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-$z_r$ region.

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1 Introduction

Jet measurements offer opportunities to test perturbative calculations in quantum chromodynamics and to probe the properties of the QGP \cite{1,2}. In these proceedings, we consider measurements of sub-jets, defined by first inclusively clustering jets with the anti-$k_T$ algorithm \cite{3} with radius $R$, and then reclustering the jet constituents with the anti-$k_T$ algorithm with sub-jet radius $r < R$ \cite{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 \cite{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 \cite{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

![Figure 1](image-url)
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 \( z_r \rightarrow 1 \). 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 \( z_r \rightarrow 1 \), 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](image-url)

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].
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


