Isolated jet production with multi-Regge kinematics at Tevatron and LHC

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2012-03/26

We study isolated jet hadroproduction with multi-Regge kinematics invoking the hypothesis of parton Reggeization in t-channel exchanges at high energy. In this approach, the leading contribution is due to the fusion of two Reggeized gluons into a Yang-Mills gluon. Adopting the Kimber-Martin-Ryskin and Blümlein prescriptions to derive unintegrated gluon distribution function of the proton from their collinear counterparts, we evaluate cross section distributions in transverse momentum (p_T) and rapidity (y). Without adjusting any free parameters, we find good agreement with measurements by the CDF and D0 Collaborations at the Tevatron and by the ATLAS Collaboration at the LHC in a wide region of p_T, especially using Blümlein's unintegrated gluon distribution function.

1 Introduction

The study of jet inclusive production at high-energy colliders, such as the Fermilab Tevatron and the CERN LHC, is of great interest because it allows us to test perturbative quantum chromodynamics (QCD) and to extract information on the parton distribution functions (PDFs) of the proton.

The total collision energies, $\sqrt{s} = 1.8$ TeV and 1.96 TeV in Tevatron runs I and II, respectively, and $\sqrt{s} = 7$ TeV or 14 TeV at the LHC, sufficiently exceed the characteristic scale μ of the relevant hard processes, which is of order of p_T, *i.e.* we have $\Lambda_{\rm QCD} \ll \mu \ll \sqrt{s}$. In this high-energy regime, the contribution of partonic subprocesses involving t-channel parton exchanges to the production cross section can become dominant. Then the transverse momenta of the incoming partons and their off-shell properties can no longer be neglected, and we deal with "Reggeized" t-channel partons. If the particles produced in the collision are strongly separated in rapidity, they obey multi-Regge kinematics (MRK). In the case of isolated jet inclusive production, this means the following: A single jet is produced in the central region of rapidity, while other particles are produced with large modula of rapidities.

Previously, in Ref. [1], single jet inclusive production was studied in the Regge limit of QCD using the Balitsky-Fadin-Kuraev-Lipatov (BFKL) framework [2], and it was shown that the discrepancy between data and theory in the region of small values of $x_T = 2p_T/\sqrt{S}$ may be accounted for by the BFKL Pomeron. However, Pomeron exchange should be a dominant

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mechanism only at asymptotically large energies. In fact, in the energy range of the Tevatron and the LHC, the mechanism of Reggeized gluon and quark exchanges should be more adequate [3].

The parton Reggeization framework [4] is particularly appropriate for this kind of high-energy phenomenology. It is based on an effective quantum field theory implemented with the non-Abelian gauge-invariant action including fields of Reggeized gluons [5] and Reggeized quarks [6].

In this paper, we assume the MRK production mechanism to be the dominant one at small x_T values. We compare our results with experimental data taken by the CDF [7] and D0 [8] Collaborations at the Tevatron with $\sqrt{s} = 1.8$ TeV and 1.96 TeV and by the ATLAS Collaboration [9] at the LHC with $\sqrt{s} = 7$ TeV. We also present predictions for the p_T and y distributions of isolated jet inclusive production at the LHC with $\sqrt{s} = 14$ TeV.

2 Gluon-gluon fusion amplitude with multi-Regge kinematics

We examine isolated jet inclusive production in proton-antiproton collisions at the Tevatron and in proton-proton collisions at the LHC. To leading order (LO) in the parton Reggeization framework, the relevant hard-scattering process is $\mathcal{R}+\mathcal{R} \to g$, where $\mathcal{R}$ is a Reggeized gluon and g is a Yang-Mills gluon. Working in the center-of-mass (c.m.) frame, we write the four-momenta of the incoming hadrons as $P_{1,2}^{\mu} = (\sqrt{s}/2)(1, 0, 0, \pm1)$ and those of the Reggeized partons as $q_i^{\mu} = x_i P_i^{\mu} + q_{iT}^{\mu}$ $(i = 1, 2)$, where x_i are the longitudinal momentum fractions and $q_{iT}^{\mu} = (0, \mathbf{q}_{iT}, 0)$, with $\mathbf{q}_{iT}$ being transverse two-momenta, and we define $t_i = -q_{iT}^2 = \mathbf{q}_{iT}^2$. The gluon produced in the $2 \to 1$ partonic subprocess has four-momentum $p^{\mu} = q_1^{\mu} + q_2^{\mu} = (p^0, \mathbf{p}_T, p^3)$, with $\mathbf{p}_T^2 = t_1 + t_2 + 2\sqrt{t_1 t_2}\cos\phi_{12}$, where ϕ_{12} is the azimuthal angle enclosed between $\mathbf{q}_{1T}$ and $\mathbf{q}_{2T}$. Introducing the light-cone vectors $n_{\mu}^{\pm} = (1, 0, 0, \pm1)$, we define $k^{\pm} = k \cdot n^{\pm}$ for any four-vector k^{μ}.

The Fadin-Kuraev-Lipatov effective $\mathcal{R}\mathcal{R}g$ vertex reads [2, 10]:

$$C_{\mathcal{R}\mathcal{R}}^{g,\mu}(q_1, q_2) = -g_s f^{abc} \frac{q_1^+ q_2^-}{2\sqrt{t_1 t_2}} \left[(q_1 - q_2)^{\mu} + \frac{(n^+)^{\mu}}{q_1^+} \left(q_2^2 + q_1^+ q_2^- \right) - \frac{(n^-)^{\mu}}{q_2^-} \left(q_1^2 + q_1^+ q_2^- \right) \right], \quad (1)$$

where $g_s = \sqrt{4\pi\alpha_s}$, α_s is the strong-coupling constant, a and b are the color indices of the Reggeized gluons with incoming four-momenta q_1 and q_2, and f^{abc} are the structure constants of the color group SU(3). The squared amplitude of the partonic subprocess $\mathcal{R} + \mathcal{R} \to g$ is straightforwardly found from Eq. (1) to be

$$\overline{|\mathcal{M}(\mathcal{R}\mathcal{R} \to g)|^2} = \frac{3}{2} \pi \alpha_s \mathbf{p}_T^2. \quad (2)$$

3 Cross sections in high-energy factorization

Exploiting the hypothesis of high-energy factorization, we may write the hadronic cross sections $d\sigma$ as convolutions of partonic cross sections $d\hat{\sigma}$ with unintegrated PDFs Φ_a^h of Reggeized partons a in the hadrons h, as

$$d\sigma\left(p\overline{p}\to jX\right)=\int\frac{dx_1}{x_1}\int\frac{d^2q_{1T}}{\pi}\int\frac{dx_2}{x_2}\int\frac{d^2q_{2T}}{\pi}\Phi_g^p(x_1,t_1,\mu^2)\Phi_g^{\overline{p}}(x_2,t_2,\mu^2)d\hat{\sigma}\left(\mathcal{R}\mathcal{R}\to g\right), \tag{3}$$

and similarly for pp collisions. We also present here a compact formula for the double differential distribution in $p_T=|\mathbf{p_T}|$ and y, which follows from Eq. (3) and reads:

$$\frac{d\sigma}{dp_T\,dy}\left(p\overline{p}\to jX\right)=\frac{1}{p_T^3}\int d\phi_1\int dt_1\Phi_g^p(x_1,t_1,\mu^2)\Phi_g^{\overline{p}}(x_2,t_2,\mu^2)\overline{\left|\mathcal{M}\left(\mathcal{R}\mathcal{R}\to g\right)\right|^2}, \tag{4}$$

where ϕ_1 is the azimuthal angle enclosed between $\mathbf{q}_{1T}$ and $\mathbf{p}_T$,

$$x_{1,2}=\frac{p_T\exp(\pm y)}{\sqrt{s}},\qquad t_2=t_1+p_T^2-2p_T\sqrt{t_1}\cos\phi_1. \tag{5}$$

Since we work at LO, the produced jet has zero invariant mass m, so that transverse energy E_T and transverse momentum p_T coincide and so do rapidity y and pseudorapidity η.

In our numerical analysis, we adopt the Kimber-Martin-Ryskin (KMR) [11] and Blümlein (B) [12] prescriptions to obtain the unintegrated gluon PDF of the proton from the conventional integrated one. As input for this procedure, we use the LO set of the Martin-Roberts-Stirling-Thorne (MRST) [13] proton PDFs as our default.

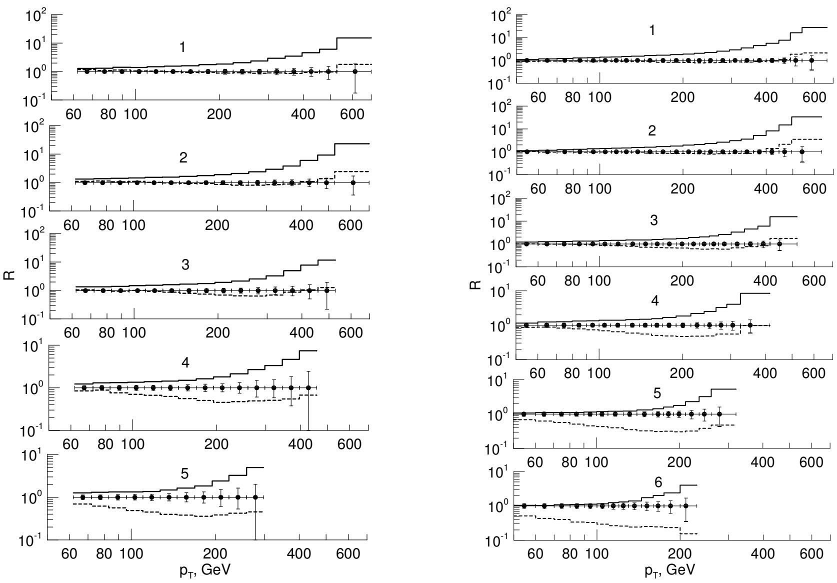

Figure 1: Ratio ($Theory/Experiment$) for p_T distributions of single jet inclusive hadroproduction in $p\overline{p}$ collisions at $\sqrt{s}=1.96$ TeV evaluated at LO in the MRK approach using the KMR (solid histograms) and B (dashed histograms) unintegrated PDFs normalized to the CDF [7] (left panel) and D0 [8] (right panel) data.

4 Results

Recently, the CDF [7] (D0 [8]) Collaboration presented new data from Tevatron run II, which correspond to an integrated luminosity of 1.13 fb^{-1} (0.70 fb^{-1}) and cover the kinematic range 62 GeV $< p_T <$ 700 GeV (50 GeV $< p_T <$ 600 GeV) and $|y| < 2.1$ ($|y| < 2.4$). The CDF and D0 data are compared with our MRK predictions in Fig. 1 for the following rapidity intervals:

1. $|y| < 0.1$ (CDF) and $|y| < 0.4$ (D0)
2. $0.1 < |y| < 0.7$ (CDF) and $0.4 < |y| < 0.8$ (D0)
3. $0.7 < |y| < 1.1$ (CDF) and $0.8 < |y| < 1.2$ (D0)
4. $1.1 < |y| < 1.6$ (CDF) and $1.2 < |y| < 1.6$ (D0)
5. $1.6 < |y| < 2.1$ (CDF) and $1.6 < |y| < 2.0$ (D0)
6. $2.0 < |y| < 2.4$ (D0)

In case of the KMR unintegrated gluon PDF, we find agreement with the data for $p_T <$ 100 GeV in all rapidity intervals, which corresponds to $x_T < 0.1$, while our predictions overshoot the data for higher values of p_T. In case of the B unintegrated gluon PDF, we find good agreement for $p_T <$ 500 GeV, but only at small absolute values of rapidity, for $|y| < 1.1$.

This may be understood by observing that the average values of the scaling variables x_1 and x_2 in Eq. (4) are of order x_T, and the MRK picture ceases to be valid for $x_i \geq 0.1$. For $x_T \geq 0.1$, one needs to resort to the collinear parton model, which starts with $2 \to 2$ partonic subprocesses at LO.

The solid and dashed curves in Fig. 1 clearly demonstrate the main theoretical uncertainties in the present study. The theoretical uncertainties due to the freedom in the choices of the renormalization and factorization scales are about 10–20 % and are not shown.

Moving on from the Tevatron to the LHC, which is currently running at $\sqrt{S} = 7$ TeV, being about 3.5 times larger than at the Tevatron, one expects the p_T range of validity of the MRK picture to be extended by the same factor, to $p_T <$ 350 GeV. This expectation is nicely confirmed in Fig. 2, where a recent measurement by the ATLAS Collaboration [9], which is based on an integrated luminosity of 17 nb^{-1} and covers the kinematic range 60 GeV $< p_T <$ 600 GeV and $|y| < 2.8$, is compared with our MRK predictions for the p_T and y distributions. In fact, useful agreement is found even up to the largest p_T values accessed by this measurement. The difference between the theoretical predictions based on the MRK and B unintegrated gluon PDFs are insignificant, as the average values of the scaling variables x_1 and x_2 are smaller at the LHC.

Note that, in Ref. [9], jets are identified using the anti-k_t jet-clustering algorithm with two different values of the jet-size parameter $R = \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$. The ATLAS data shown in Fig. 2 refer to $R = 0.6$. The agreement is somewhat worse for $R = 0.4$. Our LO prediction does not yet depend on R.

In Fig. 3, we repeat the MRK analyses of Figs. 1 and 2 for the LHC design c.m. energy $\sqrt{s} = 14$ TeV, where we expect the p_T range of validity to be roughly $p_T <$ 700 GeV.

5 Conclusions

The Tevatron and, even more so, the LHC are currently probing particle physics at terascale c.m. energies $\sqrt{s}$, so that the hierarchy $\Lambda_{\mathrm{QCD}} \ll \mu \ll \sqrt{s}$, which defines the MRK regime, is satisfied for a wealth of QCD processes of typical energy scale μ.

In this report, we studied a QCD process of particular interest, namely single jet inclusive hadroproduction, at LO in the MRK approach, in which it is mediated by a $2 \to 1$ partonic subprocess initiated by Reggeized gluons. Despite the great simplicity of our analytic expressions, we found excellent agreement with single jet [9] data taken just recently by the ATLAS Collaboration in pp collisions with $\sqrt{s} = 7$ TeV at the LHC. By contrast, in the collinear parton model of QCD, it is necessary to take into account NLO corrections and to perform soft-gluon resummation in order to obtain a comparable degree of agreement with the data for jet inclusive production.

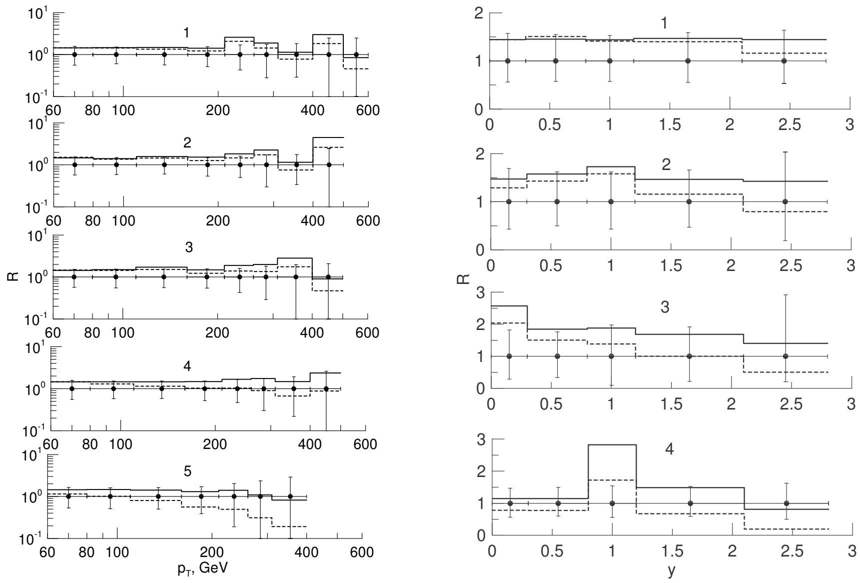

Figure 2: Ratio ($Theory/Experiment$) for p_T (left panel) and y (right panel) distributions of single jet inclusive hadroproduction in pp collisions at $\sqrt{s} = 7$ TeV evaluated at LO in the MRK approach using the KMR (solid histograms) and B (dashed histograms) unintegrated PDFs normalized to the ATLAS [9] data.

On the other hand, comparisons with data taken by the CDF and D0 Collaborations at the Tevatron in $p\overline{p}$ collisions with $\sqrt{s} = 1.8$ TeV and 1.96 TeV, which is roughly a factor of 3.5 below the value presently reached by the LHC, disclosed the limits of applicability of the MRK picture. In fact, the MRK approximation appears to break down for $x_T > 0.1$ in the case of single jet production.

These findings are in line with our previous studies of the MRK approach, applied to the production of prompt photons, diphotons, charmed mesons, bottom-flavored jets, charmonia, and bottomonia [14]. Here and in Ref. [14], parton Reggeization was demonstrated to be a powerful tool for the theoretical description of QCD processes in the high-energy limit.

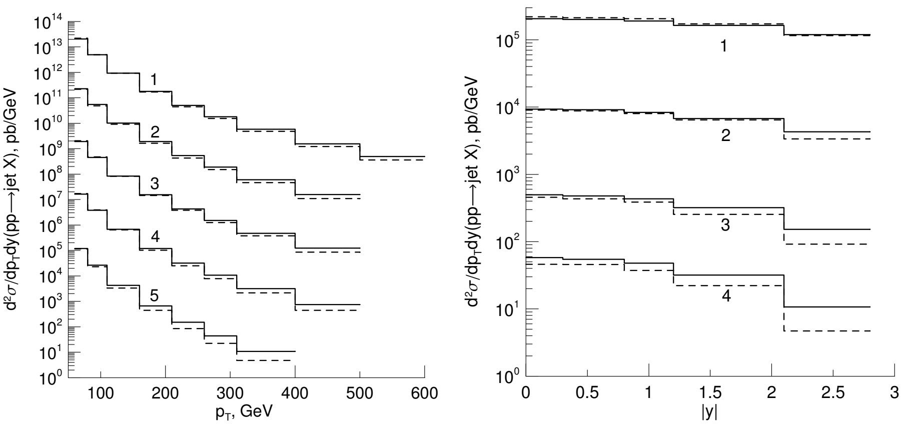

Figure 3: p_T distributions (left panel) integrated over the y intervals (1) $|y| < 0.3$ ($\times 10^8$), (2) $0.3 < |y| < 0.8$ ($\times$ 10^6), (3) $0.8 < |y| < 1.2$ ($\times$ 10^4), (4) $1.2 < |y| < 2.1$ ($\times$ 10^2), and (5) $2.1 < |y| < 2.6$ and y distributions (right panel) integrated over the p_T intervals (1) 60 GeV $< p_T <$ 80 GeV, (2) 110 GeV $< p_T <$ 160 GeV, (3) 210 GeV $< p_T <$ 250 GeV, and (4) 310 GeV $< p_T <$ 400 GeV of single jet inclusive hadroproduction in pp collisions at $\sqrt{s} = 14$ TeV evaluated at LO in the MRK approach using the KMR (solid histograms) and B (dashed histograms) unintegrated PDFs.

Acknowledgments We are grateful to V.S. Fadin, E.A. Kuraev, and L.N. Lipatov for useful discussions. The work of B.A.K. is supported in part by BMBF Grant No. 05 HT6GUA, by HGF Grant No. Ha 101, by NSF Grant No. NSF PHY05-51164, and by the Claussen-Simon-Stiftung. The work of V.A.S. and A.V.S. is supported in part by the Russian Foundation for Basic Research under Grant No. 11-02-00769-a and by the Federal Ministry for Science and Education of the Russian Federation under Contract No. 14.740.11.0894.

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