High-p_T Azimuthal Correlations of Z+jet and Multi-jet Production

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In this study, we present our latest findings regarding azimuthal distributions in vector boson + jets and multi-jet production at the Large Hadron Collider (LHC). These findings result from matching next-to-leading order (NLO) perturbative matrix elements with transverse momentum dependent (TMD) parton branching. We conduct a comprehensive comparative analysis of azimuthal correlations between Z boson-jet and jet-jet systems in the back-to-back region. These distinct azimuthal correlation patterns can help identify potential factorization-breaking effects in this region. Such effects depend on the different color and spin structures of the final states and their interactions with the initial states.

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1. Introduction

Experiments conducted at the Large Hadron Collider (LHC) involve precise measurements of azimuthal correlations within the context of Z bosons + jets [1–4] and multi-jet [5–9] final states. This comprehensive understanding of these correlations plays a pivotal role in advancing our knowledge of the Quantum Chromodynamics (QCD) sector within the framework of the Standard Model (SM). Additionally, it contributes to the exploration of potential scenarios Beyond-the-SM (BSM).

Azimuthal correlations between Z bosons and jets or multi-jets provide a sensitive probe of various QCD aspects. At leading order in the strong coupling α_s, these correlations exhibit a characteristic back-to-back configuration ($\Delta\phi \simeq \pi$), with deviations indicating higher-order QCD radiation. The $\Delta\phi \simeq \pi$ region mainly involves soft gluon radiation, while smaller $\Delta\phi$ regions are associated with hard QCD radiation. The large-$\Delta\phi$ region, where the probed outgoing products are nearly back-to-back, is influenced by both perturbative and non-perturbative QCD contributions, with the balance dependent on the transverse momentum imbalance between the studied products. The resummation of soft multi-gluon emissions in this region allows the probing of initial state parton transverse momenta, described by transverse momentum-dependent (TMD) parton distribution functions (PDFs) [10]. Recent theoretical predictions for Z boson + jet production, including soft gluon resummation, have been presented [11–13].

In Ref. [14], we explored the $\Delta\phi_{12}$ correlation in high-p_T multi-jet events, employing TMD PDFs, parton showers, and NLO calculations. We also highlight the relevance of multi-jet events in studying azimuthal correlations, as they provide sensitivity to factorization-breaking effects [15–17], particularly in the presence of colored final states. We propose a systematic comparison between the azimuthal correlation $\Delta\phi_{12}$ in multi-jet and Z+jet production, extending the investigation of azimuthal correlations in Z+jet events, as discussed in Ref. [12], which addresses factorization-breaking.

In Ref. [18], we offered a detailed comparison of high-p_T multi-jet and Z+jet production using the PB TMD method [19–21] matched with NLO calculations. Our multi-jet study [14] demonstrated that NLO PB TMD predictions accurately describe multi-jet azimuthal correlations [22, 23]. In Ref. [18], we extend the same method to calculate Z+jet production and present corresponding predictions. By employing the same kinematic region for high-p_T multi-jet and Z+jet production, we enable a direct comparison of angular observables between the two cases.

2. NLO matching with PB TMD

The PB approach [19–21] 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 [24].

A method to match TMD evolution with NLO perturbative matrix elements has been developed for the case of the Drell-Yan process in Refs. [25, 26] using the framework of MAD-GRAPH5_AMC@NLO [27]. We next apply this method to the case of the jet production process [14], matching PB TMD distributions and parton showers with multi-jet NLO matrix elements

from MADGRAPH5_AMC@NLO. Further details on the NLO matching method with PB TMD are given in Ref. [18], where a comparison of MCatNLO+CASCADE3 [24] and MCatNLO+HERWIG6 [28] matching is performed.

3. Azimuthal correlations in Z+jet and multi-jet production

In Fig.1, we present the results of our matching method. Specifically, we display the predicted azimuthal correlations $\Delta\phi_{Zj}$ for Z+jet production in the back-to-back region. To provide context, we also include predictions for azimuthal correlations $\Delta\phi_{12}$ in multi-jet production within the same kinematic region. These predictions are compared to multi-jet production measurements obtained by CMS [23]. Our findings reveal that the $\Delta\phi_{Zj}$ distribution in Z+jet production, for $p_T^{\text{leading}} > 200$ GeV, exhibits a stronger correlation towards π in comparison to the $\Delta\phi_{12}$ distribution in multi-jet production. This discrepancy diminishes for $p_T^{\text{leading}} > 1000$ GeV.

Variations in $\Delta\phi$ between Z+jet and multi-jet production arise from differences in the initial state's flavor composition, transverse momenta, and parton showers. These distinctions also result from variations in final state showering due to the differing numbers of colored final state partons. Factorization-breaking effects, caused by interference between initial and final state partons, depend on the final state's structure and the number of colored final state partons.

Another key point regarding Fig.1 is the strong agreement between multi-jet production measurements and MCatNLO+CAS3 predictions, as extensively discussed in Ref.[14]. Notably, this agreement holds for most cases, except at very high p_T^{leading}, where a deviation from measurements appears. This discrepancy might indicate a factorization violation. Thus, it is crucial to measure $\Delta\phi$ distributions in other factorization-consistent processes.
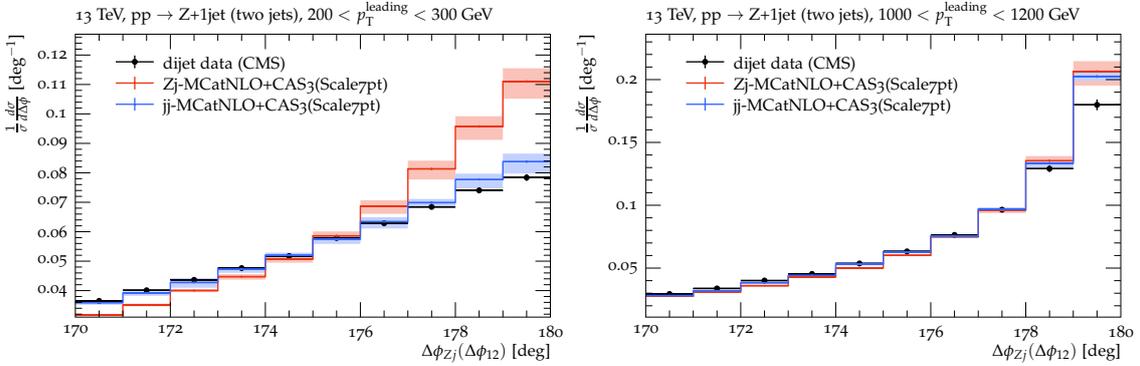
Figure 1: Azimuthal correlation predictions ($\Delta\phi_{Zj}$ and $\Delta\phi_{12}$) for Z+jet and multi-jet processes are shown in the back-to-back region, both for $p_T^{\text{leading}} > 200$ GeV (left) and $p_T^{\text{leading}} > 1000$ GeV (right). These predictions use the MCatNLO+CAS3 framework, with depicted uncertainties from scale variation. We include CMS multi-jet correlation measurements [23] for reference.

Our findings reveal that, in the region of leading transverse momenta around $p_T \approx \mathcal{O}(100)$ GeV, the boson-jet final state exhibits stronger azimuthal correlations than the jet-jet final state. As transverse momenta increase beyond the electroweak symmetry breaking scale ($p_T \approx \mathcal{O}(1000)$ GeV), this difference diminishes, and the boson-jet and jet-jet correlations become more similar.

We attribute this behavior to the characteristics of partonic initial state and final state radiation in both cases. As potential factorization-breaking effects arise from color interferences of initial-state and final-state radiation, different breaking patterns are expected for strong and weak azimuthal correlations, impacting the boson-jet and jet-jet cases differently. Consequently, we advocate for a systematic comparison of multi-jet and Z+jet distributions, spanning 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).

Assessing the impact of final state radiation on the $\Delta\phi_{12}$ correlations proves challenging, as the subtraction terms in the NLO matrix element computation are also contingent on the final state parton shower characteristics. To gauge the influence of final state showering, we compare $\Delta\phi_{12}$ correlation calculations in the back-to-back region achieved through two methods: MCatNLO+CAS3 and MCatNLO+Pythia8 (as displayed in Fig.2). In the MCatNLO+Pythia8 calculation, we incorporate Pythia8's subtraction terms into the MadGraph5_aMC@NLO framework, utilize NNPDF3.0 parton density, and tune CUETP8M1 [29].

Fig. 2 illustrates discrepancies in the distributions stemming from the distinct parton showers employed in Cascade and Pythia8. Nevertheless, it's noteworthy that the ratio of distributions between Z+jet and multi-jet production follows a consistent trend: for Z+jet-production, the distribution is steeper (indicating stronger correlation) at lower p_T^{leading}, while at higher p_T^{leading}, the distributions adopt similar shapes. From this, we deduce that the primary contributor to $\Delta\phi$ decorrelation is initial state radiation. Consequently, the shape of the $\Delta\phi$ decorrelation in the back-to-back region aligns between Z+jet and multi-jet processes at high p_T^{leading} when similar initial partonic states come into play.

4. Conclusion

In this article we have discussed predictions from PB TMD parton showers for final state observables at the LHC, focusing on the azimuthal correlations of multi-jets and Z+jet. The azimuthal correlations $\Delta\phi_{Zj}$, obtained in Z+jet production are steeper compared to those in jet-jet production ($\Delta\phi_{12}$) at transverse momenta $\mathcal{O}(100)$ GeV, while they become similar for very high transverse momenta, $\mathcal{O}(1000)$ GeV, which is a result of similar initial parton configuration of both processes.

In Z+jet production the color and spin structure of the partonic final state is different compared to the one in multi-jet production, and differences in the azimuthal correlation patterns can be used to search for potential factorization - breaking effects, involving initial and final state interferences. In order to experimentally investigate those effects, we propose to measure the ratio of the distributions in $\Delta\phi_{Zj}$ for Z+jet and $\Delta\phi_{12}$ for multi-jet production at low and at very high p_T^{leading}, and compare the measurements to predictions obtained assuming that factorization holds.
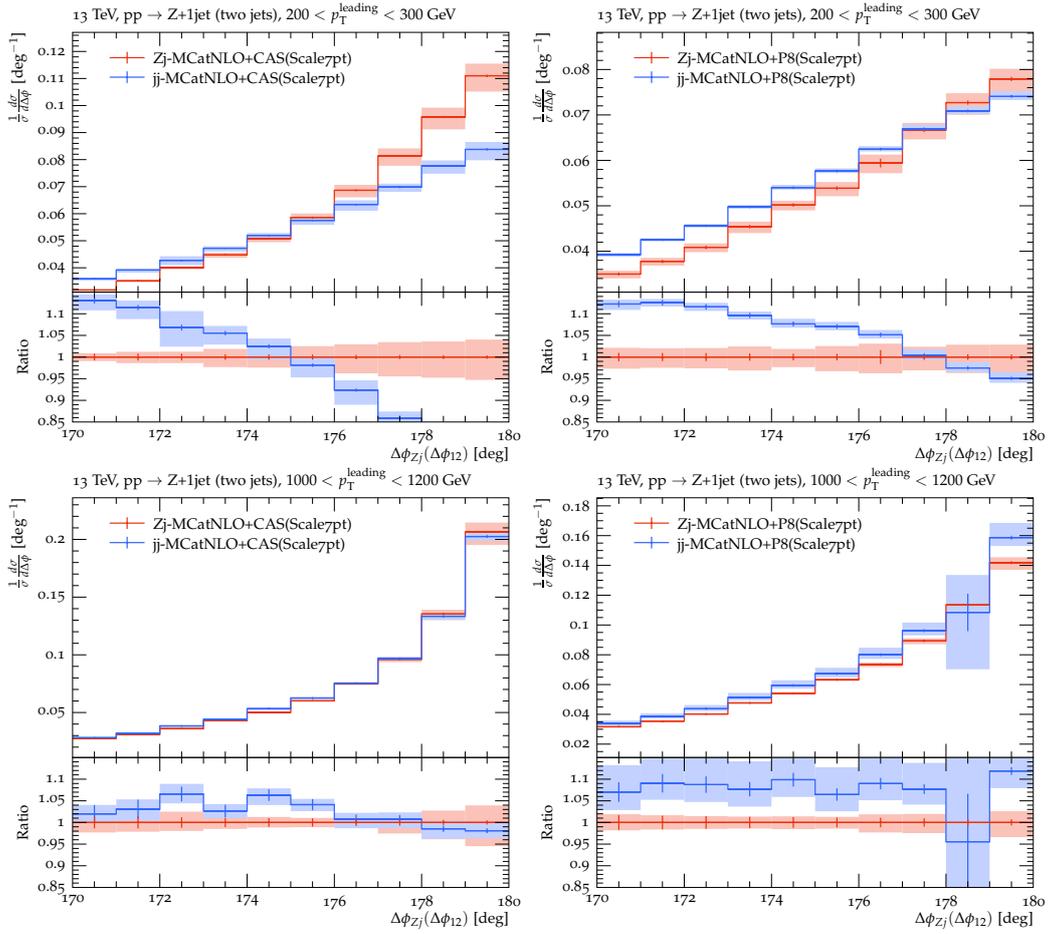
Figure 2: Predictions for the azimuthal correlation $\Delta\phi_{Zj}(\Delta\phi_{12})$ in the back-to-back region for Z+jet and multi-jet production obtained with MCatNLO+CAS3 (left column) and MCatNLO+PYTHIA8 (right column). Shown are different regions in $p_T^{\text{leading}} > 200$ GeV (upper row) and $p_T^{\text{leading}} > 1000$ GeV (lower row). The bands show the uncertainties obtained from scale variation.

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