FORWARD JET PRODUCTION AT THE LARGE HADRON COLLIDER*

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We discuss jet production at forward rapidities at the LHC. In this region QCD logarithmic corrections in the hard transverse momentum and in the large rapidity interval may both be quantitatively significant. We describe results of using high-energy factorization techniques, which allow one to take into account both kinds of corrections to higher orders in QCD.

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Experiments at the Large Hadron Collider (LHC) will explore the forward region in high-energy hadronic collisions both with general-purpose detectors and with dedicated instrumentation, including forward calorimeters and proton taggers [1–6]. The physics program in the forward region involves a wide range of topics, from new particle discovery processes [3, 7, 8] to new aspects of strong interaction physics [6, 9] to heavy-ion collisions [10, 11]. Owing to the large center-of-mass energy and the good experimental coverage at large rapidities, it becomes possible for the first time to investigate forward-region physics with high-$p_\perp$ probes.

The hadroproduction of a forward jet associated with hard final state X is pictured in Fig. 1. The kinematics of the process is characterized by the large ratio of sub-energies $s_1/s \gg 1$ and highly asymmetric longitudinal momenta in the partonic initial state, $k_1 \cdot p_2 \gg k_2 \cdot p_1$. At the LHC the use of forward calorimeters allows one to measure events where jet transverse momenta $p_\perp > 20$ GeV are produced several units of rapidity apart, $\Delta y \gtrsim 4 \div 6$ [1, 6, 12]. Working at polar angles that are small but sufficiently far from the beam axis not to be affected by beam remnants, one measures azimuthal plane correlations between high-$p_\perp$ events widely separated in rapidity [6, 13].

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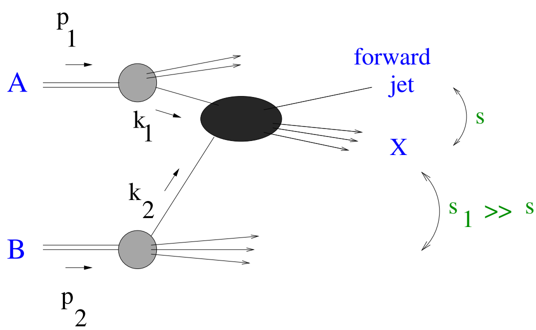

Fig. 1. Jet production in the forward rapidity region in hadron–hadron collisions.

The presence of multiple large-momentum scales implies that, as recognized in [14–16], reliable theoretical predictions for forward jets can only be obtained after summing logarithmic QCD corrections at high energy to all orders in $\alpha_{\rm s}$. Analogous observation applies to forward jets associated to deeply inelastic scattering [17, 18]. Indeed, measurements of forward jet cross-sections at Hera [19, 20] have illustrated that either fixed-order next-to-leading calculations or standard shower Monte Carlos, *e.g.* Pythia or Herwig, are not able to describe forward jet *ep* data [20–22]. This motivates efforts [22–25] to construct new algorithms for Monte Carlo event generators capable of describing jet production beyond the central rapidity region.

It is emphasized in [13] that in the LHC forward kinematics realistic phenomenology of hadronic jet final states requires taking into account at higher order both logarithmic corrections in the large rapidity interval (of high-energy type) and logarithmic corrections in the hard transverse momentum (of collinear type). The theoretical framework to resume consistently both kinds of logarithmic corrections in QCD perturbation theory is based on high-energy factorization at fixed transverse momentum [26].

The high-energy factorized form of the forward-jet cross-section is represented in Fig. 2. Initial-state parton configurations contributing to forward production are asymmetric, with the parton in the top subgraph being probed near the mass shell and large x, while the parton in the bottom subgraph is off-shell and small-x[1]. The jet cross-section differential in the final-state transverse momentum $Q_{\rm T}$ and azimuthal angle φ is given by [13, 26]

$$\frac{d\sigma}{dQ_{\rm T}^2 d\varphi} = \sum_a \int d\xi_1 \, d\xi_2 \, d^2k_{\rm T} \, \phi_{a/A}(\xi_1) \times \frac{d\widehat{\sigma}}{dQ_{\rm T}^2 d\varphi}(\xi_1\xi_2 S, k_{\rm T}, Q_{\rm T}, \varphi) \, \phi_{g^*/B}(\xi_2, k_{\rm T}) \,, \qquad (1)$$

[1] Studies of subleading corrections to jet production in the high-energy limit are given in [27], with a view to applications to measurements of jet correlations. [28, 29].

where the sum goes over parton species, ϕ are parton distributions defined from unintegrated Green's functions, [30, 33] and $\widehat{\sigma}$ is the hard-scattering kernel, calculable from the high-energy limit of perturbative amplitudes (Fig. 2 (b)). Results for the factorizing high-energy amplitudes are given in [13] in fully exclusive form. For phenomenological studies it is of interest to couple Eq. (1) to parton showers to achieve a full description of the associated final states.

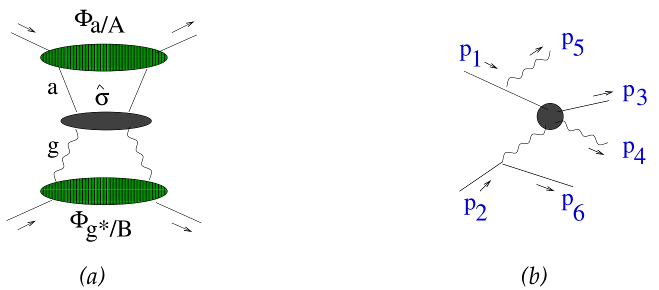

Fig. 2. (a) Factorized structure of the cross-section; (b) a graph contributing to the qg channel matrix element.

Work to develop methods for the evolution of unintegrated parton distributions in parton-shower form is currently underway by several authors. See for instance the recent proposal, [31] which incorporates NLO corrections to flavor non-singlet QCD evolution in a shower Monte Carlo at unintegrated level. The approach is based on the generalized ladder expansion of [32]. This expansion is extended to the high-energy region in [33] and used to resume high-energy logarithmic corrections to space-like jet evolution. It is thus likely that the approach [31] can be applied more generally, including flavor-singlet evolution, to treat forward hard processes. Overviews of theoretical issues on unintegrated distributions and related calculational programs can be found in [34, 35].

Eq. (1) incorporates high-energy corrections to forward jet production through the $k_\perp$ dependence of both ϕ and $\widehat{\sigma}$. The quantitative importance of finite-$k_\perp$ corrections is associated with effects of coherence of multiple gluon emission for small parton momentum fractions [26, 30]. Potentially significant coherence effects involve both the short-distance factor $\widehat{\sigma}$ and the long-distance factor ϕ. An illustration is shown in Fig. 3, [13] giving results for the short-distance matrix element in the quark channel $a = q$. We show separately contributions proportional to color factors $C_{\rm F}^2$ and $C_{\rm A} C_{\rm F}$. In the notation of Fig. 2, the final state transverse variable $Q_{\rm T}$ is defined as [13]

$$Q_{\rm T} = (1-\nu) p_{\rm T4} - \nu p_{\rm T3} \,, \qquad \text{where} \qquad \nu = (p_2\, p_4)/[(p_2\, p_1) - (p_2\, p_5)] \,, \quad (2)$$

and the azimuthal angle φ is measured with respect to the di-jet transverse momentum. The curves in Fig. 3 measure the k_{T} distribution of the jet system recoiling against the leading di-jets. The leading-order process with two back-to-back jets corresponds to the region $k_{\mathrm{T}}/Q_{\mathrm{T}} \to 0$. The dependence on k_{T} and φ plotted in Fig. 3 is the result of higher-order gluon radiation, treated according to the high-energy asymptotics.

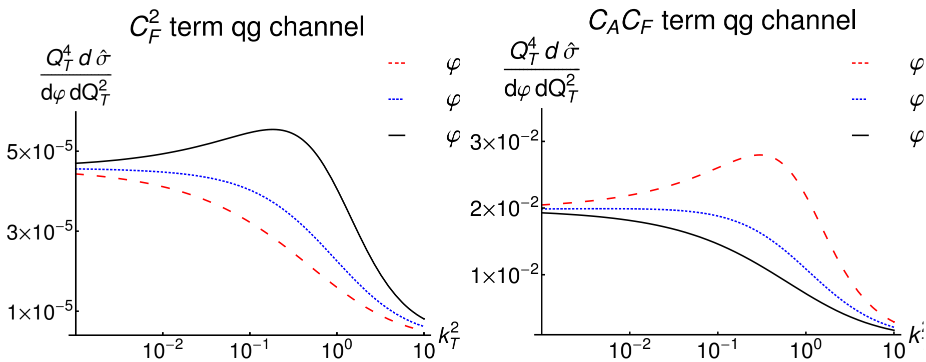

Fig. 3. The factorizing qg hard cross-section at high energy:[13] (left) C_{F}^2 term; (right) $C_{\mathrm{A}}C_{\mathrm{F}}$ term.

Fig. 3 illustrates that the role of coherence from multi-gluon emission is to set the dynamical cut-off at values of k_{T} of order Q_{T} [13]. Non-negligible effects arise at high energy from the finite k_{T} tail. These effects are not included in collinear-branching generators (and only partially in fixed-order perturbative calculations), and become more and more important as the jets are observed at large rapidity separations. Monte Carlo implementations of Eq. (1) and the coherent matrix elements (Fig. 3) are underway [36]. The usefulness of these matrix elements comes from the fact that in the high-energy limit they factorize not only in the collinear emission region but also in the large-angle emission region. It will be of interest to investigate their role also with respect to the transverse-momentum and rapidity cut-off scales [34, 37] that enter calculations in the parton-shower formalism at the unintegrated level.

A qualitatively similar behavior to that in Fig. 3 is observed in gluonic channels [13]. We find that quark and gluon channels give contributions of comparable size to forward jets in the LHC kinematics. Note also that since the forward kinematics selects asymmetric parton momentum fractions, effects due to the $x \to 1$ endpoint behavior [37] at fixed transverse momentum may become phenomenologically significant as well.

Let us finally recall that if effects of high-density parton matter [9] show up at the LHC, they will affect high-$p_\perp$ forward physics [6, 38]. The theoretical framework described above implies partonic distributions dependent on both longitudinal and transverse degrees of freedom, and is likely most natural to discuss issues of parton saturation. Studies of forward jets in this context are warranted.

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