# Azimuthal di-jet correlations with parton branching TMD distributions

A. Bermudez Martinez<sup>a</sup> and F. Hautmann<sup>b,c,d</sup>

<sup>a</sup>Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany
<sup>b</sup>CERN, Theoretical Physics Department, CH 1211 Geneva 23, Switzerland
<sup>c</sup>Elementaire Deeltjes Fysica, Universiteit Antwerpen, B 2020 Antwerpen, Belgium
<sup>d</sup>RAL, Chilton OX11 0QX and University of Oxford, Oxford OX1 3PU, UK

Presented at DIS2022: XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects, Santiago de Compostela, Spain, May 2-6 2022

# Abstract

The parton branching formulation of TMD evolution has recently been used to make predictions for jet observables at the Large Hadron Collider (LHC), including perturbative matching at next-to-leading order (NLO). This contribution presents results for the azimuthal  $\Delta \phi$ correlations in events with di-jets at large transverse momentum. It focuses on the back-toback region of large  $\Delta \phi$  and discusses prospects for detailed studies of QCD dynamics in this region at the LHC.

# 1 Introduction

Azimuthal correlations between two jets have been measured at the LHC by the ATLAS and CMS collaborations [1, 2, 3, 4, 5]. A detailed understanding of these correlations is important for studies of the Quantum Chromodynamics (QCD) sector of the Standard Model (SM) and searches for Beyond-the-SM (BSM) scenarios with di-jet signatures.

At leading order (LO) in the strong coupling  $\alpha_s$ , two jets are produced back-to-back, i.e., with azimuthal angle  $\Delta \phi = \pi$ . Deviations from this configuration measure higher-order QCD radiation. In the region near  $\Delta \phi = \pi$  this is primarily soft gluon radiation, while in the region of small  $\Delta \phi$  it is primarily hard QCD radiation. Since initial-state parton radiation moves the jets away from the  $\Delta \phi = \pi$  region, it is relevant to investigate the influence of transverse momentum recoils in the QCD showers [6, 7, 8], taken into account via transverse momentum dependent (TMD) [9] parton distributions, on the description of the  $\Delta \phi$  measurements.

In this article we discuss this by using the Parton Branching (PB) approach [10, 11] to TMD distributions. This approach has successfully been used at next-to-leading order (NLO) to extract TMD parton distributions [12] from precision deep-inelastic data [13] using xFitter [14, 15] (results are available from the repository [16, 17]). It has also been successfully used to make predictions for Drell-Yan transverse momentum spectra both at the LHC [18] and in lower energy experiments [19]. We here apply this approach to di-jet production, presenting results from the work in Ref. [20]. We compute predictions for di-jet azimuthal correlations, using the PB TMD evolution matched with NLO perturbative matrix elements.

In the region near the back-to-back configuration the QCD Sudakov process depends on the soft function [21]. Unlike the case of Drell-Yan di-lepton production, factorization breaking effects [22, 23, 24] can arise in the case of di-jets due to long-timescales soft-gluon correlations between initial and final states. We examine the possibility of investigating these effects with high transverse momentum jets at the LHC.

The article is organized as follows. In Sec. 2 we briefly describe the main elements of the PB TMD calculation at NLO. In Sec. 3 we illustrate the results for di-jet azimuthal distributions, and compare them with LHC experimental measurements. Conclusions are given in Sec.4.

# 2 NLO matching with PB TMD

The PB approach [10, 11] provides evolution equations for TMD distributions in terms of Sudakov form factors and splitting probabilities, and a corresponding TMD parton shower in a backward evolution scheme. PB TMD distributions and parton showers are implemented in the Monte Carlo event generator CASCADE3 [25].

A method to match TMD evolution with NLO perturbative matrix elements has been developed for the case of the Drell-Yan process in Refs. [18, 19] using the framework of MAD-GRAPH5\_AMC@NLO [26]. We next apply this method to the case of the jet production process [20], matching PB TMD distributions and parton showers with di-jet NLO matrix elements from MADGRAPH5\_AMC@NLO. Further details on the NLO matching method with PB TMD are given in Ref. [27], where a comparison of MCatNLO+CASCADE3 [25] and MCatNLO+HERWIG6 [28] matching is performed.

Fig. 1 illustrates the result of applying the matching method. It shows the differential distribution in the azimuthal angle  $\Delta \phi$  between the two leading jets as obtained from the calculations at fixed NLO (blue curve), at the (unphysical) level including the subtraction terms from the matching (LHE level, green curve), and after inclusion of PB TMDs (red curve). We observe the rising cross section of the fixed NLO calculation towards large  $\Delta \phi$  (corresponding to the divergent behavior of the NLO calculation in the back-to-back configuration), the decay towards large  $\Delta \phi$ once the subtraction terms are included, and the smooth prediction once the TMD distributions and showers are included.

#### 3 Di-jet azimuthal distributions

We now use the method of the previous section to compute NLO-matched PB TMD predictions for di-jet distributions in the phase space of the CMS measurements [4, 5].

We consider selection cuts for leading jets with transverse momentum  $p_T > 200$  GeV and  $p_T > 1000$  GeV. With this event selection one is able to explore TMD dynamical effects over a broad range both in the transverse momentum of the TMD distribution, set by the  $p_T$  imbalance between the jets, and in its evolution scale, set by the hard scale of the event, e.g. the leading jet  $p_T$ . In particular, in a neighborhood of order 0.1 rad from  $\Delta \phi = \pi$ , the  $p_T$  imbalance ranges from a few ten GeV for the highest  $p_T$  jets down to few GeV. At large  $p_T$  imbalance, the evolution of the transverse momentum is dominated by perturbative contributions to the evolution kernels and can be explored through directly measurable jets, while at lower  $p_T$  imbalance both perturbative and non-perturbative components can be investigated.

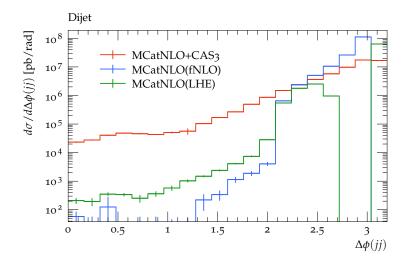


Figure 1: Azimuthal  $\Delta \phi$  distributions obtained from the fixed NLO calculation (MCatNLO(fNLO)), the (unphysical) LHE level (MCatNLO(LHE)), and after inclusion of PB TMDs (MCatNLO+CAS3) [20].

In Fig. 2 we report the NLO-matched PB TMD results (labelled MCatNLO+CAS3), together with CMS data [4, 5] and collinear shower calculations from MCatNLO+PYTHIA8 [29]. The shape of the  $\Delta\phi$  distribution is different between the TMD and collinear shower calculations, emphasizing the relevance of the detailed dynamics of QCD shower evolution. The uncertainty bands on the MCatNLO+CAS3 predictions are obtained from scale variations and TMD uncertainties [20]. The uncertainty bands on the MCatNLO+PYTHIA8 predictions are obtained from scale and associated shower variations according to the method of [30] together with the guidelines of [31]. For the MCatNLO+PYTHIA8 calculation the effect of multi-parton interactions (MPI) is also shown, using the parameters of the tune CUETP8M1 [32]. For leading jet  $p_T > 200$  GeV, the MPI effect is not large.

MCatNLO+CAS3 describes the measurements well at large and intermediate  $\Delta \phi$ . In the decorrelated region at low  $\Delta \phi$  a deficit is observed. This is due to missing higher-order contributions from multiple QCD emissions beyond NLO. To take these contributions into account, one needs to go beyond the framework of the present calculation, for example by employing TMD multi-jet merging techniques [33, 34].

In Fig. 3 we focus on the large  $\Delta \phi$  region of nearly back-to-back jets. This region is of special interest, as possible factorization-breaking effects have long been conjectured to arise for back-to-back jets due to soft-gluon interactions between initial and final states. We see from Fig. 3 that the measurements are well described by the MCatNLO+CAS3 predictions. Only in the highest bin  $(\Delta \phi > 179^{\circ})$  a deviation of about 10% is observed. Detailed phenomenological studies in this region are warranted, using fine binning in angle.

As discussed in Ref. [27], further insight may be gained from the combined analysis of  $\Delta \phi$  correlations in di-jet and Z-boson + jet events. At low  $p_T$  the boson-jet state is more strongly correlated azimuthally than the jet-jet state, while for  $p_T$  far above the electroweak scale the behaviors become more similar. This can be connected to features of the partonic initial-state and final-state radiation in the boson-jet and jet-jet cases. Initial-state and final-state radiation (see the recent studies [35, 36] in the Z + jet process) may give rise to color interferences and potential factorization-breaking effects [22, 24, 37]. If so, different breaking patterns can be expected

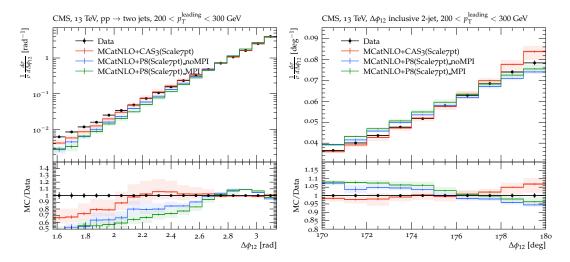


Figure 2: Azimuthal correlation over a wide  $\Delta \phi$  range (left) and in the back-to-back region (right) [20]. CMS data [4, 5] are compared with results from MCatNLO+PYTHIA8 and MCatNLO+CAS3.

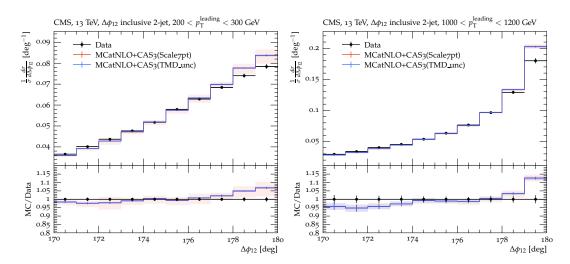


Figure 3: Azimuthal correlation in the back-to-back region for leading jet  $p_T > 200$  GeV (left) and  $p_T > 1000$  GeV (right) as measured by CMS [5] compared with predictions from MCatNLO+CAS3 [20]. Shown are the uncertainties coming from the scale variation as well as the uncertainties coming from the TMD.

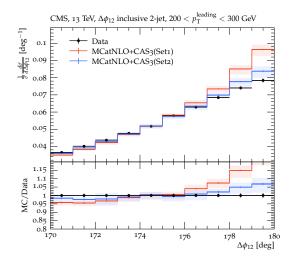


Figure 4: Impact of the transverse momentum  $q_T$  scale in the running coupling at large  $\Delta \phi$  [20]. As discussed in the text, the  $q_T$  scale is used in the result Set 2, not in the result Set 1.

for strong and weak azimuthal correlations, influencing differently the boson-jet and jet-jet cases. Systematic measurements of di-jet and *Z*-boson + jet distributions are thus proposed [27], scanning the phase space from low transverse momenta  $p_T \approx \mathcal{O}(100 \text{ GeV})$  to high transverse momenta  $p_T \approx \mathcal{O}(1000 \text{ GeV})$ .

Fig. 4 illustrates another aspect of the QCD dynamics in the back-to-back region, namely, the sensitivity to soft-gluon angular ordering [38, 39, 40, 41] in the TMD evolution [11, 42]. The MCatNLO+CAS3 curves labelled Set1 and Set 2 in Fig. 4 refer to two sets of PB TMD distributions [12] differing by the scale in the QCD running coupling: Set 2 fulfills the soft-gluon angular ordering conditions by using the transverse momentum emitted at each branching as a scale for  $\alpha_s$ , while Set 1 uses the branching scale as a scale for  $\alpha_s$ , as in DGLAP ordered evolution. We see that the shape of the azimuthal correlation is sensitive to angular ordering effects in the back-to-back region. Set 2 provides a better description of the measurements in this region.

# 4 Conclusion

In this article we have discussed predictions from PB TMD parton showers for final state observables in jet production at the LHC, focusing on the azimuthal correlations of jets with large transverse momenta.

The PB TMD shower matched with NLO calculations provides a good description of experimental measurements of di-jet production at the LHC in the correlation region of high azimuthal separations  $\Delta \phi$  between the jets, down to the region of intermediate  $\Delta \phi$ . The shape of the  $\Delta \phi$ distribution is sensitive to the detailed dynamics of the shower evolution. We have studied effects of TMD versus collinear shower and of soft-gluon angular ordering.

In the back-to-back region near  $\Delta \phi = \pi$ , potential factorization breaking contributions can arise due to colored final states. We have discussed that these effects can be explored through future dedicated measurements with large- $p_T$  jets and fine binning in  $\Delta \phi$ .

In the decorrelated region of low  $\Delta \phi$ , we observe a deficit in the predictions due to missing

higher-order contributions from multiple QCD emissions beyond NLO. Including multiple emissions requires further methodologies, for instance multi-jet merging [34], which have not yet been applied here.

Given the observed sensitivity of the  $\Delta \phi$  distribution to angular ordering, it will be of interest to include recent developments of TMD branching such as the parton distribution fits with angular-ordered resolution scale [43]. Also, it will be relevant to investigate the role of the recently proposed branching with TMD splitting functions [44] on the azimuthal asymmetries.

# Acknowledgments

The results discussed in this contribution are based on the work in Ref. [20]. Many thanks to all co-authors for collaboration. We are grateful to the organizers of DIS2022 for the invitation to present these results at the workshop.

# References

- [1] ATLAS Coll., Phys.Rev.Lett. 106 (2011) 172002 [arXiv:1102.2696 [hep-ex]].
- [2] CMS Coll., Phys. Rev. Lett. 106 (2011) 122003 [arXiv:1101.5029 [hep-ex]].
- [3] CMS Coll., Eur. Phys. J. C 76 (2016) 536 [arXiv:1602.04384 [hep-ex]].
- [4] CMS Coll., Eur. Phys. J. C 78 (2018) 566 [arXiv:1712.05471 [hep-ex]].
- [5] CMS Coll., Eur. Phys. J. C 79 (2019) 773 [arXiv:1902.04374 [hep-ex]].
- [6] F. Hautmann and H. Jung, JHEP 10 (2008) 113; arXiv:0804.1746 [hep-ph].
- [7] H. Jung et al., Eur. Phys. J. C 70 (2010) 1237 [arXiv:1008.0152 [hep-ph]].
- [8] S. Dooling et al., Phys. Rev. D 87 (2013) 094009 [arXiv:1212.6164 [hep-ph]].
- [9] R. Angeles-Martinez et al., Acta Phys. Pol. B 46 (2015) 2501 [arXiv:1507.05267].
- [10] F. Hautmann et al., Phys. Lett. B 772 (2017) 446 [arXiv:1704.01757 [hep-ph]].
- [11] F. Hautmann et al., J. High Energy Phys. 01 (2018) 070 [arXiv:1708.03279 [hep-ph]].
- [12] A. Bermudez Martinez et al., Phys. Rev. D99 (2019) 074008 [arXiv:1804.11152].
- [13] ZEUS, H1 Coll., H. Abramowicz et al., Eur. Phys. J. C75 (2015) 580 [arXiv:1506.06042].
- [14] S. Alekhin et al., Eur. Phys. J. C75 (2015) 304 [arXiv:1410.4412 [hep-ph]].
- [15] H. Abdolmaleki et al. [xFitter Developers' Team], arXiv:2206.12465 [hep-ph].
- [16] N. A. Abdulov et al., Eur. Phys. J. C 81 (2021) 752 [arXiv:2103.09741 [hep-ph]].
- [17] F. Hautmann et al., Eur. Phys. J. C 74 (2014) 3220 [arXiv:1408.3015 [hep-ph]].
- [18] A. Bermudez Martinez *et al.*, Phys. Rev. D **100** (2019) 074027 [arXiv:1906.00919].
- [19] A. Bermudez Martinez et al., Eur. Phys. J. C 80 (2020) 598 [arXiv:2001.06488 [hep-ph]].
- [20] M. I. Abdulhamid *et al.*, Eur. Phys. J. C **82** (2022) 36 [arXiv:2112.10465 [hep-ph]].
- [21] J.C. Collins and F. Hautmann, Phys. Lett. B 472 (2000) 129 [hep-ph/9908467].
- [22] T. C. Rogers and P. J. Mulders, Phys. Rev. D81 (2010) 094006 [arXiv:1001.2977].
- [23] W. Vogelsang and F. Yuan, Phys. Rev. D 76 (2007) 094013 [arXiv:0708.4398 [hep-ph]].
- [24] J. Collins and J.-W. Qiu, Phys. Rev. D75 (2007) 114014 [arXiv:0705.2141 [hep-ph]].
- [25] S. Baranov et al., Eur. Phys. J. C 81 (2021) 425 [arXiv:2101.10221 [hep-ph]].
- [26] J. Alwall et al., JHEP 1407 (2014) 079 [arXiv:1405.0301 [hep-ph]].
- [27] H. Yang et al., arXiv:2204.01528 [hep-ph].
- [28] G. Corcella *et al.*, hep-ph/0210213.

- [29] T. Sjöstrand et al., Comput. Phys. Commun. 191 (2015) 159 [arXiv:1410.3012 [hep-ph]].
- [30] S. Mrenna and P. Skands, Phys. Rev. D94 (2016) 074005 [arXiv:1605.08352 [hep-ph]].
- [31] L. Gellersen and S. Prestel, Phys. Rev. D101 (2020) 114007 [arXiv:2001.10746].
- [32] CMS Coll., Eur. Phys. J. C 76 (2016) 155 [arXiv:1512.00815 [hep-ex]].
- [33] A. Bermudez Martinez, F. Hautmann and M. L. Mangano, Phys. Lett. B 822 (2021) 136700 [arXiv:2107.01224 [hep-ph]].
- [34] A. Bermudez Martinez, F. Hautmann and M. L. Mangano, arXiv:2208.02276 [hep-ph]; arXiv:2109.08173 [hep-ph].
- [35] H. Bouaziz, Y. Delenda, and K. Khelifa-Kerfa, arXiv:2207.10147 [hep-ph].
- [36] Y.-T. Chien et al., arXiv:2205.05104 [hep-ph].
- [37] T. C. Rogers, Phys. Rev. D 88 (2013) 014002 [arXiv:1304.4251 [hep-ph]].
- [38] A. Bassetto, M. Ciafaloni, and G. Marchesini, Phys. Rept. 100 (1983) 201.
- [39] Y. L. Dokshitzer, V. A. Khoze, S. I. Troian, and A. H. Mueller, Rev. Mod. Phys. 60 (1988) 373.
- [40] G. Marchesini and B. R. Webber, Nucl. Phys. B **310** (1988)461.
- [41] S. Catani, B. R. Webber, and G. Marchesini, Nucl. Phys. B 349 (1991) 635.
- [42] F. Hautmann et al., Nucl. Phys. B949 (2019) 114795 [arXiv:1908.08524 [hep-ph]].
- [43] S. Sadeghi Barzani, arXiv:2207.13519 [hep-ph].
- [44] F. Hautmann et al., Phys. Lett. B 833 (2022) 137276 [arXiv:2205.15873 [hep-ph]].