PROCEEDINGS OF SCIENCE

Vector boson plus jets production in the TMD formalism

F. Hautmann
Physics and Astronomy, University of Sussex, Brighton BN1 9QH
Rutherford Appleton Laboratory, Chilton OX11 0QX
Theoretical Physics, University of Oxford, Oxford OX1 3NP
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 study final-state distributions for W-bosons plus jets at the LHC using transverse momentum dependent (TMD) parton density functions recently determined from fits to high-precision DIS data.

Photon 2013,
20-24 May 2013
Paris, France

`http://pos.sissa.it/`

High-mass final states with large jet multiplicity are central to many aspects of the Large Hadron Collider (LHC) physics program. Baseline predictions for these processes depend on perturbative hard-scattering matrix elements, combined with parton shower event generators. In typical applications, the matrix elements are either multi-leg tree-level matrix elements, or next-to-leading-order matrix elements including virtual emission processes, or possibly, in the future, a combination of both (see e.g. [1, 2] for recent references and reviews). 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] and references therein). Examples of such correlations in multi-jet deep inelastic scattering (DIS) final states are studied in [4]. Here it is observed that the DIS multi-jet measurements [5] enter a kinematic region in x and $\Delta\phi$, where x is the longitudinal momentum fraction and $\Delta\phi$ is the azimuthal separation between leading jets, in which NLO predictions (e.g. by the NLOJET [6] event generator), while describing reliably inclusive jet rates, are affected by large theoretical uncertainties for jet correlations, and that these uncertainties are underestimated by the standard method of varying renormalization and factorization scales around a central value. On the other hand, resummation by collinear parton showering methods (e.g. by HERWIG [7]) is not sufficient to describe the shape of the jet angular distributions.

As was noted already long ago in [8], these high-energy effects on final-state distributions can be taken into account by treating the QCD evolution of the initial-state parton distributions via transverse-momentum dependent branching algorithms coupled [9] to hard matrix elements at fixed transverse momentum. This allows one to include soft gluon coherence [10] not only for collinear-ordered emissions but also in the non-ordered region that opens up at high $\sqrt{s}/p_{\perp}$ and large $p_{\perp}$. For the kinematic region of DIS multi-jets [5] it is found [4] that sizeable multi-parton emission contributions arise from regions 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. By taking these contributions into account, calculations [4] based on transverse-momentum dependent branching give results similar to NLO perturbation theory, where this is applicable, and are much closer to angular correlation measurements [5] in a region where significant higher-order terms are expected.

Besides the dynamical effects described above, it has recently been pointed out [11, 12] that including the correct transverse momentum kinematics in branching algorithms gives rise to non-negligible kinematic shifts in longitudinal momentum distributions compared with collinear approximations. This effect is found [11] to contribute a large fraction of parton showering corrections relevant both for jets [13] and for massive final states at the LHC.

Both these dynamical and kinematical considerations motivate the present investigation of vector bosons plus jets final states at the LHC. To do this, we rely on our recent study of the high-precision deep inelastic scattering (DIS) combined data [14, 15], in which the first determination of the transverse momentum dependent (TMD) gluon density function [16, 17] has been made including theoretical and experimental uncertainties, based on QCD high-energy factorization [9] at fixed transverse momentum and CCFM evolution [10]. In this theoretical framework, Ref. [16] performs fits to the precision measurements of the F_2 structure function [14] in the range $x < 0.005$, $Q^2 > 5$ GeV^2, and the precision measurements of the charm structure function $F_2^{(\mathrm{charm})}$ [15] in the range $Q^2 > 2.5\ \text{GeV}^2$. Good fits to F_2 and $F_2^{(\text{charm})}$ are obtained, and based on these the TMD gluon distribution is determined at the initial evolution scale. The best fit to $F_2^{(\text{charm})}$ gives χ^2 per degree of freedom $\chi^2/ndf \simeq 0.63$, and the best fit to F_2 gives $\chi^2/ndf \simeq 1.18$. To carry out this analysis the paper [16] develops a parton branching Monte Carlo implementation of the CCFM evolution equation based on [8], which is made available within the `herafitter` program [14, 18]. The results of [16] indicate that, despite the limited kinematic range, the great precision of the combined data [14, 15] provides a compelling test of the approach — in particular, of both the transverse momentum and the polarization dependence of the TMD gluon density at small x.

To treat the Drell-Yan (DY) vector boson production and compute predictions for W-boson + jets final states, we use the TMD gluon and valence quark distributions obtained in [16] from DIS (with valence quarks taken into account according to the method [19]), convoluted with high-energy matrix elements [20, 21] with off-shell partons [22, 23] for weak boson production. We observe that the production of final states with W boson and multiple jets at the LHC receives contributions from a non-negligible fraction of events with large separations in rapidity between final-state particles [24]. This calls for parton branching methods beyond the collinear approximation [8], and suggests the application of the results [16]. On the other hand, the average values of x in the W-boson + jets cross sections at the LHC are not very small. Thus to study such cross sections means to push the limits of the approach [16], and it amounts to probing the method in a region where its theoretical uncertainties increase, and where the DIS experimental data [14, 15] do not constrain well the TMD gluon distribution. We come back to this below.

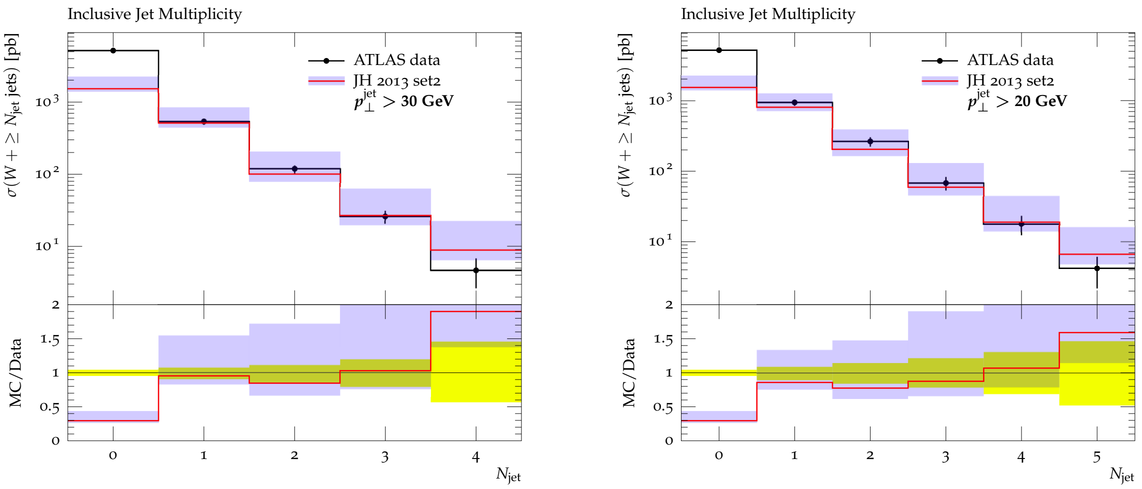

Figure 1: *Inclusive jet multiplicities associated with W-boson production at the LHC, using the TMD gluon density JH-2013-set2 [16]: (left) $p_\perp^{(\text{jet})} > 30$ GeV; (right) $p_\perp^{(\text{jet})} > 20$ GeV. The experimental data are from [25]. The yellow band is the experimental uncertainty. The blue band is the theory uncertainty.*

Fig. 1 shows results for the inclusive jet multiplicity distributions, for different values of the minimum jet transverse momentum. The measurements [25] of the jet multiplicities are well described, within the uncertainties, by the predictions based on the TMD gluon density JH-2013-set2 [16] obtained from DIS precision data and high-energy factorization. For comparison, it is noted in [24] that the $p_\perp$-ordered PYTHIA shower [26] cannot reproduce these distributions in the region of high jet multiplicities. The theoretical uncertainties, represented by the blue band, come from the treatment of the TMD distribution [16] and they are large, in particular larger than the experimental uncertainties. This reflects the fact that this observable is sensitive to the region of medium to large x.

The dominant uncertainty comes from variation of the factorization scale. This is varied by a factor of 2 above and below a central value, which depends on both the W mass and the transverse momentum. Conservatively, the variation is applied to both these contributions.

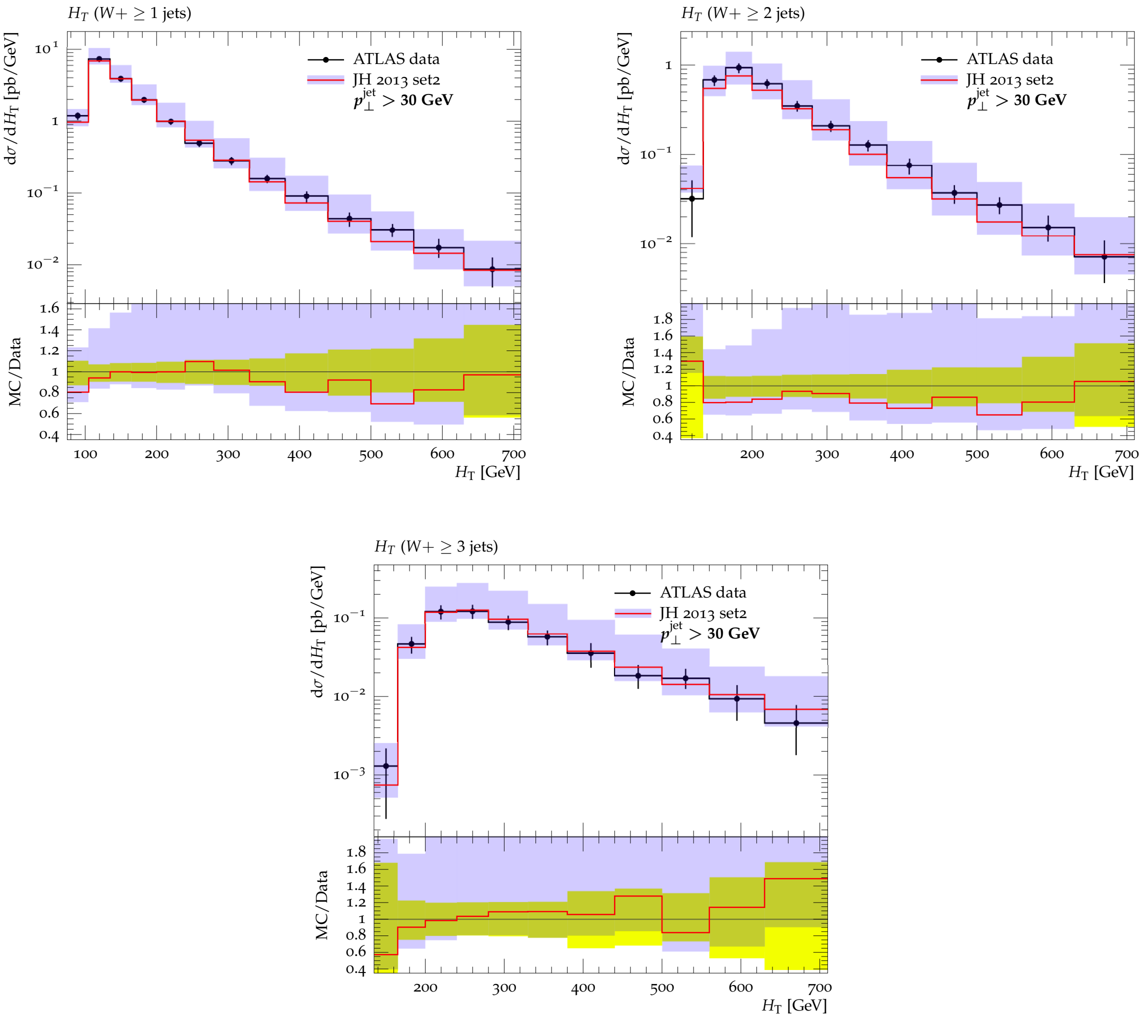

Figure 2: *Total transverse energy H_T distribution in final states with W-boson + n jets at the LHC, for $n \geq 1$, $n \geq 2$, $n \geq 3$. The experimental data are from [25]. The yellow band is the experimental uncertainty. The blue band is the theory uncertainty.*

Fig. 2 shows the total transverse energy distribution H_T for production of W-boson $+n$ jets, for different values of the number of of jets n: $n \geq 1$, $n \geq 2$, $n \geq 3$. In this case also we see that the main features of the final states are described by the predictions, including high jet multiplicities.

We next consider the p_T spectra of the individual jets. Fig. 3 shows the spectra of the leading jet for W-boson + n jets, with n from 1 to 4. The description of the measurements [25] is satisfactory

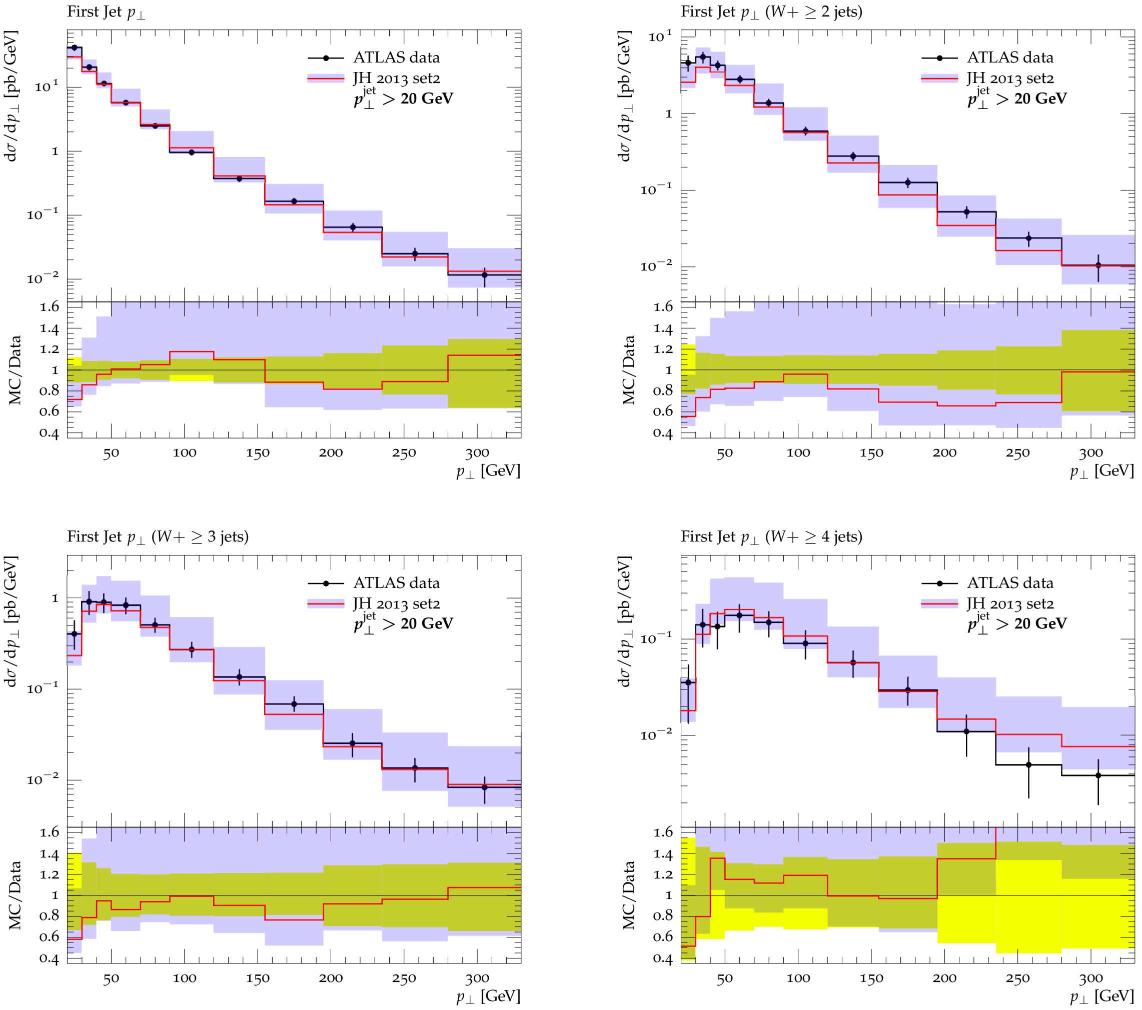

Figure 3: *Leading jet p_T spectra in W-boson + n jets at the LHC, for different jet multiplicities. The experimental data are from [25]. The yellow band is the experimental uncertainty. The blue band is the theory uncertainty.*

throughout the p_T range. In contrast, it is noted in [24] that the leading order PYTHIA [26] result starts to deviate from the measurements in the high-p_T region of these spectra, implying that in this framework the description of the high $p_\perp$ region is to be improved by supplementing the parton shower with next-to-leading-order corrections to the matrix element, e.g. via matched NLO-shower calculations [27] such as POWHEG. The TMD approach, in contrast, including at the outset large-angle, finite-$k_\perp$ emissions [4, 28], can describe the shape of the spectrum also at large transverse momentum.

Figs. 4 and 5 look into the structure of the multi-jet final states in closer detail by examining the $p_\perp$ spectra of the second jet and the third jet associated with W production. It is interesting that not only the leading jet and the global distribution of transverse energy in Figs. 3 and 2 are well described but also the detailed shapes of the subleading jets in Figs. 4 and 5 can be obtained from the TMD formalism's predictions, even though these are evaluated in a large-x region where their

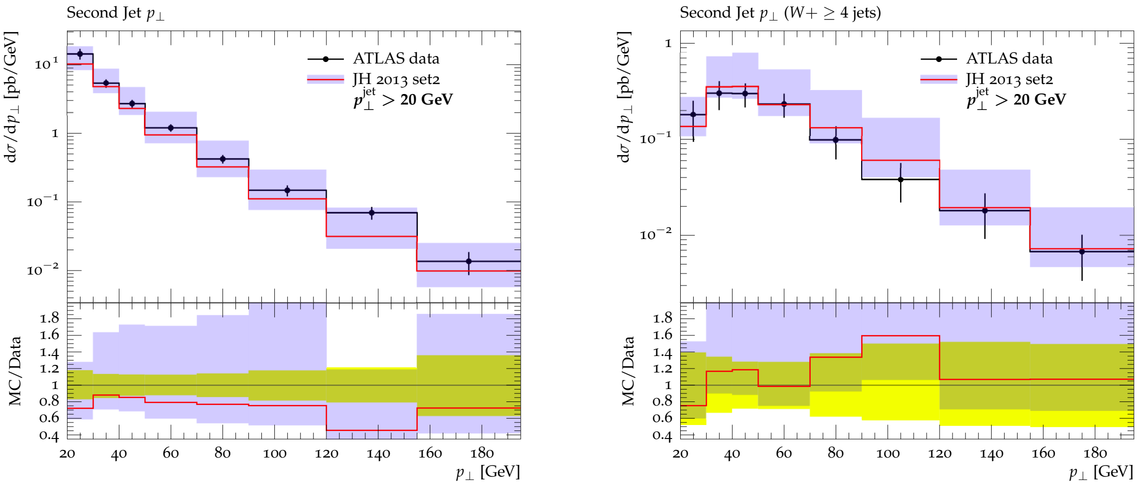

Figure 4: *Transverse momentum spectra of the second jet associated with W-bosons: (left) inclusive; (right) $n \geq 4$. The experimental data are from [25]. The yellow band is the experimental uncertainty. The blue band is the theory uncertainty.*

accuracy is expected to decrease, and both the theoretical and the experimental uncertainties on the transverse momentum dependence of the initial-state parton distributions are large.

In conclusion, we recall that vector boson plus jet final states are important for the LHC program of Standard Model (SM) physics, and as a background to searches for signals of physics beyond the SM. They are a benchmark process for QCD studies of multi-parton interactions [29], and may help shed light on topical issues in the physics of forward jet production [30]. The work presented in this article studies W-boson + n-jet processes by taking into account soft but finite-angle multi-gluon emission via QCD high-energy factorization and evolution. Such effects go beyond next-to-leading-order perturbation theory matched with collinear parton showers (see e.g. [31]), and give potentially significant higher-order radiative effects to multi-jet distributions in the high-energy limit. The calculations in this article use the transverse momentum dependent gluon density function recently determined from fits to high-precision DIS measurements [16]. Although affected by sizeable theoretical and experimental uncertainties, the use of this TMD density in the comparison with the LHC W + n-jet data indicates that detailed features of the associated final states can be obtained both for the leading jet and the subleading jets, and emphasizes the consistency of the physical picture, which can be extended from DIS to Drell-Yan processes to describe QCD multi-jet dynamics. It also points to the relevance of Monte Carlo event generators which aim at including parton branching at transverse momentum dependent level (see e.g. [32, 33]). Future applications may employ vector boson pp data to advance our knowledge of transverse momentum parton distributions [18, 34]. Also, a program combining Drell-Yan and Higgs measurements may be viable at high luminosity [35] to carry out precision QCD studies accessing gluon transverse momentum and polarization distributions [35, 36, 37].

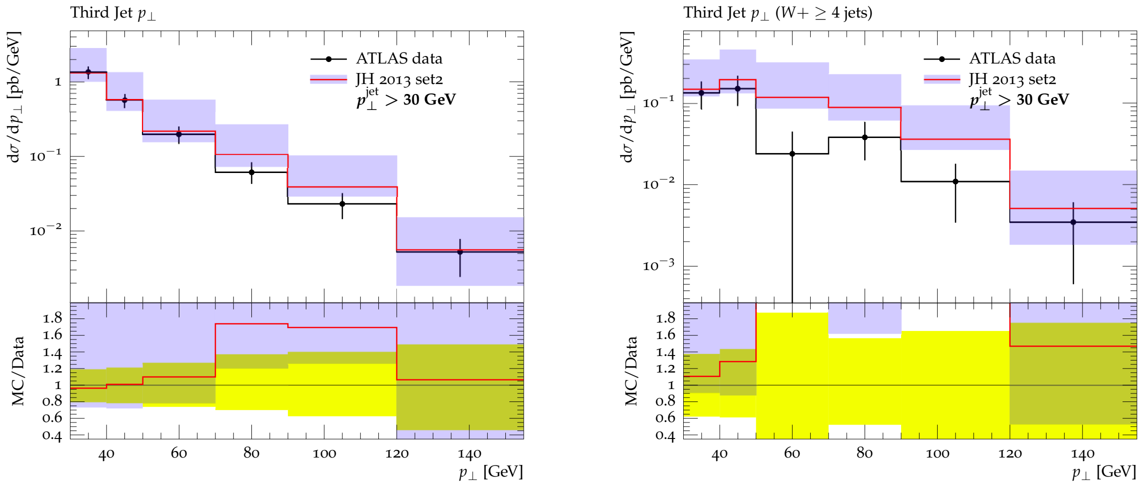

Figure 5: *Transverse momentum spectra of the third jet associated with W-bosons: (left) inclusive; (right) $n \geq 4$. The experimental data are from [25]. The yellow band is the experimental uncertainty. The blue band is the theory uncertainty.*

References

[1] S. Plätzer, arXiv:1307.0774 [hep-ph]; arXiv:1211.5467 [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:0712.0568; arXiv:0804.1746 [hep-ph].

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

[6] Z. Nagy and Z. Trocsanyi, Phys. Rev. Lett. **87** (2001) 082001 [arXiv:hep-ph/0104315].

[7] G. Corcella *et al.*, JHEP **0101** (2001) 010 [arXiv:hep-ph/0011363]; G. Corcella *et al.*, arXiv:hep-ph/0210213.

[8] G. Marchesini and B.R. Webber, Nucl. Phys. **B386** (1992) 215, Nucl. Phys. **B349** (1991) 617.

[9] 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.

[10] 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.

[11] S. Dooling et al., Phys. Rev. D**87** (2013) 094009; arXiv:1304.7180 [hep-ph]; PoS DIS2013 (2013) 156.

[12] F. Hautmann and H. Jung, Eur. Phys. J. C **72** (2012) 2254; Nucl. Phys. Proc. Suppl. **234** (2013) 51; F. Hautmann, arXiv:1304.8133 [hep-ph].

[13] 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.

[14] F. Aaron *et al.*, JHEP **1001** (2010) 109.

[15] H. Abramowicz *et al.*, Eur. Phys. J. C **73** (2013) 2311.

[16] F. Hautmann and H. Jung, arXiv:1312.7875 [hep-ph].

[17] F. Hautmann and H. Jung, PoS DIS2013 (2013) 053; arXiv:1206.1796 [hep-ph].

[18] "HERAFitter" (2012), https://www.herafitter.org/; F. Aaron *et al.*, Eur. Phys. J. **C64** (2009) 561; F. James and M. Roos, Comput. Phys. Commun. **10** (1975) 343.

[19] M. Deak, F. Hautmann, H. Jung and K. Kutak, arXiv:1012.6037 [hep-ph]; Eur. Phys. J. C **72** (2012) 1982; arXiv:1206.7090 [hep-ph]; PoS ICHEP2010 (2010) 108.

[20] R.D. Ball and S. Marzani, Nucl. Phys. B**814** (2009) 246; arXiv:0906.4729 [hep-ph].

[21] F. Hautmann, M. Hentschinski and H. Jung, Nucl. Phys. B**865** (2012) 54; arXiv:1205.6358 [hep-ph]; arXiv:1207.6420 [hep-ph]; arXiv:1209.6305 [hep-ph].

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

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

[24] F. Hautmann and H. Jung, PoS DIS2013 (2013) 157.

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

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

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

[28] F. Hautmann, Acta Phys. Polon. B **40** (2009) 2139; PoS ICHEP2010 (2010) 150.

[29] G. Aad *et al.* (ATLAS Coll.), New. J. Phys. **15** (2013) 033038.

[30] F. Hautmann, Acta Phys. Polon. B **44** (2013) 761; arXiv:1205.5411 [hep-ph]; M. Grothe et al., arXiv:1103.6008 [hep-ph]; M. Deak et al., JHEP **0909** (2009) 121.

[31] S. Höche, F. Krauss, M. Schönherr and F. Siegert, Phys. Rev. Lett. **110** (2013) 052001.

[32] S. Jadach, M. Jezabek, A. Kusina, W. Placzek and M. Skrzypek, Acta Phys. Polon. B **43** (2012) 2067.

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

[34] S. Mert Aybat and T.C. Rogers, Phys. Rev. D**83** (2011) 114042.

[35] P. Cipriano et al., Phys. Rev. D**88** (2013) 097501.

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

[37] D. Boer et al., Phys. Rev. Lett. **108** (2012) 032002.

PoS(Photon 2013)003