QCD dynamics studied with jets in ALICE

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Precise measurements and calculations of the internal structure of hadronic jets produced in high energy proton or lead collisions have become a prominent research area in recent years. Jet substructure provides information about quantum chromodynamics (QCD) and plays an important role in the study of the evolution of the quark-gluon plasma. The ALICE experiment is uniquely suited to provide insight into the smallest splitting angles due to high efficiency in the reconstruction of charged particles. In this proceeding, we present an overview of recent ALICE results on jet substructure in pp collisions involving measurements of generalized angularities of groomed and inclusive jets, a new double-differential measurement of the Lund jet radiation plane for jets with a transverse momentum ($p_T$) between 20 and 120 GeV/c, the first direct measurement of the dead-cone effect, and substructure measurements of heavy flavor tagged jets. These latest results provide new insights into the jet evolution by comparing to various theoretical predictions.

1 Introduction

Collimated sprays of particles known as jets provide a variety of opportunities to test QCD dynamics. As aggregate objects, the overall jet structure and internal substructure are sensitive to the evolution of the jet and its splittings. Such splittings contain a wealth of information complementary to the overall jet properties, presenting the opportunity to make stringent and detailed tests of QCD predictions.

In order to investigate and test QCD, ALICE [1] has made a variety of such jet structure and substructure measurements. ALICE is particularly well suited for these measurements due to the precise charged-particle tracking in the central barrel, based around the Inner Tracking System and Time Projection Chamber. This enables the measurement of small splitting angles at high efficiency. The electromagnetic calorimeter (EMCal) allows for a more complete measurement of the jet energy, but with more limited acceptance.

Jets are reconstructed for a variety of jet resolution parameters, $R$, using the anti-$k_T$ algorithm provided in FastJet [2]. These jets were reconstructed in pp collisions at $\sqrt{s} = 5.02$ and 13 TeV, which were recorded in 2016, 2017, and 2018. Two classes of jets are discussed: charged-particle jets, where only charged particles are used for jet reconstruction, and full jets, where both charged particles and EMCal cluster information are incorporated. Jets are required to be contained fully within the acceptance of the central barrel or EMCal, respectively.

2 Systematic study of jets splittings with the Lund plane

In order to characterize the full set of jet splittings, their properties can be recorded in the Lund plane [3], which describes the jet splitting phase space. After $R = 0.4$ charged-particles jets are reconstructed, the jet constituents are reclustered using the Cambridge/Aachen algorithm,
producing an angular ordered tree of splittings, with each node connected to subjets. This clustering is unwound, recording \( \ln\left(\frac{R}{\Delta R}\right) \) (where \( \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \)) and \( \ln(k_T) = \ln(p_{T,\text{sublead}} \sin \Delta R) \) for each splitting, and then proceeding to the next one, iteratively following the harder subjet. This set of splittings contribute to the measurement of the primary Lund plane density

\[
\rho(\Delta R, k_T) = \frac{1}{N_{\text{jets}}} \frac{d^2n}{d \ln(R/\Delta R) d \ln k_T}.
\]

For this measurement, Bayesian iterative unfolding was utilized to correct for detector effects \[4\]. Unfolding was performed in three dimensions for the first time in ALICE, incorporating \( p_{T,\text{jet}}^{ch} \), \( \ln(R/\Delta R) \), and \( \ln(k_T) \) \[5\]. The measurement is corrected for the purity and efficiency of non-uniquely matched subjets, and subjet mismatches are corrected in the unfolding. The number of jets normalization is determined through a separate one-dimensional unfolding.

The fully corrected primary Lund plane density is shown in Fig. 1 for \( 20 < p_{T,\text{jet}}^{ch} < 120 \) GeV/c measured in pp collisions at 13 TeV. The most common splittings are those at wide angles and low \( k_T \), steeply falling with increasing \( k_T \). This measurement is at a substantially lower \( p_{T,\text{jet}} \) than the ATLAS measurement \[6\], providing complementary information. In order
Figure 3 – Angular separation of $D^0$-tagged subjets compared to inclusive jets as a function of the incoming energy of the splitting (left) and the number of iterative splittings which pass the Soft Drop condition (right) $R = 0.4$. $D^0$-tagged charged-particle jets in pp collisions at $\sqrt{s} = 13$ TeV. Both show modifications of low $p_T$ jets consistent with the dead cone effect.

to make more quantitative statements, data are restricted into a variety of regions in phase space and are compared to models, including PYTHIA8 Monash [7], HERWIG 7 [8], and SHERPA 2.28 [9] with two different hadronization algorithms: AHADIC and Lund. A selection of these comparisons are shown in Fig. 2, illustrating the different behaviors for narrow vs wide splittings. Most of the models show some disagreement with the data for narrow splittings at high $k_T$, while the models are able to describe the wider splittings within 10–20%.

3 Observation of the Dead Cone

Further tests of QCD are possible by focusing on the substructure of charm quark tagged jets. Low energy splittings containing a $D^0$ meson introduce mass effects from the charm quark, namely the suppression of splittings at small angles due to the QCD dead cone [10].

To access this effect, ALICE has measured the inverse of the splitting angle $1/\theta$ for all splittings in both $D^0$-tagged and inclusive charged-particles jets measured via the Lund plane in pp collisions at $\sqrt{s} = 13$ TeV. In order to isolate the impact of the dead cone, splittings are selected according to the energy incoming to each splitting, $E_{\text{radiator}}$. The ratio of the rate of these splittings is shown on the left of Fig. 3. The class of lower $E_{\text{radiator}}$ splittings, which are more comparable to charm mass, are more suppressed at small splitting angles compared to higher energies. This effect is consistent with the QCD dead cone.

A similar effect can also be seen when selecting only a subset of splittings, namely those which pass the Soft Drop [11] condition, $z_{\text{cut}} > 0.1$ [12]. The number of splittings which pass this condition, $n_{SD}$, are compared for $D^0$-tagged and inclusive jets on the right of Fig. 3. The reduced number of splittings for $D^0$-tagged jets is consistent with expectations from color factors and the impact of the dead cone.

4 Selecting specific splitting with groomed jet substructure

In addition to $D^0$-tagged jets, ALICE has performed detailed studies of splittings in inclusive jets which are selected via a variety of grooming methods. Systematic studies with Soft Drop [11] using $z_{\text{cut}} > 0.1$ have been performed for $R = 0.2$-0.5 full jets measured in pp collisions at $\sqrt{s} = 13$ TeV. A selection of these results at low $p_{T,\text{jet}}$ are shown on the left of Fig. 4, indicating that the shared momentum fraction is more symmetric for smaller $R$ jets. This $R$ dependence disappears at high $p_{T,\text{jet}} (> 160$ GeV/c).
ALICE has also measured additional grooming methods, including the first measurements using Dynamical Grooming [13], studying $R_g$, $z_g$, and hardest $k_T$ for $R = 0.4$ charged jets. The hardest $k_T$ splittings are shown for a selection of grooming methods on the right of Fig. 4, illustrating the convergence of the selected splittings at high $k_T$ regardless of the method. Recent analytical calculations [14] show that the inclusion of non-perturbative contributions is essential for describing the data.

5 Conclusion and outlook

ALICE has measured a wide variety of jet substructure measurements in pp collisions at $\sqrt{s} = 5.02$ and 13 TeV, including the Lund plane for inclusive charged jets, $D^0$-tagged jet substructure, and groomed jet substructure for inclusive charged-particle and full jets. Beyond these proceedings, relevant ALICE measurements include full jet cross section ratios [15] and systematic studies of charged-particle jet angularities. Taken together, these observables provide substantial opportunity to test QCD dynamics. Looking ahead, the Lund plane analysis is a blueprint for future measurements, such as utilizing heavy flavor tagged jets. These results will also serve as a baseline for comparison with measurements in Pb–Pb collisions.

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