The QCD approach to diffractive dissociation of virtual photons

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A short overview on diffractive deep inelastic scattering is given with emphasis on the photon wave function as unique QCD-result. The $q\bar{q}$- and $q\bar{q}g$-components of the wave function are largely responsible for the shape of the β-spectrum. The dipole cross section which describes the scattering of the partons on the target is governed by less simple dynamics. Different models lead to different $x_{I\!P}$-distributions.

Diffraction is intuitively described in the following way: in the target (proton) restframe the photon dissociates into a $q\bar{q}$-pair or a $q\bar{q}g$-state far upstream the target. All partons scatter quasi elastically on the proton via a colourless two-gluon (or even multi-gluon) exchange (see Fig.1). Theoretically both states, $q\bar{q}$ and $q\bar{q}g$, can be described by dipole wave functions. For $q\bar{q}g$, however, it is only an effective description which relies on the assumption that the quark-antiquark pair represents a gluon state, i.e. the quark and antiquark are strongly localized in impact parameter space and their colour combines into that of a gluon. This assumption is justified at large enough photon virtualities Q^2.

Important to note is the fact that the wave functions are derived from perturbation theory. They are responsible for the basic shape of the diffractive β-distribution. The corresponding dipole cross section, on the other hand, is governed by more complicated dynamics. The exchanged gluons undergo multiple interactions which do not follow a simple perturbative expansion. The optical theorem, however, provides a link between the diffractive and inclusive cross section, and the strategy in general will be to construct a model based on the inclusive data and then apply it to diffractive scattering. The x_{IP}-distribution crucially depends on the characteristics of the model.

Our main objective in Ref. [1] was to derive a simple parametrization based on the fact that the β-spectrum is largely determined by the dipole wave functions. We have introduced three contributions, two related to the production of $q\bar{q}$-pairs by transverse and longitudinally polarized photons and a third, owing to the radiation of an additional gluon. The corresponding wave functions will be sketched only, the complete expressions can be found in Ref. [1]:

1. $q\bar{q}$ with longitudinally polarized photons:

$$\Psi^L_{q\bar{q}} \sim \frac{\alpha(1-\alpha)\;Q}{k_t^2+\alpha(1-\alpha)Q^2} \tag{1}$$

2. $q\bar{q}$ with transverse polarized photons:

$$\Psi^T_{q\bar{q}} \sim \frac{\vec{k}_t}{k_t^2+\alpha(1-\alpha)Q^2} \tag{2}$$

3. $q\bar{q}g$ with transverse polarized photons ($\mu,\nu = 1,2$):

$$\Psi^{\mu\nu}_{q\bar{q}g} \sim \frac{1}{\sqrt{\alpha Q^2}}\;\frac{k_t^2\;g_t^{\mu\nu}\;-\;2\;k_t^\mu k_t^\nu}{k_t^2+\alpha Q^2} \tag{3}$$

All the possible couplings of the two t-channel gluons to the dipole in Fig.1 can be cast into the following form:

$$2\;\Psi(\alpha,k_t)\;-\;\Psi(\alpha,k_t+l_t)\;-\;\Psi(\alpha,k_t-l_t) \tag{4}$$

Large l_t refers to the hard regime and small l_t to the soft regime. We can estimate both regimes, hard and soft, by analyzing the second derivatives of the wave functions or the wave functions themselves. Employing the kinematical relation for a two-body final state $\alpha(1-\alpha)M^2 = k_t^2$ one finds in the limit $M \to 0$: the contribution due to longitudinally produced $q\bar{q}$-pairs is constant,

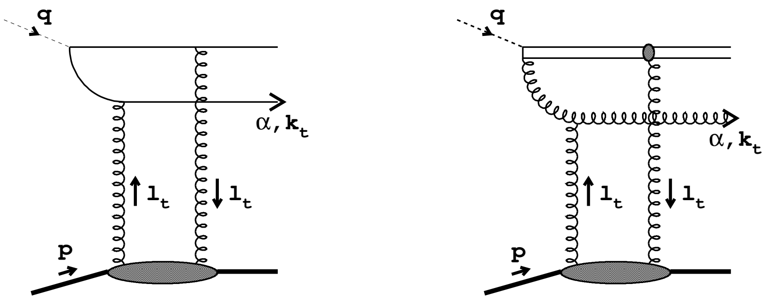

Figure 1. Diffractive production of a $q\bar{q}$-pair (left) and the emission of an additional gluon (right).

the contribution due to transverse polarized $q\bar{q}$-pairs vanishes proportional to M and the contribution due to $q\bar{q}g$ vanishes proportional to M^2. This behaviour holds in both regimes, hard or soft, which is essential for the determination of the β-spectrum. At large M the dependence of the cross section on M is given by the spin of the exchanged particle. The previous estimates of the wave function can be translated into the β-dependence of the diffractive structure function:

$$F^L_{q\bar{q}} \sim \frac{Q_0^2}{Q^2} \ln\left(\frac{Q^2}{4Q_0^2\beta}\right) \beta^3(1-2\beta)^2 \tag{5}$$

$$F^T_{q\bar{q}} \sim \beta\,(1-\beta) \tag{6}$$

$$F^T_{q\bar{q}g} \sim \alpha_s \ln\left(\frac{Q^2}{Q_0^2}\right) (1-\beta)^3 \ . \tag{7}$$

In order to accommodate a Q^2-dependent Pomeron intercept we introduced a slowly with Q^2 varying exponent. The fit provides a good description of the data. The β-spectrum has a characteristic decomposition into three contributions which reside in separate regions with only little overlap, $q\bar{q}g$-production at low β, transverse $q\bar{q}$-production at medium and the longitudinal $q\bar{q}$-production at large β (see also Fig.2). One finds a slight dependence of the intercept on Q^2 which makes it rise above the soft value. This observation might be related to an effective scale inside the Pomeron which is larger than a pure soft, hadronic scale.

In Ref. [2] a saturation model has been proposed for the dipole cross section. The increase in energy (decrease in x) leads to an increase of the parton density which eventually becomes so high that the partons start to recombine. This mechanism leads in the end to a complete saturation (see also Ref. [4]). The model can be best presented in impact parameter space (see Ref. [5]):

$$\begin{aligned} \sigma_{T,L} &= \int d^2\mathbf{r} \int_0^1 d\alpha\, |\Psi_{T,L}(\alpha,\mathbf{r})|^2 \\ &\quad \times \hat{\sigma}(x,r^2) \end{aligned} \tag{8}$$

$$\begin{aligned} \sigma^D_{T,L} &= \int d^2\mathbf{r} \int_0^1 d\alpha\, |\Psi_{T,L}(\alpha,\mathbf{r})|^2 \\ &\quad \times \frac{\hat{\sigma}^2(x,r^2)}{16\pi B_D} \ . \end{aligned} \tag{9}$$

The wave functions $\Psi_{T,L}$ are simply the Fourier transforms of eqs.(1-2) and B_D is the diffractive slope.

Our strategy was to find in a first step a model that fits all inclusive small-x data and to use it in a second step to predict the diffractive cross section. We have chosen the following parameterization:

$$\begin{aligned} \hat{\sigma}(x,r^2) &= \sigma_0 \left\{1 - \exp\left(-\frac{r^2}{4R_0^2(x)}\right)\right\} \\ R_0(x) &= \frac{1}{GeV} \left(\frac{x}{x_0}\right)^{\lambda/2} \ . \end{aligned} \tag{10}$$

The dipole cross section $\hat{\sigma}$ has the property of colour transparency for small r, i.e. $\hat{\sigma} \sim r^2$ for $r < R_0$, and of saturation for large r, i.e. $\hat{\sigma} \sim \sigma_0$ for $r > R_0$. The aspect of low-x saturation has been implemented by introducing an x-dependent radius R_0.

Saturation has the interesting phenomenological upshot that the ratio of diffractive versus inclusive scattering is roughly constant when plotted as a function of W [3]. The reason lies in the fact that the infrared cut-off is provided by the saturation scale R_0^2. This observation is highly interesting, since the ZEUS-data [6] indeed indicate a constant ratio.

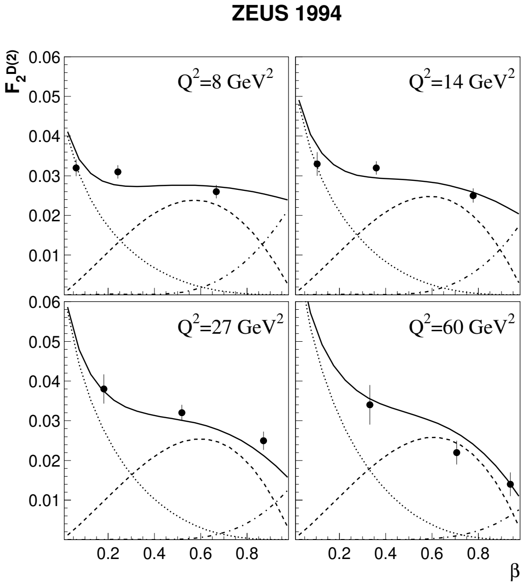

Figure 2. F_2^D for $x_{IP} = 0.0042$. Dot-dashed line: longitudinal $q\bar{q}$, dashed lines: transverse $q\bar{q}$, dotted lines: transverse $q\bar{q}g$, and solid lines: total.

The fit includes all inclusive data below x=0.01 and provides a good description of both the inclusive and diffractive data. The β-spectrum is depicted in Fig. 2 together with ZEUS-data [6]. We see the characteristic decomposition into the three regions of high, medium and low β which is large due to the wave functions. The x_{IP}-distribution as shown in Fig. 3 is model dependent and can be viewed as a real test for saturation or any other model. The overall agreement with the H1-data [7] is good, in particular at large β where the longitudinal $q\bar{q}$-contribution has a strong component.

Closely related QCD approaches can be found in Refs. [8–10]. The fact that all these approaches bear high resemblance points towards a consistent treatment of diffraction within QCD. It seems that the dipole wave functions of the virtual photon which describe the dissociation into a $q\bar{q}$- and a $q\bar{q}g$-state are unambiguously determinable. The

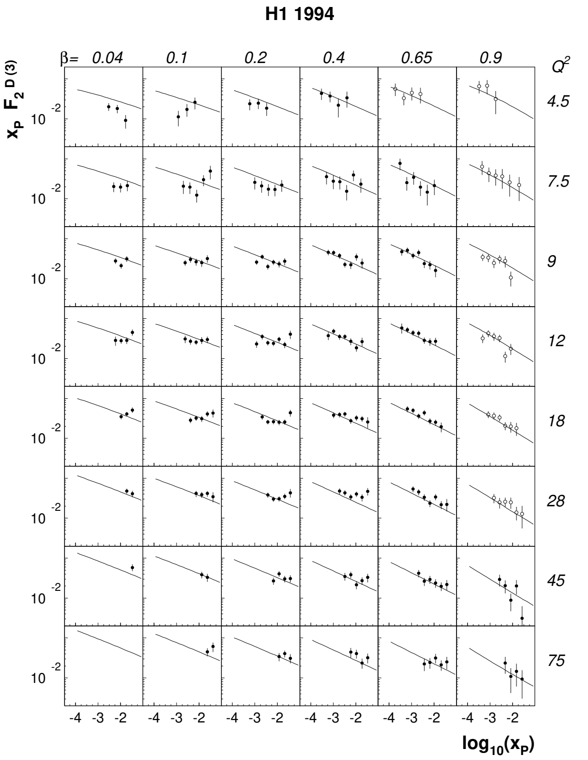

Figure 3. F_2^D as a function of x_{IP} (Q^2 in GeV^2).

differences appear mainly in the treatment of the dipole cross section.

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