresolved photon contribution than for the hadronic component.

The gap survival probability P accounts for the soft interactions of the constituents which do not participate in the hard process. The estimate of P for $p\bar{p}$ collisions within the eikonal approximation has been made in [84, 85] and leads to the universal function of dimensionless parameter:$\frac{\sigma_{tot}}{B}$ where B is the slope of the t dependence of the scattering amplitude. The universality follows from the fact that hard partons are concentrated at considerably smaller impact parameters as compared to the soft ones [86]. The dependence of P on the projectile is seen to be rather weak. Gluon radiation should be also projectile independent since its effects cancel out in the ratio of events with and without large rapidity gap. Thus the expectation of CT is very different from the above [86]. A significant difference in the gap survival probability for projectiles of different size would have to be interpreted as evidence for CT.

The recent measurements of ZEUS [24] show a substantially larger gap survival probability than observed in CDF [25] and D0 [26]. In the kinematics of the ZEUS experiment one of the jets carries a significant fraction (≈ 0.7) of the photon momentum, a configuration which favors the direct photon contribution. This observation could well be the first experimental hint that small size configurations for which initial and final state interactions are suppressed lead to a larger gap survival probability.

These data are in line within the assumption that color of a hard gluon can be neutralized in hard diffractive processes by the exchange of a relatively soft gluon located at the same impact parameter [53, 87, 88, 84, 89, 46, 79].

In particular the observed practical independence of the ratio on pseudo-rapidity implies that the LRG events follow a $\frac{1}{t^2}$ Rutherford scattering distribution, just like the non-gap dijet events to which they are normalized and which are dominated by single gluon exchange in the t channel [45].

To demonstrate in a model independent way that the explanation lays within CT it is necessary to measure the gap survival probability as a function of the resolved photon contribution. The advantage of using a photon target is that the kinematical region in which one of the jets carries a significant fraction ($z \approx 0.7$) of the photon momentum [90] enhances the small size configurations while requesting $z \leq 0.4 - 0.5$ will enhance the resolved contribution. Note that the region of large z is suppressed in the wave function of hadrons. The gap survival probability for the resolved contribution should be smaller. A naive estimate would lead to reduction of a factor two.

3.6.1 Proton fragmentation region

The proton fragmentation region in the reactions $\gamma^* + p \to X + Y$, where X and Y, the states corresponding to the dissociation of the photon and proton respectively, are separated by a large rapidity gap are expected to be sensitive to the previously unexplored features of QCD.

By definition the Pomeron type factorization means that the ratio of diffractive events with state X accompanied by proton dissociating into state Y and with the proton scattered elastically,

$$R_X = \frac{d\sigma(\gamma^* + p \to X + Y)/dt}{d\sigma(\gamma^* + p \to X + p)/dt}, \tag{4}$$

should not depend on the choice of the hadronic state X. This factorization follows from the assumption that high energy processes are dominated by the exchange of a Regge pole - the Pomeron [6]. As a first step, it is important to check this Pomeron type factorization for soft diffractive processes as a test of possible shadowing effects.

The violation of the Pomeron type factorization is expected as a consequence of QCD evolution from large to small scale. As is known the evolution leads to a Q^2 dependence of the slope of the energy dependence. As a result the total DIS cross section as well as cross sections for hard diffractive processes cannot really be described as the exchange of one or several vacuum poles. It is also expected, in line with the experimental measurements, that the slope of the t distribution depends on the hardness of the process. In particular the slope for elastic photo-production of ρ mesons at HERA energies is $B \simeq 10$ GeV^2 [66, 91] while for larger Q^2 it turns out to be smaller $B \simeq 5 - 7$ GeV^2 [92, 93]. Both effects may influence the value of R_X when going from the soft regime to the harder one [90]. Approximate factorization may be also valid in the hard regime where two gluon exchange dominates. This is because in R_X the non-universal x and t dependence cancel out to large extent.

In QCD, the proton is represented at a given light-cone time $\tau = t + z$ as a superposition of quark and gluon Fock states $|uud>$, $|uudg>$, $|uudgg>$, $|uudQ\bar{Q}>$, etc. Thus when the proton is expanded on a free quark and gluon basis, it is a fluctuating system of arbitrarily large particle number [94]. The light-cone wave-functions $\psi_n(x_i, k_{\perp i}, \lambda_i)$ are the probability amplitudes which describe the projections of the proton state on this Hilbert space. The structure functions measured in deep inelastic lepton scattering are directly related to the light-cone x momentum distributions of the quarks and gluons determined by the $|\psi_n|^2$.

Fluctuations in the wave-functions of the proton can be studied in hard diffractive processes as diffraction is a measure of color fluctuations. Using completeness of the hadron states resulting from the fragmentation of the proton one can deduce the following relation between the fluctuations of the gluon distribution in the proton and the hard diffractive cross sections:

$$\frac{\sum_n < p|G(x,Q^2)|n >^2}{< p|G(x,Q^2)|p >^2} = \frac{< p|G(x,Q^2)^2|p >}{< p|G(x,Q^2)|p >^2} = \sum_Y \frac{d\sigma(\gamma_L^* + p \rightarrow X + Y)/dt}{d\sigma(\gamma_L^* + p \rightarrow X + p)/dt}|_{t=0} \ , \qquad (5)$$

where G is the two gluon operator whose diagonal matrix element gives the gluon distribution in the proton, and the state $|n >$ is a product of the proton fragmentation. The state X can be any state produced by a small size configuration of the initial photon. Let us consider a kind of a bag model where a proton consists of 3 bare quarks (or models where the color is concentrated within the constituent quarks). At sufficiently large Q^2 the transverse momenta of the exchanged gluons become large and as a result both gluons scatter from the same quark. In this case only diagonal transitions would survive at sufficiently large Q^2. Thus within this model the ratio in eq.(5) should tend to one at large Q^2. In general non-diagonal transitions are non zero at large Q^2, because quarks and gluons belong to different representations of SU(3) color group. The left hand side of the equation can be treated as a measure of the fluctuations of color density in the proton. Preliminary HERA data suggest a value of 2 for the ratio on the right hand side. This is an indication that color fluctuations may indeed be large.

4 Experimental Aspects

In the first part of this section we shall discuss the implications of present data in deep inelastic diffractive scattering on our understanding of diffractive physics. The second part of this section is devoted to a discussion of future aspects.

4.1 Indication for non-trivial QCD dynamics in HERA data

The measured diffractive cross section [95, 95, 96, 97] as a function of Q^2 shows a significant leading twist effect. This observation indicates that there is an important contribution from non-perturbative QCD effects for the following reasons:

- Unless the Pomeron is introduced by hand, DGLAP evolution starting at rather low scale Q_0^2, as advocated by GRV [98], would lead to a very small fraction of diffractive scattering in DIS: the radiation of gluons, governed by DGLAP evolution would fill the gap in rapidity, thus leading to an exponentially suppressed probability of finding large rapidity gap events.

- Processes in hard diffractive scattering (initiated by a projectile in a spatially small configuration), that can be calculated in QCD, like vector meson - or high p_T dijet production, turn out to be higher twist processes.

Thus the only way to obtain a significant leading twist effect is by assuming AJM [31, 32, 33], or QCD AJM [40], by scattering on partons in a non perturbative Pomeron [37], or by introducing a non-perturbative mechanism to recover a rapidity gap after pQCD radiation has taken place [19, 20].

On the other hand there are also hints in the present HERA data for an onset of hard diffractive scattering, which cannot be explained with the assumption of a soft Pomeron, but can be explained within the framework of QCD and CT. Present data on electro-production of vector mesons (ρ, ω and ϕ at sufficiently large Q^2 and J/ψ even in photo-production) [92, 93] are in disagreement with the assumption of a soft Pomeron and can be broadly described with:

$$\sigma(\text{hard diffractive}) \approx \left[xG_p(x, Q^2_{eff})\right]^2 \tag{6}$$

A fast increase of the cross section with energy, as in eq.(6) due to the strong increase of the number of gluons at small x, is a signature of a hard QCD process and a signature of color transparency.

Another observation beyond a soft Pomeron is the significant fraction of high p_T dijet events with a large rapidity gap between the jets compared to those without, as observed in photo-production in ZEUS [24] and in $p\bar{p}$ by CDF [25] and D0 [26]. The factor of seven enhancement in the rapidity gap survival probability for photon initiated processes, as compared to $p\bar{p}$ scattering, can be hardly explained as due to the difference in the cross sections of $p\bar{p}$ and Vp scattering, or due to gluon bremsstrahlung. This enhancement has a natural explanation within CT where the interaction cross section is proportional to the transverse volume occupied by color in the projectile.

If this interpretation is correct, it means that we start to understand the role of perturbative QCD in diffraction and its connection to inclusive deep inelastic scattering. Moreover a variety of new processes is expected.

4.2 Future Prospects

Inclusive measurements of the diffractive cross sections are relatively easy to perform, and do not require highest luminosity, since the cross section is about 10% of the inclusive deep inelastic cross section. However the interpretation in terms of QCD is more difficult: even if there is a regime of hard diffractive scattering, that can be calculated in QCD, one expects a mixture of soft and hard QCD processes, since the inclusive cross section will be dominated by small k_t processes where pQCD calculations are not applicable. Since we aim to study pQCD in diffraction, we discuss first diffractive processes like high p_T jet, open charm and vector meson production, since there pQCD calculations can be attempted. Then we discuss inclusive measurements and the importance of measuring the proton fragmentation region. At the end we mention a interesting class of processes in diffraction, the charged current interactions.

4.2.1 Diffractive high p_T dijet production

The calculation of diffractive dijet production can be performed using pQCD for large photon virtualities Q^2 and high p_T of the $q(\bar{q})$ jets [48, 57, 59, 68, 80]:

$$e + p \to e' + q\bar{q} + p \tag{7}$$

The process is mediated by two gluon exchange. Different assumptions on the nature of the exchanged gluons have been made: in [57] they are taken from a NLO parameterization of the proton structure function [98], in [68] the gluons are non perturbative and in [48] they are a hybrid of non perturbative and perturbative ones. The cross section is essentially given by

$$d\sigma \sim \left[x_{\mathbb{P}} G_p \left(x_{\mathbb{P}}, \mathrm{k}_t^2 \frac{Q^2 + M_X^2}{M_X^2} \right) \right]^2 \tag{8}$$

at the scale explicitly given.

Due to the different gluon densities a different $x_{\mathbb{P}}$ dependence of the cross section is expected and further discussed in [99], where also numerical estimates are presented. Thus by itself the measurement of the dijet cross section as a function of $x_{\mathbb{P}}$ would yield information on the gluons involved in the process.

A striking feature of the dijet production via two gluon exchange is the azimuthal asymmetry between one of the jets and the electron in the jet - jet center of mass system. This asymmetry is present, independent of the nature of the gluons, i.e. calculated for both perturbative [73] and non-perturbative [74] gluons. Moreover this azimuthal asymmetry is completely different from the one known for boson gluon fusion processes, where only one hard gluon interacts.

However one has to worry about the experimental separation of this processes: due to jet finding algorithms there could be a contribution of processes $ep \to e' + q\bar{q}g + p$, where one of the quarks or the gluon has small k_t, which could possibly be interpreted as a Pomeron remnant. By requiring exclusively 2 jets, where the 2 jets take all available M_X, or equivalently selecting $x_g^{\mathbb{P}} \simeq 1$, the contribution from processes with additional particles becomes small [100]. Here we defined $x_g^{\mathbb{P}}$ as $x_g^{\mathbb{P}} = (Q^2 + \hat{s})/(Q^2 + M_X^2)$ with $\hat{s}$ being the invariant mass of the two jets. For $Q^2 > 10$ GeV^2 and $p_T^2 > 5$ GeV^2 the measurement can be performed for $x_{\mathbb{P}} > 10^{-3}$. With an estimated overall selection efficiency of ~ 70 % a statistical error of ~ 10 % can be achieved with an integrated luminosity of ~ 100 pb^{-1} and at least 4 bins per decade in $x_{\mathbb{P}}$. With such a measurement one can clearly distinguish between the soft non-perturbative gluon input and the perturbative approach [100].

To differentiate between the azimuthal asymmetry for the two gluon exchange process and the boson gluon fusion with the gluon originating from a partonic Pomeron, a statistical error of ~ 10 % in 7 bins in ϕ is needed corresponding to an integrated luminosity of ~ 250 pb^{-1}. With such a statistical error the separation between one or two gluon exchange mechanisms can be made at the $4\,\sigma$ level. Both measurements, the $x_{\mathbb{P}}$ dependence and the ϕ asymmetry are of great importance. The ultimate prove of the 2 gluon exchange mechanism would be the observation of the specific ϕ asymmetry, which is completely different from the one expected from boson gluon fusion models. The $x_{\mathbb{P}}$ dependence of the cross section would give more inside on the nature of the gluons involved in the hard interaction.

The calculations so far are restricted to a region of relatively large $\beta > 0.1$. For small β, or equivalently large M_X, gluon radiation is expected to play a important role and final states like $q\bar{q}g$ have to be considered. The inclusion of these higher order diagrams is difficult and various approaches exist to estimate the next-to-leading order contributions [48, 80, 101, 102]. A systematic investigation of $q\bar{q}g$ jets is a urgent and important task.

4.2.2 Diffractive Open Charm Production

Diffractive open charm production can be a significant contribution both to hard and soft QCD [59, 68, 58, 71]. Having in mind that preliminary data on diffractive charm production [72] are in broad agreement with the expectations from a partonic Pomeron, the measurements to differentiate between hard and soft gluon exchange would require measurements of the $x_{I\!P}$, Q^2 and β dependence of the cross section. Most probably there is no way to select exclusive 2 charm final states, since due to the mass threshold charm production can only happen at relatively large masses M_X and therefore higher order corrections like radiation of hard gluons which transform into a $c\bar{c}$ pair are expected to be non negligible.

A Monte Carlo [39] simulation of the process $e + p \to e' c\bar{c}g + p$ with subsequent decay $c \to D^* \to D^0\pi$ was used together with the H1[103] parameterization of the gluon density in the Pomeron to to identify charm production and to determine efficiencies and acceptances [104]. The criteria to identify the decay products of the D^{*+} are given in [104]. With an overall detection efficiency of ~ 50 % it was shown that for 2 bins per decade in $Q^2 > 25$ GeV^2 and $x_{I\!P}$ and 3 bins in $0.01 \le \beta \le 0.9$ a 30 % statistical error can be achieved for a integrated luminosity of ~ 30 pb^{-1}. A more precise measurement at high β values can be made with ~ 250 pb^{-1}, but for a precision measurement with 5 bins per decade in Q^2 and $x_{I\!P}$ and 7 bins in $0.01 \le \beta \le 0.9$ and a statistical error of 10 % a luminosity of ~ 2000 pb^{-1} is needed.

With a measurement of $F^D_{2\,charm}$ the gluon dominance in hard diffractive scattering can be demonstrated and a decision whether soft or perturbative gluons interact can be easily made. However special care has to be taken for higher order corrections which might be important.

4.2.3 Vector Meson Production

Diffractive vector meson production $e + p \to e' + \mathrm{VM} + p$ is another example of processes where pQCD calculations are expected to be applicable, at high Q^2 for the light vector mesons, and for heavy vector mesons like J/ψ or Υ even in photo-production (for a discussion see [54, 79, 105]). Strictly speaking for the case of vector mesons, built of light quarks, the QCD calculation can only be performed for longitudinally polarized photons. This is just because of the spatially small configuration occupied by the $q\bar{q}$ pair which then forms a vector meson. In such a configuration again the cross section is driven by $\left[xG_p(x, Q^2_{eff})\right]^2$. The extension of the QCD calculations beyond this approach is model dependent and there is no consensus on the applicability of all the predictions [105].

In all calculations the γ^* couples to the vector meson through the same quark loop. There is agreement on helicity conservation and that at large Q^2 the longitudinal cross section dominates. The different approaches differ in the way the gluons couple to the proton and to the wave function of the vector meson which is poorly known. The advantage of vector meson production is the possibility to select experimentally the contribution of longitudinal photons and therefore the possibility to enter the hard pQCD regime.

Another group of processes calculable in QCD are reactions $\gamma^* + p \to V + Y$ with large momentum transfer squared t to the vector meson V and with Y representing the state in which the proton dissociates. The idea is that at sufficiently large t the contribution of spatially small configurations in the wave function of the photon and the vector meson would dominate. (The soft Pomeron exchange should be highly suppressed due to the steeply falling t distribution.)

As a result of screening of color charge and asymptotic freedom it would be possible to justify applicability of the methods of pQCD to calculate cross sections of discussed processes [53, 30, 106, 107]. The prospective kinematical region is $-t > 2 - 4$ GeV^2 where the phenomena characteristic for soft diffraction disappear.

Depending on the kinematical restrictions on the proton dissociation different hard QCD phenomena may reveal themselves such as the scattering off valence, sea quarks or gluons of the proton target [30, 106, 56]. The contribution of the BFKL type dynamics is enhanced in this case due to larger intercept for the x dependence [106, 56]. It is worth to note that if the running of coupling constant is taken into account the intercept for the x dependence of BFKL amplitude depends on t.

In order to distinguish soft Pomeron initiated vector meson production from the pQCD region the following measurements are important:

- the absolute value, the x and the Q^2 dependence of the longitudinal and transverse photon absorption cross sections,
- the relative yields of various vector meson production including their excited states in photo-production and electro-production,
- the slope of the t dependence as a function of x and Q^2 and polarization of the vector meson,
- the energy dependence of the large t vector meson production.

Based on an extrapolation of existing data to a integrated luminosity of 250 pb^{-1} we expect 60000 ρ, 6000 Φ and 3000 J/ψ events with $Q^2 > 7$ GeV^2 giving a reasonable small statistical error up to $Q^2 \sim 20 - 30$ GeV^2. The total systematic errors are presently ~ 13 % and could be reduced to ~ 7 % by better understanding of reconstruction errors, errors related to non-resonant background and proton dissociation. The largest error comes from proton dissociation background. If the proton is tagged by a Leading Proton Spectrometer, this sort of background might be negligible, but the acceptance of such a device is only $\sim$ 10 % in the best case, leading to a much lower rate of tagged events. Thus the understanding of proton dissociation is important for all the conclusions drawn from the energy and t dependence of the cross sections.

The measurement of the t distribution should allow to distinguish clearly between soft and hard pQCD regime, since the B slope in soft interactions is energy dependent because of $\alpha' \simeq 0.25$ whereas in pQCD $\alpha' \simeq 0$. Again the error on the determination of α' is dominated by the proton dissociation background, and is estimated to be of the order of $\Delta\alpha' \simeq 0.1$ requiring tagging of proton dissociation down to 1.5 mrad. If tagging is possible only down to 6 mrad, then the error on α' is twice as large, and no conclusion on shrinkage can be drawn [108]. This shows clearly the importance of the ability to measure in the very forward region of the HERA detectors.

The model independent measurement of the longitudinal cross section or the ratio $R = \sigma_L/\sigma_T$ can be done best with a reduced e beam energy ($E_e = 12$ GeV), since the fluxes of transverse and longitudinal photons differ most strongly at high y. With only 10 pb^{-1} at each electron beam energy the statistical error will be above 50 %. With 100 pb^{-1} the error in the highest W bin is reduced to 25 % [108].

Production of J/ψ vector mesons at large t, $e + p \to e' + J/\psi + Y \to e' + \mu^+\mu^- + Y$, has a reasonable high cross section: $\sigma \sim 6$ nb in photo-production for $0.01 < y < 0.3$, $0.003 < x < 1$, $Q^2 < 4$ GeV^2 and $2 < -t < 100$ GeV^2 ($\sigma \sim 0.4$ nb for $Q^2 > 4$ GeV^2) for the leptonic decay of the J/ψ and the leptons within the detector acceptance [108]. Interesting here is the measurement of the t distribution, which should show no shrinkage, as well as its energy dependence. However a precise determination of t requires a measurement of the scattered electron unless the measurement is restricted to very low Q^2. The large cross section should enable us to measure this process in the very near future.

4.2.4 Inclusive diffractive cross sections at high Q^2

The measurements of the inclusive diffractive cross section show that it is predominantly a leading twist phenomena. As discussed earlier in this report, processes calculated using perturbative QCD are of higher twist. Thus we expect the inclusive diffractive cross section to be dominated by soft, non perturbative effects. However in the region of large β, or equivalently in the small mass region, perturbative effects could be important, analogous to vector meson production by longitudinally polarized photon or high p_T jet production. The small β region, on the other hand, could be dominated by soft Pomeron exchange processes and QCD evolution of parton densities in the Pomeron. This would lead to the following picture:

- $\boldsymbol{\beta} \lesssim \mathbf{0.1}$: Exchange of a soft Pomeron with a partonic substructure dominates. The partons in the Pomeron evolve according to the DGLAP evolution equation. Due to soft Pomeron exchange, factorization is expected,

$$F_2^D(\beta, Q^2, x_{I\!P}, t) = f(x_{I\!P}, t) F_2^{I\!P}(\beta, Q^2, t)\,. \tag{9}$$

- $\boldsymbol{\beta} \gtrsim \mathbf{0.8}$: Hard pQCD processes contribute significantly, leading to a violation of the factorization in eq.(9) and to large higher twist effects.

- $\mathbf{0.1} \lesssim \boldsymbol{\beta} \lesssim \mathbf{0.8}$: Intermediate region. The amount of factorization breaking depends on the interplay between soft Pomeron physics and hard pQCD physics.

To clearly establish the above picture, the $x_{I\!P}$ dependence of the cross section as a function of β has to be measured precisely in a region of $x_{I\!P} \lesssim 0.01$ where no significant contribution from other possible Regge trajectories is expected. In such a scenario one could expect for $\beta < 0.1$ $f(x_{I\!P}, t) \sim x_{I\!P}^{1-2\alpha_{I\!P}}$. Another important ingredient for soft Pomeron exchange is the measurement of the t distribution. If soft Pomeron exchange dominates, then shrinkage of the t - slope is expected, whereas in the hard pQCD regime $\alpha' \simeq 0$.

The relative cross sections for large and small β also yield information on the underlying mechanism. In the soft Pomeron picture the cross section at large β should decrease with increasing Q^2. Within pQCD calculations in the large β region a large contribution from longitudinally polarized virtual photons is expected [35, 48, 109, 99, 110, 30, 80] which is absent in the partonic soft Pomeron picture.

Recent measurements of F_2^D show a deviation of factorization at large $x_{I\!P}$ [103], which could be interpreted as a contribution from higher Regge trajectories. However to safely exclude such a contribution we will restrict our discussion to the region $x_{I\!P} < 0.01$.

Thus the following measurements are needed:

- Measurement of $F_2^D(x_{\mathbb{P}}, t, \beta, Q^2)$ with $x_{\mathbb{P}} < 0.01$ and largest possible range in β and Q^2.
- Measurement of $F_L^D(x_{\mathbb{P}}, t, \beta, Q^2)$ with special emphasis on the large $\beta > 0.8$ region.

Since the inclusive diffractive cross section is large ($\sigma_{diff} \sim 4$ nb for $Q^2 > 10$ GeV^2 and $x_{\mathbb{P}} < 0.01$) the Leading Proton Spectrometer can be used to identify diffraction. A systematic error of ~ 7 % can be achieved with the LPS [111]. A measurement of $F_2^D(x_{\mathbb{P}}, t, \beta, Q^2)$ with 2 bins in $0.07 < |t| < 0.0.35$ GeV^2, 3 bins in $4 < Q^2 < 30$ GeV^2, 7 bins in $0.001 < \beta < 0.3$ and 5 bins in $0.001 < x_{\mathbb{P}} < 0.1$ is possible for 20 pb^{-1} with a statistical error of ~ 10 % in each bin [111].

For a measurement of $F_2^{D(3)}(x_{\mathbb{P}}, \beta, Q^2)$ (integrated over t) using the present experience one can hope to achieve an overall systematic error (except for the error coming from proton dissociation) of ~ 5 %. To achieve a statistical error of ~ 5 % with 5 bins per decade in Q^2 and $x_{\mathbb{P}}$ and 7 bins in $0.01 < \beta < 0.9$ an integrated luminosity of 8 pb^{-1} is needed for F_2^D. To achieve $\sim 3(1)$ % statistical errors one would need 22 (200) pb^{-1} [104].

If factorization is proven to be valid, one can measure $F_L^{\mathbb{P}}$ directly using the wide band beam of Pomerons by changing $x_{\mathbb{P}}$. With a luminosity of 15 pb^{-1} and a fine granularity at high y one can measure $R^{\mathbb{P}}$ within 50 % for $y < 0.8$ [104].

If factorization does not hold, then a measurement of the longitudinal cross section can be performed only by lowering the proton beam energy (from $E_p = 820$ GeV to $E_p = 500$ GeV). Changing the proton beam energy would lead to better acceptance in the high mass region. On the other hand, as stated in the section on vector mesons, changing the electron beam energy gives better acceptance in the low mass region (at high β). A luminosity of 2 pb^{-1} for $E_p = 500$ GeV is required to achieve a precision of the ratio of transverse to longitudinal cross section of the order of ~ 50 % [104].

4.2.5 Proton fragmentation region

So far we considered only processes (the ones that can be calculated within pQCD as well as processes mediated by soft Pomeron exchange) where a quasi elastic proton can be found (at least in principle) in the hadronic final state. This is easiest done by using the Leading (Forward) Proton Spectrometers, where both energy and transverse momentum of quasi-elastic protons can be measured, at the expense of event rates. Experimentally it is necessary to have clear measurements of the proton fragmentation region in order to subtract possible contributions from double dissociation and to control the background from non-diffractive events.

Proton dissociation is interesting on its own for the following reasons:

- If the cross section for inclusive diffractive scattering is mainly due to soft Pomeron exchange, then one should observe that the ratio $R_X = \sigma(e + p \to e' + X + Y)/\sigma(e + p \to e' + X + p)$, where Y is the proton dissociation system separated in rapidity from the system X, should not depend on the system X.
- In the hard diffractive regime, when spatially small size configurations are selected (high p_T dijets or vector mesons), it is interesting to test the factorization hypothesis. A change of regime cannot be a priori excluded.

- In going from large rapidity gaps between X and Y in $e+p \to e'+Xq+Y$ to smaller and vanishing rapidity gaps, the transition between diffraction and inclusive deep inelastic scattering can be studied [112].
- In the spirit of studying the fluctuations in the wave function of the proton it has been advocated that the intrinsic charm contribution may not be negligible [113]. Intrinsic heavy quarks Fock states could be materialized by the virtual photon probe and released in the proton fragmentation region. This effect if present would lead to spectacular events with two muons produced in the very forward region.

Experimentally the proton dissociation system can be effectively measured with tagging devices in a rapidity range of $\eta < 5.9$ with ~ 100 % efficiency for masses $M_Y > 3$ GeV starting with an efficiency of ~ 10 % at masses $M_Y > 1$ GeV. In order to determine the slope of the distribution:

$$\frac{d\sigma}{dM_Y^2} = C\left(\frac{1}{M_Y^2}\right)^a \tag{10}$$

one needs to measure M_Y at least in 2 ranges. The dominant uncertainty comes from the badly known multiplicity and p_T distributions of the particles in the system M_Y. The error on a is estimated to be $\Delta_a \simeq 0.14$ for tagging up to rapidities of $\eta < 5.9$ [114]

High efficiency tagging of proton dissociation or even better performing calorimetric measurements in $\eta < 5.9$ requires detector upgrades'[115]. In addition one has to ensure as little dead material as possible in front of the tagging device or calorimeter.

It should be stated very explicitly that if magnets for an improvement of the HERA luminosity [116] are installed in a region of $\eta > 3.5(\simeq 70\text{mrad})$ then even tagging of the system M_Y is made difficult.

4.2.6 Charged Currents

So far we discussed only neutral current processes, but also charged current processes (via W exchange) should occur in diffraction at large $x_{I\!P}$. As in inclusive deep inelastic scattering, only at very high Q^2 the cross sections for neutral current and charged current processes are of similar size. Since the Pomeron is a flavor singlet system, one would expect the charged current cross sections for electron and positron beams to be the same.

The cross section can be estimated [117] using the present knowledge of the diffractive structure function F_2^D,

$$\sigma_{CC}^{Diff.} \sim 2\text{pb} \tag{11}$$

for $x_{I\!P} < 0.1$. The rapidity gap for charged current events is smaller than for neutral current events since high diffractive masses are involved due to the W mass. With cuts on the transverse momentum and the transverse energy and a missing transverse momentum of 4 GeV the diffractive charged current efficiency is ~ 35 %. With a luminosity of 1000 pb^{-1} the cross section could be measured with a precision of ~ 5 %. With such a luminosity also the β dependence of the cross section can be determined with a $20-30$ % statistical error. This measurement requires an efficient tagging of the non-diffractive background. The use of the LPS is impossible because of the small acceptance and therefore devices to tag proton dissociation and non-diffractive background are essential.

5 Expected Significance of Hard Diffractive Scattering: Limit of Applicability of the DGLAP Evolution Equation

It is widely expected that the fast increase of parton distributions at small x cannot be sustained without running into conflict with the unitarity of the S matrix (see e.g. [118]) for the interaction of small size wave packages, that is with the positiveness of probabilities for physical processes. However the most stringent restriction on the region of applicability of the DGLAP or BFKL equations follows from the requirement of positiveness for single particle density in the central rapidity region [55].

At sufficiently small x, LO and NLO $\alpha_s \ln \frac{Q^2}{\Lambda^2_{QCD}}$ approximations as well as the leading $\alpha_s \ln x$ approximation predict a fast increase of the amplitudes for hard processes which run in conflict with probability conservation. The restriction on the applicability of the DGLAP evolution is that the leading twist contribution to the cross section of a small size $q\bar{q}$ pair scattering off a proton target should be much larger than the next-to-leading twist effect. Since this cross section is well formulated only in the pQCD regime, the reasoning below may only give restriction on the region of applicability of conventional QCD methods. To estimate this restriction let us consider the scattering of a $q\bar{q}$ pair off a target . Let us decompose the cross section in powers of $1/Q^2$. Let us denote by σ_1 the inelastic single scattering cross section due to the exchange of one ladder and by σ_2 the double scattering inelastic cross section due to the exchange of two ladders. The application of the Abramovsky, Gribov and Kanchely cutting rules [119] leads to the following relations between the cross sections:

$$\sigma_{tot} = \sigma_1 - \sigma_2 \,, \tag{12}$$
$$\sigma_2 = \sigma_{el} + \sigma_{diff} \,, \tag{13}$$
$$\sigma_1 \geq 4\sigma_2 \,, \tag{14}$$

where the subscripts el and $diff$ denote the elastic and diffractive cross sections. The last equation follows from the requirement of positiveness of single particle densities. One of the consequences of the above equations is that in models in which shadowing is due to the exchange of two ladders (due to triple BFKL type diagrams [118, 109]) it may cause not more than 25% depletion in parton distributions. That is to say that shadowing calculated within these models is unable to prevent the increase of parton densities without violating the positiveness of single particle densities. Further eikonal diagrams cannot be used since more than two rescatterings of the $q\bar{q}$ pair leads to violation of energy conservation in multi-particle production.

The optical theorem implies that

$$\sigma_2 = \frac{\sigma^2_{tot}}{16\pi B}(1+\eta^2)(1+\kappa) \,, \tag{15}$$

where

$$\eta = \frac{ReA}{ImA}\frac{\pi}{2}\frac{d}{d\ln x} \ln xImA(x,Q^2) \,, \tag{16}$$

with A – the amplitude for $q\bar{q}$ pair scattering off the proton, κ – the fraction of events due to inelastic proton dissociation and B – the slope of the t dependence as measured in hard diffractive processes. This can now be used to put restrictions on the region of applicability of QCD evolution equation by requiring that

$$\sigma_1 \geq 4\frac{\sigma^2_{tot}}{16\pi B}(1+\eta^2)(1+\kappa)\,. \tag{17}$$

Numerical estimates indicate that, for Q^2 of the order of few GeV^2, the kinematical region where the DGLAP equation becomes inapplicable for the diffractive processes and for the structure functions seems to be within the kinematics of HERA. To conclude, the decomposition over powers of Q^2 may be violated at small x in the HERA regime. Since the numerical estimates rely also on experimental measurements of B and κ the improvement in those will make the limits tighter.

Another restriction on the region of validity of the pQCD evolution follows from the unitarity of the S matrix applied to hard processes,

$$\sigma_{\mathrm{tot}} \gg \sigma_{\mathrm{el}} + \sigma_{\mathrm{proton\ dissociation}}. \tag{18}$$

Using the optical theorem we obtain an estimate for the kinematics where the increase of parton distributions should slow down [30],

$$\sigma_{tot} \geq \frac{\sigma^2_{tot}}{16\pi B}(1+\eta^2)(1+\kappa)\,. \tag{19}$$

One may even include the increase of B with energy, $B = r_N^2/4 + 2\alpha_s[\ln s/s_o]^n$ to obtain a strict inequality. For Pomeron exchange $n=1$ while $n=2$ for the Froissart regime. Again numerical estimates suggest that for hard diffractive processes this boundary may be within the HERA kinematics.

Both constraints leads to the expectation that we may become sensitive to the unitarity limit within HERA kinematics [30, 55] (see also [120]). The features which are being investigated include the x and Q^2 dependence of the diffractive jet photo-production, charm production and production of vector mesons.

Characteristic features of unitarity corrections near the unitarity limit are the slowing down of the increase of parton distributions at small x and a fast increase of the effective slope of the t dependence with energy and t [30].

The interesting question remains whether the manifestation of the unitarity limit can also be reached for $\sigma(\gamma^* p) = \frac{4\pi\alpha}{Q^2}F_2 \sim \pi r_n^2$. There is no doubt that for small Q^2 higher-twist contributions become important and participate in the transition from the strong rise of F_2 to the soft Pomeron in the photo-production cross section. It is not yet clear at which Q^2 values this transition will start. On the one hand it has been demonstrated that one can find input distributions to the DGLAP equations which describe the data down to $Q^2 \sim 1$ GeV^2 [98]. However it would be premature to draw from this the conclusion that higher twist corrections are negligible. So far no systematic analysis of higher twist corrections at small x has been performed. Furthermore, it has been shown that for flat input distributions the DGLAP is sensitive to higher order corrections (re-summation of singular terms in the anomalous dimension). All this leads to the impression that the issue of unitarity corrections to F_2 at low Q^2 is still waiting for clarification. The reason why hard diffraction may be a better place to look for a manifestation of the unitarity limit is that, by varying the final state we have a handle on the transverse size of the $q\bar{q}$ pair, whereas in F_2 the size is always small (of the order of $b^2 \sim 1/Q^2$).

The behavior of small x processes at extremely small x is still a challenge for theory. Theoretical investigations of one hard scale processes like onium-onium scattering [121] suggest the existence of a new QCD regime of large parton densities where all interactions can be described in terms of pQCD. In the two scale processes (for example F_2 at small x) soft QCD physics is probably not suppressed: this follows from the analysis of the multiple (≥ 3) rescatterings of a small size $q\bar{q}$ pair off a nucleon. However the elastic eikonal approximation is known to have problems with probability and energy conservation in multi-particle processes [122] and ignores the leading diagrams in pQCD. It therefore seems likely that the unitarization of F_2 at small x is a non-perturbative issue.

6 Summary

The scientific program that emerges from the studies and discussions in the Working Group is as follows:

1. Inclusive measurements of $F_2^{D(3)}$ and $F_L^{D(3)}$ as a function of x, Q^2, $x_{\mathbb{P}}$, β and t in as wide a range of variables as possible. One should be able to establish the region of dominance of soft and hard physics. Assuming that we need to differentiate $\alpha_{\mathbb{P}}$ in the range of 1.05 to 1.25, it would be desirable to measure $\alpha_{\mathbb{P}}$ with a precision of $\Delta\alpha_{\mathbb{P}} = 0.04$. The required luminosity, assuming the forward tagging capability down to $\eta \simeq 6$, are:

Q^2 [GeV^2]	luminosity $\int Ldt$ [pb^{-1}]
$Q^2 < 100$	~ 10
$100 < Q^2 < 500$	~ 60
$2000 < Q^2 < 3500$	~ 250

The cross section for charm production depends strongly on the regime of the physics behind diffractive processes. The predictions vary between 10 to 40 % of the inclusive cross section. For the integrated luminosities above, given the low tagging efficiency, a statistical error of 30% is achievable by decreasing the number of bins.

Hard physics should be accompanied by a change in the Q^2 dependence, from a leading twist to higher twist effect. The most sensitive probe is given by the measurements of F_L. A model independent determination of F_L requires running at lower energies. The error is determined by the run with lowest luminosity. An error of 25% on $F_L/(F_2 - F_L)$ requires an integrated luminosity of 10 pb^{-1} with the proton beam energy of 500 GeV.

The t dependence is essential to establish whether the observed tendencies are due to the change from soft to hard physics. This can be done only with the forward/leading proton spectrometers. It is estimated on the basis of existing data that for an integrated luminosity of 40 pb^{-1} in the present running conditions one could expect 20000 events with the proton tagged by the LPS for $4 < Q^2 < 30$ GeV^2). That would allow to establish the lack of shrinkage at the 3σ level and to determine $\alpha_{\mathbb{P}}$ with the same precision as in the inclusive case down to $\beta \simeq .001$. To cover the region of $Q^2 > 100$ GeV^2 with the same precision a 10 fold increase in luminosity would be required.

2. To test in depth the dynamics of vector meson production we need to measure the longitudinal cross section as a function of x, Q^2 and t for at least the ρ, ϕ and J/ψ vector mesons. To achieve a precision of $\Delta\alpha_{I\!P} = 0.06$ about 100 events per Q^2 are required. In order to probe the region of $Q^2 > 30$ GeV^2, be it for the ρ meson, an integrated luminosity of 100 pb^{-1} is required. An integrated luminosity of 250 pb^{-1} would allow measurements for the ϕ and J/ψ in the same region with comparable significance. For the latter luminosity also few Υ events are expected in the higher Q^2 region. A meaningful measurement of shrinkage could be performed only for the ρ meson and up to $Q^2 \simeq 30$ GeV^2. Assuming SCHC and 100 events per bin an error of 40 % on R can be achieved. A similar precision without assuming SCHC would require running at lower electron beam energy with at least 10 pb^{-1} integrated luminosity. All the estimates are obtained assuming that proton dissociation can be controlled at a 5% level. A useful cross check could be done with the LPS for low Q^2, ρ production. Here again the ideal measurement would be with a tagged proton in the LPS.

   The large t vector meson production does not require any special environment. For large t diffraction the expected cross sections are relatively large.

3. For diffractive exclusive large p_T jet production the region of interest is that of $M_X^2 \lesssim Q^2$. Since color is well localized in the wave function function of the projectile photon and the hard scale is defined as $p_T^2/(1-\beta)$ relatively low p_T jets (with $p_T \approx$ few GeV) can be considered. A typical integrated cross section for $p_T^2 > 5$ GeV^2, $Q^2 > 10$ GeV^2 and in the range $50 < W < 220$ GeV turns out to be of the order of 20 pb assuming a two perturbative gluon exchange as the dominant mechanism and is about 2.5 times larger than expected from non-perturbative gluons. For an integrated luminosity of 250 pb^{-1} about 2500 events identified in the detectors are expected in the best case. To be able to establish the two gluon exchange mechanism the azimuthal asymmetry has to be measured and in order to exclude an asymmetry typical of boson-gluon fusion whole statistics is necessary.

   Here again not only the $x_{I\!P}$ and Q^2 dependence is of interest but also the t dependence which is the barometer for the hardness of the interaction. However this is beyond the reach of HERA experiments unless the LPS would be operational throughout the whole integrated luminosity.

4. Study of large rapidity gap events in charged current interactions offers many attractive possibilities to study the parameters of the Standard Model. The main advantages are due to the isoscalar nature of the Pomeron and the point-like coupling of the W boson to quarks. One could imagine that by tagging for example $W \to cs$ transition with a large rapidity gap one could measure the V_{cs} element of the Kobayashi-Maskawa mixing matrix without the uncertainty of final state interactions.

   However estimates of the detectable cross section for CC diffractive scattering lead to an number of events of the order of 1/pb^{-1}. This estimate would decrease by factor 2 if the forward taggers in the proton fragmentation region were not available.

5. Two options for measuring the invariant mass of the proton dissociation system have been considered. Assuming high efficiency forward taggers covering the region down to $\eta = 5.9$ the mass distribution can be determined at best with a systematic error of 13%, mainly due to the uncertainty in the hadronization process. This error can be substantially

improved by introducing calorimetry and running at lower proton energy. This knowledge is of interest in its own right. It affects all the inclusive diffractive measurements without LPS tagging. In the present estimates this is the major source of systematic error. Tagging of the forward region with high efficiency could decrease this error by factor 3. This is of particular importance if diffractive measurements are to be continued after the HERA upgrade.

The polarization options have not been discussed in depth. The expressed opinions were very much in favor of diffractive measurements with polarized beams. It was felt that it could have an impact on a deeper understanding of the diffractive mechanism.

The emerging scenario is the following:

- The inclusive measurements of the diffractive structure functions could be completed with 100 pb^{-1}. Roughly speaking this would lead to an understanding of hard diffractive physics similar to what was known about the DIS structure of the proton before HERA. An integrated luminosity of 10 pb^{-1} at lower proton energy is highly recommended for model independent measurements of the longitudinal structure functions.
- The program of hard diffractive physics, vector meson and exclusive jet production at high Q^2, could in principle be continued after the HERA upgrade. This will have to be investigated further. However, based on the present understanding, this will not be meaningful unless the tagging of the forward region is preserved and unless there is a good understanding of the systematics acquired before the upgrade. Given the importance of diffractive scattering in understanding QCD we recommend that the design of the upgrade takes into account the need for preserving high efficiency forward tagging.

Acknowledgments

We are indebted to all those who contributed to make this workshop a success, either by participating actively or by expressing their encouraging interest. The list is very long and goes far beyond the list of contributions to this workshop, suffice to say that the mailing list consisted of more than 100 names. Very special thanks go to W. Bartel who kept us informed on the progress made in the accelerator upgrade group.

References

[1] A. Mueller, in *Proceedings of the Conference on Hard Diffractive Scattering* (Eilat, 1996).

[2] V. Gribov, *Sov. Phys. JETP* **8** (1961) 40.

[3] V. Gribov, *Sov. Phys. JETP* **14** (1962) 478.

[4] V. Gribov, *Sov. Phys. JETP* **26** (1968) 414.

[5] L. Caneschi, in *Regge Theory of low p_T hadronic interactions*, edited by L. Caneschi (North-Holland, 1989).

[6] V. Gribov, I. Pomeranchuk, *Sov. Phys. JETP* **4** (1962) 42.

[7] V. Gribov, I. Pomeranchuk, *Phys. Rev. Lett.* **2** (1962) 195.

[8] A. Donnachie, P. Landshoff, *Nucl. Phys. B* **267** (1986) 690.

[9] H. Cheng, J. Walker, T. Wu, *Phys. Lett. B* **44** (1973) 97.

[10] A. Mueller, *Nucl. Phys. B (Proc. Suppl.)* **18C** (1991) 125.

[11] B. Blättel et al., *Phys. Rev. Lett.* **70** (1993) 896.

[12] L. Frankfurt, G. Miller, M. Strikman, *Phys. Lett. B* **304** (1993) 1.

[13] L. Frankfurt, A. Radushkin, M. Strikman, in preparation.

[14] J. Bartels, H. Lotter, M. Wüsthoff, *Z. Phys. C* **68** (1995) 121.

[15] L. Frankfurt, V. Khoze, in *Proceedings of the Leningrad School on Particle Physics* (1975).

[16] Y. Dokshitzer, Materials of this Workshop.

[17] Y. Dokshitzer, in *Proceedings of the Conference on Hard Diffractive Scattering* (Eilat, 1996).

[18] B. Andersson et al., *Phys. Rep.* **97** (1983) 31.

[19] W. Buchmüller, A. Hebecker, *Phys. Lett. B* **355** (1995) 573.

[20] A. Edin, G. Ingelman, J. Rathsman, *Phys. Lett. B* **366** (1996) 371.

[21] A. Edin, G. Ingelman, J. Rathsman, *J. Phys. G* **22** (1996) 943.

[22] A. Edin, G. Ingelman, J. Rathsman, *DESY 96-060*

[23] L. Lönnblad, *J. Phys. G* **22** (1996) 947.

[24] ZEUS Collaboration; M. Derrick et al., *Phys. Lett. B* **369** (1996) 55.

[25] CDF Collaboration; F. Abe et al., *Phys. Rev. Lett.* **74** (1995) 855.

[26] D0 Collaboration; S. Abbachi et al., *Phys. Rev. Lett.* **72** (1994) 2332.

[27] V. Gribov, B. Ioffe, I. Pomeranchuk, *Sov. J. Nucl. Phys.* **2** (1969) 549.

[28] B. Ioffe, *Phys. Lett. B* **30** (1969) 123.

[29] C. Llewellyn-Smith, *Phys. Rev. D* **4** (1971) 2392.

[30] H. Abramowicz, L. Frankfurt, M. Strikman, *DESY 95-047*

[31] J. Bjorken, in *Proceedings of the International Symposium on Electron and Photon Interactions at High Energies* (Cornell, 1971), p. 281.

[32] J. Bjorken, J. Kogut, *Phys. Rev. D* **8** (1973) 1314.

[33] J. Bjorken, in *Proceedings of the Colloqium on High Multiplicity Hadronic Interactions*, edited by A. Krzywicki (Paris, 1994).

[34] V. Gribov, *Sov. Phys. JETP* **10** (1969) 57.

[35] N. Nikolaev, B. Zakharov, *Z. Phys. C* **53** (1992) 331.

[36] A. Solano, contribution to this workshop.

[37] G. Ingelman, P. Schlein, *Phys. Lett. B* **152** (1985) 256.

[38] P. Bruni, G. Ingelman, *DESY 93-187*

[39] H. Jung, *Comp. Phys. Comm.* **86** (1995) 147.

[40] L. Frankfurt, M. Strikman, *Phys. Rep.* **160** (1988) 235.

[41] F. Low, *Phys. Rev. D* **12** (1975) 163.

[42] S. Nussinov, *Phys. Rev. Lett.* **334** (1975) 1286.

[43] J. Gunion, D. Soper, *Phys. Rev. D* **15** (1977) 2617.

[44] V. Gribov, *Yad. Fiz.* **5** (1967) 399.

[45] D. Zeppenfeld, *MADPH-95-933* (1995) .

[46] J. Collins, L. Frankfurt, M. Strikman, *Phys. Lett. B* **307** (1993) 161.

[47] J. Bartels, M. Wüsthoff, *J. Phys. G* **22** (1996) 929.

[48] M. Wüsthoff, *DESY 95-166*

[49] A. Donnachie, P. Landshoff, *Phys. Lett. B* **202** (1988) 131.

[50] A. Donnachie, P. Landshoff, *Phys. Lett. B* **296** (1992) 227.

[51] A. Capella et al., *Phys. Lett. B* **37** (1994) 358.

[52] A. Capella, in *Proceedings of the Conference on Hard Diffractive Scattering* (Eilat, 1996).

[53] L. Frankfurt, M. Strikman, *Phys. Rev. Lett.* **64** (1989) 1914.

[54] M. Ryskin, *Z. Phys. C* **57** (1993) 89.

[55] W. Koepf, contribution to this workshop.

[56] J. Bartels, in *Proceedings of the Conference on Hard Diffractive Scattering* (Eilat, 1996).

[57] J. Bartels, H. Lotter, M. Wüsthoff, *Phys. Lett. B* **379** (1996) 239.

[58] E. Levin et al., *DTP/96/50*, hep-ph/9606443.

[59] M. Genovese, N. Nikolaev, B. Zakharov, *Phys. Lett. B* **378** (1996) 347.

[60] S. Catani, F. Fiorani, G. Marchesini, *Phys. Lett. B* **234** (1990) 339.

[61] S. Catani, F. Fiorani, G. Marchesini, *Nucl. Phys. B* **336** (1990) 18.

[62] P. Landshoff, in *Proceedings of the Conference on Hard Diffractive Scattering* (Eilat, 1996).

[63] P. Landshoff, contribution to this workshop.

[64] V. D. Duca, contribution to this workshop.

[65] V.Khoze, Talk at Durham Workshop on HERA physics.(1965).

[66] ZEUS Collaboration; M. Derrick et al., *Z. Phys. C* **69** (1995) 39.

[67] H. Abramowicz, in *Proceedings of the International Conference on High Energy Physics* (Warsaw, 1996), (see references there in).

[68] M. Diehl, Charm versus Light Flavors in Diffraction: Jet Production and the Diffractive Structure Function, Talks at this workshop, 1996.

[69] W. Buchmüller, A. Hebecker, *DESY 95-208, SLAC-PUB-7064*, hep-ph/9512329.

[70] T. Teubner, Diffractive Open Charm Production at HERA, contribution to this workshop.

[71] H. Lotter, PhD thesis (to be published).

[72] H1 Collaboration, A Measurement of the Production of $D^{*\pm}$ Mesons in Deep–Inelastic Diffractive Interactions at HERA, ICHEP 1996, pa02-60, 1996.

[73] J. Bartels et al., *DESY 96-085*, hep-ph/9605356.

[74] M. Diehl, Azimuthal Angles and Photon Helicity, Talk at proc96, 1996.

[75] T. Arens et al., *HD-THEP-96-06*

[76] W. Buchmüller, A. Hebecker, M. F. McDermott, *DESY 96-126, SLAC-PUB-7204*, hep-ph/9607290.

[77] J. Collins, L. Frankfurt, M. Strikman, in preparation (unpublished).

[78] A. V. Radyushkin, *hep-ph* (1996) .

[79] S. Brodsky et al., *Phys. Rev. D* **50** (1994) 3134.

[80] E. Gotsman, E. Levin, U. Maor, *CNBPF-NF-021/96, TAUP 2333896/96*, hep - ph 9606280.

[81] H. Dosch et al., *HD-THEP-96-31* (1996) .

[82] L. Frankfurt, G. Miller, M. Strikman, *Ann. Rev. Nucl. Part. Sci.* **44** (1994) 501.

[83] E665 Collaboration; M. Adams et al., *Phys. Rev. Lett.* **74** (1995) 1525.

[84] J. Bjorken, *Int. J. Mod. Phys. A* **7** (1992) 4189.

[85] E. Gotsman, E. Levin, U. Maor, *Phys. Lett. B* **309** (1993) 199.

[86] L. Frankfurt, M. Strikman, contribution to Working Group: Light and Heavy Nuclei in HERA, this workshop.

[87] A. Mueller, W. Tang, *Phys. Lett. B* **284** (1992) 123.

[88] L. Frankfurt, Hard diffractive processes at colliders, in *Proceedings of the FAD meeting* (Dallas, 1992).

[89] J. Bjorken, *Phys. Rev. D* **47** (1993) 101.

[90] M. Strikman, This Workshop.

[91] H1 Collaboration, Elastic ρ' Electroproduction at High Q^2, ICHEP96, pa01-088.

[92] H1 Collaboration; S. Aid et al., *Nucl. Phys. B* **468** (1996) 3.

[93] ZEUS Collaboration, ICHEP96, pa02-028.

[94] S. Brodsky, in materials of the working group (unpublished).

[95] H1 Collaboration; T. Ahmed et al., *Nucl. Phys. B* **249** (1994) 477.

[96] ZEUS Collaboration; M. Derrick et al., *Phys. Lett. B* **315** (1993) 481.

[97] ZEUS Collaboration; M. Derrick et al., *Z. Phys. C* **68** (1995) 569.

[98] M. Glück, E. Reya, A. Vogt, *Z. Phys. C* **53** (1992) 127.

[99] J. Bartels et al., Quark - Antiquark Jets in DIS Diffractive Dissociation, in *this workshop* (Hamburg, 1996).

[100] M. Grothe et al., Studies of Diffractive Dijet Production in DIS, contribution to this workshop.

[101] M. Ryskin, M. Besancon, Heavy Photon Dissociation in Deep Inelastic Scattering, in *Proceedings of the workshop Physics at HERA*, edited by W. Buchmüller, G. Ingelman (Hamburg, 1991).

[102] E. M. Levin, M. Wüsthoff, *Phys. Rev. D* **50** (1994) 4306.

[103] H1 Collaboration, A Measurement and QCD Analysis of the Diffractive Structure Function $F_2^{D(3)}$, ICHEP 1996, pa02-61, 1996.

[104] J. Phillips, A. Mehta, B. Waugh, Future Diffractive Structure Function Measurements at HERA, in *this workshop* (Hamburg, 1996).

[105] W. Koepf et al., Vector Meson Production in $ep \to epV$, in *this workshop* (Hamburg, 1996).

[106] J. Forshaw, M. Ryskin, *Z. Phys. C* **68** (1995) 137.

[107] J. Bartels et al., *Phys. Lett. B* **375** (1996) 301.

[108] H. Abramowicz et al., Future Aspects of Vector Meson Production at HERA, in *this workshop* (Hamburg, 1996).

[109] E. Laenen, E. Levin, *Ann. Rev. Nucl. Part. Sci.* **44** (1994) 199.

[110] M. Diehl, *Z. Phys. C* **66** (1995) 181.

[111] E. Gallo et al., Measurements with the Leading Proton Spectrometer, in *this workshop* (Hamburg, 1996).

[112] E. Edin, G. Ingelman, J. Rathsman, QCD in the Forward Region, in *this workshop* (Hamburg, 1996).

[113] S. Brodsky, W. Tang, P. Hoyer, *Phys. Rev. D* **52** (1995) 6285.

[114] H. Abramowicz et al., Proton Diffractive Dissociation at HERA. Studying Proton Dissociation using Forward Taggers or Calorimeters, in *this workshop* (Hamburg, 1996).

[115] A. Bamberger et al., Diffractive and Jet Physics with a Forward PLUG Calorimeter at ZEUS, in *this workshop* (Hamburg, 1996).

[116] W. Bartel, HERA Machine Upgrade, in *this workshop* (Hamburg, 1996).

[117] J. Pliszka, A. Zarnecki, Diffraction in Charged Current DIS, in *this workshop* (Hamburg, 1996).

[118] L. Gribov, E. Levin, M. Ryskin, *Phys. Rep.* **100** (1983) 1.

[119] V. Abramovsky, V. Gribov, O. Kanchely, *Sov. J. Nucl. Phys.* **18** (1973) 388.

[120] E. Gotsman, E. Levin, U. Maor, *Nucl. Phys. B* **464** (1996) 251.

[121] A. Mueller, G. Salam, *CU-TP-746*

[122] H. Cheng, T. Wu, *Expanding Protons: Scattering at High Energy* (MIT-Pr, 1987).