Jet measurements with ALICE: substructure, dead cone, charm jets

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A selection of recent jet measurements are presented from the ALICE experiment at the CERN LHC in proton-proton collisions at $\sqrt{s} = 13$ TeV, focusing on substructure results for inclusive and charmed jets. The groomed jet momentum fractions ($z_g$) of inclusive full jets are shown for various jet resolution parameters, and $z_g$, the groomed splitting radius ($\theta_g$) as well as the number of soft drops ($n_{SD}$) of inclusive and charmed charged-particle jets are compared. The first direct measurement of the dead cone in heavy-flavor jets is also presented. Furthermore, the parallel momentum fractions of charmed $D^0$ mesons and $\Lambda_c^+$ baryons are shown. Besides serving as a reference for jet structure modification measurements in heavy-ion collisions, these results provide new insight to QCD parton shower properties and flavor-dependent fragmentation processes.

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1. Introduction

Measurement of jets in small collision systems serve as fundamental tests of pQCD and hadronization models \[1\]. Furthermore, these measurements provide a baseline for modification of jet production rates and structures in heavy-ion collisions by their interactions with the medium that is present in such collisions \[2\]. Identification of jets with heavy flavor allows for the investigation of flavor-dependent production stemming from mass and color-charge effects, and the understanding of mass-dependent fragmentation. In this contribution, recent groomed substructure measurements of inclusive and heavy-flavor jets are presented, as well as the first direct measurement of the dead cone, and the parallel momentum fraction of charmed D\(^0\) mesons and \(\Lambda_c\) baryons. Approximately 59 pb\(^{-1}\) integrated luminosity is used from pp collisions at \(\sqrt{s} = 13\) TeV. Charged-particle jets are reconstructed in the ALICE \[3\] central barrel in the central pseudorapidity region \(|\eta| < 0.9\) from tracks identified in the Time Projection Chamber and the Inner Tracking System (ITS). Full jets are reconstructed in a more limited acceptance within the pseudorapidity and azimuthal angle range \(|\eta| < 0.7\) and \(1.4 < \varphi < \pi\), also using information from the Electromagnetic Calorimeter. Heavy-flavor hadrons are fully reconstructed from their decays (in the D\(^0/\bar{D}^0\rightarrow K^*\pi^\pm\) and \(\Lambda_c^+ ightarrow pK_S^0\) channels), aided by ITS based on statistical selection of tracks originating from a secondary vertex.

2. Groomed substructure of inclusive jets

Measurements of groomed jet substructures allow for access to the hard parton structure of a jet, while mitigating the effects of the underlying event and hadronization \[4\]. Ideally, it provides a direct interface with QCD calculations. Soft-drop grooming is a novel technique that is able to remove wide-angle soft radiation (such as initial-state radiation) as well as that of the underlying event \[5\]. In this method, the jets that had previously been reconstructed with the anti-\(k_T\) algorithm \[6\] are first declustered and then reclustered using the Cambridge-Aachen algorithm \[7\] to form a clustering tree that follows angular ordering. Then the soft branches are iteratively removed if not fulfilling the so-called soft-drop condition,

\[
z > z_{cut} \theta^\beta, \quad \text{where } z = \frac{p_{T,2}}{p_{T,1} + p_{T,2}} \quad \text{and } \theta = \frac{\Delta R_{1,2}}{R},
\]

are the momentum fraction taken by the second prong (\(p_{T,1}\) and \(p_{T,2}\) being the momenta of the two prongs), and the splitting radius (defined as the ratio of the \(\Delta R_{1,2}\) splitting angle between the two prongs and the resolution parameter of the anti-\(k_T\) clustering). The soft threshold is set to \(z_{cut} = 0.1\). The angular exponent \(\beta\) is responsible for rejecting soft radiation. The jet groomed momentum fraction \(z_g\) and the groomed radius \(\theta_g\), defined as the values of \(z\) and \(\theta\) corresponding to the first hard splitting fulfilling the soft-drop condition. Fig. 1 shows \(z_g\) (left panel) and \(\theta_g\) (right panel) for charged-particle based jets for different choices of \(\beta\). For smaller \(\beta\) values, more soft splittings are groomed away, leading to more collimated jets. This is clearly visible in the case of \(\theta_g\) where the weight of the distribution shifts toward smaller angles with decreasing \(\beta\).

Figure 2 shows the full-jet groomed momentum fraction \(z_g\) in the 30 < \(p_{T}^{jet}\) < 40 GeV/c transverse for different \(R\) values. The difference suggests that jets with small radii tend to split more symmetrically, while in case of larger radii there is a higher sensitivity to non-perturbative effects. Trends observed both in the \(R\) and the \(\beta\)-dependent groomed jet substructure results are reproduced rather well by Monte-Carlo event generators \[8, 9\].
Figure 1: Charged-particle jet $z_g$ (left) and $\theta_g$ (right) in pp collisions at $\sqrt{s} = 13$ TeV for different $\beta$ values, compared to PYTHIA 8 simulations.

Figure 2: Full jet $z_g$ for different jet resolution parameter values compared to PYTHIA simulations, in pp collisions at $\sqrt{s} = 13$ TeV.

Figure 3: Ratio of the angular distribution of splittings with different $k_T$ cuts for $D^0$-tagged jets over inclusive jets, shown for $5 < E_{rad} < 15$ GeV.

3. Structure and fragmentation of heavy-flavor jets

In gauge theories, charged particles with a mass $m > 0$ and energy $E$ emit radiation that is suppressed below angles $\theta \approx m/E$ with respect to the axis of the radiator. This so-called dead-cone effect is expected to be present in jets containing heavy flavor [10, 11]. The ALICE collaboration presented the first direct measurement of the dead cone in heavy-flavor jets, following the iterative declustering method proposed in Ref. [12]. A cut on the relative transverse momentum fraction of the splitting, $k_T$, is applied to remove non-perturbative effects. Fig. 3 shows the ratio of the angular distribution of splittings for $D^0$-tagged jets over inclusive jets for radiator energy of $5 < E_{rad} < 15$ GeV. The $D^0$-tagged jets show a significant suppression toward smaller splitting angles. This suppression becomes stronger if the $k_T$ cut is set to higher values, corresponding to a
cleaner dead-cone signature with less contamination by non-perturbative effects.

The reconstruction of heavy-flavor hadrons within a jet allows for direct access to the fragmentation properties, and also allows for a comparison of meson and baryon fragmentation. The parallel momentum fraction $z_k$ of $D^0$ mesons and $Λ_c^+$ baryons, shown in Fig. 4 left and right panels respectively, exhibit similar trends in the chosen momentum range. It is to be noted however, that a quantitative description of the observations still poses a challenge to some of the most popular model calculations [9, 13, 14].

The groomed jet substructure of $D^0$-tagged jets has been measured for the first time, and compared to that of inclusive jets. Trends in $z_k$ (Fig. 5 left) and $θ_R$ (Fig. 5 center) are slightly different for charmed and inclusive jets, giving a hint about flavor-dependent jet substructure. A more obvious difference is present in the distribution of the number of splittings fulfilling the soft-drop condition, $n_{SD}$ (Fig. 5 right). The fact that charm jets typically have less hard splittings than inclusive jets is consistent with harder heavy-flavor fragmentation caused by mass and color charge effects.

Figure 4: Parallel momentum fraction $z_k$ of charged-particle jets tagged with $D^0$ mesons (left) and $Λ_c^+$ baryons (right).

Figure 5: Substructure variables $z_k$ (left), $θ_R$ (center) and $n_{SD}$ (right) of $D^0$-tagged charged-particle jets compared to inclusive charged-particle jets, in pp collisions at $p_{\text{T}} = 13$ TeV.
4. Summary

In this contribution, recent jet-related results were presented from the ALICE experiment in pp collisions at $\sqrt{s} = 13$ TeV. Soft-drop groomed substructure measurements of full and charged jets provide an excellent opportunity to test perturbative QCD and hadronization models, besides serving as a baseline for heavy-ion collisions. We also presented the first direct measurement of the dead cone in heavy-flavor jets. Parallel momentum fractions of charmed $D^0$ mesons and $\Lambda_c^+$ baryons provide great discrimination power among models on heavy-flavor fragmentation. Charmed jets have been found to typically have less hard splittings than inclusive jets, suggesting a harder fragmentation of heavy than light flavor. The upcoming Run–3 phase of LHC with higher luminosity will allow for high-precision measurements of jets, charmed baryons as well as beauty-jets, further facilitating model developments and moving toward a deeper understanding of the strong interaction [15].

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