Azimuthal di-jet correlations with parton branching TMD distributions

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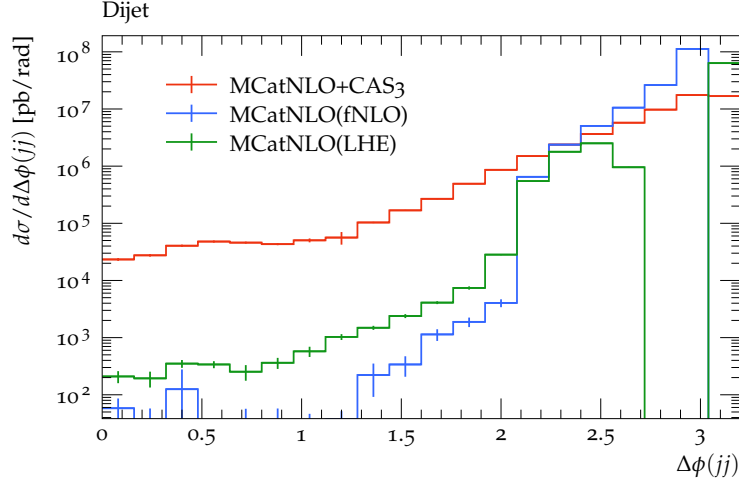
Figure 1: Azimuthal $\Delta\phi$ distributions obtained from the fixed NLO calculation (MCatNLO(fNLO)), the (unphysical) LHE level (MCatNLO(LHE)), and after inclusion of PB TMDs (MCatNLO+CAS3) [20].

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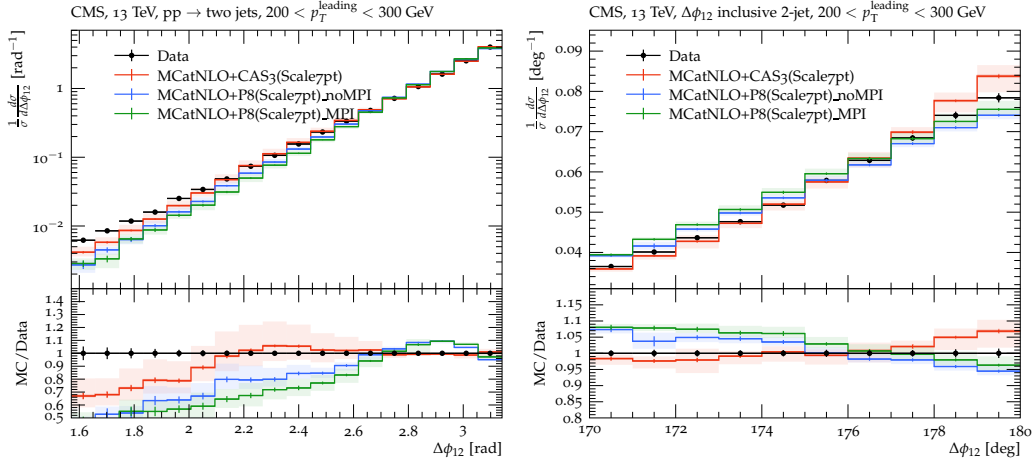
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Figure 2: Azimuthal correlation over a wide $\Delta\phi$ range (left) and in the back-to-back region (right) [20]. CMS data [4, 5] are compared with results from MCatNLO+PYTHIA8 and MCatNLO+CAS3.

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.

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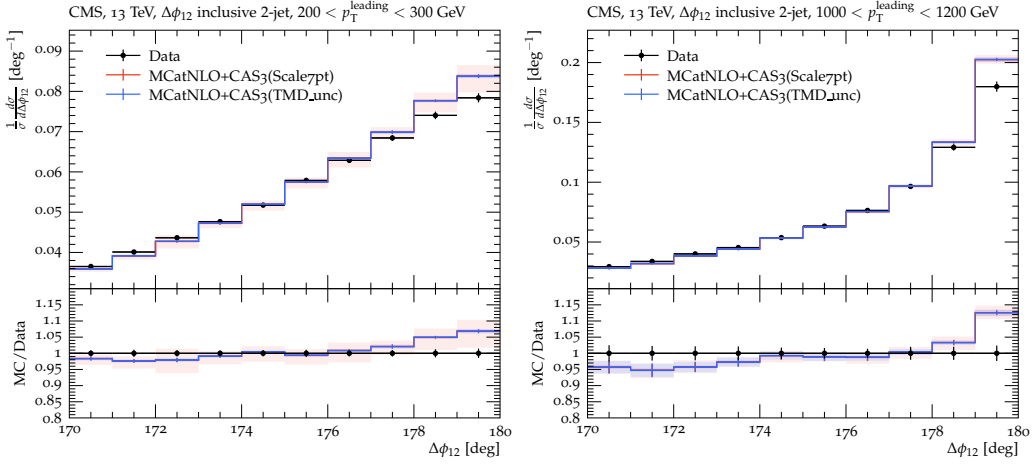
Figure 3: Azimuthal correlation in the back-to-back region for leading jet $p_T > 200$ GeV (left) and $p_T > 1000$ GeV (right) as measured by CMS [5] compared with predictions from MCatNLO+CAS3 [20]. Shown are the uncertainties coming from the scale variation as well as the uncertainties coming from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

the highest bin ($\Delta\phi > 179^o$) 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 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 $p_T \approx \mathcal{O}(100$ GeV$)$ to high transverse momenta $p_T \approx \mathcal{O}(1000$ 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 α_s, while Set 1 uses the branching scale as a scale for α_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
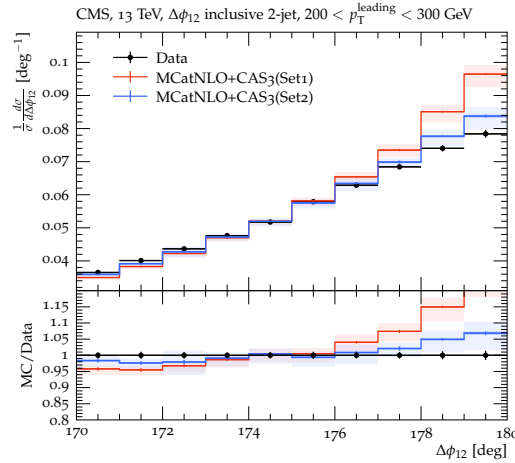
Figure 4: Impact of the transverse momentum q_T scale in the running coupling at large $\Delta\phi$ [20]. As discussed in the text, the q_T scale is used in the result Set 2, not in the result Set 1.

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

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