Hard Diffractive Scattering: Partons and QCD*

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ABSTRACT

The HERA diffractive structure function data are interpreted in terms of 'diffractive parton distributions' which satisfy DGLAP evolution. These distributions are modeled assuming that the scattering takes place off a colour singlet 'pomeron' target. A quantitative test of the universality of diffractive parton distributions is proposed.

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Measurements of deep inelastic scattering events with a large rapidity gap at HERA [1, 2, 3, 4, 5] have generated renewed interest in the idea of ‘diffractive hard scattering’. It now appears that in a significant fraction of these events there is a diffractively scattered proton in the final state [6]. One can therefore introduce the idea of ‘diffractive parton distributions’, i.e. parton distributions in the hadron under the condition that the hadron is diffractively scattered. Just as the total deep inelastic structure function, measured in the process $\gamma^* p \rightarrow X$, can be written as a sum over parton distributions, i.e.

$$F(x, Q^2) = \sum_q \int dx f_q(p, \mu^2) \hat{F}_{2q}(x, Q^2, \mu^2)$$

with $\hat{F}_{2q} = e_q^2 \delta(1-x_B/x) + O(\alpha_s)$, we may define a similar decomposition for the diffractive structure function, measured in the process $\gamma^* p \rightarrow pX$,

$$\frac{dF^P_2(x_B, Q^2; x_P, t)}{dx_P dt} = \sum_q \int dx \frac{df_{q/p}(x, \mu^2; x_P, t)}{dx_P dt} \hat{F}_{2q} \left(\frac{x_B}{x}, Q^2, \mu^2\right).$$  \hspace{1cm} (1)

Here $1-x_P$ ($x_P \ll 1$) and $t$ ($|t| \ll Q^2$) are respectively the longitudinal energy fraction and the $t$-channel momentum transfer of the proton in the final state. The quantities $df_{q/p}(x, \mu^2; x_P, t)/dx_P dt$ can then be regarded as diffractive parton distributions. A rather detailed theoretical discussion of such diffractive structure functions has recently been presented in Ref. [6]. In particular it has been shown that an operator definition exists, and that the diffractive distributions should satisfy the same (DGLAP) evolution equations as the usual parton distributions. However it is not yet clear whether the concept of short-distance factorization generalizes to any diffractive hard scattering process, for example the production of large-mass Drell-Yan lepton pairs or large $E_T$ jets in hadron-hadron collisions [9]. Even if factorization is violated for diffractive hard scattering in such collisions, the effect may be weak at high energy. It therefore seems to us not unreasonable to assume the approximate validity of universal factorization and to test its consequences. The purpose of the present study is to explore further the idea of hard diffractive factorization by using the HERA $F^P_2$ data to model diffractive parton distributions, and then to use these to make quantitative predictions for other diffractive hard-scattering processes, in particular for the production of $W$ bosons in $p\bar{p}$ collisions at the Tevatron.

An important property of the HERA diffractive events [10] is the approximate factorization of the structure function $F^P_2$ (integrated over $t$) into a function of $x_P$ times a function of $\beta = x_B/x_P$: $F^P_2 \sim x_P^{-n} F(\beta, Q^2)$. This, together with the observed rapidity-gap topology of the events, strongly suggests that the deep inelastic scattering takes place off a slow-moving colourless target $P$ ‘emitted’ by the proton, $p \rightarrow Pp$, and with a fraction $x_P \ll 1$ of its momentum.\footnote{Similar quantities (‘fracture functions’) were introduced in Ref. [11].} If this emission is described by a universal flux function $f_P(x_P, t)dx_P dt$, then the diffractive structure function $F^P_2$ is simply a product of this and the structure function of the colourless object, $F^P_2(\beta, Q^2)$. Since the scattering evidently takes place off point-like charged objects, we may write the latter as a sum over quark-parton distributions, i.e.

$$F^P_2(\beta, Q^2) = \beta \sum_q e_q^2 q_P(\beta, Q^2),$$

in leading order. In this way we obtain a model for the

\footnote{This physical picture refers to the infinite momentum frame of the proton. Although it is rather different, it is not \textit{a priori} inconsistent with the so-called aligned quark picture [12] which is valid in the rest frame of the proton.}

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1
diffractive parton distributions introduced above:

$$\frac{df_{q/p}(x, \mu^2; x_P, t)}{dx_P dt} = f_P(x_P, t) f_{q/p}(\beta = x/x_P, \mu^2).$$  \hfill (2)

Many recent studies have analysed the HERA diffractive structure function data using this theoretical framework. A popular choice is to assume that the colour-neutral target is the Regge pomeron, in which case the emission factor

$$f_P(x_P, t)$$

is already known from soft hadronic physics (for a review see Ref. [11]). In its simplest version, this model would predict

$$F^D_2(x, Q^2; x_P, t) = f_P(x_P, t) F^P_2(\beta, Q^2)$$

with

$$F_P^P(t) = F_P(t) x_P^{2\alpha(t) - 1},$$

i.e. a factorized structure function with $n \approx 2\alpha_P(0) - 1 \approx 1.16$. This model is based on the notion of 'parton constituents in the pomeron' first proposed by Ingelman and Schlein [12] and supported by data from UA8 [13]. In such a model, a modest amount of factorization breaking, such as that observed in the more recent H1 and ZEUS analyses [4, 5, 6], could be accommodated by invoking a sum over Regge trajectories, each with a different intercept and structure function:

$$F^D_2(\beta, Q^2; x_P, t) = \sum_R F^R_2(\beta, Q^2) x_P^{2\alpha_R(t) - 1} F^R_2(\beta, Q^2),$$  \hfill (3)

which would yield an effective $n$ which depends on $\beta$ but is approximately independent of $Q^2$. Note that since in practice the variables $x_P$ and $t$ are integrated over, what is measured is a linear combination of $F^R_2$ structure functions or, equivalently, the parton distributions in an effective colour-neutral target:

$$\int dx_P dt F^D_2(\beta, Q^2; x_P, t) = \sum_R A_R F^R_2(\beta, Q^2) = \beta \sum_q e^2_q \sum_R A_R q_R(\beta, Q^2),$$  \hfill (4)

where the coefficients $A_R$ are independent of $\beta$ and $Q^2$. Since the DGLAP equations are linear in the parton distributions, the $Q^2$ evolution of the integrated structure function $F^D_2$ should also be calculable perturbatively. In the present study we assume, for simplicity, pomeron exchange only (i.e. $R = P$) and use the parametrization of Ref. [13] for $\alpha(t)$ and $F_P(t)$. The $x_P$ dependence of the diffractive structure function predicted by this type of 'soft pomeron’ model is roughly consistent within errors with the H1 [4] and ZEUS [3, 4] data, although there is some indication from the latter that a somewhat steeper $x_P$ dependence is preferred.

Various models for the parton distributions in the ‘pomeron’ $f_{q/p}(x, \mu^2)$ have been proposed, ranging from the two extremes of mainly gluons to mainly quarks. Recent studies in the framework of perturbative QCD DGLAP evolution can be found in Refs. [4, 16, 17, 18, 19, 20]. As we shall demonstrate below, models of both types can be constructed to agree with the HERA data. A key issue concerns the existence of a momentum sum rule for the colourless object $P$. This is a matter of some dispute, and there is indeed no theoretical proof

\footnote{For a recent quantitative study see Ref. [14].}

\footnote{In principle, for the integrated structure function there is a correction to the evolution equations from the small but finite probability that the final-state proton is produced in the hard-scattering process. However if the integration is only over a limited region in $t$, as in the present context, this correction will be completely negligible.}
that such a sum rule should exist. Of course because it is the product of $f_{q/P}$ and $f_{P}$ that appears in the expression for the structure function, one can simply impose a momentum sum rule on the parton distributions and absorb an overall normalization $\mathcal{N}$, unchanged by $Q^2$ evolution, into $f_{P}$. This is the approach we shall adopt here.

Since our purpose is to explore the consequences of a parton interpretation of deep inelastic diffractive scattering for other processes, we consider three qualitatively different models of diffractive parton distributions. The first is purely quark-like at the chosen starting scale $\mu_0^2$, with gluons generated only at higher scales through standard DGLAP evolution. The second contains a mixture of quarks and gluons at $\mu_0^2$, and the third is predominantly gluonic. Since in each case the quark content is constrained by structure function data, and since we choose to impose a momentum sum rule, the overall normalization factors $\mathcal{N}$ are different in the three models (see below). In each case the starting distributions are chosen to give satisfactory agreement with the H1 \cite{2} and ZEUS \cite{3} data. Since the errors on these data are quite large, it is not necessary to perform detailed multiparameter fits. The starting distributions (at $\mu_0^2 = 2$ GeV$^2$) are given in the following Table:

| Model | $q(x, \mu_0^2)$ | $g(x, \mu_0^2)$ | $\mathcal{N}$ |
|-------|-----------------|-----------------|---------------|
| 1     | $0.314x^{1/3}(1-x)^{1/3}$ | 0               | 1.62          |
| 2     | $0.2x(1-x)$      | $4.8x(1-x)$     | 2.85          |
| 3     | $0.081x(1-x)^{0.5}$ | $9.66x^8(1-x)^{0.2}$ | 1.57          |

Here $q$ refers to an individual light-quark distribution with SU(3) flavour symmetry assumed, i.e. $q = u = \bar{u} = d = \bar{d} = s = \bar{s}$, so that the momentum sum rule constraint at $\mu_0^2$ is $\int_0^1 dx x(6q + g) = 1$. Charm quarks are generated by massless DGLAP evolution ($g \to c\bar{c}$) at higher scales. The Table also lists the normalization factors required to fit the data. We emphasize that these are correlated to our use of the Donnachie-Landshoff parametrization of $f_{P}(x_{P}, t)$ \cite{5}. Different emission factors will lead to different normalizations. Fig. \cite{4} shows the quality of the fits to the H1 diffractive structure function data \cite{2}. The fits to the ZEUS data are comparable in quality and are not shown. More details about the fits and the different $Q^2$ evolution in the three models will be given elsewhere \cite{21}.

The concept of ‘universal pomeron structure’ can be tested in hard diffractive processes in hadron-hadron collisions. The cleanest process to study would appear to be weak boson production at the Tevatron $p\bar{p}$ collider. This was first studied in Ref. \cite{22}, where it was estimated that the single diffractive component of the total $W$ cross section could be as large as 20%. More recently, the CDF collaboration \cite{23} has searched for such diffractive events, and derived a preliminary upper limit on the single diffractive cross section of ‘a few per cent’. Using the three models discussed above, it is straightforward to compute the single diffractive $W$ cross section:

$$\sigma^{SD}(W) \sim 2\bar{q}_\beta \otimes \mathcal{N} f_{P} q_{P},$$

where the factor of two corresponds to either the proton or antiproton being quasi-elastically scattered. To avoid uncertainties from high-order corrections it is sensible to normalize this

\footnote{We integrate the $x_P$ and $t$ variables over the range appropriate for the HERA experiments.}
prediction to the total $W$ cross section, $\sigma^{\text{tot}}(W) \sim \bar{q}_p \otimes q_p$. For the parton distributions in the proton we use the MRS($A'$) set \cite{24}. The factorization scale is chosen to be $Q = M_W$, and we sum over (four) flavours of quarks in the initial-state proton and pomeron. Following Ref. \cite{22}, we define ‘single diffractive’ events by $x_P < 0.1$, integrating over all $t$. In practice, the events are defined by rapidity gaps of a certain minimum size, and therefore the observed diffractive cross section must be corrected to the theoretical prediction based on, say, $x_P < 0.1$ using a Monte Carlo simulation \cite{23}. With the above choice of parameters and cuts we find

$$\frac{\sigma^{\text{SD}}(W)}{\sigma^{\text{tot}}(W)} = \begin{cases} 
5.3\% & \text{Model 1} \\
6.5\% & \text{Model 2} \\
7.4\% & \text{Model 3} 
\end{cases} \tag{6}$$

The important point to note here is that the model predictions are quite similar: the hypothesis of hard diffractive factorization has yielded a well-constrained prediction for the single diffractive cross section. This result can be understood in terms of the evolution of

Figure 1: Fits (solid line: Model 1, dashed line: Model 2, long-dashed line: Model 3) to the H1 $F_2^D$ data \cite{2}.
the quark densities in the pomeron. The single diffractive \( W \) cross section at the Tevatron samples the quarks in the pomeron at \( \langle x_q/p \rangle \sim 0.4 \). At low \( Q^2 \) the quark distributions at this \( x \) value are constrained by the HERA \( F^D_2 \) data to be roughly the same. As \( Q^2 \) increases the distributions diverge, reflecting the quantitatively different gluon contributions to the DGLAP evolution. However at \( Q^2 \sim 10^4 \) GeV\(^2\), the relevant value for \( W \) production, the difference between the quarks in the three models is still not very large, and the predictions for \( \sigma^{SD}(W) \) are correspondingly similar, see Fig. 1. We stress that failure to observe a diffractive \( W \) cross section of the order of the values given in Eq. (6) would cast serious doubt on the ‘universal pomeron structure’ hypothesis.

In summary, we have shown how the HERA diffractive structure function data can be understood in terms of diffractive parton distributions, which satisfy DGLAP evolution and can be modelled in terms of various combinations of quarks and gluons in an effective colour-neutral target. We have discussed the concept of the universality of such distributions, and shown how the measurement of the single diffractive \( W^\pm \) cross section at the Tevatron will provide a stringent test of the universality property.

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