The Physics Case for a Forward Detector Upgrade

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Abstract: We summarize the conclusions of a number of contributions to the working groups on *Jets and High*$-E_\perp$ *Phenomena* and *Diffractive Hard Scattering* concerning issues related to the forward phase space region. They imply strong physics reasons to upgrade the HERA detectors in the forward (proton) direction and we recommend such options to be seriously considered, although they may be in conflict with planned luminosity upgrades.

Introduction. Deep inelastic scattering (DIS) is an excellent way to study the structure of the proton and the HERA results have indeed attracted much attention. This concerns, in particular, the observed rise of the structure function F_2 at small x. Although this had been predicted in perturbative QCD (pQCD), the proper theoretical interpretation is still unclear. There is presently vigorous theoretical research on 'QCD at small x' and different observables based on the hadronic final state are considered in order to improve our understanding. The available experimental data have shown interesting effects, but are not yet sufficient to give clear conclusions.

Confinement and non-perturbative QCD are still major unsolved problems in particle physics. Related to this is the hadronization of the proton remnant in DIS, which has not yet been properly investigated. In particular at small x, this remnant may be a complex many-parton system whose development is far from being understood. General questions such as 'how should the remnant system be described?' and 'what is the proper color-field structure in DIS events?' remain to be answered. These are important problems in their own right and they also have consequences for tests of pQCD issues, since observables can be strongly affected by hadronization effects.

The discovery of large rapidity gap events in DIS at HERA has stimulated enormous interest. Although these events can be phenomenologically described in terms of pomeron models based on Regge concepts, there is no satisfactory understanding of the dynamics creating them. There are conceptual and theoretical problems with the pomeron approach. Efforts are made to use pQCD, which is theoretically better defined, for diffractive processes where a large momentum scale or small size object is present. Furthermore, new ideas have been proposed to describe diffractive scattering in terms of soft color interactions between the scattered partons and the 'background' color field of the proton. Thus, there are fundamental problems to be solved concerning diffractive interactions and their connection to normal DIS, which preferably should both be described in a common theoretical framework. In addition, there are many other unsolved problems concerning various details of the diffractive processes. It is therefore important to experimentally observe as much as possible of the hadronic systems produced in diffractive scattering.

All of these issues, which are elaborated on in the following, require additional measurements and increased forward acceptance to be properly investigated.

Perturbative QCD. In spite of recent results on the structure of the proton we are still far from a satisfactory understanding of the underlying QCD dynamics in the small-x region. Although the rise of the structure function F_2 at small x was predicted by pQCD, it does not yet have a clear and unique theoretical interpretation. A rise is compatible with the BFKL equation [1], but also with conventional DGLAP evolution [2]. To understand the QCD dynamics it is important to sort out which of these approximation schemes are applicable in different regions of phase space. DGLAP should be appropriate for large Q^2 but not too small x and BFKL at small x. It is, however, not theoretically known how far down in x one needs to go in order for the predicted, but not experimentally verified, BFKL dynamics to become noticeable or dominant. In recent theoretical progress these two approximation schemes have been included in a more general one. The CCFM equations [3] incorporate DGLAP and BFKL which are thus reproduced in the relevant limits. The Linked Dipole Chain (LDC) model [4] goes further along this line by also offering an explicit model for Monte Carlo simulation of parton emissions [5].

If the parton density increases without limit as x decreases, it would eventually lead to a violation of unitarity. The high density, or 'overcrowding', of partons in the proton does, however, imply that parton–parton interactions can no longer be neglected. Thus, gluon recombination $gg \to g$, i.e. the reverse of the gluon splitting process, should reduce the parton density and restore unitarity. The GLR equation [6] attempts to describe such gluon recombination effects and predicts novel non-linear phenomena in QCD. Numerical estimates indicate that these effects are too small to be observable at HERA using the inclusive structure function. The effect may, however, be larger if the partons are not distributed evenly in the proton, but there exist smaller regions with higher than average density, so-called 'hot spots'.

To test these theoretical frameworks and develop them further requires detailed comparison with experimental data. Progress in our understanding with inclusive measurements requires very precise data. To be really conclusive, one must exploit the information contained in the hadronic final state, which is of course affected by the radiation processes summed over in the inclusive structure function.

An increased forward transverse energy ($E_\perp$) flow has been suggested as a sign of BFKL dynamics [7]. The observations at HERA are indeed consistent with BFKL dynamics, but can also be reproduced by DGLAP-based models depending on the model for the hadronization of the proton remnant [8]. This observable is thus sensitive to hadronization corrections. However, as discussed in Ref. [9], the BFKL and DGLAP scenarios are still expected to show differences in the $E_\perp$ flow closer to the proton direction than can presently be observed. Here one should keep in mind that 'forward' in the HERA laboratory frame corresponds to the central region in the hadronic cms, and the large effects are therefore to be found much closer to the proton remnant.

To discriminate between BFKL and DGLAP dynamics it would be advantageous to use observables that enhance the genuine perturbative QCD effects relative to soft hadronization effects. One method is to look for jets with $p_\perp^2 \approx Q^2$ in the forward region [10]. Such a measurement has already been done [11], but the result was not quite conclusive, although it has been shown that a fixed order α_S^2 calculation alone cannot describe the data [12, 13]. According to BFKL, the forward jet cross-section should rise like a power of x_{jet}/x_B for large rapidity intervals $\Delta y = \ln x_{\mathrm{jet}}/x_B$ between the current and the forward jet, while for pure DGLAP dynamics, such jets would be heavily suppressed. In Refs. [14, 15, 16] a number of suggestions are made for how to improve this measurement in the future, and it is clear that extending the jet search closer to the proton direction is a vast improvement.

Another way of investigating perturbative effects is to use high$-p_\perp$ particles, which are exponentially suppressed in non-perturbative mechanisms. In Ref. [17] it is shown that such a measurement is feasible and would greatly improve with increased tracking coverage in the forward direction.

Also in photoproduction there are important studies which would benefit greatly from an increase of the forward detector coverage. It is, for example, possible to investigate the important QCD phenomenon of color coherence in the initial state parton emission processes [18]. Such studies are also possible at e.g. $p\bar{p}$ colliders, but γp has the advantage of reduced smearing effects from the underlying event. Another issue is large rapidity gaps between jets or between a jet and a high-$p_\perp$ meson [19, 20] related to the diffractive phenomena discussed below.

Diffraction. Diffractive processes are conventionally related to soft physics, but through the introduction of a large momentum scale in *diffractive hard scattering* [21], perturbative methods may also be used to explore them.

Instead of describing diffraction based on the old Regge formalism, there is a growing field using perturbative QCD methods where the pomeron is represented by Feynman diagrams of gluons. These range from the simplest case of two gluons, via the addition of next-to-leading corrections, to more complicated ladder diagrams. For a special class of hard diffractive processes, vector-meson production by longitudinally polarized photons and high-$p_\perp$ dijet production, it has been shown that perturbative QCD is applicable (for a review see Ref. [22]).

Another approach to understand rapidity gap events has recently been introduced based on non-perturbative soft color interactions [23]. These may be seen as partons interacting with the 'background' color field of the proton [24]. The perturbative phase of the interaction is then supposedly as in usual events, but the color structure is altered through the soft gluon exchanges. In this way the hard scattering system and the proton remnant system may each become color singlets and thereby decouple in the hadronization such that a rapidity gap between them arises. The proper rate of gap events can be obtained and an explicit model [8] seems to reproduce the salient features of the data. This approach may also offer a more 'continuous' theoretical description of all kinds of events, such that gap events and non-gap events can be described in the same framework [8, 9].

Thus, there are different theoretical approaches to the problem and, since they are not on a firm ground, there is a strong need for more experimental information. Ideally, one would like to test the models more generally in comparison to data that covers also the transition from diffractive gap events to 'normal' DIS events, i.e. from large to smaller and vanishing rapidity gaps. Furthermore, the system Y in front of the gap in the process $e + p \to e' + X + Y$, need not be a single proton but can represent proton dissociation or some more general state of higher mass and other quantum numbers. It is desirable to develop a more general description covering also these possibilities. All of this requires as complete detector coverage as possible.

Diffractive events at HERA have mainly been selected by the requirement of a large rapidity gap. This prevents a clear observation of large diffractive masses (M_X) since the X-system is then extending to more forward rapidities. In the present detector configurations it is possible to tag such events with a forward proton spectrometer. However, the only way to study the topology of these events is by extending the angular coverage of the calorimeters. It would then be of interest to establish whether large mass diffraction ($M_X^2 \gg Q^2$) exhibits properties different from those expected in soft diffractive interactions [25]. From a theoretical point of view the regime of large diffractive masses, or small $\beta = Q^2/(Q^2+M_X^2)$, corresponds to the triple regge limit of diffractive scattering and novel effects are expected. An experimental investigation of this regime is important for increasing our understanding of diffractive scattering.

It has been postulated that the study of hard diffractive scattering, in which the virtual photon fluctuates into a small size quark-antiquark configuration which then interacts with the proton, may be a sensitive probe of the deviations from the DGLAP evolution equation [22]. The properties of reactions, such as vector meson production by longitudinally polarized photons [26] or high-$p_\perp$ dijet production [27], may be affected by proton dissociation. Current experimental estimates of this uncertainty are at the 5–10 % level [28]. This percentage can be expected to decrease significantly with an upgrade of the forward region.

The change of regime from soft to hard scattering is expected to affect the slope of the momentum transfer (t) dependence [29]. This in turn may affect the probability of proton dissociation [30]. This calls for a precise measurement of proton dissociation for different configurations of the photon diffracted state X. A clear measurement of the proton fragmentation region is also of experimental importance in order to isolate genuine diffractive events and control the background from non-diffractive events.

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, should not depend on the system X. The change in the energy dependence of the total $\gamma^* p$ cross section in the DIS regime may be the first indication that the exchange of one or several vacuum poles may not be appropriate and that pomeron-type factorization is violated. This is expected as a consequence of QCD evolution. It is thus of interest to test the factorization hypothesis in the regime of hard diffractive scattering involving interactions of small size configurations (vector meson production by longitudinally polarized photons or high-$p_\perp$ dijet production). The latter are believed to be driven mainly by perturbative QCD [26, 27].

An interesting observation is that the percentage of double dissociation can be related to the level of gluon fluctuations in the wave function of the proton [22]. A systematic study of double dissociation for various configurations of the photon diffracted state, i.e. vector-mesons and high-$p_\perp$ dijets, initiating the diffractive scattering may therefore shed some light on the distribution of color in the proton.

Furthermore, a clear test of color transparency [22] can be made by measuring the probability of survival of large rapidity gaps between two high-$p_\perp$ jets in photoproduction as a function of the transverse size of the "photon" [31]. Since color transparency predicts the suppression of initial and final state interactions, the large rapidity gaps are more likely to survive when the hard interaction is initiated by an unresolved photon as opposed to a resolved one. In order to measure the gap survival probability for resolved photons, an efficient reconstruction of jets in the forward region is essential [19].

Finally, the study of charged current induced diffraction would also profit from extending the coverage of the forward region as shown in Ref. [32].

With a suitable forward detector upgrade, these physics issues (excluding the charged current studies) could be well explored with an integrated luminosity of 100–150 pb^{-1}.

Non-perturbative QCD. To understand soft, non-perturbative strong interaction processes remains a main challenge in QCD. Hadronization is here an important problem which is not solved, although there are well functioning phenomenological models. DIS events provide an interesting source of information since the presence of the initial proton gives a richer structure than e^+e^- annihilation, without giving the full complications of hadron collisions.

Compared to e^+e^- the main new ingredient is the proton remnant. Although it is normally considered a spectator relative to the hard scattering process, it does influence the final state significantly. If the remnant system can be considered as a single color charge, it is natural to have a single color-field connection to the hard scattering system. However, with a more complex remnant the color-field structure may be more complicated leading to another result of the hadronization. An example of this is when the remnant is not a simple diquark, but a more complex parton system remaining when a sea quark or gluon has entered the hard scattering process. Depending on how these cases are described, different final states will result. The effects are not just localized at very large rapidity, but can also have effects rather centrally depending on the model [8]. Although some information will come from the tagging of highly energetic protons which were formed after a hard, non-diffractive interaction [33], more experimental information from the forward region is crucial for an improved understanding of these issues.

In addition, one cannot avoid considering these problems when studying the above perturbative QCD issues since, as mentioned, hadronization corrections may be substantial and must in any case be well controlled in order to reach safe conclusions.

Measuring particles in the forward region would also give data to be used in the context of fracture functions [34]. These are recently introduced theoretical concepts that combine structure function and fragmentation function information. They can, e.g., specify an incoming parton under the condition of a certain particle being produced in the final state. Fracture functions factorize with respect to the hard interaction and their scale evolution is calculable within pQCD.

The target proton wave function may have different types of fluctuations which can be probed. One interesting case is intrinsic charm quarks [35], i.e. the possibility of some (small) probability of having a $c\bar{c}$ pair in the Fock state decomposition of the proton wave function. An interaction with the proton can then realize this charm pair and produce charm particles. At HERA there are two main possibilities for this interaction. The photon can couple directly to either the c or $\bar{c}$, leaving the other in the proton remnant system. The scattered charm quark will typically emerge at a small forward angle due to the large momentum fraction x of intrinsic charm quarks. Alternatively, the photon couples to a non-charm quark in the proton, such that both the c and $\bar{c}$ are materialized in the proton remnant hadronization, i.e. very forward. Not only open charm (e.g. D-mesons and Λ_c) can be produced, but also large-momentum J/ψ's that could be observed through the decay into a muon pair in the very forward region. Predictions for these processes at HERA are available [36] based on detailed Monte Carlo simulations and show that upgraded forward detectors would be essential.

Monte Carlo models. One should not forget or underestimate the importance of having theoretically well founded event generators which give a good description of data. This is crucial for most measurements at HERA. Although these models are steadily improving, with substantial progress within this workshop [37], there are still important discrepancies with respect to data. To improve these event generators even more, one should compare them with data where they differ the most. These differences are typically found in the treatment of initial-state parton showers, and in the hadronization of the proton remnant. Thus, they mainly affect the hadronic final state in the forward region. Improving generators to better describe the forward region will, however, also set constraints on how they behave in other parts of phase space. Learning more about the forward region will thereby increase our confidence in the generators in general. Indirectly this will also affect the results and conclusions of measurements seemingly unrelated to the forward region.

Conclusions. Taken together the above physics issues make up a compelling case for intensifying the studies of *forward physics* at HERA with an upgraded forward detector. This would also most certainly be beneficial for the study of other issues, which have not been covered in this workshop due to limited time and manpower. Our two working groups have, however, investigated designs of forward detector upgrades, which would be appropriate at ZEUS and H1 as reported in Refs. [16, 17].

Forward detector upgrades are, unfortunately, incompatible with the proposed scheme for increased luminosity with magnets in the forward (and backward) regions. Such magnets placed within the present detectors will severely hinder the above forward physics program and in most cases totally exclude it. Note also that these magnets prevent electrons scattered at very small angles (low Q^2) to be detected, hence the data will not extend to as small x values as are presently reachable. We therefore urge the HERA community to consider these incompatible options in a proper way. It should be stressed that most of the physics issues presented here do not require very large luminosity [22, 38] and could be completed in a fairly limited time. Therefore such a forward upgrade, if speedily implemented, should not exclude a luminosity upgrade, although some delay to the final stage of the latter may be implied.

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