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Three-jet DIS final states from $k_\perp$-dependent parton showers

F. Hautmann*
University of Oxford
E-mail: hautmann@thphys.ox.ac.uk

H. Jung
DESY
E-mail: jung@mail.desy.de

Experimental measurements of angular correlations in three-jet final states have recently been performed in DIS. Next-to-leading-order QCD results for these observables are affected by large theoretical uncertainties in the kinematic region of the data. We discuss the effects of multiple QCD radiation at higher order using parton-shower methods based on transverse-momentum dependent parton distributions and matrix elements. We present Monte-Carlo results for azimuthal two-jet and three-jet distributions, and discuss the comparison with experimental data.

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The study of hadronic final states with multiple jets at the Tevatron, HERA and LHC colliders relies both on perturbative multi-jet calculations (see [1] for a recent overview) and on realistic event simulation by parton-shower Monte-Carlo generators (see e.g. [2, 3]). These complex processes, characterized by multiple hard scales, are potentially sensitive to effects of QCD initial-state radiation that depend on the finite transverse-momentum tail of partonic matrix elements and distributions [3, 4]. In perturbative multi-jet calculations truncated to fixed order in α_s [1], finite-$k_\perp$ contributions are taken into account partially, order-by-order, through higher-loop corrections. On the other hand, in standard shower Monte-Carlos such as HERWIG [5] and PYTHIA [6], based on collinear evolution of the initial-state jet, finite-$k_\perp$ contributions are not included, but rather correspond to corrections [7, 8] to the angular or transverse-momentum ordering implemented in the parton-branching algorithms.

In this article we discuss the role of initial-state radiative effects in the study of angular correlations for multi-jet processes, concentrating on the case of three-jet DIS production, for which new experimental data have recently appeared [9] and next-to-leading-order (NLO) calculations are available [10]. In the first part we recall the experimental results [9] and observe that while inclusive jet cross sections are reliably predicted by NLO perturbation theory, jet correlations are affected by significant higher-order corrections, increasing as the momentum fraction x decreases, giving large theoretical uncertainties at NLO. Sizeable contributions arise from regions [4] with three well-separated hard jets in which the partonic lines along the decay chain in the initial state are not ordered in transverse momentum. In the second part we move on to the description of multi-jet correlations by parton showers that incorporate finite-$k_\perp$ corrections to the transverse-momentum ordering [11]. The results compare well with experimental data, and give quite distinctive features of the associated jet distributions compared to standard showers such as HERWIG.

1. Jet distributions from NLO calculations

DIS multi-jet distributions associated with $Q^2 > 10$ GeV^2 and $10^{-4} < x < 10^{-2}$ have recently been measured by the ZEUS collaboration [9], and compared with next-to-leading-order calculations [10]. Results for di-jet distributions are shown in Fig. 1 [9]. The plot on the left in Fig. 1

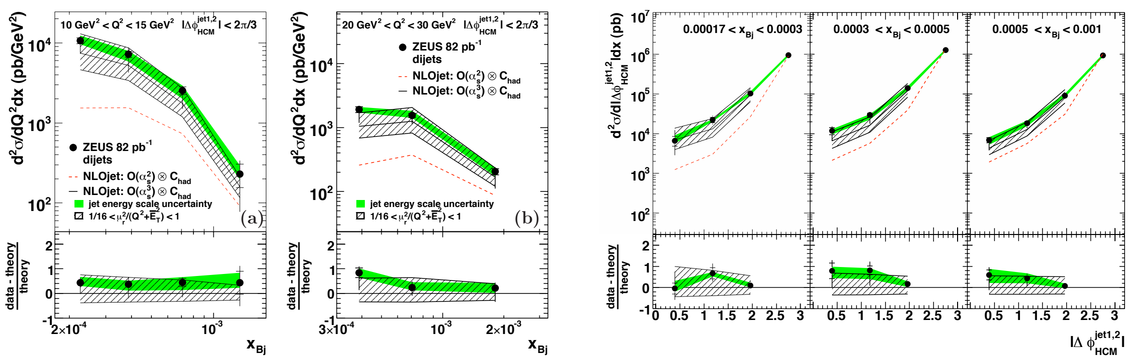

Figure 1: (left) Bjorken-x dependence and (right) azimuth dependence of di-jet distributions at HERA as measured by ZEUS[9].

shows the x-dependence of the di-jet distribution integrated over $\Delta\phi < 2\pi/3$, where $\Delta\phi$ is the azimuthal separation between the two high-E_T jets. The plot on the right shows the di-jet distribution in $\Delta\phi$ for different bins of x. The overall agreement of data with NLO results is within errors. However, the variation of the predictions from order-α_s^2 to order-α_s^3 is significant. Given the large difference between order-α_s^2 and order-α_s^3 results, the theoretical uncertainty at NLO appears to be underestimated by the error band obtained from the conventional method of varying the renormalization/factorization scale.[1]

The stability of predictions for the jet observables in Fig. 1 depends on a number of physical processes. Part of these concern nonperturbative dynamics, including jet clustering and hadronization[2], part concern radiative corrections at higher order. Fixed-order calculations beyond NLO are not within present reach for multi-jet processes in hadronic collisions. Resummed calculations of contributions from multiple infrared emissions are performed in [12]. These contributions are enhanced in the region where the two high-E_T jets are nearly back-to-back, and are also taken into account by parton-shower methods as in HERWIG [5]. Note however that sizeable corrections in Fig. 1 arise for decreasing $\Delta\phi$, where the two jets are not close to back-to-back and one has effectively three well-separated hard jets [4]. The corrections increase as x decreases. By analyzing the angular distribution of the third jet, Ref. [11] finds significant contributions from configurations where the transverse momenta in the initial-state shower are not ordered. These contributions are not included in standard parton showers, e.g. HERWIG [5] and PYTHIA [6]. The next section describes results of parton-shower calculations that take these contributions into account.

2. Parton showers with $k_\perp$-branching and jet correlations

Corrections to the initial-state shower due to non-ordering in $k_\perp$ can be incorporated in Monte-Carlo event generators [13, 14, 15, 16], with logarithmic accuracy for $x \ll 1$, by implementing unintegrated parton distributions defined through high-energy factorization [8]. Although none of the above generators are as developed as standard Monte-Carlos like HERWIG [5] or PYTHIA [6], they have the potential advantage of a more accurate treatment of the initial-state radiative effects that the observations of Sec. 1 suggest to be relevant for multi-jet correlations.

Fig. 2 shows results [11] for the azimuthal distribution of di-jet and three-jet cross sections obtained by the $k_\perp$-shower Monte-Carlo CASCADE [16] and by HERWIG [5], compared with the measurement [9]. The shape of the distribution is different for the two Monte-Carlos. CASCADE gives large differences from HERWIG in the region where the azimuthal separations $\Delta\phi$ between the leading jets are small. It becomes closer to HERWIG as $\Delta\phi$ increases. This is consistent with the expectation that both Monte-Carlos give reasonable approximations near the back-to-back region. The description of the measurement by CASCADE is good, whereas HERWIG is not sufficient to describe the measurement in the small $\Delta\phi$ region.

In the $k_\perp$-shower calculation both the parton distributions (unintegrated pdf's, fitted from experiment) and the hard matrix elements (ME's, computed perturbatively) are transverse-momentum dependent. The parton branching includes regions that are not ordered in $k_\perp$ along the initial-state decay chain. Fig. 3 shows different approximations to the azimuthal dijet distribution normalized

[1] Besides angular correlations, sizeable uncertainties at NLO also affect other associated distributions such as momentum correlations. On the other hand, NLO results are much more stable for inclusive jet cross sections [9].

[2] See [11] and references therein for more discussion of these effects.

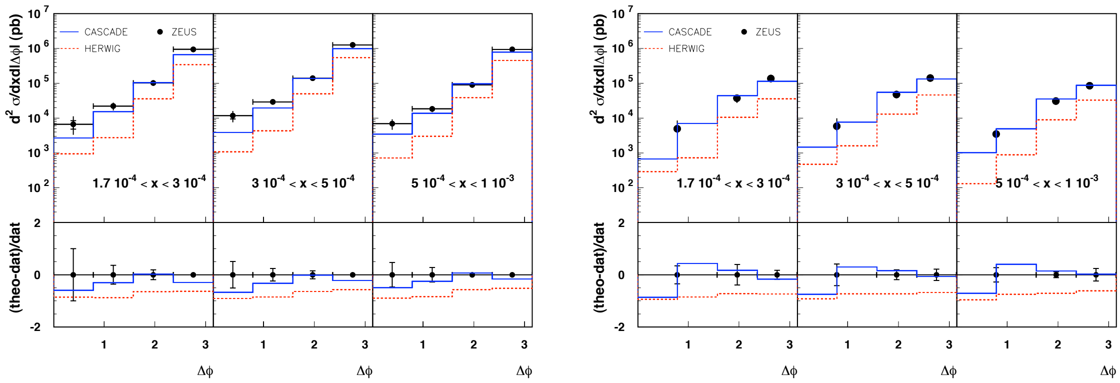

Figure 2: Angular jet correlations [11] obtained by CASCADE and HERWIG, compared with ZEUS data [9]: (left) di-jet cross section; (right) three-jet cross section.

to the back-to-back cross section. The solid red curve is the full result. The dashed blue curve is obtained from the same unintegrated pdf's but not including the transverse-momentum dependence of the hard ME. We see that the high-$k_\perp$ component in the hard ME is essential to describe jet correlations particularly for small $\Delta\phi$. The dotted violet curve is obtained from the unintegrated pdf without any resolved branching, corresponding to nonperturbative, predominantly low-$k_\perp$ modes. The results of Fig. 3 illustrate that the $k_\perp$-dependence in the unintegrated pdf alone is not sufficient to describe jet production quantitatively.

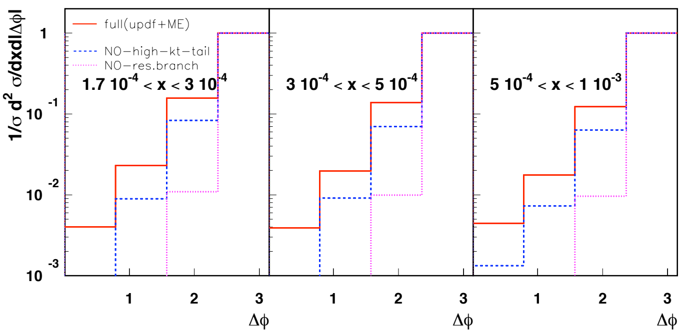

Figure 3: Azimuthal distribution normalized to the back-to-back cross section [11]: (solid red) full result (u-pdf $\oplus$ ME); (dashed blue) no finite-$k_\perp$ correction in ME (u-pdf $\oplus$ $ME_{collin.}$); (dotted violet) u-pdf with no resolved branching.

Jet multiplicities and jet momentum correlations are analyzed in [11] along lines similar to those discussed above for azimuthal distributions. The largest differences between HERWIG and the $k_\perp$-showering are found in the contribution of high multiplicities and correlations in the transverse-momentum imbalance between the leading jets.

In summary, the results give a consistent parton-shower picture of distributions associated to multi-jet production, including correlations. This is expressed in terms of unintegrated pdf's convoluted with transverse-momentum dependent hard kernels.[3] The physical picture reflects the

[3]The u-pdf's are defined gauge-invariantly [8] for small x. General operator definitions, including the region $x \sim 1$, and issues of lightcone singularities are discussed e.g. in [17, 18] and references therein.

growth of the $k_\perp$ transmitted along the initial-state jet, and includes corrections to the collinear ordering implemented in standard showers such as HERWIG and PYTHIA. We have considered production of jets in the non-forward region. Results for jet correlations are less dependent on details of u-pdf evolution models than in the case of forward-region observables. Owing to the large phase space available for jet production, the DIS kinematic region under consideration may be relevant for understanding the extrapolation of initial-state showering effects to the LHC, despite the lower energy.

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