Diffractive Interactions: Theory Summary

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I review various theory issues in diffraction that have been presented and discussed in the working group, and a few points concerning the comparison of theory with data. Some common notation used in diffractive DIS is given in an appendix.

1. DIFFRACTION IN DIS

There has been an ongoing effort in the last years to describe diffractive DIS within the framework of QCD. Progress has been made in understanding the connections between different approaches, and we have had presentations about modelling the nonperturbative input needed in a QCD description.

Soper [1] recalled that to leading twist accuracy, i.e. up to corrections in powers of $1/Q^2$, the inclusive diffractive cross section factorises into a hard photon-parton scattering subprocess and diffractive parton distributions. This factorisation has been shown to hold to all orders in perturbative QCD [2] and may be regarded on the same footing as the corresponding theorem for the inclusive DIS cross section. Diffractive parton distributions are defined through quark and gluon field operators in a similar way as ordinary parton distributions or fragmentation functions; consequences of this are that they are process independent, and that their dependence on the factorisation scale is governed by the usual DGLAP equations.

Two tasks follow from this: to test experimentally where and how well these theory predictions are satisfied, and to measure the diffractive parton densities as a source of information on the nonperturbative physics at work in diffraction.

Two models for diffractive parton densities at a low starting scale have been presented. Soper et al. [1] have evaluated them for a small-size hadron, coupling to a heavy quark-antiquark pair, which can be calculated perturbatively. Under the hypothesis that the basic features of the answer survive in the nonperturbative regime relevant for a proton target the result is then compared with data on F_2^D, and does indeed show the correct qualitative behaviour. In a similar spirit Mueller's dipole approach to the BFKL pomeron, which is based on heavy onium scattering, is being used by Peschanski et al. [3] for the description of F_2 and F_2^D.

Hebecker et al. [4] have taken the opposite extreme of a very large hadron and modelled diffractive and non-diffractive parton distributions of the proton in their semiclassical approach. Note that this description is originally formulated in a frame where the target proton is at rest: the fast-moving γ^* splits into $q\bar{q}$ or $q\bar{q}g$ partonic states which are scattered in the colour field of the target. The expression of the amplitude obtained in this way can however be re-interpreted in the Breit frame: to leading accuracy in $1/Q^2$ it displays factorisation into a hard photon-parton scattering and diffractive or non-diffractive parton densities, including their QCD evolution. In a simple model for the colour field of a large target Hebecker et al. obtain parton distributions in fair agreement with the data on F_2 and F_2^D.

It is remarkable that two rather opposite model assumptions of a very small and a very large hadron give results that have several similarities. One is the large amount of gluons compared with quarks in the diffractive distributions, and the other the behaviour of these distributions at small and large parton momentum fraction z with respect to the Pomeron momentum $x_{I\!P} p$:

$$\frac{dq(z)}{dx_{I\!P}\,dt} \overset{z\to 0}{\sim} \text{const}\,, \qquad \frac{dq(z)}{dx_{I\!P}\,dt} \overset{z\to 1}{\sim} (1-z) \qquad (1)$$

for quarks and

$$\frac{dg(z)}{dx_{I\!P}\,dt} \overset{z\to 0}{\sim} \frac{1}{z}, \qquad \frac{dg(z)}{dx_{I\!P}\,dt} \overset{z\to 1}{\sim} (1-z)^2 \tag{2}$$

for gluons. Notice that such gluon distributions gently fall off as $z \to 1$ and do not correspond to a "super-hard" gluon.

Wüsthoff [5] has pointed out that the wave function of a γ^* splitting into $q\bar{q}$ or $q\bar{q}g$ appears in these calculations, as well as in the evaluation of two-gluon exchange by Bartels et al. [6], in earlier work by Nikolaev [7], and in the dipole approach to BFKL [3]. It is the idea underlying the BEKW parametrisation [5,8] that the kinematic factors provided by the photon wave functions control the behaviour of F_2^D at the endpoints $\beta \to 0$ and $\beta \to 1$. For the leading twist part this is related with the endpoint behaviour of the diffractive parton densities; in particular a gluon density going like $(1-z)^n$ for $z \to 1$ corresponds to a $(1-\beta)^{n+1}$ behaviour at $\beta \to 1$ for the contribution of boson-gluon fusion to F_2^D. It would be interesting to understand in more detail to which extent the perturbative physics of the photon wave function can account for the β-dependence of F_2^D and to which extent this dependence reflects the nonperturbative dynamics of gluons in the proton.

In the comparison of theory with experiment the large-z behaviour of the diffractive gluon density still remains to be understood; a reflection of this is the existence of two solutions in the BEKW fit to the H1 data [8], one corresponding to a very "hard" gluon, the other to a fairly "soft" one.

An important part of the programme to investigate diffractive parton densities, and to constrain their shapes, is to look at other processes where diffractive factorisation is expected to hold. With densities obtained from an analysis of F_2^D data it is indeed possible to describe diffractive dijet production in $\gamma^* p$ collisions, and in γp collisions in the region where they are dominated by the direct, pointlike component of the photon [9].

What the implications are of the H1 and ZEUS data on diffractive charm production [10,11] is too early to say and will have to be clarified. It has been emphasised in the discussions that if this process is compared with the results of two-gluon exchange calculations then both the $c\bar{c}$ and $c\bar{c}g$ final states must be taken into account, the latter being important at small β. Note also that the $c\bar{c}$ final state is not included in a description based on diffractive parton densities (unless one introduces a diffractive charm quark distribution).

Further information can be expected from studies of the diffractive final state. At this point it is important to remember that part of the final state configurations is not included in the leading-twist description with diffractive parton distributions. An example is a $q\bar{q}$-pair with large relative transverse momentum, originating from a longitudinally polarised γ^*. Its importance for the analysis of F_2^D at large β has been stressed [3,5], in particular because of its influence on the scaling violation pattern. Bartels [6] has reported on work to calculate the $q\bar{q}g$ final state in the two-gluon exchange picture for a wider part of phase space than where it is known so far, namely for configurations where quark and antiquark do not balance in transverse momentum and where the gluon is not approximately collinear with the initial proton. One motivation of this study is that for configurations with only high-p_T partons in the diffractive system one may expect a steeper energy dependence than for the inclusive cross section as a manifestation of hard pomeron dynamics.

Williams et al. [12] have investigated the restrictions on the diffractive system imposed by a rapidity gap cut in the HERA frame, following earlier work by Ellis and Ross. They find that no effect is to be expected with presently used values of η_{max}, but advocate to use data with stronger cuts as a means to study the structure of the final state in a way that is sensitive to the diffractive mechanism.

2. LEADING BARYONS IN DIS

The concept of diffractive factorisation can be extended to non-diffractive production of a leading proton or neutron; in fact diffractive parton densities are a special case of fracture functions [13], which describe semi-inclusive particle production in the target fragmentation region. The data on leading baryon production [14] do indeed

indicate that this factorisation is satisfied, and in particular show that in DIS leading baryon production is a leading twist phenomenon, as is diffraction. It is further found that, when the cross section is integrated over a certain range of momentum fraction for the leading baryon, its dependence on Bjorken-x follows that of the inclusive cross section, which supports the idea of limiting fragmentation [14].

3. THE ENERGY DEPENDENCE AND THE BFKL POMERON

The same similarity in energy dependence has been observed some time ago in the diffractive regime, and led Whitmore et al. to compare diffractive quantities (integrated over a certain range in $x_{I\!P}$ at fixed x) with inclusive ones at the level of parton densities [11]. It should also be noticed that a number of models can actually make simultaneous predictions for F_2^D and F_2 [3–5], and one may hope that more will be learnt from confronting the dynamics of inclusive and diffractive DIS.

While for the dependence of F_2^D on Q^2, and to a lesser degree on β, a number of predictions can be made in QCD and a certain convergence between theory approaches has been achieved, it is fair to say that the energy or $x_{I\!P}$-dependence is still poorly understood.

Applying the ideas of Regge phenomenology to diffractive parton densities one arrives at the Ingelman-Schlein proposal [15]. In this scenario diffractive parton distributions factorise into a flux factor $f_{I\!P/p}$ and parton distributions $F_{q,g/I\!P}$ of the pomeron, cf. Fig. 1 (a),

$$\frac{dq, dg(z, x_{I\!P}, t)}{dx_{I\!P}\, dt} = f_{I\!P/p}(x_{I\!P}, t)\, F_{q,g/I\!P}(z, t)\,, \qquad (3)$$

where the flux factor can be obtained from the Regge phenomenology of soft hadronic reactions. A slightly more general ansatz with a sum over contributions from the pomeron and various reggeons turns out to work rather well as analyses of the data for F_2^D and for leading baryons show [8,14]. As is well known the pomeron intercept extracted in diffractive DIS is larger than the one found in hadron-hadron scattering and in photoproduction. It remains to be understood how such a Regge description can go together with the observed similarity in the energy dependence of F_2 and F_2^D mentioned above.

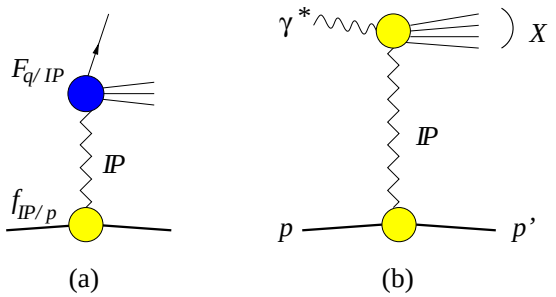

Figure 1. Two different types of Regge factorisation discussed in the text: (a) of a diffractive parton density and (b) of a diffractive scattering process.

It may be worthwhile to notice that if at some factorisation scale Q_0^2, large enough to use DGLAP evolution, the $x_{I\!P}$-dependence of the diffractive parton distributions factorises as in (3), then this dependence remains unchanged when one evolves to higher Q^2, and with it the energy dependence of the leading twist part of F_2^D [1,16]. This is very much in contrast to the x-dependence in F_2, which is made steeper by evolution.

Yet another kind of factorisation is Regge factorisation (or k_T factorisation in the context of perturbative QCD) of the entire diffractive process $\gamma^* p \to X p'$ into pomeron exchange and impact factors, describing the transitions $\gamma^* \to X$ and $p \to p'$, cf. Fig. 1 (b). It should be remembered that this factorisation goes beyond leading twist, as the $\gamma^* \to X$ impact factor contains more than the leading power in $1/Q^2$. The role of a large scale Q^2 here is to introduce perturbative QCD dynamics into the process.

To probe the pomeron in a dynamical situation where it is as much dominated by hard physics as possible, two types of "gold plated" processes

are being discussed: high energy $\gamma^*\gamma^*$ collisions, where the pomeron couples to a hard scale at both ends, and diffraction at high t, where a large momentum is transferred across the t-channel.

Royon et al. [17] have studied the total $\gamma^*\gamma^*$ cross section in the dipole BFKL approach. Choosing similar virtualities of the two photons should provide a means to separate BFKL from DGLAP dynamics (which describes the evolution between two different momentum scales), something which cannot be achieved in the proton structure functions F_2 or F_2^D. It may be worth noting that the leading order BFKL prediction for $\gamma^*\gamma^* \to X$ is excluded by the L3 data [17,18]. In a phenomenological estimate of NLO corrections Royon et al. find that the effect of BFKL resummation over bare two-gluon exchange could be seen at a linear collider, while the discriminating power of LEP2 is marginal.

Theory aspects of high-t diffraction in ep or hadron-hadron collisions have been discussed by Forshaw [19]. He emphasised that within the BFKL resummation even a moderately large momentum transfer across the gluon ladder is very efficient in suppressing the dangerous infrared regions in the phase space integrations, where the results of perturbation theory become doubtful. He also pointed out the virtues of large-t diffractive production of J/Ψ, light mesons or real photons, processes which do not suffer from the difficulties of hadronisation effects and rapidity gap survival encountered in forward high-p_T jet production, and according to estimations give observable event rates in large parts of phase space. Inclusive high-t diffraction $\gamma p \to XY$, defined by the largest rapidity separation in the event has been discussed by Cox [20].

On the theoretical side progress has been reported in understanding the structure of the BFKL pomeron. Kotsky [21] has verified that the impact factors occurring in the BFKL equation at NLO satisfy a condition of self-consistency for the reggeisation of the gluon. At the level of LO accuracy the subject of multi-pomeron couplings and unitarity corrections has received much interest. Ewerz [22] recalled that in order to satisfy the unitarity bound the leading $\log(1/x)$ approximation has to be relaxed to take into account diagrams with more than 2 reggeised gluons in the t-channel. Investigating the transitions between 2 and up to 6 gluons he found a structure consistent with the unitarity of an underlying effective field theory at high energy, based on conformal invariance, which remains to be formulated. In the dipole approach Peschanski [3] has obtained several exact results for multi-pomeron vertices, noting that the corresponding pomeron configurations may be phenomenologically accessible in the triple Regge regime of ep diffraction and for various types of gap-jet events at the Tevatron. Gay Ducati [23] presented an evolution equation for F_2 which incorporates unitarity corrections and contains the Gribov-Levin-Ryskin equation as a limiting case. This equation can be derived within the dipole pomeron approach, where it corresponds to parton recombination in the colour dipole cascade initiated by the virtual photon.

4. DIFFRACTION IN $p\bar{p}$ AND ep COLLISIONS

The confrontation of rapidity gap events at the Tevatron with those at HERA provides an opportunity to learn about the interplay between hard and soft dynamics and about the transition from partons to hadrons in reactions with a hard scale.

While in diffractive DIS there is a factorisation theorem for the inclusive cross section and factorisation is expected to hold for hard diffractive γp processes where they are dominated by the pointlike component of the photon, there are theory arguments that in hadron-hadron diffraction factorisation should break down due to interactions between the spectator partons of the participating hadrons. This expectation is borne out in the comparison between HERA and Tevatron data: the presentations by Whitmore [11] and the experiments [24] consolidate previous statements that with diffractive parton distributions which fit the inclusive F_2^D and diffractive jet production data at HERA (and which are thus required to contain a significant amount of gluons) predictions for Tevatron processes come out far too big. There are also hints for factorisation breaking in diffractive jet photoproduction in the region of x_γ where the hadronic component of the photon

becomes important [9].

A way of quantifying the phenomenon of factorisation breaking is the concept of gap survival probability, according to which a potential rapidity gap left by a hard subprocess is filled by hadrons produced in collisions between spectator partons. Gotsman [25] presented a model for the survival probability, where in particular a strong dependence of gap survival on the total energy in the reaction is found.

The experimental observation that the transverse energy spectra in double diffractive, single diffractive and non-diffractive jet production at the Tevatron look very similar [24,11] supports the picture that in all cases one has to do with the same hard partonic subprocesses, and that it is mainly soft interactions which may or may not destroy the rapidity gap, while not modifying the large-E_T spectrum of the jets.

A particular implementation of the idea that hard diffractive and non-diffractive events can be described by a perturbative subprocess and nontrivial dynamics of hadronisation which determines whether there will be a rapidity gap or not, is the soft colour interactions model. Ingelman [26] showed that in this model a number of processes both at the Tevatron and at HERA can be fairly well described, without incurring the huge discrepancies in rates of the factorisation ansatz. The physics assumption underlying soft colour interactions is a rearrangement, before hadronisation, of the colour strings between partons due to their interaction with a colour background field. Ingelman further presented an alternative mechanism based on re-interactions among the strings themselves, with the hypothesis that these interactions tend to minimise the phase space area "swept out" by the strings. This rather simple model is able to give a reasonable description of F_2^D.

5. LIGHT MESON PRODUCTION

Exclusive vector meson production has long been a major source of information in diffractive physics. Within perturbative QCD it has been shown [27] that in the Bjorken limit of large Q^2 at fixed x and t, and for longitudinal polarisation of the initial photon, the amplitude for $\gamma^* p \to Mp'$ factorises into a skewed parton distribution in the proton, a hard parton scattering and the distribution amplitude of the meson M, cf. Fig. 2. The amplitude for transverse photons should be power suppressed by $1/Q$. How far one is from the asymptotic regime can thus in particular be studied with polarisation observables. The data on the ratio $R = \sigma_L/\sigma_T$ of cross sections for longitudinal and transverse photons have indicated for some time that there is a substantial amount of transverse cross section even at a Q^2 of 10 GeV^2 or more, and the measurements of the full decay angular distributions [28] provide a wealth of information about nonleading twist phenomena and the physics of the photon-ρ transition in a perturbative regime. In this sense their importance goes well beyond the statement that s-channel helicity is not conserved to an accuracy better than some 10%. The simplest descriptions of the ρ, be it through a distribution amplitude, where the relative transverse momentum between quark and antiquark is integrated out, or as a nonrelativistic bound state where a constituent $q\bar{q}$-pair equally shares the meson momentum, are both too simple to describe this process beyond a 10% accuracy, and the data on the ρ polarisation density matrix strongly indicate that the inclusion of transverse momentum of the $q\bar{q}$-pair is essential. Three implementations of this, using rather different frameworks and physics assumptions, have been presented by Kirschner, Nikolaev and Royen [29–31]. Within the present experimental errors they can all account for the data, in particular for the pattern of s-channel helicity violation, but they differ among themselves to an extent that it may in the future be possible to learn which are the adequate degrees of freedom in the transition from γ^* to ρ.

In diffractive ρ-production at large t, already mentioned in connection with the search for the perturbative pomeron [19], the photon-ρ transition can again be studied in a region where one should be able to describe it within perturbative QCD. Also here polarisation observables can provide important insight into the dynamics, and it will be interesting to understand the results on the ρ polarisation at high t shown by Crittenden

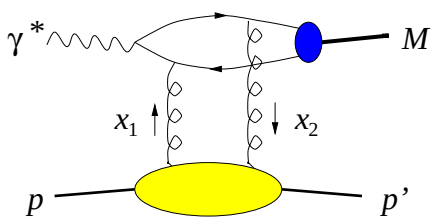

Figure 2. Leading-twist factorisation of meson production from a longitudinal photon into a skewed parton distribution in the proton, a hard scattering and the distribution amplitude of the meson.

[32].

Polyakov [33] has shown that the leading twist description of ρ-production can be extended to the production of a $\pi^+\pi^-$-pair with invariant mass $M^2_{\pi\pi} \ll Q^2$, be it on or off the ρ-peak. The corresponding generalised distribution amplitude describes how a pion pair is formed out of a fast-moving $q\bar{q}$-pair, and is related by crossing with the parton distributions of the pion. It offers a new way to look at the distribution amplitude of a resonance, and also shows that in the factorising regime it is not necessary to extract a "ρ-signal" from the pion invariant mass spectrum in order to study, say, the $x_{I\!P}$- and t-dependence of the process and the physics of skewed parton distributions.

The cornerstone of understanding diffraction in QCD is the gluon exchange picture, which has as a natural implication that an odderon should exist as the negative charge conjugation partner of the pomeron. No experimental evidence for this object exists so far. Exclusive production of a pseudoscalar instead of a vector meson offers a way to look for odderon exchange in ep collisions. Using the description of high-energy scattering developed by the Heidelberg group, which accounts quite well for data on elastic hadron-hadron scattering and exclusive ρ-production, Berger [34] has presented an estimate of the cross section for photoproduction of a π^0, going along with proton dissociation. He found rates that should make it possible to discover the odderon at HERA.

6. HEAVY MESON PRODUCTION AND SKEWED PARTON DISTRIBUTIONS

Since the first data on exclusive Υ photoproduction have been presented a year ago there have been improvements in the theory of this process, for which at the time predictions were far below the measured cross sections (while with the same model assumptions J/Ψ-production could be described rather well). A number of simplifying assumptions had to be refined, and the presentations by McDermott and Teubner [35,36] showed that while differing in details both groups obtain cross sections in fair agreement with the data. Points of debate are mainly the choice of factorisation scale in the gluon distribution, and the question of how good a nonrelativistic approximation is for the Υ wave function (in addition, Teubner et al. also give a result based on parton-hadron duality). An effect which increases the cross section compared with the "naive" result is the inclusion of the real part of the scattering amplitude, whose importance is related with the very steep energy dependence of the skewed gluon distribution at the high factorisation scale provided by the Υ mass. Perhaps even more spectacular is the effect of the "skewedness" in the gluon distribution, i.e. the difference between the momentum fractions x_1 and x_2 of the two exchanged gluons (cf. Fig. 2), which is fixed at $x_1 - x_2 = (M_V^2 + Q^2)/W^2$ for the production of a meson with mass M_V. Estimations find that due to the large mass of the Υ the effect of this asymmetry amounts to a factor of 2 to 3 in the cross section, compared to just approximating the skewed gluon distribution by the ordinary one, where $x_1 = x_2$.

Important theory progress has been made in the understanding of skewed parton distributions, in particular concerning their evolution (cf. also the presentations in the spin working group of this workshop). Martin [37] has given arguments why for small x_1 and $x_1 - x_2$ the effect of the

asymmetry between x_1 and x_2 at a low factorisation scale becomes more and more washed out as one evolves to large scales, so that the asymmetry there becomes increasingly dominated by the dynamics of the evolution. One thus expects to obtain a good approximation of skewed distributions at a high factorisation scale by evolving them from a low scale, approximating the skewed distributions at the starting scale by the ordinary ones in an appropriate manner. Different ways of performing this approximation have been presented by Martin and by Golec-Biernat [38]. This procedure then relates skewed and ordinary distributions in a nontrivial but controlled way.

In the small-x regime the measurement of skewed parton (mainly gluon) distributions may in such a way be used to obtain information on the ordinary gluon distribution. For larger x, where also the asymmetry $x_1 - x_2$ is larger, one can expect that the skewed quantities (now mainly the quark distributions) will contain nonperturbative information on the proton structure that cannot be obtained from the ordinary ones. The kinematics at HERMES allows one to study this regime, and the first comparison of exclusive ρ-production data [39] with an estimate based on skewed quark distributions is encouraging for the applicability of this description at lower energies.

Freund [40] has emphasised that the most direct information on skewed distributions may be obtained in deeply virtual Compton scattering, $\gamma^* p \to \gamma p$. On one hand there is no second nonperturbative unknown like a meson wave function, and on the other hand the interference of Compton scattering with the Bethe-Heitler process in $ep \to e\gamma p$ offers a possibility to measure the new distributions at *amplitude* level. In particular the different ways how the skewed distributions enter in the real and imaginary parts of the Compton amplitude contains valuable information. The interference term is accessible through an azimuthal asymmetry, and even more directly through the asymmetries in the beam lepton charge (e^+ vs. e^-) or polarisation.

With Υ-production providing probably the first evidence for nontrivial effects of skewedness, it can be hoped that future data on various processes will enable us to make use of skewed parton distributions as an additional tool to study hadron structure.

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APPENDIX

This appendix gives some commonly used notation in diffractive DIS. Four-momenta are defined in Fig. 3.

- General DIS variables:

$$\begin{aligned} Q^2 &= -q^2 = -(k-k')^2 \\ W^2 &= (p+q)^2 \\ x &= \frac{Q^2}{2p\cdot q} = \frac{Q^2}{W^2+Q^2-m_p^2} \\ s &= (p+k)^2 \\ y &= \frac{q\cdot p}{k\cdot p} = \frac{W^2+Q^2-m_p^2}{s-m_p^2} \end{aligned}$$

- Diffractive DIS variables:

$$\begin{aligned} t &= (p-p')^2 \\ M_X^2 &= (p-p'+q)^2 \\ M_Y^2 &= p'^2 \\ x_{I\!P} &= \frac{(p-p')\cdot q}{p\cdot q} = \frac{M_X^2+Q^2-t}{W^2+Q^2-m_p^2} \\ \beta &= \frac{Q^2}{2(p-p')\cdot q} = \frac{Q^2}{M_X^2+Q^2-t} = \frac{x}{x_{I\!P}} \end{aligned}$$

  It is also common to write ξ instead of $x_{I\!P}$.

- Diffractive structure functions:

$$\frac{d^4\sigma(ep\to eXY)}{dx\,dQ^2\,dx_{I\!P}\,dt} = \frac{4\pi\alpha_{em}^2}{xQ^4} \times\left[\left(1-y+\frac{y^2}{2}\right)F_2^{D(4)} - \frac{y^2}{2}F_L^{D(4)}\right]$$

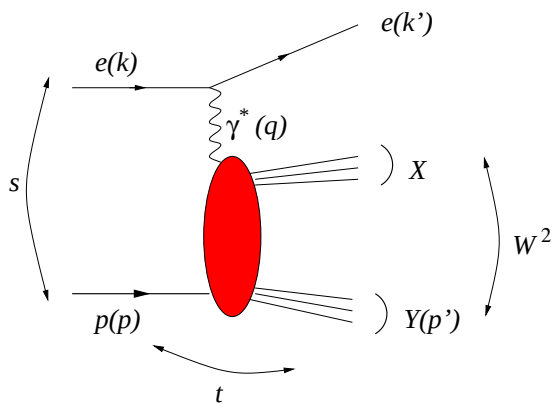

Figure 3. Definition of some kinematic variables in a generic diffractive process $ep \to eXY$. It includes the special cases when Y is a proton or X a vector meson. Between the hadronic systems X and Y there is a gap in rapidity.

$$F_2^{D(4)} = F_T^{D(4)} + F_L^{D(4)}$$

- t-integrated diffractive structure functions:

$$F_i^{D(3)}(x_{I\!P}, \beta, Q^2) = \int_{|t|_{min}}^{|t|_{max}} d|t|\, F_i^{D(4)}(x_{I\!P}, \beta, Q^2, t)$$

with $i = 2, T, L$. Here $|t|_{min}$ is the lower kinematic limit of $|t|$ and $|t|_{max}$ has to be specified.

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