PROCEEDINGS OF SCIENCE

# Large jet multiplicity final states in vector boson production in high-energy pp collisions

**F. Hautmann**
*Theoretical Physics, University of Oxford, Oxford OX1 3NP*
*Physics and Astronomy, University of Sussex, Brighton BN1 9QH*
*E-mail:* hautmann@thphys.ox.ac.uk

**H. Jung**
*Deutsches Elektronen Synchrotron, D-22603 Hamburg*
*Elementaire Deeltjes Fysica, Universiteit Antwerpen, B 2020 Antwerpen*
*E-mail:* hannes.jung@desy.de

We consider the application of $k_\perp$-dependent parton branching methods to high-mass and high-multiplicity production processes in hadronic collisions. We present results for multiplicity distributions and transverse momentum spectra in final states with $W$ boson + jets at the LHC.

*XXI International Workshop on Deep Inelastic Scattering and Related Subjects*
*April 22-26, 2013*
*Marseille, France*



PoS(DIS 2013)157

Complex final states with high particle multiplicity in hadronic collisions are central to many aspects of high energy physics. Baseline predictions for these processes depend on parton shower event generators, combined with perturbative hard-scattering matrix elements. These are either multi-leg tree-level matrix elements, or next-to-leading-order matrix elements including virtual emission processes, or, possibly, a combination of both (see e.g. [1, 2] for recent reviews and references). In this picture the parton showers are based on collinear evolution of jets developing from the hard event, while the matrix elements take into account hard large-angle radiation.

When this picture is pushed to higher and higher energies, however, new effects arise in the multiplicity distributions and the structure of angular correlations, due to soft but finite-angle multi-gluon emission (see e.g. [3]). Examples of such correlations in multi-jet deep inelastic scattering final states are studied in [4]. As was noted already in [5], these effects can be taken into account by using transverse-momentum dependent showering algorithms coupled [6] to hard matrix elements at fixed transverse momentum. This allows one to include soft gluon coherence [7] not only for collinear-ordered emissions but also in the non-ordered region that opens up at high $\sqrt{s}/p_\perp$ and large $p_\perp$.

Besides these dynamical effects, it has recently been pointed out [8] that taking into account the correct transverse momentum kinematics in branching algorithms gives rise to non-negligible kinematic shifts compared with collinear approximations, and in fact contributes a large fraction of parton showering corrections relevant both for jets [9] and for massive final states at the LHC.

Motivated by both these dynamical and kinematical considerations, in [10] we investigate the application of the transverse-momentum dependent showering approach to final states at the LHC containing vector bosons and multiple jets. To this end, we use high-energy matrix elements [11, 12] with off-shell partons [13, 14] for weak boson production, and unintegrated parton distributions [15] determined from high-precision DIS data [16] (including pdfs uncertainties), implemented in the CCFM shower Monte Carlo [17]. We focus on $W+n$ jets. This process is important both for standard model physics and for new physics searches. In particular it is relevant to studies of parton distribution functions and of Monte Carlo event generators, including signals of multi-parton interactions, for which $W+2$ jets is a classic channel [18, 19].

Fig. 1 shows results for the jet multiplicity distribution. The solid red curve and dashed blue curve are the results from the $k_\perp$-shower calculation implemented in the CASCADE Monte Carlo [17], corresponding to the uncertainty on the unintegrated pdfs (JH1+ and JH1-) [15]. The dot-dashed black curve is the leading-order parton shower result obtained from the $p_t$-ordered PYTHIA 8 [20] shower. The dots are the ATLAS measurements [21]. The $k_\perp$-shower calculation produces jets both from matrix element and from showering and can describe the jet multiplicity distribution, while the $p_t$-ordered PYTHIA shower cannot predict higher jet multiplicities.

In Fig. 2 we concentrate on $W+2$ jets and compute the transverse momentum spectrum of the first jet. The color coding is as in Fig. 1. The $p_\perp$ distribution is reasonably well described. We see that the leading order PYTHIA result starts to deviate from measurements at high $p_\perp$. In this framework the description of the high $p_\perp$ is to be improved by supplementing the parton shower with next-to-leading-order corrections to the matrix element, via matched NLO-shower calculations [22] such as POWHEG. CASCADE, on the other hand, contains large-angle, finite-$k_\perp$ emissions, and can describe the shape of the spectrum also at large transverse momentum.

In Fig. 3 we go to higher jet multiplicities and investigate the spectrum of the first jet and of

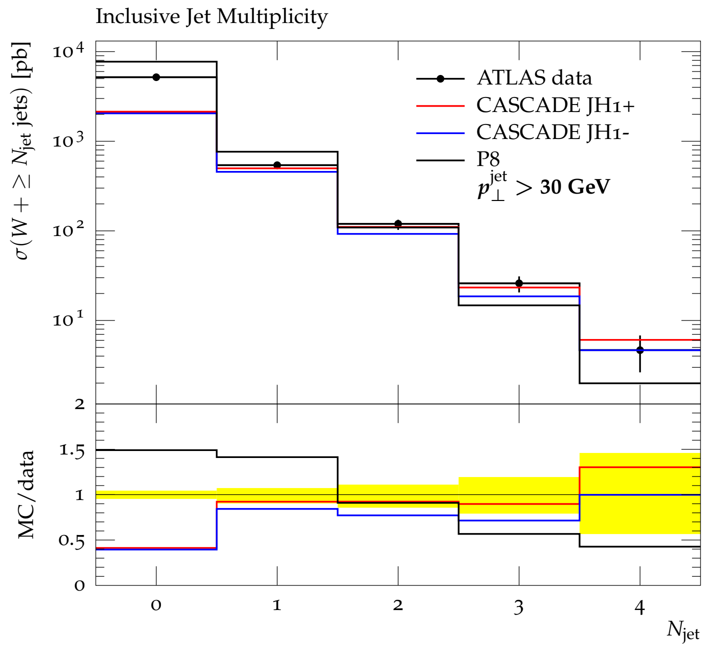


**Figure 1:** Jet multiplicity distribution associated with $W$ boson production.

the nonleading jets. We shows results for $W+4$ jets. On the left is the $\mathrm{p}_\perp$ spectrum of the first jet; on the right is the $\mathrm{p}_\perp$ spectrum of the third jet. As expected from Figs. 1 and 2, the collinear $p_t$-ordered PYTHIA shower cannot describe the multi-jet case. The $\mathrm{k}_\perp$-shower calculation is capable of describing the shape of the spectrum for the first jet and also for the nonleading jets. This is a meaningful test of the physical picture underlying the calculation. The third jet comes from $\mathrm{k}_\perp$-dependent parton branching.

We may look into the detailed structure of the final state by computing angular correlations. Fig. 4 reports results for the cross section versus the azimuthal distance between the leading jets. In the collinear picture the first and second jets are decorrelated at leading order. Correspondingly, the $p_t$-ordered PYTHIA shower cannot predict the shape of the angular distribution. In contrast, CASCADE contains correlations between the first and second jets, and describes well both the back to back region and the decorrelation region.

**Acknowledgments**. Many thanks to the workshop organizers for the opportunity to present this work and for putting up a very interesting conference.

## References

[1] S. Plätzer, arXiv:1307.0774 [hep-ph].

[2] S. Höche, SLAC preprint SLAC-PUB-14498 (2011).

[3] F. Hautmann, arXiv:0909.1240 [hep-ph].

[4] F. Hautmann and H. Jung, JHEP **0810** (2008) 113; arXiv:0804.1746; arXiv:0712.0568.

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

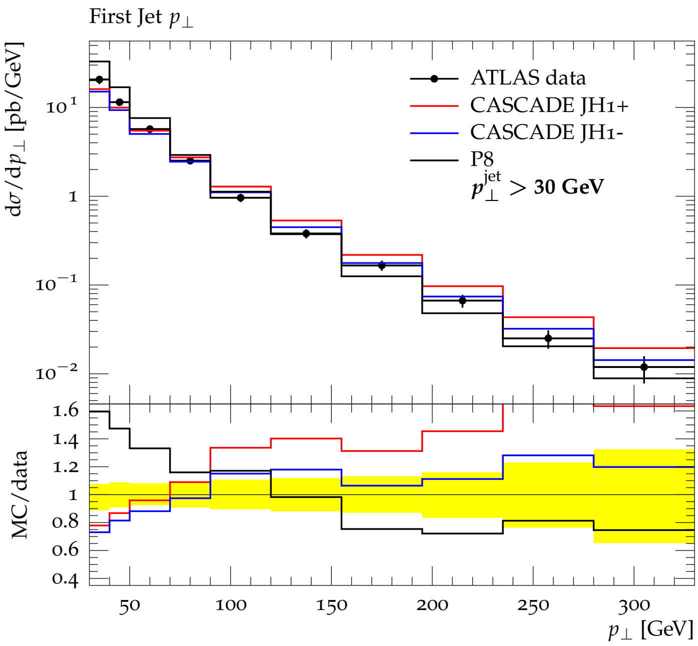


**Figure 2:** $W + 2$ jets production: the $p_\perp$ spectrum of the first jet.

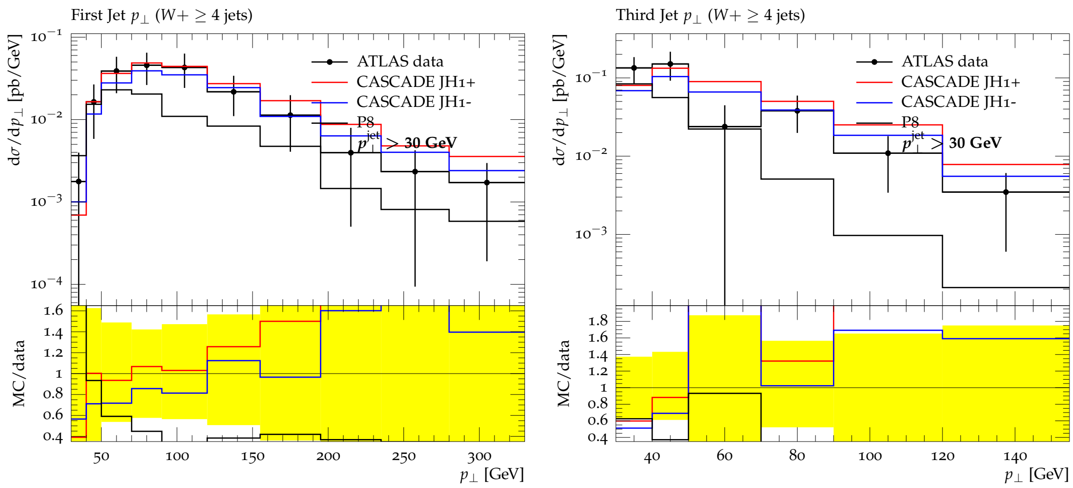


**Figure 3:** $W + 4$ jets production: (left) $p_\perp$ spectrum of the first jet; (right) $p_\perp$ spectrum of the third jet.

[6] S. Catani et al., Phys. Lett. B**242** (1990) 97; Nucl. Phys. B**366** (1991) 135; Phys. Lett. B**307** (1993) 147; S. Catani and F. Hautmann, Phys. Lett. B**315** (1993) 157; Nucl. Phys. B**427** (1994) 475.

[7] M. Ciafaloni, Nucl. Phys. **B296** (1988) 49, S. Catani, F. Fiorani and G. Marchesini, Nucl. Phys. **B336** (1990) 18, G. Marchesini, Nucl. Phys. **B445** (1995) 49.

[8] S. Dooling et al., arXiv:1304.7180 [hep-ph]; Phys. Rev. D**87** (2013) 094009; F. Hautmann and H. Jung, Nucl. Phys. Proc. Suppl. **234** (2013) 51; Eur. Phys. J. C **72** (2012) 2254.

[9] ATLAS Coll. (G. Aad et al.), Phys. Rev. D **86** (2012) 014022; CMS Coll. (S. Chatrchyan et al.), Phys. Rev. D**87** (2013) 112002; Phys. Rev. Lett. **107** (2011) 132001.

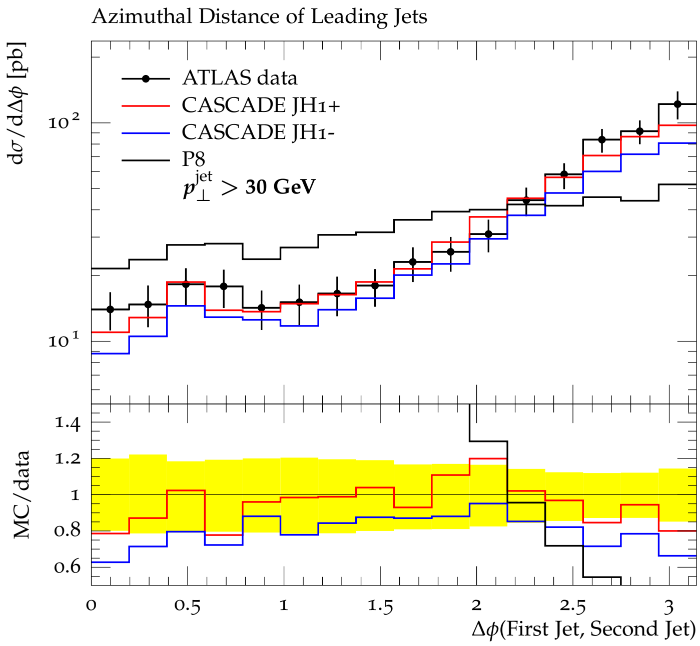


**Figure 4:** Azimuthal correlation of the first and second jet.


[10] F. Hautmann and H. Jung, in preparation.

[11] F. Hautmann, M. Hentschinski and H. Jung, Nucl. Phys. B**865** (2012) 54.

[12] R.D. Ball and S. Marzani, Nucl. Phys. B**814** (2009) 246.

[13] A.V Bogdan and V.S. Fadin, Nucl. Phys. B**740** (2006) 36.

[14] L.N. Lipatov and M.I. Vyazovsky, Nucl. Phys. B**597** (2001) 399.

[15] F. Hautmann and H. Jung, in preparation; arXiv:1206.1796 [hep-ph].

[16] F. Aaron *et al.*, JHEP **1001** (2010) 109, arXiv:0911.0884 [hep-ex].

[17] H. Jung et al., Eur. Phys. J. C **70** (2010) 1237.

[18] G. Aad et al. (ATLAS Coll.), arXiv:1301.6872 [hep-ex].

[19] P. Bartalini (CMS Coll.), talk at MPI at TAU, 2012.

[20] T. Sjöstrand, S. Mrenna and P. Skands, Comput. Phys. Commun. **178** (2008) 852.

[21] G. Aad et al. (ATLAS Coll.), Phys. Rev. D **85** (2012) 092002.

[22] P. Nason and B.R. Webber, Ann. Rev. Nucl. Part. Sci. **62** (2012) 187.


PoS(DIS 2013)157