Angular decorrelations in Mueller-Navelet jets and DIS

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Abstract
We discuss the azimuthal angle decorrelation of Mueller–Navelet jets at hadron colliders and forward jets in Deep Inelastic Scattering within the BFKL framework with a NLO kernel. We stress the need of collinear improvements to obtain good perturbative convergence. We provide estimates of these decorrelations for large rapidity differences at the Tevatron, LHC and HERA.

1 BFKL cross sections

In this contribution we discuss the results recently obtained in [1] where azimuthal angle correlations in Mueller–Navelet jets [2] and forward jets at HERA using the Balitsky–Fadin–Kuraev–Lipatov (BFKL) equation in the next–to–leading (NLO) approximation [3] were investigated (related works can be found in [4]). In this section we focus on normalized differential cross sections for Mueller–Navelet jets, which are quite insensitive to parton distribution functions. This justifies the use of partonic cross sections which can be written as

$$\frac{d\hat{\sigma}}{d^2\vec{q}_1 d^2\vec{q}_2} = \frac{\pi^2 \bar{\alpha}_s^2}{2}\frac{1}{\vec{q}_1^{\,2}\vec{q}_2^{\,2}}\int \frac{d\omega}{2\pi i} e^{\omega Y} f_\omega(\vec{q}_1,\vec{q}_2), \quad (1)$$

where $\bar{\alpha}_s = \alpha_s N_c/\pi$, $\vec{q}_{1,2}$ are the transverse momenta of the tagged jets, and Y their relative rapidity. The Green's function carries the bulk of the Y dependence and is the solution to the NLO BFKL equation,

$$\left(\omega - \bar{\alpha}_s \hat{K}_0 - \bar{\alpha}_s^2 \hat{K}_1\right)\hat{f}_\omega = \hat{1}, \quad (2)$$

which acts on the basis including the azimuthal angle, *i.e.*,

$$\langle\vec{q}|\nu,n\rangle = \frac{1}{\pi\sqrt{2}}\left(q^2\right)^{i\nu-\frac{1}{2}} e^{in\theta}. \quad (3)$$

As Y increases the azimuthal dependence is mainly driven by the kernel and therefore we use LO jet vertices which are simpler than the NLO ones [5]. The differential cross section in the azimuthal angle $\phi = \theta_1 - \theta_2 - \pi$, with θ_i being the angles of the two tagged jets, reads

$$\frac{d\hat{\sigma}(\alpha_s, Y, p_{1,2}^2)}{d\phi} = \frac{\pi^3\bar{\alpha}_s^2}{4\sqrt{p_1^2 p_2^2}}\sum_{n=-\infty}^{\infty} e^{in\phi}\, \mathcal{C}_n(Y), \quad (4)$$

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where

$$C_n(Y) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\frac{d\nu}{\frac{1}{4}+\nu^2}\left(\frac{p_1^2}{p_2^2}\right)^{i\nu} e^{\bar\alpha_s(p_1p_2)\chi\left(|n|,\frac{1}{2}+i\nu,\bar\alpha_s(p_1p_2)\right)Y}; \tag{5}$$

and the NLO kernel can be written as

$$\chi(n,\gamma,\bar\alpha_s) = \bar\alpha_s\chi_0(n,\gamma)+\bar\alpha_s^2\left(\chi_1(n,\gamma)-\frac{\beta_0}{8N_c}\frac{\chi_0(n,\gamma)}{\gamma(1-\gamma)}\right). \tag{6}$$

The eigenvalue of the LO kernel is $\chi_0(n,\gamma)=2\psi(1)-\psi\left(\gamma+\frac{n}{2}\right)-\psi\left(1-\gamma+\frac{n}{2}\right)$, with ψ the logarithmic derivative of the Euler function. The action of $\hat{K}_1$, in $\overline{MS}$ scheme, can be found in [6]. The full cross section only depends on the $n=0$ component,

$$\hat\sigma = \frac{\pi^3\bar\alpha_s^2}{2\,p_1^2p_2^2}C_0(Y). \tag{7}$$

The average of the cosine of the azimuthal angle times an integer projects out the contribution from each of these angular components:

$$\frac{\langle\cos(m\phi)\rangle}{\langle\cos(n\phi)\rangle} = \frac{C_m(Y)}{C_n(Y)} \tag{8}$$

The normalized differential cross section is

$$\frac{1}{\hat\sigma}\frac{d\hat\sigma}{d\phi} = \frac{1}{2\pi}\sum_{n=-\infty}^{\infty}e^{in\phi}\frac{C_n(Y)}{C_0(Y)} = \frac{1}{2\pi}\left\{1+2\sum_{n=1}^{\infty}\cos(n\phi)\langle\cos(n\phi)\rangle\right\}. \tag{9}$$

The BFKL resummation is not stable at NLO for zero conformal spin. A manifestation of this lack of convergence is what we found in the gluon–bremsstrahlung scheme where our NLO distributions have an unphysical behavior whenever the $n=0$ conformal spin appears in the calculation. To solve this problem we imposed compatibility with renormalization group evolution in the DIS limit following [7] for all conformal spins. The new kernel with improvements to all orders reads [1]

$$\begin{aligned}\omega = {}& \bar\alpha_s(1+\mathcal{A}_n\bar\alpha_s)\left(2\psi(1)-\psi\left(\gamma+\frac{|n|}{2}+\frac{\omega}{2}+\mathcal{B}_n\bar\alpha_s\right)\right.\\ & \left.-\psi\left(1-\gamma+\frac{|n|}{2}+\frac{\omega}{2}+\mathcal{B}_n\bar\alpha_s\right)\right)+\bar\alpha_s^2\left\{\chi_1(|n|,\gamma)-\frac{\beta_0}{8N_c}\frac{\chi_0(n,\gamma)}{\gamma(1-\gamma)}\right.\\ & \left.-\mathcal{A}_n\chi_0(|n|,\gamma)+\left(\psi'\left(\gamma+\frac{|n|}{2}\right)+\psi'\left(1-\gamma+\frac{|n|}{2}\right)\right)\left(\frac{\chi_0(|n|,\gamma)}{2}+\mathcal{B}_n\right)\right\};\end{aligned} \tag{10}$$

where $\mathcal{A}_n$ and $\mathcal{B}_n$ are collinear coefficients [1]. After this collinear resummation our observables have a good physical behavior and are independent of the renormalization scheme. It is very important to remark that the asymptotic behavior of the BFKL resummation is convergent for non zero conformal spins. In this sense the ideal distributions to investigate experimentally are those of the form $\langle\cos(m\phi)\rangle/\langle\cos(n\phi)\rangle$ with $m,n\neq 0$, we will see that in this case the difference between the LO and higher orders results is small.

2 Phenomenology for Mueller–Navelet jets

The DØ [8] collaboration analyzed data for Mueller–Navelet jets at $\sqrt{s} = 630$ and 1800 GeV. For the angular correlation LO BFKL predictions were first obtained in [9] and failed to describe the data estimating too much decorrelation. An exact fixed NLO analysis using JETRAD underestimated the decorrelation, while HERWIG was in agreement with the data.

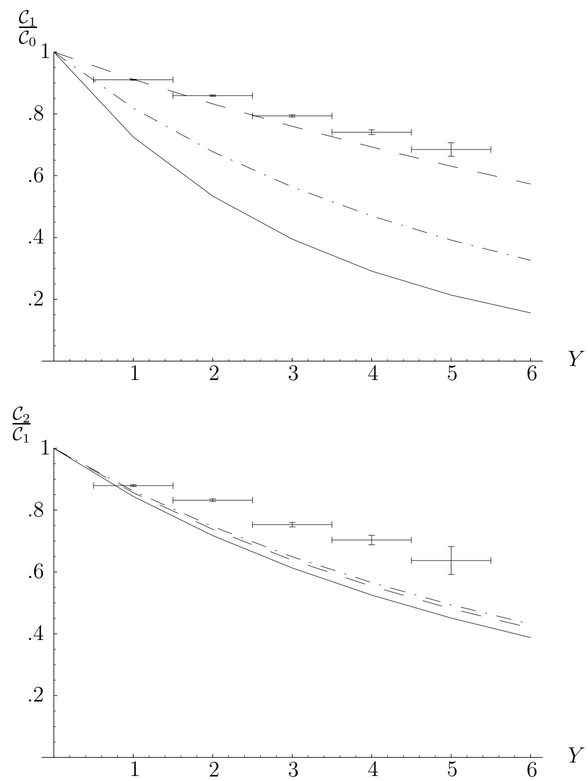

Fig. 1: Top: $\langle \cos\phi \rangle = C_1/C_0$ and Bottom: $\frac{\langle \cos 2\phi \rangle}{\langle \cos\phi \rangle} = \frac{C_2}{C_1}$, at a $p\bar{p}$ collider with $\sqrt{s}$ = 1.8 TeV for BFKL at LO (solid) and NLO (dashed). The results from the resummation presented in the text are shown as well (dash–dotted).

In Fig. 1 we compare the Tevatron data for $\langle \cos\phi \rangle = C_1/C_0$ with our LO, NLO and resummed predictions. For Tevatron's cuts, where the transverse momentum for one jet is 20 GeV and for the other 50 GeV, the NLO calculation is instable under renormalization scheme changes. The convergence of our observables is poor whenever the coefficient associated to zero conformal spin, C_0, is involved. If we eliminate this coefficient by calculating the ratios defined in Eq. (8) then the predictions are very stable, see Fig. 1.

The full angular dependence studied at the Tevatron by the DØ collaboration was published in [8]. In Fig. 2 we compare this measurement with the predictions obtained in our approach. For the differential cross section we also make predictions for the LHC at larger Y in Fig. 3. We estimated several uncertainties in our approach which are represented by gray bands.

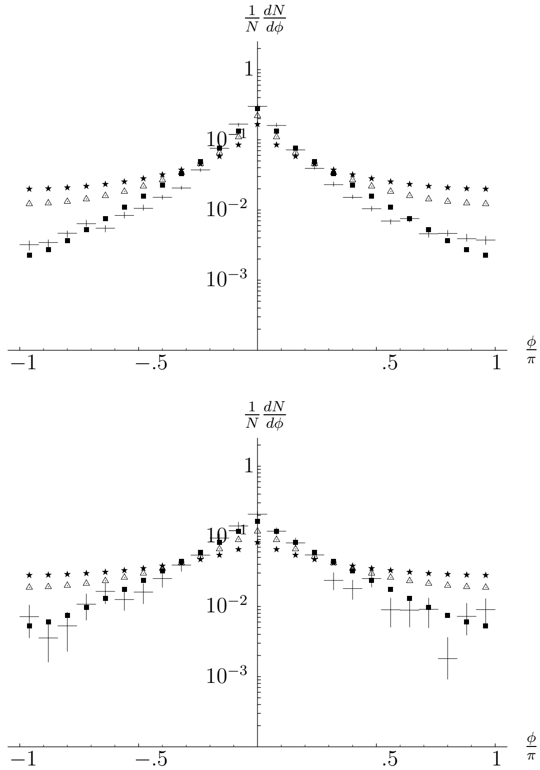

Fig. 2: $\frac{1}{N}\frac{dN}{d}$ in a $p\bar{p}$ collider at $\sqrt{s}$=1.8 TeV using a LO (stars), NLO (squares) and resummed (triangles) BFKL kernel. Plots are shown for Y = 3 (top) and Y = 5 (bottom).

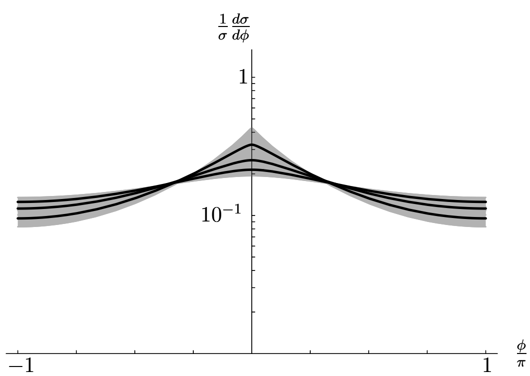

Fig. 3: $\frac{1}{}\frac{d}{d}$ in our resummation scheme for rapidities Y = 7, 9, 11 from top to bottom. The gray band reflects the uncertainty in s_0 and in the renormalization scale .

3 Forward jets at HERA

In this section we apply the BFKL formalism to predict the decorrelation in azimuthal angle between the electron and a forward jet associated to the proton in Deep Inelastic Scattering (DIS). When the separation in rapidity space between the scattered electron and the forward jet is large and the transverse momentum of the jet is similar to the virtuality of the photon resolving the hadron, then the dominant terms are of BFKL type. This process is similar to that of Mueller–Navelet jets, the only difference being the substitution of one jet vertex by the electron vertex describing the coupling of the electron to the BFKL gluon Green's function via a quark–antiquark pair. Azimuthal angles in forward jets were studied at LO in [10]. We improved their calculation by considering the NLO BFKL kernel.

In the production of a forward jet in DIS it is necessary to extract a parton with a large longitudinal momentum fraction x_{FJ} from the proton. When the jet is characterized by a hard scale it is possible to use conventional collinear factorization to describe the process and the jet production rate may be written as

$$\sigma(s) = \int dx_{FJ}\, f_{\rm eff}(x_{FJ}, \mu_F^2)\, \hat{\sigma}(\hat{s}), \tag{11}$$

with $\hat{\sigma}(\hat{s})$ denoting the partonic cross section, and the effective parton density [11] being

$$f_{\rm eff}(x, \mu_F^2) = G(x, \mu_F^2) + \frac{4}{9}\sum_f \left[Q_f(x, \mu_F^2) + \bar{Q}_f(x, \mu_F^2) \right], \tag{12}$$

where the sum runs over all quark flavors, and μ_F stands for the factorization scale.

The final expression for the cross section at hadronic level is of the form

$$\frac{d\sigma}{dY\, d\phi} = C_0(Y) + C_2(Y)\cos 2\phi, \tag{13}$$

with

$$C_n(Y) = \frac{\alpha^2 \alpha_s^2}{2} \int_{\rm cuts} dx_{FJ}\, dQ^2\, dy\, f_{\rm eff}(x_{FJ}, Q^2) B^{(n)}(y, Q^2, Y)\, \delta\!\left(x_{FJ} - \frac{Q^2 e^Y}{ys} \right), \tag{14}$$

where the index in the integral sign refers to the cuts

$$20\,{\rm GeV}^2 < Q^2 < 100\,{\rm GeV}^2,\quad 0.05 < y < 0.7,\quad 5\times 10^{-3} > x_{Bj} > 4\times 10^{-4}. \tag{15}$$

The integration over the longitudinal momentum fraction x_{FJ} of the forward jet involves a delta function fixing the rapidity $Y = \ln x_{FJ}/x_{Bj}$ and $B^{(n)}$ is a complicated function which can be found in [1].

Since the structure of the electron vertex singles out the components with conformal spin 0 and 2, the number of observables related to the azimuthal angle dependence is limited when compared to the Mueller–Navelet case. The most relevant observable is the dependence of the average $< \cos 2\phi > = C_2/C_0$ with the rapidity difference between the forward jet and outgoing lepton. It is natural to expect that the forward jet will be more decorrelated from the leptonic system as the rapidity difference is larger since the phase space for further gluon emission opens up.

This is indeed what we observe in our numerical results shown in Fig. 4. We find similar results to the Mueller–Navelet jets case where the most reliable calculation is that with a collinearly–improved kernel. The main effect of the higher order corrections is to increase the azimuthal angle correlation for a given rapidity difference, while keeping the decrease of the correlation as Y grows.

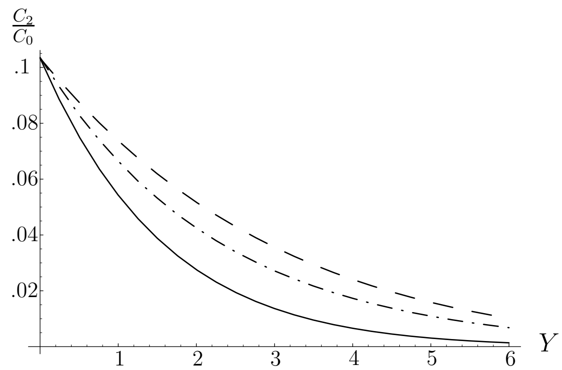

Fig. 4: $< \cos 2 \ >$ at the ep collider HERA at leading (solid), next to leading order (dashed), and for resummed kernel (dash-dotted).

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