

Multiplicity Dependence of the Jet Structures in pp Collisions at LHC Energies[†]

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Abstract: We study the charged event multiplicity dependence of the jet structure in pp collisions. We present evidence for jet shape modification due to multi-parton interactions using PYTHIA and HIJING++ Monte Carlo (MC) event generators as an input to our analysis. We introduce a characteristic jet size measure which is independent of the choice of simulation parameters, parton distribution functions, jet reconstruction algorithms and even of the presence or absence of multi-parton interactions. We also investigate heavy-flavor jets and show the sensitivity of the multiplicity-differential jet structure to flavor-dependent fragmentation.

Keywords: jet physics; jet structure; multiple-parton interactions; color reconnection; high-energy collisions

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1. Introduction

The collective behavior found in large systems created in heavy-ion collisions, such as long range correlations and a sizeable azimuthal anisotropy have traditionally been considered as proof for the creation of the quark-gluon plasma (QGP) in such systems. One of the surprises in the recent years was the discovery of collective behavior in small systems, e.g. in high-multiplicity pp or pA collisions [1,2]. While the presence of the QGP in such systems is still an open question [3], we now know that the presence of the QGP is not necessary for the explanation of collectivity, as relatively soft vacuum QCD effects such as multiple-parton interactions (MPI) can produce similar behavior [4].

Jet quenching, a key signature of the QGP in AA collisions is not expected in small systems due to the insufficiently large volume, but in principle, effects like MPI may also cause jet modification in high-multiplicity events. This paper is a continuation of our previous studies [5] aimed at the evolution of jet structure patterns and their dependence on simulation components.

2. Analysis and results

We simulated events using the PYTHIA 8.226 Monte Carlo event generator [6]. To crosscheck the results we also generated events with HIJING++ [7], a new event generator based on the still-widely-used HIJING. We investigated three different tunes including the Monash 2013 tune with the NNPDF2.3LO PDF set [8,9], as well as two others, the Monash* tune with NNPDF2.3LO [10] and tune 4C with the CTEQ6L1 PDF set [11,12]. We simulated events with MPI switched on and off and used different Color Reconnection (CR) schemes to individually investigate the effects of these physical components on the jet structures [5]. A full jet reconstruction, including both neutral and

charged particles, was carried out with a resolution parameter $R = 0.7$ using the anti- k_T algorithm of the FASTJET package [13]. We also used the k_T and the Cambridge-Aachen algorithms for cross-checks. To look for jet shape modification we analyzed the transverse momentum distribution inside the jet cones. We computed the differential jet shape (ρ), that is the radial transverse momentum distribution inside the jet cone, as well as the integral jet shape (ψ), representing the average fraction of the jet transverse momentum contained inside a cone of radius r around the jet axis. They are defined as

$$\rho(r) = \frac{1}{\delta r} \frac{1}{p_T^{jet}} \sum_{r_a < r_i < r_b} p_T^i \quad \text{and} \quad \psi(r) = \frac{1}{p_T^{jet}} \sum_{r_i < r} p_T^i \quad (1)$$

respectively, where p_T^i is the transverse momentum of a particle inside a δr wide annulus with inner radius $r_a = r - \frac{\delta r}{2}$ and outer radius $r_b = r + \frac{\delta r}{2}$ around the jet axis and p_T^{jet} is the transverse momentum of the whole jet. The distance of a given particle from the jet axis is given by $r_i = \sqrt{(\phi_i - \phi_{jet})^2 + (\eta_i - \eta_{jet})^2}$, where ϕ is the azimuthal angle and η is the pseudorapidity.

Experimental data from CMS for multiplicity-integrated differential jet shapes (i.e. where events of all charged hadron multiplicities are considered) are well described by all three tunes over a wide p_T^{jet} range [5,14]. The multiplicity-dependent analysis of the differential jet shapes, however, serve as a sensitive tool to validate simulations, as there are significant differences between predictions using otherwise equally well-performing tunes [5]. In the left panel of Figure 1 we plot the differential jet structure for low and high charged hadron multiplicity (N_{ch}) events separately, and compare them to the multiplicity-integrated curve at a given p_T^{jet} window. Jets in low-multiplicity events are typically more collimated than in high-multiplicity events, hence the curves intersect each other. The right panel of Figure 1 shows the integral jet structure calculated at $r = 0.2$ with respect to the multiplicity. We can observe a significant effect of the MPI on the jet structures: at higher multiplicities, jets are typically less collimated if MPI is turned off. Note that the contribution of the underlying event has not been separated within the modification of the jet structure [5].

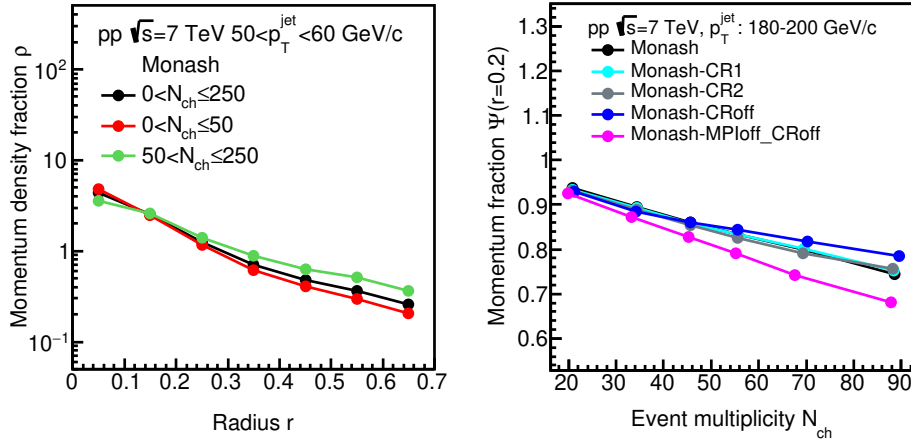


Figure 1. (Left) The differential jet structure for low and high multiplicities. (Right) The integral jet structure at $r = 0.2$ plotted against N_{ch} for different MPI and CR simulation settings [5].

In the left panel of Figure 2 we plot the ratio of differential jet structures for several N_{ch} classes over the multiplicity-integrated jet structure. We observe a common intersection point for all the curves. This suggests a multiplicity-independent characteristic jet-size (R_{fix}). Carrying out the same analysis for different tunes, settings and jet reconstruction algorithms we conclude that R_{fix} depends only on the chosen p_T^{jet} window [5]. In the central panel of Figure 2 we show the evolution of R_{fix} with respect to the transverse momentum of the jets for different tunes. To make sure R_{fix} is not simply an artefact of PYTHIA, we conducted crosschecks using events generated by HIJING++. In the right panel

60 we show that there is no difference between the two event generators and there is also no difference
61 between the different PDF sets [7,12] we used.

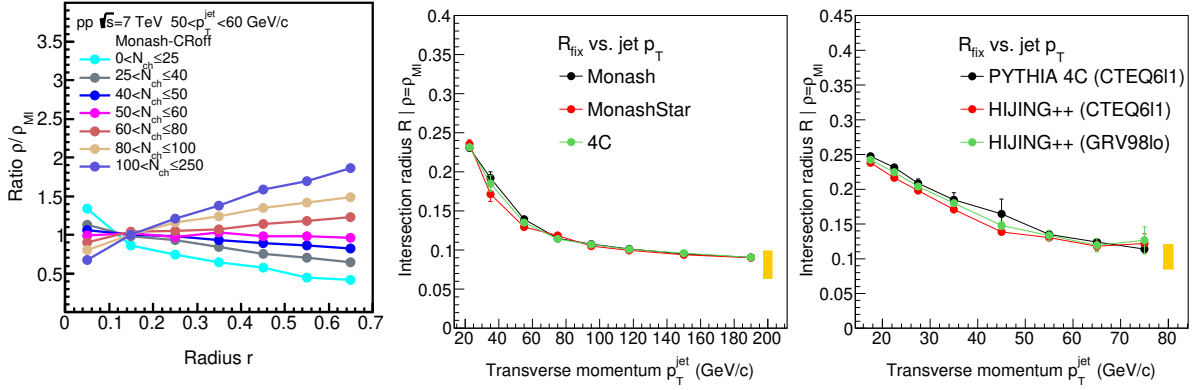


Figure 2. (Left) The differential jet structure compared for many different multiplicity bins. (Center) The p_T^{jet} dependence of R_{fix} for three different PYTHIA tunes. (Right) Comparing the p_T^{jet} dependence of R_{fix} from HIJING++ to that of PYTHIA using two different PDF sets.

62 We also investigated heavy flavor jets, to understand the flavor dependence of jet structures. In
63 the left panel of Figure 3 we compare the R_{fix} for selected leading and subleading jets with the default
64 configuration where any jet is allowed. Selecting only the leading and subleading jets from events
65 does not make a significant difference. However, the R_{fix} of leading and subleading jets with beauty
66 or charm content shows slightly different patterns. At low p_T^{jet} , c-jets have slightly lower R_{fix} than
67 inclusive and b-jets, while at high p_T^{jet} , heavy-flavor jets differ from inclusive jets. In the left panel we
68 show the integral jet structure at $r = 0.2$ for heavy-flavor jets. Here we can observe that heavy-flavor
69 jets are narrower than inclusive jets on the average. However, the effect is not ordered by mass, since
70 the beauty $\psi(r = 0.2, N_{ch})$ curve is between the inclusive and the light jets. It is also to be noted that
71 the ordering is p_T^{jet} -dependent, with a similar trend to the one observed in R_{fix} .

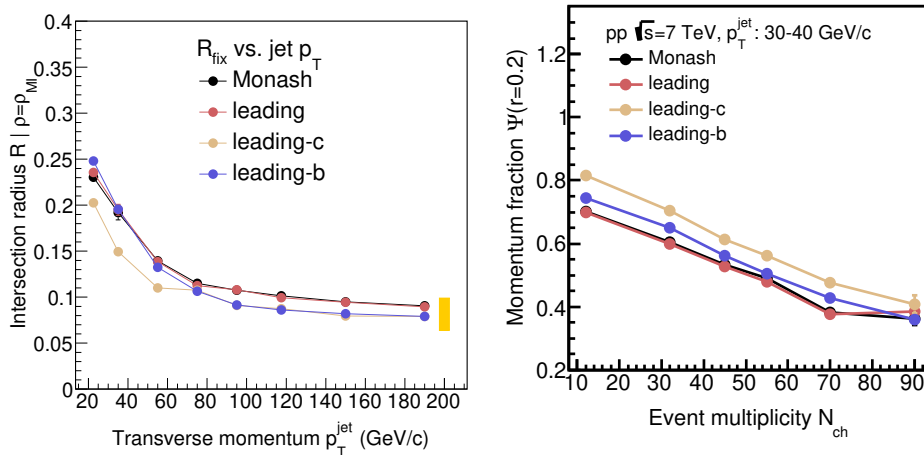


Figure 3. (Left) The p_T^{jet} dependence of R_{fix} for heavy flavors. (Right) The integral jet structure at $r = 2$ for heavy flavors.

72 3. Conclusion

73 A systematic study on the charged hadron event multiplicity dependence of the jet structures
74 has been carried out using PYTHIA and HIJING++ MC event generators. We showed that the
75 multi-parton interactions cause a significant modification of the jet structure. We have proposed
76 a multiplicity-independent characteristic jet size measure which is independent of the choice of

77 simulation parameters, parton distribution functions, jet reconstruction algorithms and even of the
78 presence or absence of multi-parton interactions. Its p_T^{jet} dependence can be qualitatively explained
79 by the Lorentz-boost of the jet [5]. Finally, we showed that multiplicity-differential jet structure
80 measurements provide a sensitive probe of flavor-dependent fragmentation. Comparing the jet
81 structures observed in heavy-flavor jets and inclusive jets shows a p_T^{jet} -dependent difference, which,
82 however, does not follow mass ordering.

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