Measurements of sub-jet fragmentation with ALICE

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Abstract

High-energy jets offer rich opportunities to study quantum chromodynamics, from investigating the limits of perturbative calculability to constraining the emergent properties of the quark-gluon plasma (QGP). In these proceedings, we present new measurements of the fragmentation properties of jets. We report distributions of the sub-jet momentum fraction $z_r$ measured in pp and Pb–Pb collisions with ALICE at the Large Hadron Collider. These measurements serve as input to test the universality of jet fragmentation in the QGP and offer a path to elucidate jet quenching effects in the large-$z$ region.

1 Introduction

Jet measurements offer opportunities to test perturbative calculations in quantum chromodynamics and to probe the properties of the QGP $[1,2]$. In these proceedings, we consider measurements of sub-jets, defined by first inclusively clustering jets with the anti-$k_T$ algorithm $[3]$ with radius $R$, and then reclustering the jet constituents with the anti-$k_T$ algorithm with sub-jet radius $r < R$ $[4]$. We focus on the fraction of transverse momentum carried by the sub-jet:

$$z_r = \frac{P_T, \text{subjet}}{P_T, \text{jet}}.$$

In pp collisions, both the inclusive and leading sub-jet $z_r$ distributions have been calculated perturbatively $[5,6]$. These calculations suggest several interesting features that can be tested by experimental data: the role of threshold resummation in the large-$z_r$ region and, in the leading sub-jet case, nonlinear evolution of the jet fragmentation function in the perturbative calculation. In heavy-ion collisions, sub-jets have been proposed as sensitive probes of jet quenching $[5-8]$. The sub-jet $z_r$ observable presents several unique opportunities:
1. Test the universality of jet fragmentation in the QGP. In vacuum, it is expected that the parton-to-jet fragmentation function, $J(z)$, is equal to the parton-to-subjet fragmentation function $J_r(z)$. However, it is unknown whether the universality of jet fragmentation functions holds in the QGP [9]. Measurements of $z_r$ are directly sensitive to $J_{r,\text{med}}(z)$, and can be used to extract it. The extracted $J_{r,\text{med}}(z)$ can then be compared to an independently extracted $J_{\text{med}}(z)$ to test the universality of in-medium jet fragmentation.

2. Probe high-$z$ fragmentation. Sub-jet fragmentation is complementary to the longitudinal momentum fraction of hadrons in jets [10, 11]. Sub-jet measurements offer the benefit of probing higher $z$ than hadron measurements, and, in doing so, offer the possibility to access a quark-dominated sample of jets and expose the interplay of soft medium-induced radiation with the relative suppression of gluon vs. quark jets.

3. Measure sub-jet energy loss at the cross-section level. Recently, a well-defined method of measuring out-of-cone energy loss at the cross-section level was proposed, by computing moments of the leading sub-jet $z_r$ distribution [6]. This “sub-jet energy loss”, describing the fraction of jet $p_T$ not carried by the leading sub-jet, can then be computed in both pp and Pb–Pb collisions, and contrasted with other measures of jet modification.

2 Results

All presented results use $R = 0.4$ jets reconstructed from charged particles with pseudorapidity $|\eta| < 0.9$, and are corrected for detector effects and (in Pb–Pb collisions) underlying-event fluctuations.

2.1 Sub-jet fragmentation in proton-proton collisions

Figure 1 shows the measured $z_r$ distributions for inclusive (left) and leading (right) sub-jets. The $z_r$-differential cross sections are normalized such that their integrals are equal to the average number of sub-jets per jet. For $z_r > 0.5$ the leading and inclusive distributions are identical. As $z_r$ becomes small, the inclusive sub-jet distribution grows due to soft radiations...
emitted from the leading sub-jet, whereas the leading sub-jet distribution falls to zero. The distributions are generally described well by PYTHIA8 Monash 2013 [12, 13], however there is disagreement at large $z_r$ – this may be due to threshold resummation (which is not directly included in PYTHIA8) or to hadronization effects. Using the leading sub-jet distributions, we also compute the “sub-jet energy loss”:

$$\langle z_{\text{loss}} \rangle = 1 - \int_0^1 dz_r z_r \frac{1}{\sigma} \frac{d\sigma}{dz_r},$$

which describes the fraction of $p_T$ inside the jet that is not contained within the leading subjet [6]. We find that $\langle z_{\text{loss}} \rangle = 0.21$ for $r = 0.1$ and decreases to $\langle z_{\text{loss}} \rangle = 0.10$ for $r = 0.2$.

### 2.2 Sub-jet fragmentation in Pb–Pb collisions

The fluctuating underlying event in heavy-ion collisions poses an additional challenge, since it can alter the number of reconstructed sub-jets. To simplify this problem, we focus on leading sub-jets at large $z_r$.\(^1\) Figure 2 shows the $z_r$ distributions in pp and Pb–Pb collisions for $r = 0.1$ (left) and $r = 0.2$ (right). For $r = 0.1$, the distributions are consistent with a mild hardening effect in Pb–Pb compared to pp collisions, which reverses as $z_r \to 1$. These results are compared to JETSCAPE [14–16] and SCET-based calculations [5, 9], both of which generally describe the data well. To understand the behavior of the data, note that in vacuum there are significant differences in the parton-to-subjet fragmentation functions between quarks and gluons [6]. If the QGP suppresses gluon jets more than quark jets, a hardening effect of the $z_r$ distribution would be expected – in line with previous measurements of hadron fragmentation [19]. On the other hand, medium-induced soft radiations can shift the distribution to smaller $z_r$. This competition can give non-trivial modification patterns. In particular, as $z_r \to 1$, the jet sample in vacuum becomes almost entirely dominated by quark jets – exposing a region depleted by soft medium-induced emissions, which is consistent with our observations.

\(^1\)Even with this restriction, underlying event fluctuations can cause the leading sub-jet to be misidentified, in analogy to groomed jet observables [17], although with improved robustness to mistagging effects [18].

![Figure 2: Measurements of sub-jet fragmentation for sub-jet radii $r = 0.1$ (left) and $r = 0.2$ (right) in pp and Pb–Pb collisions, compared to predictions [5, 9, 14–16].](image-url)
3 Conclusion

We have presented new measurements of sub-jet fragmentation with ALICE. In proton-proton collisions, these measurements provide opportunities to test non-linear evolution of jet fragmentation functions and the role of threshold resummation. In heavy-ion collisions, these measurements serve as a key ingredient to test the universality of jet fragmentation in the QGP. By probing large \( z_r \), these measurements isolate a region of quark-dominated jets that may expose a region depleted by medium-induced soft radiation. Future measurements of \( z_r \) in coincidence with other substructure observables such as the groomed jet radius \([20]\) offer the potential to disentangle this effect from the relative suppression of gluon jets to quark jets.

References

[1] A. J. Larkoski, I. Moult and B. Nachman, Jet substructure at the Large Hadron Collider: A review of recent advances in theory and machine learning, Phys. Rep. \textbf{841}, 1 (2020), doi:10.1016/j.physrep.2019.11.001.
[2] W. Busza, K. Rajagopal and W. van der Schee, Heavy Ion Collisions: The Big Picture and the Big Questions, Annu. Rev. Nucl. Part. Sci. \textbf{68}, 339 (2018), doi:10.1146/annurev-nucl-101917-020852.
[3] M. Cacciari, G. P. Salam and G. Soyez, The anti-\( k_t \) jet clustering algorithm, J. High Energy Phys. \textbf{04}, 063 (2008), doi:10.1088/1126-6708/2008/04/063.
[4] L. Dai, C. Kim and A. K. Leibovich, Fragmentation of a jet with small radius, Phys. Rev. D \textbf{94}, 114023 (2016), doi:10.1103/PhysRevD.94.114023.
[5] Z.-B. Kang, F. Ringer and W. J. Waalewijn, The energy distribution of subjets and the jet shape, J. High Energy Phys. \textbf{07}, 064 (2017), doi:10.1007/JHEP07(2017)064.
[6] D. Neill, F. Ringer and N. Sato, Leading jets and energy loss, J. High Energy Phys. \textbf{07}, 041 (2021), doi:10.1007/JHEP07(2021)041.
[7] L. Apolinário, J. Guilherme Milhano, M. Ploskon and X. Zhang, Novel subjet observables for jet quenching in heavy-ion collisions, Eur. Phys. J. C \textbf{78}, 529 (2018), doi:10.1140/epjc/s10052-018-5999-2.
[8] P. Caucal, E. Iancu, A. H. Mueller and G. Soyez, Nuclear modification factors for jet fragmentation, J. High Energy Phys. \textbf{10}, 204 (2020), doi:10.1007/JHEP10(2020)204.
[9] J.-W. Qiu, F. Ringer, N. Sato and P. Zurita, Factorization of Jet Cross Sections in Heavy-Ion Collisions, Phys. Rev. Lett. \textbf{122}, 252301 (2019), doi:10.1103/PhysRevLett.122.252301.
[10] ATLAS Collaboration, Comparison of Fragmentation Functions for Jets Dominated by Light Quarks and Gluons from pp and Pb+Pb Collisions in ATLAS, Phys. Rev. Lett. \textbf{123}, 042001 (2019), doi:10.1103/PhysRevLett.123.042001.
[11] CMS Collaboration, Measurement of jet fragmentation in PbPb and pp collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \), Phys. Rev. C \textbf{90}, 024908 (2014), doi:10.1103/PhysRevC.90.024908.
[12] T. Sjöstrand et al., An introduction to PYTHIA 8.2, Comput. Phys. Commun. \textbf{191}, 159 (2015), doi:10.1016/j.cpc.2015.01.024.
[13] P. Skands, S. Carrazza and J. Rojo, *Tuning PYTHIA 8.1: the Monash 2013 tune*, Eur. Phys. J. C 74, 3024 (2014), doi:10.1140/epjc/s10052-014-3024-y.

[14] J. H. Putschke et al., *The JETSCAPE framework*, arXiv:1903.07706.

[15] Y. He, T. Luo, X.-N. Wang and Y. Zhu, *Linear Boltzmann transport for jet propagation in the quark-gluon plasma: Elastic processes and medium recoil*, Phys. Rev. C 91, 054908 (2015), doi:10.1103/PhysRevC.91.054908.

[16] A. Majumder, *Incorporating space-time within medium-modified jet-event generators*, Phys. Rev. C 88, 014909 (2013), doi:10.1103/physrevc.88.014909.

[17] J. Mulligan and M. Płoskoń, *Identifying groomed jet splittings in heavy-ion collisions*, Phys. Rev. C 102, 044913 (2020), doi:10.1103/PhysRevC.102.044913.

[18] STAR Collaboration, *Differential measurements of jet substructure and partonic energy loss in Au+Au collisions at $\sqrt{s_{NN}}$ =200 GeV*, arXiv:2109.09793.

[19] M. Spousta and B. Cole, *Interpreting single jet measurements in Pb + Pb collisions at the LHC*, Eur. Phys. J. C 76, 50 (2016), doi:10.1140/epjc/s10052-016-3896-0.

[20] ALICE Collaboration, *Measurement of the groomed jet radius and momentum splitting fraction in pp and Pb—Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, arXiv:2107.12984.