Parton Showering Effects in Central Heavy-Boson Hadroproduction

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If large-angle multigluon radiation contributes significantly to parton showers associated with heavy boson production at the LHC, appropriate parton branching methods are required for realistic Monte Carlo simulations of final states. We report on a study illustrating such effects in the case of central scalar-boson production. We comment on the possible impact of such studies on the modelling of multi-parton interactions.

1 Introduction

Final states containing heavy bosons and jets will be crucial in a number of experimental searches at the Large Hadron Collider. Phenomenological analyses will rely both on perturbative fixed-order calculations and on parton shower Monte Carlo generators for a realistic description of the structure of these events.

Due to the presence of multiple hard scales and the large phase space opening up at LHC energies, the treatment of these final states is potentially sensitive to complex dynamical effects in the QCD showers accompanying the events. In the case of vector bosons it has been pointed out [1] that the treatment of parton showers, and in particular of the recoils in the shower, is essential for a proper description of the W/Z p_T spectrum. This affects the amount of multi-parton interactions [1, 2, 3, 4] needed to describe the events. On the other hand, parton showers which are not ordered in transverse momentum could also considerably contribute to what is typically associated with the underlying event. In the case of vector bosons this may be relevant for early phenomenology at the LHC, as the possible broadening of W and Z p_T distributions [5] affects the use of these processes as luminosity monitor [6].

For scalar boson production, the role of corrections to transverse-momentum ordered showers on the structure of final states was considered in [7, 8] in terms of the heavy-top effective theory matrix elements associated with the unintegrated gluon density [9]. In this article we report on ongoing studies [10] of mini-jet radiation accompanying scalar boson production in the central region at the LHC. It is appropriate to consider this issue in view of the progress in the quantitative understanding of unintegrated gluon contributions in multi-jet final states [11]. In the case of scalar bosons as well, such studies have implications on the role of multi-parton interactions [2, 3] in the evolution of the initial state shower.

We start in Sec. 2 with a brief discussion summarising aspects of corrections to collinear-ordered showers and the role of recent jet-jet correlation measurements. In Sec. 3 we consider the application of parton showers not ordered in transverse momentum to the case of central scalar-boson hadroproduction. We conclude in Sec. 4.

2 Corrections to Collinear Showers and Jet Correlations

In this section we briefly discuss effects of high-energy corrections to collinear parton showers on hadronic final states with multiple jets.

Let us recall that the branching algorithms underlying the most commonly used shower Monte Carlo event generators [12, 13] are based on collinear evolution of jets developing, both "forwards" and "backwards", from the hard event [14], supplemented (in the case of certain generators) by suitable constraints for angularly-ordered phase space [15]. The angular constraints are designed to take account of coherence effects from multiple soft-gluon emission [15, 16, 17].

The main new effect one observes when trying to push this picture to higher and higher energies is that soft-gluon insertion rules [16, 17] based on eikonal emission currents [18, 19] are modified in the high-energy, multi-scale region by terms that depend on the total transverse momentum transmitted down the initial-state parton decay chain [20, 21, 22]. As a result, the physically relevant distribution to describe initial-state showers becomes the analogue not so much of an ordinary parton density but rather of an "unintegrated" parton density, dependent on both longitudinal and transverse momenta.[1]

The next observation concerns the structure of virtual corrections. Besides Sudakov form-factor effects included in standard shower algorithms [12, 13], one needs in general virtual-graph terms to be incorporated in transverse-momentum dependent (but universal) splitting functions [20, 29, 30, 31] in order to take account of gluon coherence not only for collinear-ordered emissions but also in the non-ordered region that opens up at high $\sqrt{s}/p_{\perp}$.

These finite-$k_{\perp}$ corrections to parton branching have important implications for multiplicity distributions and the structure of angular correlations in final states with high multiplicity. Refs. [11, 35] analyze examples of such effects in the case of di-jet and 3-jet production in ep [32, 33] and $p\bar{p}$ [34] collisions. In particular, the accurate measurements [32] of azimuthal and transverse-momentum correlations are compared with results from collinear shower (Herwig [36]) and $k_{\perp}$-shower (Cascade [37]). The region of large azimuthal separations between the leading jets, $\Delta\phi \sim 180^o$, is dominated by soft gluon emission effects, while the region of small azimuthal separations, down to $\Delta\phi \sim 30^o$, is driven by hard parton radiation, thus offering a significant test of the quality of hard to semi-hard parton showers over the full region of phase space. The description of the angular correlation measurements by the $k_{\perp}$-shower is good, and provides confidence on the wider applicability of the method for multi-jet processes. Results based on collinear parton showers (Herwig) cannot describe the shape of the $\Delta\phi$ distribution.

The $k_{\perp}$-shower predictions involve both transverse-momentum dependent pdfs and matrix elements. Fig. 1 [35] illustrates the relative contribution of these different components to ep di-jet cross sections showing different approximations to the azimuthal dijet distribution normalised to the back-to-back cross section. The solid red curve is the full result [11]. The dashed blue curve is obtained from the same unintegrated pdf's but by taking the collinear approximation in the hard matrix element. The dashed curve drops much faster than the full

[1] See [23] for recent reviews of unintegrated pdfs. Aspects of u-pdfs from the standpoint of QCD high-energy factorisation are discussed in [24]. Associated phenomenological aspects are discussed in [8, 23, 25], and references therein; see [26, 27, 28] for recent new work. The papers in [29] contain first discussions of a more general, nonlocal operator formulation of u-pdfs applied to parton showers beyond leading order.

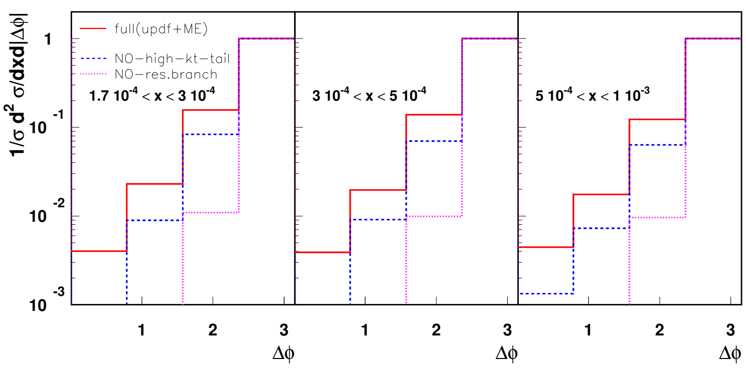

Figure 1: The dijet azimuthal distribution [35] normalised to the back-to-back cross section: (solid red) full result (u-pdf $\oplus$ ME); (dashed blue) no finite-k$_\perp$ correction in ME (u-pdf $\oplus$ ME$_{collin.}$); (dotted violet) u-pdf with no resolved branching.

result as $\Delta\phi$ decreases, indicating that the high-k$_\perp$ component in the ME [30] is necessary to describe jet correlations for small $\Delta\phi$. The dotted (violet) curve is the result obtained from the unintegrated pdf without any resolved branching. This represents the contribution of the intrinsic distribution only, corresponding to non-perturbative, predominantly low-k$_\perp$ modes. That is, in the dotted (violet) curve one retains an intrinsic k$_\perp \neq 0$ but no effects of coherence. We see that the resulting jet correlations in this case are down by an order of magnitude. The inclusion of the perturbatively computed high-k$_\perp$ correction distinguishes the calculation [11] from other shower approaches that include transverse momentum dependence in the pdfs but not in the matrix elements, see e.g. [38].

The corrections to collinear showers described above embody the physics of the unintegrated gluon density and associated hard matrix elements. Besides jet-jet correlations, these corrections will affect the structure of final states associated with heavy mass production. In the next section we consider implications of the unintegrated gluon density and non-collinear contributions to showering on the jet activity accompanying production of heavy scalars in the central region at the LHC.

3 Central Scalar Boson Production at the LHC

To study the effect of non-collinear parton showers and its contribution to the underlying event, Ref. [10] investigates a gluon induced process which produces a colour singlet scalar system in the final state, here $gg \to h^0$. We consider radiation associated with standard model Higgs boson production, following the CDF analysis of the underlying event [39]. As shown in Fig. 2, the direction of the Higgs boson in the azimuthal plane defines the origin of the system, and four regions in the azimuthal plane are defined.

Fig. 3 [10] shows results for the average multiplicity for mini-jets with $E_t > 15$ GeV and with $E_t > 5$ GeV at LHC energies ($\sqrt{s} = 14$ TeV) in the 4 different regions of ϕ as a function of the Higgs transverse momentum.

The predictions of the k$_\perp$-shower Monte Carlo generator CASCADE [37] are compared with predictions from PYTHIA [1]. For comparison, CASCADE is also run in collinear mode (cascade-

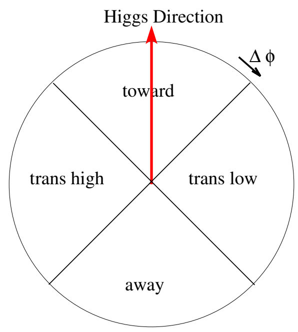

Figure 2: Different regions in ϕ with respect to the Higgs direction.

dglap), with the off-shell matrix element [9] replaced by the on-shell approximation and the parton showers are evolved with the one-loop splitting function and an upper restriction on the transverse momentum $p_t < \sqrt{m_h^2 + p_{t\,h}^2}$. For mini-jets with $E_T > 15$ GeV CASCADE in collinear mode reproduces the prediction of PYTHIA without multiparton interactions in both transverse regions. The full CASCADE run gives higher activities in the transverse as well as in the toward regions, and is close or larger than the prediction of PYTHIA including multiparton interactions. In the away region the slope is steeper than predicted from PYTHIA. Lowering the transverse momentum cut of the mini-jets to $E_T > 5$ GeV, CASCADE still predicts a larger multiplicity than PYTHIA without multiparton interactions, but falls clearly below the prediction including multiparton interactions. This illustrates the onset of hard perturbative contributions from the parton showers, which are simulated in PYTHIA with multiparton interactions.

The phase space region where soft radiation plays a significant role is the region of minimal transverse energy in the ϕ plane. This is the region where multiparton interactions should be visible. We have also studied the multiplicity of charged particles (with $p_t > 150$ MeV) in the process $gg \to h^0$. The study in [10] indicates that the result from PYTHIA including multiparton interactions is above the result from CASCADE, however the multiplicity predicted from CASCADE is significantly larger than the one predicted by PYTHIA without multiparton interactions. The result using full unintegrated-pdf evolution shows significantly more activity in all regions. Thus even for the soft contribution in the charged particle multiplicity the treatment of parton showers is important.

In the region of minimum bias events, elastic and soft diffractive processes will also play a role. This is not (yet) implemented in CASCADE.

More details of this study will be reported in a forthcoming publication. We note that the effects described above can influence the description of soft underlying events and minijets [1, 4] as well as the use of exclusive scalar production channels [7].

4 Outlook

The production of final states containing heavy bosons and multiple jets will be characterised at the LHC by the large phase space opening up at high centre-of-mass energies, and the presence of multiple hard scales, possibly widely disparate from each other. This brings in

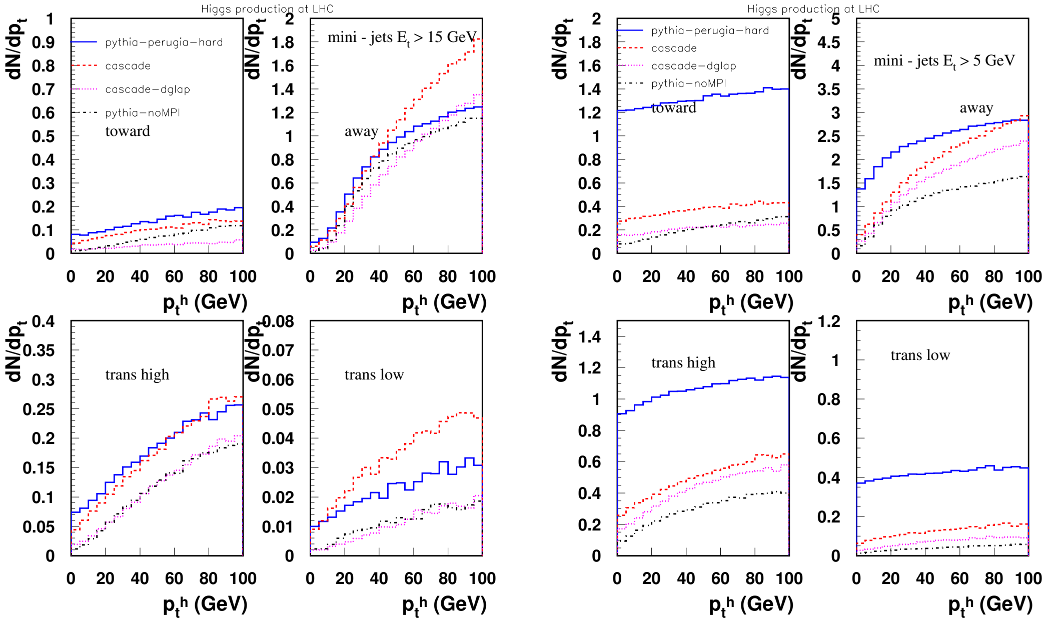

Figure 3: Multiplicity of jets as a function of the transverse momentum of the Higgs in different regions of ϕ as predicted from $k_\perp$-shower (Cascade) and collinear shower (Pythia). Shown is also the prediction using Cascade in collinear mode (cascade-dglap). The left figure shows results for mini-jets with $E_T > 15$ GeV, the right figure for $E_T > 5$ GeV.

potentially large perturbative corrections to hard-scattering events and potentially new effects in the parton-shower components of the process.

If large-angle multigluon radiation gives significant contributions to the QCD showers accompanying heavy boson production at the LHC, appropriate generalisations of parton branching methods are required. In this study we have considered jet radiation associated with heavy scalars produced centrally at the LHC, and we have described applications of transverse-momentum dependent kernels [7, 8, 9, 24, 25] for parton showering. We have focused on associated minijet distributions and discussed a comparison of showering effects with multi-parton interactions effects.

This study lends itself to extensions in several directions. First, we have considered here mini-jet and effects that could be associated with the underlying event. However, the approach is much more general (see e.g. discussions in [11, 23, 26, 29]) and could be used to investigate hard radiation as well.

Next, we have considered scalar boson production which is dominated by the physics of initial-state gluonic showers, expressible in terms of unintegrated gluon densities. But treatments of quark contributions to showers at unintegrated level are also being worked on (see e.g. [26, 27, 28]). In this respect, theoretical results for splitting kernels [30] already applied to inclusive phenomenology can also be of use in calculations for exclusive final states [40]. This will have direct applications to parton showers in vector boson production.

Further, relevant areas of experimental studies will involve jet physics in the forward rapidity region [41] at the LHC. In this article we have limited ourselves to considering production processes in the central rapidity region. Note that techniques are being developed [42] to allow one to also address multi-particle hard processes at forward rapidities.

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References

[1] P.Z. Skands, arXiv:0905.3418 [hep-ph] in Proc. Perugia Workshop (2008).

[2] R. Corke and T. Sjöstrand, arXiv:0911.1909 [hep-ph].

[3] M. Bähr, S. Gieseke and M. Seymour, JHEP **0807** (2008) 076.

[4] G. Gustafson, talk at Desy Workshop, Hamburg, March 2007; G. Gustafson, L. Lönnblad and G. Miu, JHEP **0209** (2002) 005.

[5] F.I. Olness, talk at HERA-LHC Workshop, CERN, May 2008; S. Berge, P.M. Nadolsky, F.I. Olness and C.P. Yuan, hep-ph/0508215.

[6] A.M. Cooper-Sarkar, arXiv:0707.1593 [hep-ph].

[7] L. Lönnblad and M. Sjödahl, JHEP **0402** (2004) 042.

[8] H. Jung, Mod. Phys. Lett. A **19** (2004) 1.

[9] F. Hautmann, Phys. Lett. B **535** (2002) 159.

[10] M. Deak, A. Grebenyuk, F. Hautmann, H. Jung and K. Kutak, in Proc. DIS09 Workshop (Madrid, 2009).

[11] F. Hautmann and H. Jung, JHEP **0810** (2008) 113.

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

[13] R.K. Ellis, W.J. Stirling and B.R. Webber, *QCD and collider physics*, CUP 1996; Yu.L. Dokshitzer, V.A. Khoze, A.H. Mueller and S.I. Troian, *Perturbative QCD*, Ed. Frontieres, Gif-sur-Yvette (1991).

[14] J.C. Collins, D.E. Soper and G. Sterman, Adv. Ser. Direct. High Energy Phys. 5 (1988) 1.

[15] B.R. Webber, Ann. Rev. Nucl. Part. Sci. **36** (1986) 253.

[16] A. Bassetto, M. Ciafaloni and G. Marchesini, Phys. Rept. **100** (1983) 201.

[17] Yu.L. Dokshitzer, V.A. Khoze, A.H. Mueller and S.I. Troian, Rev. Mod. Phys. **60** (1988) 373.

[18] V.N Gribov, Sov. J. Nucl. Phys. **5** (1967) 399; F.E. Low, Phys. Rev. **110** (1958) 974.

[19] J. Frenkel and J.C. Taylor, Nucl. Phys. **B246** (1984) 231; R. Doria, J. Frenkel and J.C. Taylor, Nucl. Phys. **B168** (1980) 93.

[20] M. Ciafaloni, Nucl. Phys. **B296** (1988) 49.

[21] S. Catani, M. Ciafaloni and F. Hautmann, Phys. Lett. B**242** (1990) 97.

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

[23] F. Hautmann, Acta Phys. Polon. B **40** (2009) 2139; F. Hautmann and H. Jung, Nucl. Phys. Proc. Suppl. **184** (2008) 64 [arXiv:0712.0568 [hep-ph]].

[24] S. Catani, M. Ciafaloni and F. Hautmann, Nucl. Phys. B**366** (1991) 135; Phys. Lett. **B307** (1993) 147.

[25] J.R. Andersen *et al.*, Eur. Phys. J. C **48** (2006) 53; B. Andersson *et al.*, Eur. Phys. J. C **25** (2002) 77.

[26] H. Jung *et al.*, Proceedings of the Workshop “HERA and the LHC”, arXiv:0903.3861 [hep-ph].

[27] S. Jadach and M. Skrzypek, arXiv:0905.1399 [hep-ph]; arXiv:0909.5588 [hep-ph].

[28] A.D. Martin, M.G. Ryskin and G. Watt, arXiv:0909.5529 [hep-ph].

[29] J.C. Collins and X. Zu, JHEP **0503** (2005) 059; J.C. Collins, Phys. Rev. D **65** (2002) 094016; J.C. Collins and F. Hautmann, JHEP **0103** (2001) 016.

[30] S. Catani and F. Hautmann, Nucl. Phys. B**427** (1994) 475; Phys. Lett. B**315** (1993) 157.

[31] F. Hautmann, Phys. Lett. B **655** (2007) 26.

[32] S. Chekanov *et al.* [ZEUS Collaboration], Nucl. Phys. B **786** (2007) 152 [arXiv:0705.1931 [hep-ex]].

[33] A. Aktas *et al.* [H1 Collaboration], Eur. Phys. J. C **33** (2004) 477 [arXiv:hep-ex/0310019].

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

[35] F. Hautmann and H. Jung, arXiv:0804.1746 [hep-ph], in Proceedings of the 8th International Symposium on Radiative Corrections RADCOR2007; arXiv:0808.0873 [hep-ph].

[36] G. Corcella *et al.*, JHEP **0101** (2001) 010.

[37] H. Jung, Comput. Phys. Commun. **143** (2002) 100.

[38] S. Höche, F. Krauss and T. Teubner, Eur. Phys. J. C**58** (2008) 17.

[39] CDF Coll., Phys. Rev. D **65** (2002) 092002.

[40] H. Jung *et al.*, in progress.

[41] D. d'Enterria, arXiv:0911.1273 [hep-ex].

[42] M. Deak *et al.*, arXiv:0908.0538 [hep-ph]; arXiv:0908.1870 [hep-ph].