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Boson-jet and jet-jet azimuthal correlations at high transverse momenta

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We discuss our recent results on azimuthal distributions in vector boson + jets and multi-jet production at the LHC, obtained from the matching of next-to-leading order (NLO) perturbative matrix elements with transverse momentum dependent (TMD) parton branching. We present a comparative analysis of boson-jet and jet-jet correlations in the back-to-back region, and a study of the theoretical systematic uncertainties associated with the matching scale in the cases of TMD and collinear parton showers.

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Experiments at the Large Hadron Collider (LHC) carry out accurate measurements of azimuthal correlations in vector-boson plus jets [1, 2] and multi-jet [3–7] final states. When a boson and a jet, or two jets, recoil nearly back-to-back, reliable QCD predictions call for soft-gluon resummation of Sudakov processes — see recent studies of Refs. [8–14] in the boson-jet case and Refs. [15–18] in the di-jet case. This region probes the transverse momentum dependent (TMD) [19–21] parton distribution of the initial state.

With the increase in luminosity at the LHC, it becomes possible to explore this region experimentally over a wide kinematic range in the hard scale of the process, set by the highest transverse momentum p_T^{leading} produced into the final state, from $p_T^{\text{leading}} \approx O(100$ GeV) to $p_T^{\text{leading}} \approx O(1000$ GeV). In particular, at the highest scales the nearly back-to-back region accessible with the experimental angular resolution of about 1 degree is characterized by transverse momentum imbalances of a few ten GeV, which can be investigated by analyzing jets with measurable transverse momenta.

The combined study of the p_T^{leading} and p_T-imbalance dependence of TMD dynamics is especially important, because the production of colored states near the back-to-back region may be influenced by factorization-breaking effects [22–25], due to interferences of gluon exchange in the soft region [26] with collinear radiation.

The present article is based on our work [27], in which we perform studies of azimuthal correlations as a function of p_T^{leading}, enabling one to explore p_T imbalances from a jet scale of several ten GeV down to the few GeV scale, and propose systematic measurements of ratios of boson-jet to jet-jet distributions, for varying transverse momenta, to investigate potential effects of soft-gluon interferences.

The studies [27] employ the parton branching (PB) approach [28, 29] to TMD evolution, and its matching [30–32] to next-to-leading-order (NLO) matrix-element calculations. The PB TMD evolution and corresponding parton shower are implemented in the Monte Carlo event generator Cascade3 [33], and the NLO matching is performed using MadGraph5_aMC@NLO [34] (we label this calculational framework as MCatNLO+CAS3 in the following). TMD parton distributions at the starting scale of evolution are obtained from fits [35] to precision deep-inelastic scattering data [36] using the xFitter analysis framework [37, 38].

The comparison of NLO PB-TMD predictions and collinear-shower predictions with the measurements of di-jet azimuthal correlations [6, 7] is discussed in Refs. [32, 39]. The description of jet correlation data by NLO PB-TMD is good, and the comparison underlines the importance of transverse momentum recoils in the parton showers [40–43] and of angular ordering [44–46] in achieving this. For the boson-jet case, the measurements performed so far do not yet have TeV-scale transverse momenta and sufficiently fine binning to investigate detailed QCD features.

Fig. 1 [27] shows NLO-matched predictions from TMD shower (left) and collinear shower [47] (right), illustrating spectra in the $\Delta\phi$ azimuthal separation in Z + jet and di-jet systems. We concentrate on the large-$\Delta\phi$ region, as the low-$\Delta\phi$ decorrelation region requires going beyond the framework of the present calculation to include the contributions of higher jet multiplicities, e.g. via multi-jet merging techniques [48, 49]. For low p_T^{leading} the boson-jet final state is more strongly correlated azimuthally than the jet-jet final state (top panels). When the transverse momenta increase, the boson-jet and jet-jet states become more similarly correlated (bottom panels). One can connect this behavior to features of the partonic initial state and final state radiation in the two cases [27]. Since potential factorization-breaking effects arise from color interferences of initial-

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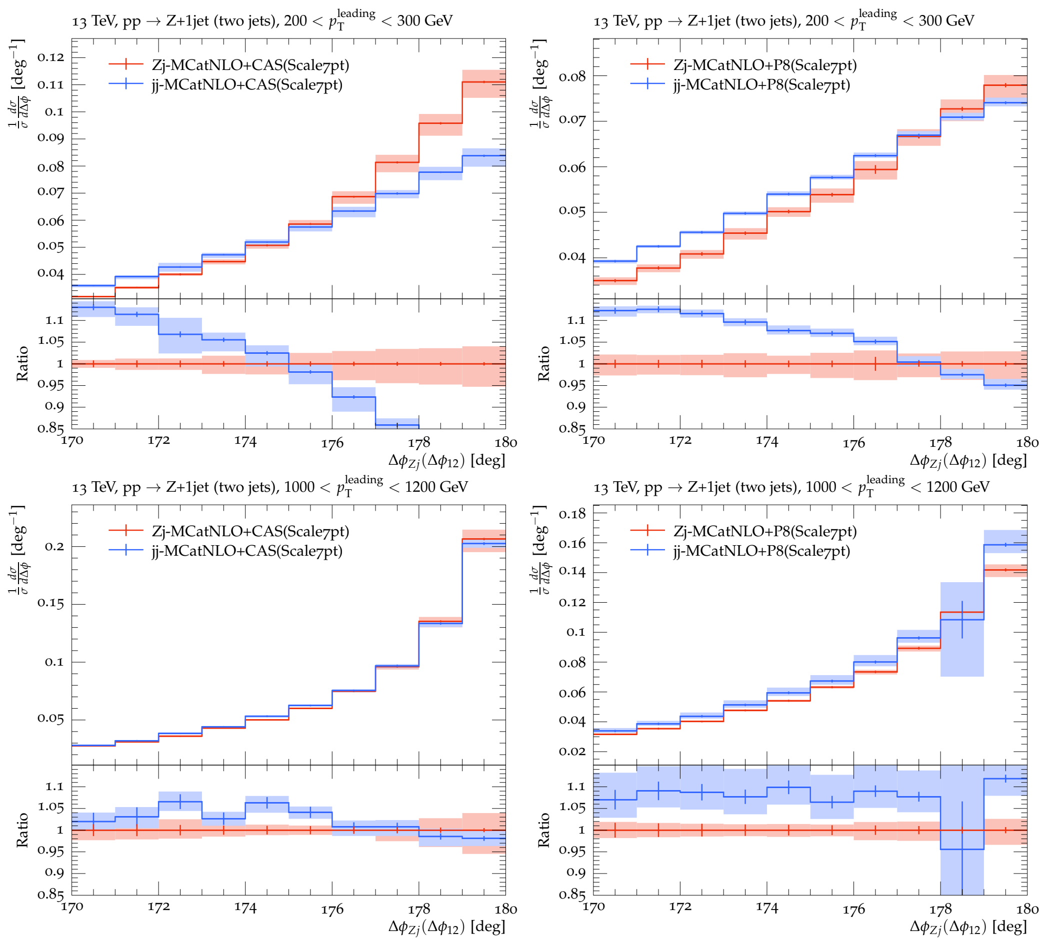

Figure 1: Predictions for the azimuthal correlation in the back-to-back region for Z+jets and multijet production obtained with MCatNLO+CAS3 (left column) and MCatNLO+PYTHIA8 (right column) [27]. Shown are different regions in $p_T > 200$ GeV (upper row) and $p_T > 1000$ GeV (lower row). The bands give an estimate of theoretical uncertainties obtained from scale variations as described in [27].

state and final-state radiation, different breaking patterns can be expected for strong and weak azimuthal correlations, influencing differently the boson-jet and jet-jet cases. Thus we propose to compare measurements of di-jet and Z + jet distributions systematically, scanning the phase space from low to high $p_T^{leading}$.

An important source of theoretical systematic uncertainties is given by the matching scale μ_m, limiting the hardness of parton shower radiation. In Fig. 2 we study this theoretical systematics for TMD shower (left) and collinear shower (right) calculations. Variations of the matching scale lead to more stable predictions in the TMD case, with the relative reduction of the matching scale theoretical uncertainty becoming more pronounced for increasing transverse momenta [27].

In conclusion, azimuthal distributions provide useful observables to gain insight into TMD dynamics and factorization — see e.g. [9, 32]. By varying the leading transverse momentum, the relative influence on the p_T imbalance can be studied from perturbative components and non-perturbative effects, e.g. [50, 51]. Sensitivity to TMD splitting probabilities [52] could also be

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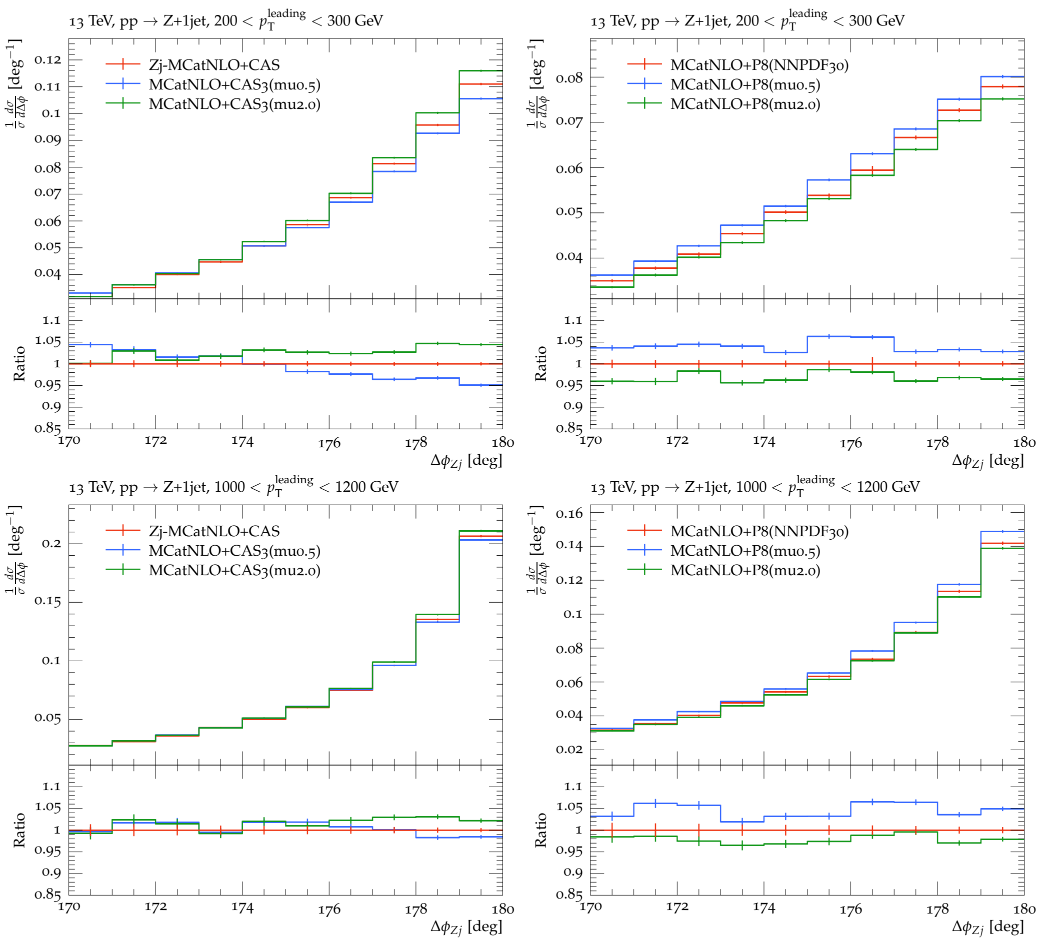

Figure 2: The dependence on the variation of the matching scale μ_m in predictions for the azimuthal correlation in the back-to-back region [27]. Shown are predictions obtained with MCatNLO+CAS3 (left column) and MCatNLO+PYTHIA8 (right column) for $p_T > 200$ GeV (upper row) and $p_T > 1000$ GeV (lower row). The predictions with different matching scales μ_m varied by a factor of two up and down are shown.

observed through azimuthal correlations.

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