Multi-particle production and TMD distributions

F. Hautmann
Theoretical Physics Department, University of Oxford, Oxford OX1 3NP
DOI: http://dx.doi.org/10.3204/DESY-PROC-2009-01/51

Abstract
We present a brief discussion on the application of transverse-momentum dependent (TMD) parton distributions to jet physics and parton showers.

1 Introduction

The interpretation of experimental data for multi-particle final states at the Large Hadron Collider will rely both on perturbative calculations for multi-leg scattering amplitudes and on realistic event simulation by parton-shower Monte Carlo generators.

Owing to the complex kinematics involving multiple hard scales and the large phase space opening up at very high energies, high-multiplicity events are potentially sensitive to effects of QCD initial-state radiation that depend on the finite transverse-momentum tail of partonic matrix elements and distributions. These effects are not included in the branching algorithms of standard shower Monte Carlo event generators, based on collinear jet evolution. On the other hand, they are taken into account only partially in perturbative fixed-order calculations, order-by-order through higher-loop contributions. Such effects are present to all orders in α_s and can become logarithmically enhanced at high energy.

The phenomenological significance of finite-$k_\perp$ corrections to parton showers is largely associated with effects of coherence of multiple gluon emission for small parton momentum fractions. This report discusses results of implementing these effects in Monte Carlo calculations by using coherent-branching methods based on transverse momentum dependent (TMD) distributions and matrix elements.

2 Parton showers and color coherence effects

The approach of standard parton-shower event generators, such as HERWIG and PYTHIA, relies on the dominance of collinear gluon emission. The evolution of jets developing from the hard event (both "forwards" and "backwards") is described in the first approximation through radiation of gluons predominantly at small angle from highly energetic partonic lines.

Besides collinear, incoherent emission the approach of these generators also incorporates coherent soft-gluon emission from partonic lines carrying longitudinal momentum fraction x of order 1. The phenomenological relevance of these contributions has been emphasized by extensive collider data studies [1]. An example [1] based on recent Tevatron data for $p\bar{p}$ jet fragmentation is shown in Fig. 1. This illustrates the comparison of theory predictions with and without color coherence effects with di-jet Tevatron data and with earlier e^+e^- and e^+p data.

However at the LHC, due to the phase space opening up for large center-of-mass energies, jet production enters a new regime with a great many events characterized by multiple hard

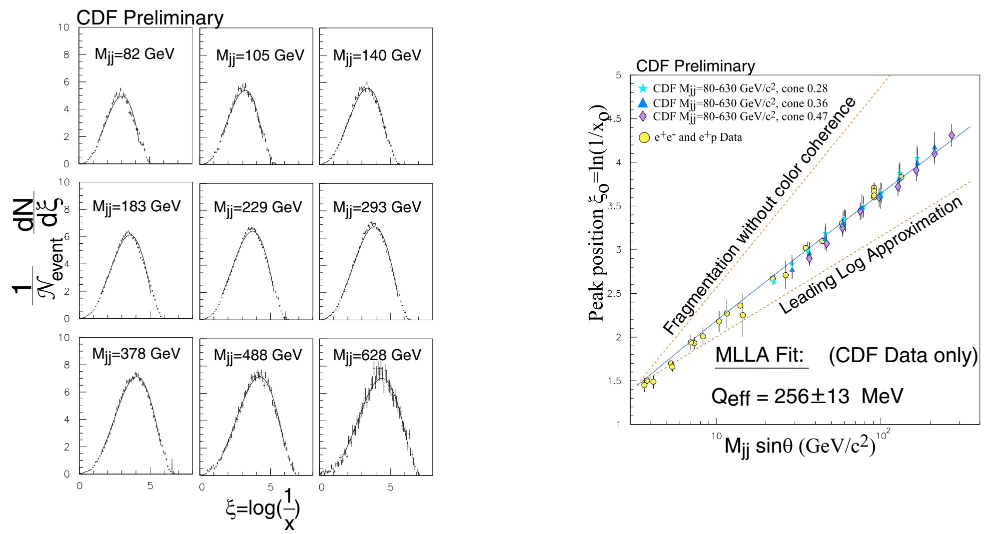

Fig. 1: Comparison [1] of predictions including soft-gluon coherence with jet fragmentation data at the Tevatron.

scales, in which (a) effects of emissions that are not collinearly ordered become increasingly non-negligible, and (b) coherence effects set in from space-like partons carrying momentum fractions $x \ll 1$. These effects are not included in standard shower Monte Carlo generators.

The theoretical framework to take account of non-collinear emission and coherence in the space-like branching requires the introduction of partonic distributions unintegrated not only in the longitudinal momenta but also in the transverse momenta [2–4]. The corrections to collinear ordering correspond to higher-order radiative terms [5, 6] in the associated jet distributions that are logarithmically enhanced in the ratio $\sqrt{s}/E_T$ of the total energy $\sqrt{s}$ to the jet transverse energy. We next turn to these corrections and discuss their role in a few examples.

3 TMD distributions

The investigation of how to define transverse-momentum dependent (TMD), or unintegrated, parton distribution functions (Fig. 2) has been the subject of much activity in the last few years. See for instance reviews and references in [2–4]. In the general case, to characterize such distributions gauge-invariantly over the whole phase space is a difficult question, and a number of open issues remain. In the case of small x, TMD distributions can be introduced in a gauge-invariant manner using high-energy factorization [5].

This result was used early on both for Monte-Carlo simulations [6] of x $\rightarrow$ 0 parton showers and for numerical resummation programs [7] for $\ln$ x corrections to QCD evolution equations [8]. For structure function's evolution, methods are being developed [9] to match the $k_\perp$-dependent, small-x dynamics with perturbative collinear dynamics. For the full simulation of exclusive components of hadronic final states, on the other hand, such matching is more complex, and will be critical for turning present event generators based on unintegrated pdf's into general-purpose Monte-Carlo tools [4, 10].

Observe that unintegrated pdf's may also provide a more natural framework to discuss the $k_\perp$ distribution of the soft underlying event [11] (minijets, soft hadrons), multiple interactions, and possibly the approach to the saturation regime [12, 13].

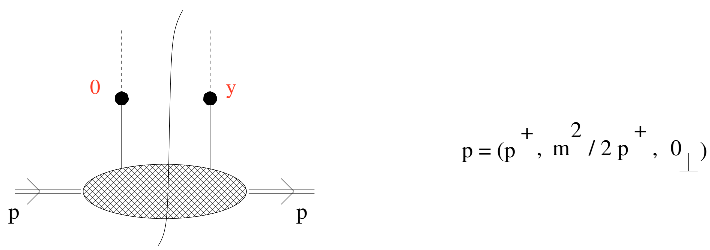

Fig. 2: Correlation function measuring the parton distribution in the target of momentum p. For TMD distributions the distance y between the two parton fields has nonzero transverse component.

It is worth noting that a physical picture of non-collinear gluon radiation that is complementary to that of TMD distributions is based on showers of color dipoles [14] and is also being applied to the initial-state jet [15]. See [16] for a study of critical issues in the relation of this approach with the parton formulation. Either at parton or dipole level, open questions involve methods for properly combining contributions from infrared regions with high-energy subgraphs. To this end we expect systematic subtraction techniques such as those in [17] to be helpful.

In the next section we give examples of Monte Carlo results implementing unintegrated distributions and applications to jet phenomenology.

4 Angular correlations in multi-jet production

The effects of coherent space-like branching based on TMD distributions are investigated in [18] for angular and momentum correlations in multi-jet final states. For a multi-jet event, consider for instance the distribution in the azimuthal angle $\Delta\phi$ between the two hardest jets. At the LHC such measurements may become accessible relatively early and be used to probe the description of complex hadronic final states by QCD and Monte Carlo generators. Experimental data on $\Delta\phi$ correlations are available from the Tevatron [19] (Fig. 3) and from Hera [20] (Fig. 4). The Tevatron measurements are dominated [18] by leading-order QCD processes, with higher radiative orders providing small corrections, and they are reasonably well described both by collinear showers (HERWIG and the new tuning of PYTHIA [19,21]) and by fixed-order NLO calculations. The Hera $\Delta\phi$ measurements, on the other hand, are much more sensitive to higher orders in the dynamics of color emission and present a more complex case, likely to be closer to the situation at the LHC.

In particular, it is noted in [18, 22] that di-jet $\Delta\phi$ correlations [20] are affected by sizeable sub-leading corrections, resulting in large theoretical uncertainties at NLO. Analogous effects are

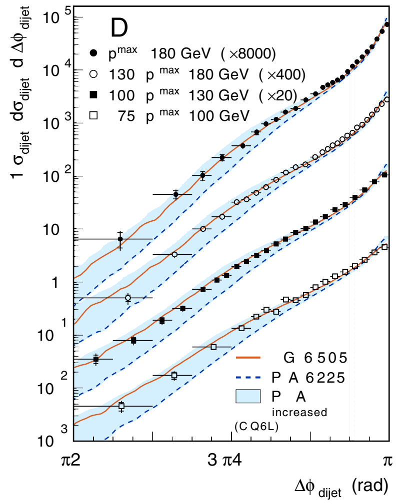

Fig. 3: Dijet azimuthal correlations measured by D0 along with the HERWIG and PYTHIA results [19].

observed in the three-jet cross section [20] particularly for the small-$\Delta\phi$ and small-x bins. The large corrections arise from regions with three well-separated hard jets in which the parton lines in the initial state decay chain are not ordered in transverse momentum. These corrections can be treated and summed to all orders, including coherence effects, by parton branching [18], using matrix elements and distributions at fixed transverse momentum $k_\perp$ according to the factorization [5]. Fig. 4 compares $k_\perp$-shower (CASCADE) and collinear-shower (HERWIG) results with the measurements [20] for the jet distributions in the azimuthal separation $\Delta\phi$ (left hand side) and in the transverse momentum imbalance $\Delta p_T^{1,2}/(2E_T^1)$ (right hand side) between the highest E_T jets.

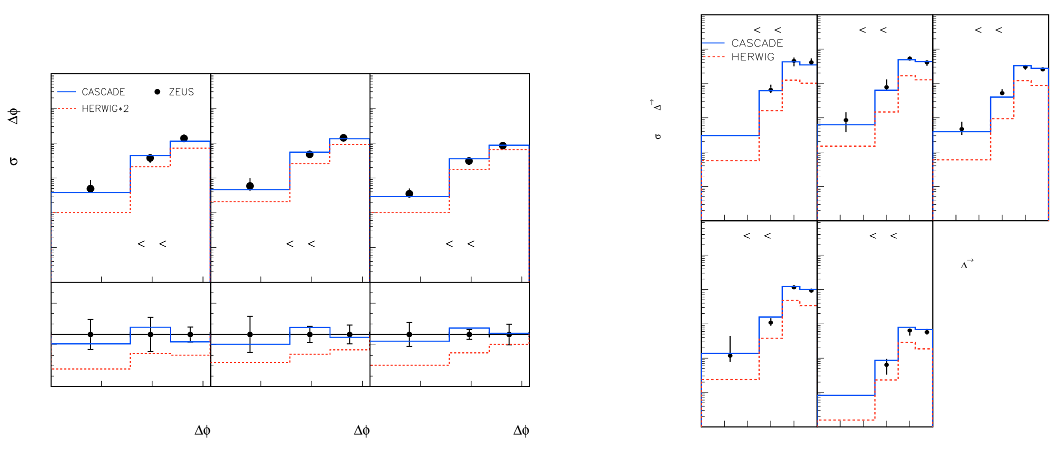

Fig. 4: (left) Angular correlations and (right) momentum correlations [18] in three-jet final states measured by [20], compared with k-shower (CASCADE) and collinear-shower (HERWIG) Monte Carlo results.

The shape of the distributions is described reasonably well by the $k_\perp$-shower, while HER-

WIG is not sufficient to describe the measurements at small $\Delta\phi$ and small Δp_T. In particular, in the plot on the left in Fig. 4 we multiply the HERWIG result by a constant factor equal to 2, which is the K-factor needed to get the normalization approximately correct in the two-jet region [18]. Still we see a noticeable difference in the shape for the three-jet cross section.

We observe that the interpretation of the jet correlation data in terms of corrections to collinear ordering is consistent with the finding [20] that while inclusive jet rates are reliably predicted by NLO fixed-order results, NLO predictions are affected by large corrections to di-jet azimuthal distributions (going from $\mathcal{O}(\alpha_s^2)$ to $\mathcal{O}(\alpha_s^3)$) in the small-$\Delta\phi$ and small-x region, and begin to fall below the data for three-jet distributions in the smallest $\Delta\phi$ bins.

The coherence effects that we have encoded in the unintegrated pdf's and matrix elements show up in the region of small $\Delta\phi$. At large $\Delta\phi$, on the other hand, the physical picture may be affected by further dynamical features. The physics of non-abelian Coulomb phase [23] can lead to quantitative effects, possibly giving rise to high-order logarithms by Coulomb/radiative mixing terms [24]. Also, contributions from endpoint singularities [10, 25, 26] affect the large-x behavior at fixed $k_\perp$. More investigations in these areas are warranted.

5 Further applications

Besides jet final states, the corrections to collinear-ordered showers that we are discussing also affect heavy mass production, including final states with heavy bosons and heavy flavor.

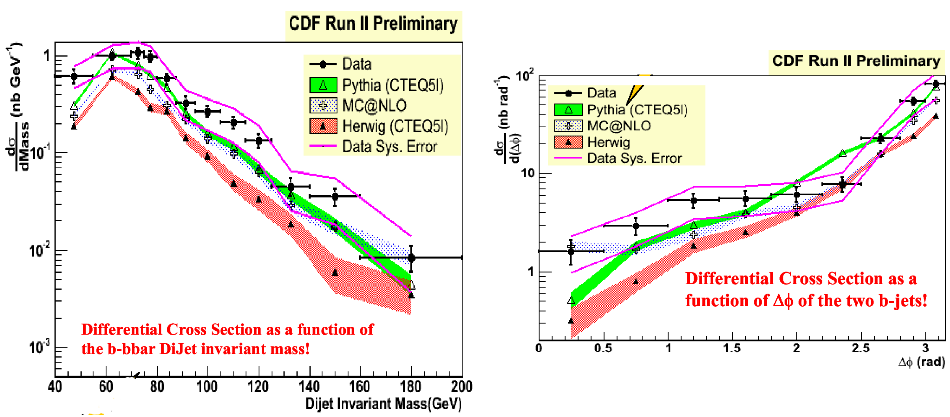

Fig. 5: Distributions in di-jet invariant mass and azimuthal separation for b-jet production at the Tevatron [1].

An example is provided by bottom-quark production. Going from the Tevatron to the LHC [27] implies a sharp increase in the relative fraction of events dominated by the $g \to b\,\bar{b}$ subprocess coupling to the spacelike jet. This is bound to affect the reliability of shower calculations based on collinear ordering (as well as the stability of NLO perturbative predictions), as these do not properly account for contributions of $b\,\bar{b}$ in association with two hard jets, with p_t of the heavy quark pair large compared to the bottom-quark mass but small compared to the transverse momenta of the individual associated jets. These kinematic regions are the analogue of the regions unordered in $k_\perp$ considered earlier for jet correlations. The contribution of unordered configurations coupling to $g \to b\,\bar{b}$ will reduce the numerical stability of collinear-based predictions (NLO, or parton-shower, or their combination [28]) with respect to renormalization/factorization scale variation in the case of LHC. On the other hand, these are precisely the configurations that the $k_\perp$ Monte Carlo shower is designed to treat.

Distributions of b-jets in invariant mass and azimuthal separation are being studied at the Tevatron. Collinear-shower descriptions of the data in Fig. 5 [1] do not appear to be fully satisfactory especially at small $\Delta\phi$. Phenomenological studies including $k_\perp$-showers would be interesting. As noted earlier, this may also affect the underlying event description.

Even more complex multi-scale effects than those discussed so far are expected [29] in the associated production of bottom quark pairs and W/Z bosons [30], and possibly in final states with Higgs bosons [31] especially for measurements of the less inclusive distributions and correlations. Vector boson production probes quark-initiated channels [32, 33] and is relevant for early phenomenology at the LHC, as the possible broadening of W and Z p_T distributions [34] affects the use of these processes as luminosity monitor [35].

The use of forward detectors at the LHC will allow one to measure correlations between hard events across large rapidity intervals. Such rapidity correlations are sensitive to coherent multi-gluon states emitted without any strong ordering in transverse momenta. An example of these effects is investigated in the study in progress [36] for high-p_T jets in the LHC forward region.

References

[1] B. R. Webber, CERN Academic Training Lectures (2008).

[2] J. C. Collins (2001). hep-ph/0106126.

[3] T. C. Rogers (2007). arXiv:0712.1195 [hep-ph].

[4] F. Hautmann and H. Jung, Nucl. Phys. Proc. Suppl. **184**, 64 (2008). arXiv:0712.0568 [hep-ph];
F. Hautmann and H. Jung, AIP Conf. Proc. **1056**, 79 (2008). arXiv:0808.0873 [hep-ph].

[5] S. Catani, M. Ciafaloni, and F. Hautmann, Phys. Lett. **B242**, 97 (1990);
S. Catani, M. Ciafaloni, and F. Hautmann, Nucl. Phys. **B366**, 135 (1991);
S. Catani, M. Ciafaloni, and F. Hautmann, Phys. Lett. **B307**, 147 (1993).

[6] G. Marchesini and B. R. Webber, Nucl. Phys. **B386**, 215 (1992).

[7] R. K. Ellis, F. Hautmann, and B. R. Webber, Phys. Lett. **B348**, 582 (1995). hep-ph/9501307.

[8] L. N. Lipatov, Phys. Rept. **286**, 131 (1997). hep-ph/9610276.

[9] G. Altarelli, R. D. Ball, and S. Forte, PoS **RADCOR2007**, 028 (2007). arXiv:0802.0968 [hep-ph];
M. Ciafaloni, PoS **RADCOR2007**, 029 (2007).

[10] F. Hautmann, Phys. Lett. **B655**, 26 (2007). hep-ph/0702196;
F. Hautmann (2007). arXiv:0708.1319 [hep-ph].

[11] G. Gustafson (2007). arXiv:0712.1941 [hep-ph].

[12] L. Motyka, K. Golec-Biernat, and G. Watt (2008). arXiv:0809.4191 [hep-ph].

[13] K. Kutak and H. Jung (2008). arXiv:0812.4082 [hep-ph].

[14] G. Gustafson, Phys. Lett. **B175**, 453 (1986).

[15] L. Lonnblad and M. Sjodahl, JHEP **05**, 038 (2005). hep-ph/0412111;
L. Lonnblad and M. Sjodahl, JHEP **02**, 042 (2004). hep-ph/0311252;
G. Gustafson, L. Lonnblad, and G. Miu, JHEP **09**, 005 (2002). hep-ph/0206195.

[16] Y. L. Dokshitzer and G. Marchesini (2008). arXiv:0809.1749 [hep-ph].

[17] J. C. Collins and F. Hautmann, JHEP **03**, 016 (2001). hep-ph/0009286;
J. C. Collins and F. Hautmann, Phys. Lett. **B472**, 129 (2000). hep-ph/9908467;
F. Hautmann, Nucl. Phys. **B604**, 391 (2001). hep-ph/0102336;
F. Hautmann (1997). hep-ph/9708496.

[18] F. Hautmann and H. Jung, JHEP **10**, 113 (2008). arXiv:0805.1049 [hep-ph].

[19] D0 Collaboration, V. Abazov *et al.*, Phys. Rev. Lett. **94**, 221801 (2005). hep-ex/0409040.

[20] ZEUS Collaboration, S. Chekanov *et al.*, Nucl. Phys. **B786**, 152 (2007). arXiv:0705.1931 [hep-ex].

[21] TeV4LHC QCD Working Group Collaboration, M. Albrow *et al.* (2006). hep-ph/0610012.

[22] F. Hautmann and H. Jung (2008). arXiv:0804.1746 [hep-ph].

[23] S. M. Aybat and G. Sterman (2008). arXiv:0811.0246 [hep-ph].

[24] J. R. Forshaw, A. Kyrieleis, and M. H. Seymour, JHEP **09**, 128 (2008). arXiv:0808.1269 [hep-ph];
M. H. Seymour (2007). arXiv:0710.2733 [hep-ph].

[25] J. C. Collins, in Perturbative QCD (ed. A. Mueller), p. 573 (1989).

[26] I. O. Cherednikov and N. G. Stefanis, Nucl. Phys. **B802**, 146 (2008). arXiv:0802.2821 [hep-ph];
I. O. Cherednikov and N. G. Stefanis (2007). arXiv:0711.1278 [hep-ph].

[27] J. Baines *et al.*, Heavy Quark Working Group: summary report (2006). hep-ph/0601164.

[28] S. Frixione, P. Nason, and B. R. Webber, JHEP **08**, 007 (2003). hep-ph/0305252.

[29] J. Bartels *et al.*, Hera-LHC Workshop Proceedings (2008);
M. Deak and F. Schwennsen, JHEP **09**, 035 (2008). arXiv:0805.3763 [hep-ph];
S. P. Baranov, A. V. Lipatov, and N. P. Zotov, Phys. Rev. **D78**, 014025 (2008). arXiv:0805.4821 [hep-ph].

[30] M. L. Mangano, Nucl. Phys. **B405**, 536 (1993).

[31] H. Jung, Mod. Phys. Lett. **A19**, 1 (2004). hep-ph/0311249;
A. Kulesza, G. Sterman, and W. Vogelsang, Phys. Rev. **D69**, 014012 (2004). hep-ph/0309264;
F. Hautmann, Phys. Lett. **B535**, 159 (2002). hep-ph/0203140.

[32] S. Marzani and R. D. Ball (2008). arXiv:0812.3602 [hep-ph].

[33] S. Catani and F. Hautmann, Nucl. Phys. **B427**, 475 (1994). hep-ph/9405388;
S. Catani and F. Hautmann, Phys. Lett. **B315**, 157 (1993).

[34] S. Berge, P. M. Nadolsky, F. I. Olness, and C. P. Yuan, AIP Conf. Proc. **792**, 722 (2005). hep-ph/0508215.

[35] A. M. Cooper-Sarkar (2007). arXiv:0707.1593 [hep-ph].

[36] M. Deak *et al.*, in progress (2008).