A determination of pomeron intercepts at colliders

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A method allowing for a direct comparison of data with theoretical predictions is proposed for forward jet production at HERA and Mueller-Navelet jets at Tevatron. An application to the determination of the *effective* Pomeron intercept in the BFKL-LO parametrization from $d\sigma/dx$ data at HERA leads to a good fit with a significantly higher *effective* intercept, $\alpha_P = 1.43 \pm 0.025(stat.) \pm 0.025(syst.)$, than for proton (total and diffractive) structure functions. It is however less than the value of the pomeron intercept using dijets with large rapidity intervals obtained at Tevatron. We also evaluate the rapidity veto contribution to the higher order BFKL corrections. We suggest to measure the dependence of the dijet cross-sections as a function of the jet transverse energies as a signal for BFKL pomeron at Tevatron.

1. Forward jet cross-section at HERA

The study of forward jets at colliders is considered as the milestone of QCD studies at high energies, since it provides a direct way of testing the perturbative resummations of soft gluon radiation. More precisely, the study of one forward jet (w.r.t. the proton) in an electron-proton collider [1] seems to be a good candidate to test the energy dependence of hard QCD cross-sections. It is similar to the previous proposal of studying two jets separated by a large rapidity interval in hadronic colliders [2], for which only preliminary results are available [3]. This test is also possible in γ^*-γ^* scattering [4] but here the statistics and the energy range are still insufficient to get a reliable determination of the physical parameters for hard QCD cross-sections. Indeed, the proposed (and favored for the moment being) set-up [1] is to consider jets with transverse momentum k_T of the order of the photon virtuality Q allowing to damp the QCD evolution as a function of k_T (DGLAP evolution [5]) in favor of the evolution in energy at fixed k_T (BFKL evolution [6]).

In contrast to full Monte-Carlo studies we want to focus on the jet cross section $d\sigma/dx$ observable itself, by a consistent treatment of the experimental cuts and minimizing the uncertainties for that particular observable. Let us remark that our approach is not intended to provide a substitution to the other methods, since the Monte-Carlo simulations have the great merit of making a set of predictions for various observables. Hence, our method has to be considered as complementary to the others and dedicated to a better determination of the *effective* Pomeron intercept using the $d\sigma/dx$ data. As we shall see, it will fix more precisely this parameter, but it will leave less constrained other interesting parameters, such as the cross-section normalization.

The cross-section for forward jet production at HERA in the dipole model reads [10]:

$$\frac{d^{(4)}\sigma}{dx\,dQ^2\,dx_J\,dk_T^2\,d\Phi} = \frac{\pi N_C\,\alpha^2\alpha_S(k_T^2)}{Q^4 k_T^2}\ f_{eff}(x,\mu_f^2)$$
$$\Sigma e_Q^2 \int_{\frac{1}{2}-i\infty}^{\frac{1}{2}+i\infty}\frac{d\gamma}{2i\pi}\left(\frac{Q^2}{k_T^2}\right)^{\gamma}\exp\{\epsilon(\gamma,0)Y\}\ \times$$
$$\times\quad\left[\frac{h_T(\gamma)+h_L(\gamma)}{\gamma}(1-y)+\frac{h_T(\gamma)}{\gamma}\frac{y^2}{2}\right] \tag{1}$$

where

$$Y = \ln\frac{x_J}{x} \tag{2}$$
$$\epsilon(\gamma,p) = \bar{\alpha}\left[2\psi(1)-\psi(p+1-\gamma)-\psi(p+\gamma)\right] \tag{3}$$
$$f_{eff}(x,\mu_f^2) = G(x,\mu_f^2)+\frac{4}{9}\Sigma(Q_f+\bar{Q}_f) \tag{4}$$
$$\mu_f^2 \sim k_T^2\ , \tag{5}$$

are, respectively, Y the rapidity interval between the photon probe and the jet, $\epsilon(\gamma,p)$ the BFKL kernel eigenvalues, f_{eff} the effective structure function combination, and μ_f the corresponding factorization scale. The main BFKL parameter is $\bar{\alpha}$, which is the (fixed) value of the effective strong coupling constant in LO-BFKL formulae. Note that we gave the BFKL formula not including the azimuthal dependence as we will stick to the azimuth-independent contribution with the dominant $\exp\{\epsilon(\gamma,0)Y\}$ factor.

The so-called "impact factors" h_T, h_L

$$\begin{pmatrix} h_T \\ h_L \end{pmatrix} = \frac{\alpha_S(k_T^2)}{3\pi\gamma}\frac{(\Gamma(1-\gamma)\Gamma(1+\gamma))^3}{\Gamma(2-2\gamma)\Gamma(2+2\gamma)}\frac{1}{1-\frac{2}{3}\gamma}$$
$$\begin{pmatrix} (1+\gamma)(1-\frac{\gamma}{2}) \\ \gamma(1-\gamma) \end{pmatrix}\ , \tag{6}$$

are obtained from the k_T factorization properties [15] of the coupling of the BFKL amplitudes to external hard probes. The same factors can be related to the photon wave functions [16,14] within the equivalent context of the QCD dipole model [17].

Our goal is to compare as directly as possible the theoretical parametrization (1) to the data which are collected in experiments [7,8]. The crucial point is how to take into account the experimentally defined kinematic cuts [7,8].

The main problem to solve is to investigate the effect of these cuts on the determination of the integration variables leading to a prediction for $d\sigma/dx$ from the given theoretical formula for $d^{(4)}\sigma$ as given in formula (1). The effect is expected to appear as bin-per-bin *correction factors* to be multiplied to the theoretical cross-sections for average values of the kinematic variables for a given x-bin before comparing to data (e.g. fitting the cross-sections) [9].

The experimental correction factors have been determined using a toy Monte-Carlo designed as follows. We generate flat distributions in the variables k_T^2/Q^2, $1/Q^2$, x_J, using reference intervals which include the whole of the experimental phase-space (the Φ variable is not used in the generation since all the cross-section measurements are ϕ independent). In practice, we get the correction factors by counting the numbers of events which fulfill the experimental cuts given in Table **I** for each x-bin. The correction factor is obtained by the ratio to the number of events which pass the experimental cuts and the kinematic constraints, and the number of events which fullfil only the kinematic constraints,i.e. the so-called reference bin. The correction factors are given in reference [9].

Weperform a fit to the H1 and ZEUS data with only two free parameters. these are the *effective* strong coupling constant in LO BFKL formulae $\bar{\alpha}$ corresponding to the *effective* Lipatov intercept $\alpha_P = 1 + 4\log 2\bar{\alpha}N_C/\pi$, and the cross-section normalisation. The obtained values of the parameters and the χ^2 of the fit are given in Table **III** for a fit to the H1 and ZEUS data separately, and then to the H1 + ZEUS data together.

fit	$\bar{\alpha}$	α_P
H1	0.17 ± 0.02 ± 0.01	1.44 ± 0.05 ± 0.025
ZEUS	0.20 ± 0.02 ± 0.01	1.52 ± 0.05 ± 0.025
H1+ZEUS	0.16 ± 0.01 ± 0.01	1.43 ± 0.025 ± 0.025
D0	0.24 ± 0.02 ± 0.02	1.65 ± 0.05 ± 0.05
fit	Norm.	$\chi^2(/dof)$
H1	29.4 ± 4.8 ± 5.2	5.7 (/9)
ZEUS	26.4 ± 3.9 ± 4.7	2.0 (/2)
H1+ZEUS	30.7 ± 2.9 ± 3.5	12.0 (/13)

Table I- Fit results

The χ^2 of the fits have been calculated using statistical error only and are very satisfactory (about 0.6 *per point* for H1 data, and 1. *per point* for ZEUS data). We give both statistical and systematic errors for the fit parameters. The values of the Lipatov intercept are close to one another and compatible within errors for the H1 and ZEUS sets of data, and indicate a preferable medium value ($\alpha_P = 1.4 - 1.5$). We also notice that the ZEUS data have the tendency to favour a higher exponent, but the number of data points used in the fit is much smaller than for H1, and the H1 data are also at lower x. The normalisation is also compatible between ZEUS and H1. The fit results are shown in Figure 1 and compared with the H1 and ZEUS measurements.

2. Comparison with Tevatron results

The final result of our new determination of the effective pomeron intercept is $\alpha_P = 1.43 \pm 0.025$ (stat.) ± 0.025 (syst.). Our method allows a direct comparison of the intercept values with those obtained in other experimental processes, i.e. $\gamma^*\gamma^*$ cross-sections at LEP [4], jet-jet cross-sections at Tevatron at large rapidity intervals [3], F_2 and F_2^D proton structure function measurements [12–14].

Let us compare our results with the effective intercept we obtain from recent preliminary dijet data obtained by the D0 Collaboration at Tevatron [3]. The measurement consists in the ratio $R = \sigma_{1800}/\sigma_{630}$ where σ is the dijet cross-section at large rapidity interval $Y \sim \Delta\eta$ for two center-of-mass energies (630 and 1800 GeV), $\Delta\eta_{1800} = 4.6$, $\Delta\eta_{630} = 2.4$. The experimental measurement is $R = 2.9 \pm 0.3$ (stat.) ± 0.3 (syst.). Using the Mueller-Navelet formula [2], this measurement allows us to get a value of the effective intercept for this process

$$R = \frac{\int_{\frac{1}{2}-i\infty}^{\frac{1}{2}+i\infty} \frac{d\gamma}{2i\pi\gamma(1-\gamma)} e^{\epsilon(\gamma,0)\Delta\eta_{1800}}}{\int_{\frac{1}{2}-i\infty}^{\frac{1}{2}+i\infty} \frac{d\gamma}{2i\pi\gamma(1-\gamma)} e^{\epsilon(\gamma,0)\Delta\eta_{630}}}. \tag{7}$$

We get α_P=1.65 ± 0.05 (stat.) ± 0.05 (syst.), in agreement with the value obtained by D0 using a saddle-point approximation [3] (see Table 1). This intercept is higher than the one obtained in the forward jet study.

Formula (7) is obtained after integration over the jet tranverse energies at 630 and 1800 GeV, E_{T_1}, E_{T_2}. We note that the non integrated formula

$$R(E_{T_1}/E_{T_2}) = \frac{\int_{\frac{1}{2}-i\infty}^{\frac{1}{2}+i\infty} \frac{d\gamma}{2i\pi} \left(\frac{E_{T_1}}{E_{T_2}}\right)^{2\gamma} e^{\epsilon(\gamma,0)\Delta\eta_{1800}}}{\int_{\frac{1}{2}-i\infty}^{\frac{1}{2}+i\infty} \frac{d\gamma}{2i\pi} \left(\frac{E_{T_1}}{E_{T_2}}\right)^{2\gamma} e^{\epsilon(\gamma,0)\Delta\eta_{630}}} \tag{8}$$

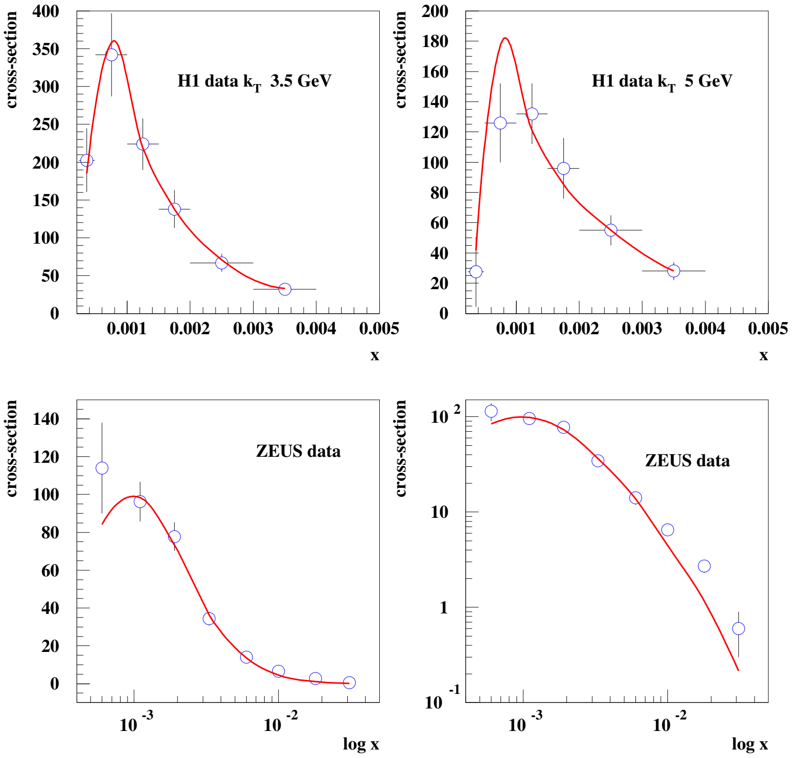

Figure 1. The H1 data ($k_T > 3.5$ GeV, $k_T > 5$ GeV), and the ZEUS data are compared with the result of the fit. ZEUS data are also displayed in logarithmic scales in vertical coordinates to show the discrepancy at high x values.

shows a sizeable dependence on E_{T_1}/E_{T_2}, which could be confronted with experiment. Let us show both the integrated and E_{T_1}/E_{T_2} dependent cross-sections in Figure 2.

The question arises to interpret the different values of the effective intercept. It could reasonably come from the differences in higher order QCD corrections for the BFKL kernel and/or in the impact factors depending on the initial probes (γ^* vs. jets). In order to evaluate the approximate size of the higher order BFKL corrections, we will use their description in terms of rapidity veto effects [18]. In formula (1), we replace $\exp(\epsilon(\gamma,0)Y)$ by

$$\Sigma_{n=0}^{\infty}\ \theta(Y-(n+1)b)\ \frac{[\epsilon(\gamma,0)\ (Y-(n+1)b)]^n}{\Gamma(n+1)}\ . \qquad (9)$$

The Heaviside function θ ensures that a BFKL ladder of n gluons occupies $(n+1)b$ rapidity interval where b parametrises the strength of NLO BFKL corrections. The value of the leading order intercept is fixed to $\alpha_p = 1.75(\alpha_S(Q^2=10)=0.28)$, where $Q^2 = 10$ GeV^2 is inside the average range of Q^2 in the forward jet measurement. The fitted value of the b parameter obtained using the forward jet data is found to be 1.28 ± 0.08 (stat.) $\pm$ 0.02 (syst.). Imposing the same value of α_P with Tevatron data gives b=0.21 $\pm$ 0.11 (stat.) $\pm$ 0.11 (syst.). Note that the theoretical value of b for the NLO BFKL kernel is expected to be of the order 2.4, which is also compatible with the result obtained for the $\gamma^*\gamma^*$ cross-section. A contribution from the NLO impact factors is not yet known, and could perhaps explain the different values of b.

3. Conclusion

To summarize our results, using a new method to disantangle the effects of the kinematic cuts from the genuine dynamical values we find that the effective pomeron intercept of the forward jet cross-sections at HERA is $\alpha_P = 1.43 \pm 0.025$ (stat.) ± 0.025 (syst.). It is much higher than the soft pomeron intercept, and, among those determined in hard processes, it is intermediate between $\gamma^*\gamma^*$ interactions at LEP and dijet productions with large rapidity intervals at Tevatron, where we get α_P=1.65 $\pm$ 0.05 (stat.) $\pm$ 0.05 (syst.).

Looking for an interpretation of our results in terms of higher order BFKL corrections expressed by rapidity gap vetoes b between emitted gluons, we find a value of b =1.3 at HERA, and 0.21 at Tevatron. The HERA value is sizeable but less than the theoretically predicted [11] value for the NLO BFKL kernel (b =2.4). The Tevatron value is compatible with zero. The observed dependence in the process deserves further more precise studies [19].

We suggest to measure the dependence of the dijet cross-sections as a function of the jet transverse energies as a signal for BFKL pomeron at Tevatron run II. The Mueller Navelet jet study would also benefit from a lower energy run at the end of Run II to allow a normalisation independence of the intercept determination and BFKL tests.

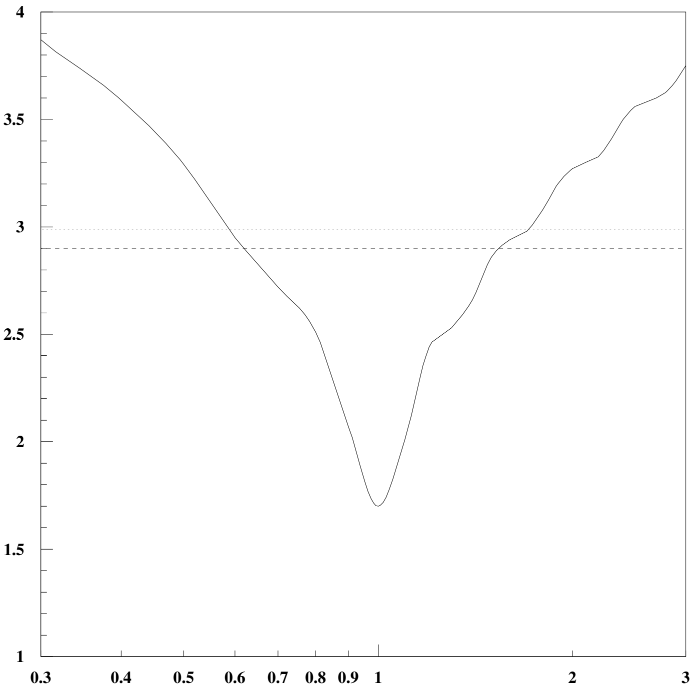

Figure 2. E_{T_1}/E_{T_2} dependence of the dijet cross-section ratio. E_{T_1}/E_{T_2} is given in the horizontal axis, and R in vertical axis. In full line is given the non integrated $R(E_{T_1}/E_{T_2})$ (see formula (8)), in dotted line, the integrated R (formula (7) and in dashed line, the saddle point approximation of R [2], for the fitted value of α_P (see table 1).

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