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Merging scale in Z + multi-jet events for varying masses

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We investigate theoretical predictions for Z-boson plus jets production using multi-jet merging algorithms. By studying the differential jet rates and their discontinuities, we develop a method to quantitatively analyze the merging algorithm and merging scale dependence on varying boson's invariant masses.

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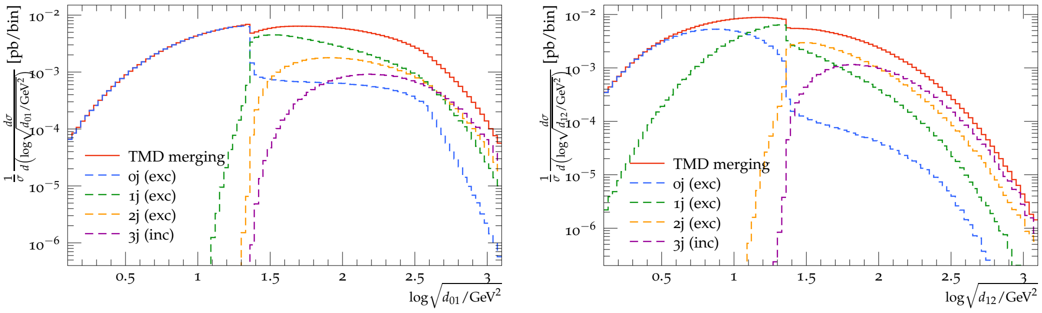
Events with vector bosons and multiple jets occur with sizeable production rates at the Large Hadron Collider (LHC) [1]. They are central to many aspects of the Standard Model and Beyond-Standard-Model physics program at the LHC, and reliable theoretical predictions for these events are of primary importance. Multi-jet merging approaches [2–12] provide the basis to make such predictions, by combining the contributions to multi-jet final states from high-multiplicity hard scattering matrix elements and from Quantum Chromodynamics (QCD) parton showers.

In these approaches, a merging scheme and merging scale are introduced to treat any phase-space point by the most appropriate approximation, either matrix element or parton shower, so as to avoid double counting or missing events. The merging scale controls the separation between the regions where either the matrix element or the parton shower dominate the emission of jets, and the dependence on this scale is one of the main theoretical systematic uncertainties in merged multi-jet predictions at leading order [7, 13–16] and next-to-leading order [8–11]. This reflects the mismatch between the matrix-element and parton-shower event weights assigned to a given final state, e.g. due to the transverse momentum recoils in the shower evolution [17]. This mismatch, and corresponding systematic uncertainty, can be reduced by improving the description of the emission probability for jets by shower evolution. This is achieved by the transverse momentum dependent (TMD) multi-jet merging of [12, 18], which uses TMD parton distributions and branching [19–24].

In [12] TMD merging predictions are obtained for Z-boson + multijets final states and a thorough comparison is performed with LHC experimental measurements [25, 26] for invariant masses near the Z-boson peak. The merging scheme and merging scale are examined based on the analysis of the differential jet rates (DJRs) [27], which have always been regarded as a powerful means [5] to test the efficiency and accuracy of the merging algorithm. The TMD merging predictions [12] are shown to have smaller merging-scale systematic uncertainties compared to the case of standard algorithms [7] based on collinear merging. The description of the experimental measurements [25] for the jet multiplicity and transverse momentum distributions in Z + multijets events near the Z mass peak is much improved in TMD merging [12] compared to the collinear merging results based on MADGRAPH [28] + PYTHIA6 [29], particularly at high multiplicities, that is, in final states with jet multiplicities larger than the largest multiplicity used in the generation of the matrix-element samples.

The jet merging methodology discussed above has been developed for vector boson plus jets events at fixed hard scale of the order of the vector boson mass. How can this methodology be extended when one moves away from the vector boson mass region to events with very different hard scales? In this article, we report on work [30, 31] investigating this question. This is especially topical, given that vector boson production measurements have recently appeared [32] across a wide range in the boson invariant mass, and high-mass Drell-Yan (DY) production will be explored with higher luminosity in forthcoming LHC runs.

The study in [30, 31] uses the TMD multi-jet merging algorithm [12, 18], implemented in the CASCADE Monte Carlo event generator [33, 34] with TMD parton distributions [35–37], and is based on the analysis of the DJRs in Z + multi-jets events for varying vector boson invariant masses. We generate six different sets of hard scattering events with Z-boson + 0, 1, or 2 jets production in LHE format [38] with MADGRAPH5_AMCATNLO [28] at various di-lepton masses $Q \equiv m_{ll}$ ranging from 60 GeV up to 800 GeV. DJRs $d_{i,(i+1)}$, which are distributions of the squared energy scale at which an i-jet event resolves in an $i+1$-jet event, are very sensitive to the merging procedure and the merging scale choice. A discontinuity in these distributions indicates either double counting of events (overpopulating the phase space) or missing phase space filling. A discontinuity in the DJR manifests close to the merging scale. DJRs are calculated from all LHE files with a different merging parameter. Jets are clustered by the kT algorithm [39, 40]. With a DY mass close to the Z boson mass and a merging scale of $\mu_m \equiv E_{\perp,\text{clus}} = 23$ GeV, there are no significant discontinuities in the DJRs [12]. At higher DY masses, discontinuities are observed in the DJRs when using this merging scale value. Fig. 1 illustrates this for the case of $Q = 800$ GeV. In the figures, “log” is a short notation for $\log_{10}$.



(a) d_{01}

(b) d_{12}

Figure 1: DJRs of TMD merged Z+jet events at masses $Q = 800$ GeV with a merging scale of $\mu_m = 23$ GeV (located at $\log(23) \approx 1.36$).

We associate the magnitude of the discontinuity with the inadequacy of the merging procedure and quantify the level of “non-smoothness” of a DJR by the parameter D:

$$D(Q, \mu_m) = \frac{|L_l(\mu_m) - L_r(\mu_m)|}{(L_l(\mu_m) + L_r(\mu_m))/2}\,, \tag{1}$$

where L_i consist of tangent lines $l_i(\mu) = a_i \log(\mu) + b_i$ that are fitted to the DJR on the left ($i = l$) and right ($i = r$) sides of the discontinuity combined with a first order shift of the size of one bin ($a_i \cdot \delta$) to take into account the first order discontinuity. Then

$$L_i(\mu) = l_i(\mu) + a_i \cdot \delta\,. \tag{2}$$

Theoretical uncertainty sources are of systematic and statistical origin. The systematic uncertainties arise mainly from the bin size of DJRs with which the discontinuity is calculated. For this reason, the bin size has been varied from the default value $\delta = 0.030$ with 0.015 up and down.

By the calculation of the quantity D for different values of Q and merging scale μ_m, an “optimal” merging scale $\mu_m^{(0)}$ can be extracted from the distributions at minimum discontinuity. For this, second order polynomials are fitted through points close to the minimum for the differently obtained D distributions. The difference due to different bin sizes defines the systematic uncertainty σ_{bin}. The total uncertainty is calculated by summing the squares of σ_{bin} and σ_{stat}.

The fits to discontinuity distributions in d_{01} and d_{12} at $m_{ll} = 800$ GeV are shown in Fig. 2. The merging scale values at the minimum are given in the legend. The final result for an optimal merging scale at fixed Q is calculated by averaging three obtained values for $\mu_m^{(0)}$.

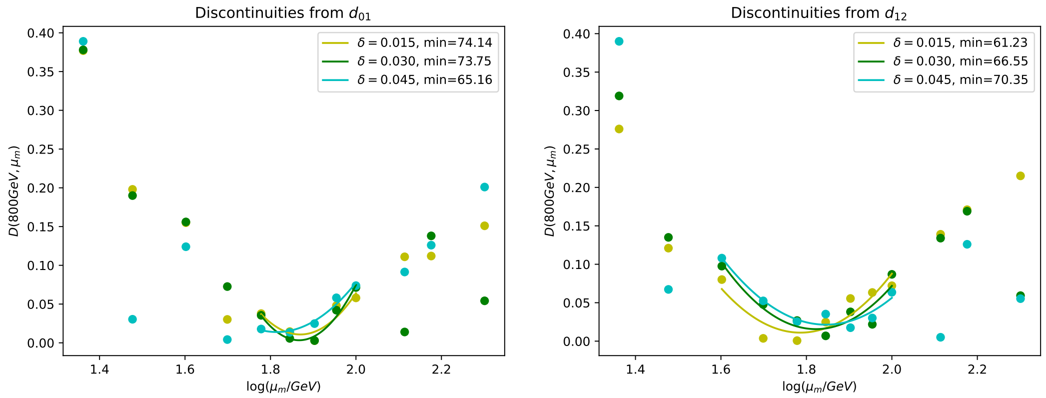


Figure 2: Discontinuity distributions from different bin sizes δ, with a hard scale of $Q = 800$ GeV. Parabolic fits are shown in the lower plots together with the merging scale values at the minima in the legends.

The results for the optimal merging scale $\mu_m^{(0)}$ at various hard scales yield a distribution $\mu_m^{(0)}(Q)$ that is shown in Fig. 3 both for the results of the analysis of DJR d_{01} and for the results of the analysis of DJR d_{12}. In Fig. 3 we also show as dashed lines the results of performing fits to the values of $\mu_m^{(0)}$ based on the functional form

$$\mu_m^{(0)}(m_{ll}) = m_Z\left(a + b\ln\left(\frac{m_{ll}}{m_Z}\right)\right). \tag{3}$$

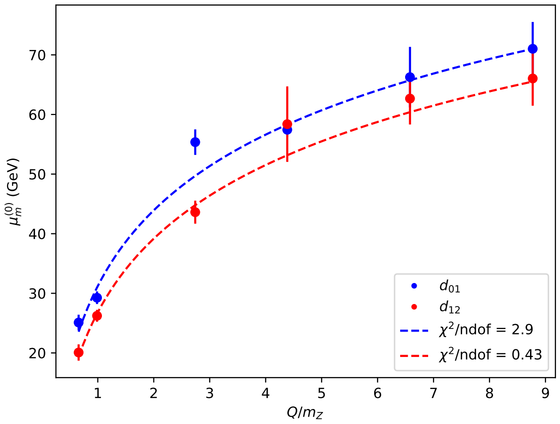


Figure 3: Merging scale distribution versus the hard scale.

The fit to the data from d_{01} gives

$$\mu_m^{(0)}(m_{ll}) = m_Z\left(0.34 + 0.20\ln\left(\frac{m_{ll}}{m_Z}\right)\right), \tag{4}$$

while the fit to the data from d_{12} gives

$$\mu_m^{(0)}(m_{ll}) = m_Z\left(0.29 + 0.20\ln\left(\frac{m_{ll}}{m_Z}\right)\right). \tag{5}$$

DJRs in high mass DY events are thus consistent with a merging scale that is logarithmically dependent on the di-lepton mass. The chi-squared values of these fits are near 1, and the results of d_{01} and d_{12} are very similar. In the limit of hard scale Q approaching m_Z, the merging scale is approximately 30 GeV, equivalent to one-third of the Z boson's mass. This aligns with the merging scale that has been used in earlier studies where the Z boson's mass was included in the phase space. The merging scale increases logarithmically for Q large compared to m_Z.

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