Studies of multi-jet merging with Parton Branching TMD evolution

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Abstract

QCD predictions for final states with multiple jets in hadron collisions make use of multi-jet merging methods, which allow one to combine consistently the contributions from hard scattering matrix elements with different parton multiplicities and parton showers. In this article I consider a multi-jet merging method that has recently been proposed to take into account the effects of transverse momentum dependent (TMD) evolution and parton shower, and present studies focusing on the application of this method to jets associated with Drell-Yan (DY) production in the region of high masses.

1 Introduction

Drell-Yan (DY) plus jets final states are important at the LHC for tests of the standard model as well as for backgrounds to Higgs studies and beyond standard model studies. Baseline predictions for this are obtained by perturbative fixed-order calculations combined with parton showers in Monte Carlo event generators. Such predictions employ PDFs, which describe initial-state partonic structure and evolution within the collinear approximation.

In certain regions of the DY plus jets phase space, however, it becomes important to treat initial state QCD effects by including transverse momentum dependent (TMD) distributions [1], going beyond collinear PDFs. TMD effects in DY plus jets have been the subject of recent studies [2–9].

In this article I apply the TMD jet merging method [6] to study the differential jet rates (DJRs) associated with DY production as a function of the DY mass. In particular, I consider the region of high DY masses, and investigate the behavior of the TMD merging method and the merging scale in this new mass region.

This article is organized as follows. I introduce the theoretical framework for TMD evolution and TMD merging in section 2. In section 3 I present numerical calculations of the DJRs and discuss their main features. In section 4 I give conclusions.

2 Parton Branching method and TMD merging

The parton branching (PB) method developed in [10, 11] describes the evolution of TMDs by means of real-emission splitting functions, Sudakov form factors and angular ordering phase space

constraints. Nonperturbative distributions at the initial scale of order 1 GeV are determined from fits to experimental data [12]. For applications, the evolved TMD distributions are matched with fixed-order hard-scattering matrix elements [4, 13]. The TMD distributions and corresponding TMD parton shower are implemented in the Monte Carlo event generator CASCADE3 [14].

Applications to DY transverse momentum spectra, using PB TMDs matched with next-to-leading-order (NLO) DY matrix elements via MC@NLO [15], have been studied in [13] for LHC energies and in [16] for lower energies. Applications for jets have been studied in [17] by the same method.

It is found in [13] that NLO-matched PB TMD predictions provide a very good description of experimental LHC measurements of the Z-boson transverse momentum q_T distribution in the low q_T region and middle q_T region ($q_T \lesssim M_Z$) while a deficit is observed in the prediction compared to experimental data in the high q_T region. The low q_T region is dominated by soft-gluon radiation emitted through TMD evolution. The high q_T region is dominated by hard, perturbative emissions, and the deficit points to the lack of higher orders beyond the first hard emission in an NLO calculation.

A method to include higher order emissions corresponding to Z + n partons has been devised in [6] based on multi-jet merging. The method extends the MLM merging [18–21] to the case of TMD parton branching, rather than collinear parton branching. It allows one to combine consistently, without double counting or missing events, high multiplicity matrix elements with the TMD parton showers and TMD parton distributions. Using the TMD merging, a good description of the Z-boson q_T spectrum is obtained not only at low q_T but also at high q_T. This observation is also made by the recent CMS collaboration analysis [22].

The key features of the TMD jet merging, compared to the collinear MLM merging are that, owing to taking into account the transverse momentum in the initial state parton cascade: i) a better description of high multiplicity jet final states is achieved, and ii) a reduction of the systematic uncertainties due to the merging parameters is observed in the theoretical predictions.

In refs. [6,23], multi-jet observables in Z + jets production are studied using the TMD merging in the region near the Z boson mass. In the next section, calculations with TMD merging away from the Z-boson mass are shown to explore the behavior of the TMD merging approach and its merging scale in the region of high masses.

3 DJRs in DY + jets at high masses

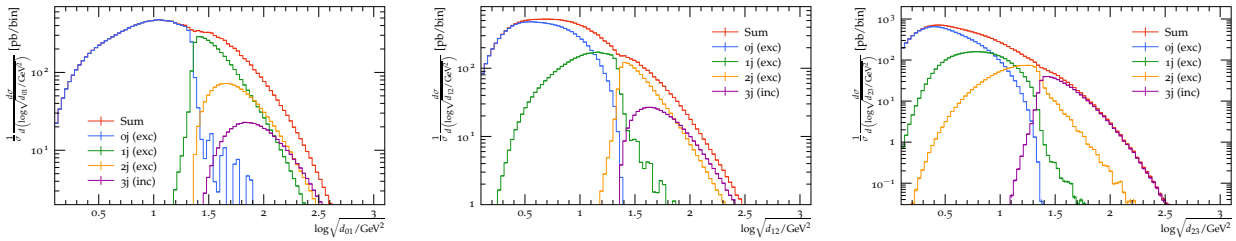
Differential jet rates (DJRs) are the distributions of the variable $d_{n,n+1}$, which is the square of the energy scale at which an n-jet configuration is resolved as an $(n+1)$-jet configuration, with jets defined according to the kT jet algorithm [24,25]. They are sensitive to the consistency of any jet merging method, which makes them appropriate quantities to validate the merging algorithm.

The calculational set-up is as follows. With MadGraph5_aMC@NLO [15] I generate Les Houches Event (LHE) files at leading order (LO) containing hard scattering events - that represent the matrix elements - for pp collisions to Z + 0, 1, 2, 3 jet final states at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. A generation cut of 16 GeV sets the lower limit of emitted transverse momentum by the partons in these events. The transverse momentum at the hard scale is generated by forward evolution [10] using the PB-TMD Set 2 [12] provided by the TMDlib library [26,27]. Parton shower emissions are generated in the TMD shower in CASCADE [14] following the PB evolution dynamics in a backwards manner. The TMD merging algorithm [6] at LO is implemented within

the event generator. Hadronization is turned off, since this enters the calculation only after the merging and would not affect the DJRs.

The merging scale in a merged calculation (indicated with $E_\perp^{\text{clus}}$) represents the minimal transverse energy of a jet to pass the merging algorithm. The effect on the DJR is that the region below the merging scale is dominated by the TMD and TMD shower, while the region above the merging scale is dominated by the matrix element.

We investigate DJRs at different hard interaction scales to study the behavior of the merging scale when the hard scale varies. For di-lepton mass around the Z-boson mass, a merging scale of 23 GeV has been applied [6]. This works well for TMD merging of Z+jets as observed in [23]. Figure 1 shows that the DJRs are smooth in this regime.



(a) d_{01} (b) d_{12} (c) d_{23}

Fig. 1: DJRs for Z+jets around the Z boson mass with a merging scale $E_\perp^{\text{clus}} = 23$ GeV.

In Figures 2 and 3, we show the DJRs resulting from studies in the scenario where the minimal mass of the di-lepton pair is set to 800 GeV. At the merging scale of 23 GeV ($\log(23) = 1.36$), a discontinuity occurs (Fig. 2). To resolve this discontinuity, higher merging scales have been applied to the calculation. Application of a merging scale of 70 GeV ($\log(70) = 1.85$) does not lead to discontinuities as with the 23 GeV merging scale (Fig. 3).

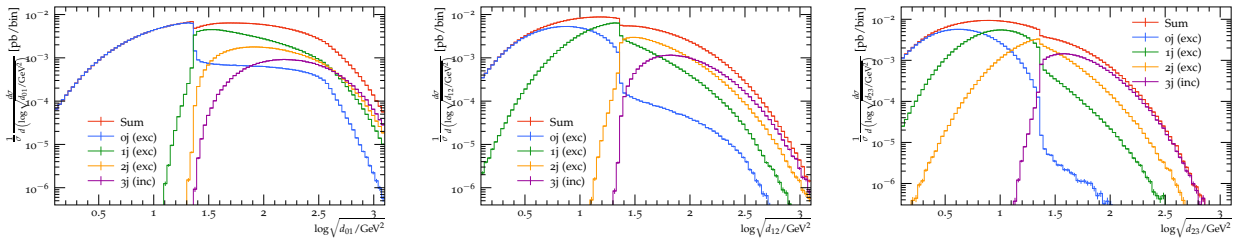


Fig. 2: DJRs for a minimal DY mass $M_{ll}^{\text{min}} = 800$ GeV and a merging scale $E_\perp^{\text{clus}} = 23$ GeV.

By applying a larger merging scale to events with high di-lepton masses, the low multiplicity samples contribute more at higher scales. For example, d_{01} is smoother when the $2 \to 2$ sample contributes largely up to 70 GeV instead of falling down rapidly at scales larger than 23 GeV.

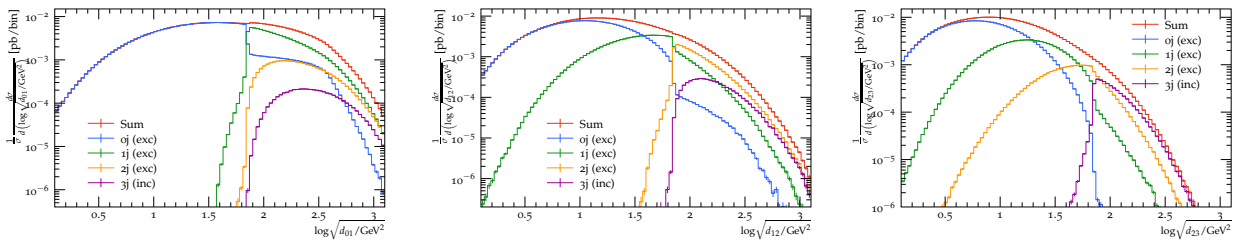


Fig. 3: DJRs for a minimal DY mass $M_{ll}^{\min} = 800$ GeV and a merging scale $E_{\perp}^{\text{clus}} = 70$ GeV.

4 Conclusion

Transverse momentum recoils in the initial-state shower, taken into account via TMD distributions, affect the theoretical systematics of predictions for jet final states [28–30]. Focusing on the case of DJR variables in DY + jets production, in this article I have investigated, within a PB TMD framework with multi-jet merging, the dependence of predictions on the merging scale as a function of the DY mass scale. I have shown in particular that the results support the possibility of a merging scale increasing with mass.

It looks to be of interest to explore this possibility further, also in the context of current developments on TMD parton branching, such as the ongoing determination [31] of PB TMD distributions via xFitter [32, 33] including effects of dynamical soft-gluon resolution scales [34] and angular ordering [11, 35, 36], and the extension of the branching evolution to incorporate TMD splitting functions [37, 38]. Besides, it will be interesting to compare the behavior of the TMD merging algorithm with that of collinear merging algorithms when the DY mass scale is varied.

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