Quark-Antiquark Jets in DIS Diffractive Dissociation

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Abstract: We report on investigations concerning the production of large transverse momentum jets in DIS diffractive dissociation. These processes constitute a new class of events that allow for a clean test of perturbative QCD and of the hard (perturbative) pomeron picture. The measurement of the corresponding cross sections might possibly serve to determine the gluon density of the proton.

1 Introduction

The subject of this report is the production of jets with large transverse momenta in diffractive deep inelastic scattering. We will concentrate on events with two jets in the final state, i.e. events with a quark– and an antiquark jet. Due to the high photon virtuality Q^2 and the large transverse momenta of the jets we can use perturbative QCD to describe this process. From a theoretical point of view, diffractive jet production should allow an even better test of pQCD than diffractive vector meson production since it does not involve the uncertainties connected with the wave function of the meson.

After defining the kinematic variables we will present in some detail the main results of our analysis that was performed for the production of light quark jets. A more extensive account of these results can be found in [1, 2]. Related and in part similar work on quark–antiquark jet production has been reported in [3, 4]. We will close this report with a comment on open charm production.

2 Kinematics

We assume the total energy s to be much larger than the photon virtuality $Q^2 = -q^2$ and much larger than the squared invariant mass $M^2 = (q + x_{\mathbb{P}} p)^2$ of the jet pair. We constrain our analysis to events with a rapidity gap and we require the momentum fraction $x_{\mathbb{P}}$ of the

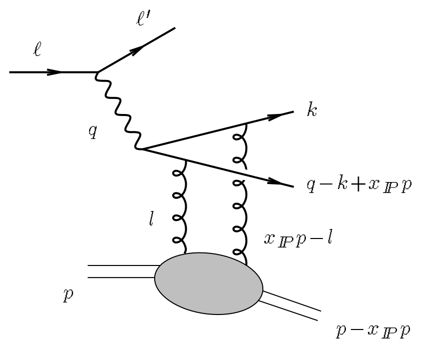

Figure 1: *One of the four diagrams contributing to the hard scattering $\gamma^* + p \to q\bar{q} + p$. The outgoing (anti)quark momenta are held fixed.*

proton's momentum carried by the pomeron to be small, $x_{I\!P} \ll 1$. $x_{I\!P}$ can be expressed as $x_{I\!P} = (M^2 + Q^2)/(W^2 + Q^2)$ where W is the invariant mass of the final state (including the outgoing proton). We keep the transverse momentum $\mathbf{k}$ of the jets fixed with $\mathbf{k}^2 \geq 1\,\mathrm{GeV}^2$. It will be convenient to use also $\beta = x_B/x_{I\!P} = Q^2/(M^2 + Q^2)$. The momentum transfer t is taken to be zero because the cross section strongly peaks at this point. An appropriate t–dependence taken from the elastic proton form factor is put in later by hand.

For large energy s (small $x_{I\!P}$) the amplitude is dominated by perturbative two gluon exchange as indicated in fig. 1, where the kinematic variables are illustrated. In fig. 2 we define the angle ϕ between the electron scattering plane and the direction of the quark jet pointing in the proton hemisphere (jet 1 in the figure). The angle ϕ is defined in the γ^*–$I\!P$ center of mass system and runs from 0 to 2π.

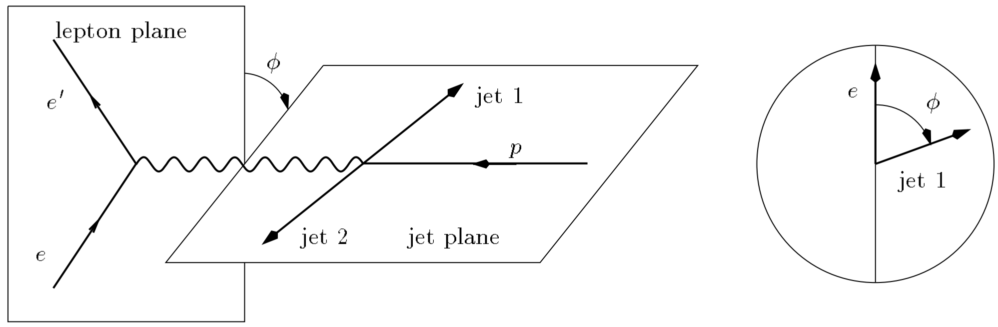

Figure 2: *Definition of the azimuthal angle ϕ in the γ^*–$I\!P$ CMS*

3 Results

In the double logarithmic approximation (DLA), the amplitude of the process can be expressed in terms of the gluon structure function. The cross section is therefore proportional to the square of the gluon structure function. The momentum scale of the latter can be calculated. We thus find as one of our main results

$$d\sigma \sim \left[x_{I\!P} G_p \left(x_{I\!P}, \mathbf{k}^2 \frac{Q^2 + M^2}{M^2} \right) \right]^2 . \tag{1}$$

Performing our numerical estimates, however, we include some of the next–to–leading corrections (proportional to the momentum derivative of the gluon structure function) which we expect to be the numerically most important ones.

From (1) one can deduce that, in our model, Regge factorization à la Ingelman and Schlein [5] is not valid, i. e. the cross section can *not* be written as a $x_{I\!P}$–dependent flux factor times a β– and Q^2–dependent function.

In the following we present only the contribution of transversely polarized photons to the cross section. The corresponding plots for longitudinal polarization can be found in [1, 2]. As a rule of thumb, the longitudinal contribution is smaller by a factor of ten. Only in the region of large β it becomes comparable in size.

Figure 3 shows the $x_{I\!P}$–dependence of the cross section for $Q^2 = 50\,\mathrm{GeV}^2$, $\beta = 2/3$ and $\mathbf{k}^2 > 2\,\mathrm{GeV}^2$. We use GRV next–to–leading order parton distribution functions [6]. Our prediction is compared with the cross section obtained in the soft pomeron model of Landshoff and Nachtmann [7, 8] with nonperturbative two–gluon exchange. Its flat $x_{I\!P}$–dependence, characteristic of the soft pomeron, is quite in contrast to our prediction.

Further, we have included (indicated by *hybrid*) a prediction obtained in the framework of the model by M. Wüsthoff [9]. This model introduces a parametrization of the pomeron based on a fit to small x_B data for the proton structure function F_2. In this fit, the pomeron intercept is made scale dependent in order to account for the transition from soft to hard regions. The $x_{I\!P}$–dependence is not quite as steep as ours but comparable in size.

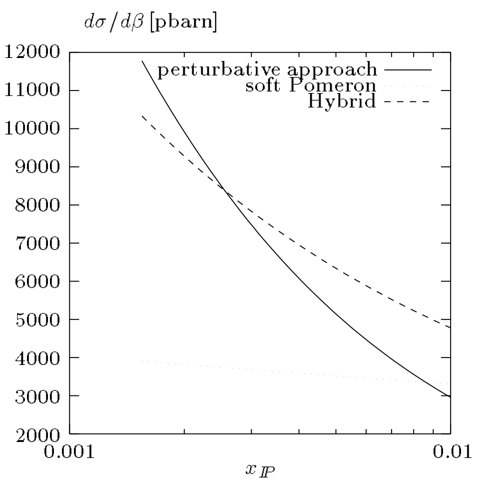

Figure 3: $x_{I\!P}$*–spectrum*

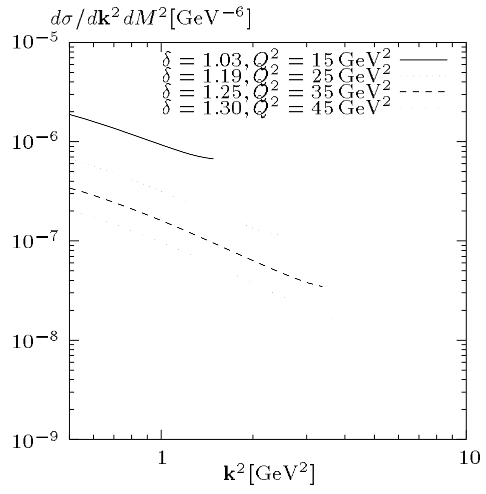

Figure 4: $\mathbf{k}^2$*–spectrum*

Figure 4 presents the $\mathbf{k}^2$–spectrum for different values of Q^2 between $15\,\mathrm{GeV}^2$ and $45\,\mathrm{GeV}^2$. Here we have chosen $x_{I\!P} = 5 \cdot 10^{-3}$ and $\beta = 2/3$. The quantity δ given with each Q^2 value describes the effective slope of the curves as obtained from a numerical fit of a power behaviour $\sim (\mathbf{k}^2)^{-\delta}$. We have taken $\mathbf{k}^2$ down to 0.5 GeV^2. For $\beta = 2/3$ the effective momentum scale of the gluon structure function in (1) equals $\mathbf{k}^2/(1-\beta) = 1.5$ GeV^2.

Integrating the cross section for different minimal values of $\mathbf{k}^2$ we find that the total cross section is dominated by the region of small $\mathbf{k}^2$. If we choose, for instance, $x_{\mathbb{P}} < 0.01$, $10\,\mathrm{GeV}^2 \leq Q^2$ and $50\,\mathrm{GeV} \leq W \leq 220\,\mathrm{GeV}$, the total cross section is

$$\begin{aligned} \sigma_{\mathrm{tot}} &= 20\,\mathrm{pb} \qquad \text{for } \mathbf{k}^2 \geq 5\,\mathrm{GeV}^2 \\ \sigma_{\mathrm{tot}} &= 117\,\mathrm{pb} \qquad \text{for } \mathbf{k}^2 \geq 2\,\mathrm{GeV}^2\,. \end{aligned}$$

In the hybrid model of [9] the corresponding numbers are

$$\begin{aligned} \sigma_{\mathrm{tot}} &= 28\,\mathrm{pb} \qquad \text{for } \mathbf{k}^2 \geq 5\,\mathrm{GeV}^2 \\ \sigma_{\mathrm{tot}} &= 108\,\mathrm{pb} \qquad \text{for } \mathbf{k}^2 \geq 2\,\mathrm{GeV}^2\,. \end{aligned}$$

In accordance with fig. 4 these number show that the cross section is strongly suppressed with $\mathbf{k}^2$. We are thus observing a higher twist effect here. For comparison, we quote the numbers which are obtained in the soft pomeron model [7]. With the same cuts the total cross section is

$$\begin{aligned} \sigma_{\mathrm{tot}} &= 10.5\,\mathrm{pb} \qquad \text{for } \mathbf{k}^2 \geq 5\,\mathrm{GeV}^2 \\ \sigma_{\mathrm{tot}} &= 64\,\mathrm{pb} \qquad \text{for } \mathbf{k}^2 \geq 2\,\mathrm{GeV}^2\,. \end{aligned}$$

The β–spectrum of the cross section is shown in fig. 5 for three different values of Q^2. Here we have chosen $x_{\mathbb{P}} = 5 \cdot 10^{-3}$ and $\mathbf{k}^2 > 2\,\mathrm{GeV}^2$. The curves exhibit maxima which, for not too large Q^2, are located well below $\beta = 0.5$. For small β we expect the production of an extra gluon to become important. First studies in this direction have been reported in [9, 10] and in [11], but a complete calculation has not been done yet.

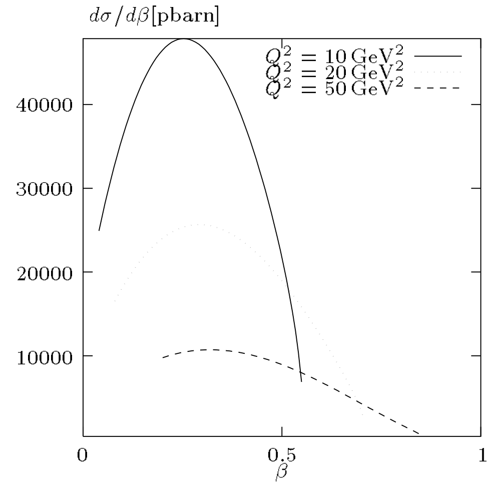

Figure 5: *β–spectrum*

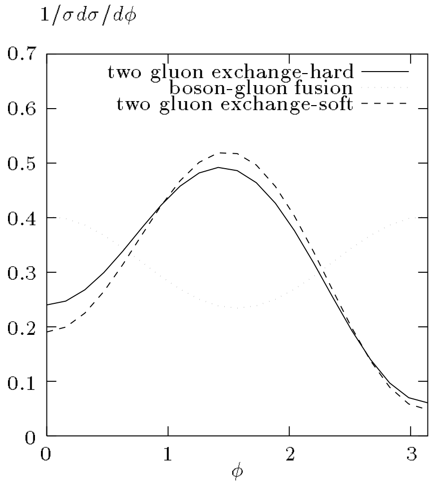

Figure 6: *Azimuthal angular distribution*

The most striking observation made in [2] concerns the azimuthal angular distribution, i. e. the ϕ–distribution of the jets. It turns out that the jets prefer a plane *perpendicular* to the electron scattering plane. This behaviour comes as a surprise because in a boson gluon fusion process the jets appear dominantly *in* the electron scattering plane [12]. The azimuthal angular distribution therefore provides a clear signal for the two gluon nature of the exchanged pomeron. This is supported by the fact that a very similar azimuthal distribution is obtained in the soft pomeron model by M. Diehl [7, 13]. Figure 6 shows the ϕ–dependence of the ep–cross section for the hard pomeron model, the soft pomeron model and for a boson gluon fusion process. We have normalized the cross section to unit integral to concentrate on the angular dependence. Thus a measurement of the azimuthal asymmetry of quark–antiquark jets will clearly improve our understanding of diffractive processes.

Finally, we would like to mention the interesting issue of diffractive open charm production. It is in principle straightforward to extend our calculation to nonvanishing quark masses [14]. A similar computation was done in [15]. A more ambitious calculation has been performed in [16] where also higher order correction have been estimated. The cross section for open charm production is again proportional to the square of the gluon density, the relevant scale of which is now modified by the charm quark mass

$$d\sigma \sim \left[x_{I\!P} G_p \left(x_{I\!P}, (m_c^2 + \mathbf{k}^2) \, \frac{Q^2 + M^2}{M^2} \right) \right]^2 . \tag{2}$$

Integrating the phase space with the same cuts as above the charm contribution to the jet cross section is found to be [14]

$$\begin{aligned} \sigma_{\rm tot} &= 8\,\mathrm{pb} \qquad \text{for } \mathbf{k}^2 \geq 5\,\mathrm{GeV}^2 \\ \sigma_{\rm tot} &= 29\,\mathrm{pb} \qquad \text{for } \mathbf{k}^2 \geq 2\,\mathrm{GeV}^2 . \end{aligned}$$

In the case of open charm production one can even integrate down to $\mathbf{k}^2 = 0$ since the charm quark mass sets the hard scale. One then finds for the $c\bar{c}$ contribution to the total diffractive cross section

$$\sigma_{\rm tot} = 101\,\mathrm{pb} \qquad \text{for } \mathbf{k}^2 \geq 0\,\mathrm{GeV}^2 .$$

In the soft pomeron model the corresponding numbers read [7]

$$\begin{aligned} \sigma_{\rm tot} &= 4.8\,\mathrm{pb} \qquad \text{for } \mathbf{k}^2 \geq 5\,\mathrm{GeV}^2 \\ \sigma_{\rm tot} &= 17\,\mathrm{pb} \qquad \text{for } \mathbf{k}^2 \geq 2\,\mathrm{GeV}^2 \\ \sigma_{\rm tot} &= 59\,\mathrm{pb} \qquad \text{for } \mathbf{k}^2 \geq 0\,\mathrm{GeV}^2 . \end{aligned}$$

In [16], where corrections from gluon radiation are taken into account, the relative charm contribution to the diffractive structure function is estimated to be of the order of 25–30%.

4 Summary and Outlook

We have presented perturbative QCD calculations for the production of quark–antiquark jets in DIS diffractive dissociation. The results are parameter free predictions of the corresponding cross sections, available for light quark jets as well as for open charm production. The cross sections are proportional to the square of the gluon density and the relevant momentum scale of the gluon density has been determined. The azimuthal angular distribution of the light quark jets can serve as a clean signal for the two–gluon nature of the pomeron in hard processes.

The two–jet final state is only the simplest case of jet production in diffractive deep inelastic scattering. The next steps should be the inclusion of order–α_s corrections and the extension to processes with additional gluon jets. Such processes become dominant in the large–M^2 region.

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