Studying jet formation in the medium with the help of correlation and jet shape observables

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Abstract. The ALICE collaboration at CERN has dedicated a significant part of its physics program to study jet formation and modification in the hot and dense environment formed in heavy-ion collisions. These proceedings will summarize the latest insights we have gained about this process using data collected during Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. In particular $\pi^0$-hadron correlations, jet mass measurements, and jet shapes of small-radius jets show a significant influence of the hot and dense medium on the measured jet fragmentation process.

1. Introduction

In recent years the qualitative investigation of jet modification in terms of jet suppression, such as $R_{AA}$ measurements of individual high-$p_T$ particles (with $p_T$ being their transverse momentum) or reconstructed jets, has been succeeded by more differential observables that dissect the jet structure itself [1, 2]. Examples of such observables are measurements of jet mass [3, 4], various jet shapes [5], jet fragmentation [6, 7, 8, 9], and jet splitting functions [10]. Through such measurements it was observed that the jets reconstructed in heavy-ion collisions have a modified structure as compared to their counterparts in pp collisions. In particular, observation of the distribution of energy inside of the jet cone showed that soft fragments appear at large angles with respect to the jet axis [11, 12]. Such a redistribution of energy among the jet fragments was confirmed by complementary observables of jet-fragment distributions as a function of the radial distance to the jet axis ($r$) [12, 13, 14] and the parton momentum fraction carried by the final state hadron ($z$) [6, 7, 8, 9].

These initial observations motivated researchers to intensify their investigation of jet substructures and the interplay between the pure jet fragmentation modification and the medium response to the presence of the jet. Measurements of the modified jet fragmentation function in Pb–Pb collisions [6] led to the discussion of “survivor bias” caused by a different quenching of quark vs. gluon jets [15].

Future measurements and their theoretical interpretation will have to disentangle the pure impact of a modified jet fragmentation due to the medium from modifications originating from medium recoils. Further, the impact of the underlying jet spectrum (increased number of quark vs. gluon jets in heavy-ion collisions) must be disentangled in the observables in order to understand the influence of the medium to the many effects that modify the measured jet profile.
Figure 1. Ratio of associated hadron per trigger yields in Pb–Pb compared to pp collisions, $I_{AA}$ as a function of $p_T$ of the associated hadrons. The left panel presents the ratio for the near-side yield and the right panel for the away-side yield. Both panels show data selected with a high-$p_T$ $\pi^0$-trigger with $p_T = 8–16$ GeV/c and a 0–10% centrality selection for the Pb–Pb data set [16].

2. Correlations of $\pi^0$s and hadrons

Jet fragmentation can be studied without necessarily reconstructing the jet as an object itself. Instead, one can rely on a high-$p_T$ trigger particle and study the pseudo rapidity ($\eta$) and azimuthal angle ($\phi$) difference ($\Delta\eta$, $\Delta\phi$) of associated hadrons with respect to the trigger particle. This combination of trigger and associated hadrons forms typical 2D correlation functions that can be studied to collect information about the associated hadron per trigger yield or the width of associated hadron distributions in $\Delta\eta$ or $\Delta\phi$.

One example of such correlation measurements with high-$p_T$ trigger particles is a measurement by ALICE of $\pi^0$-hadron correlations in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [16]. In this measurement $\pi^0$s of $p_T = 8–16$ GeV/c were correlated with hadrons of $p_T = 0.5–10$ GeV/c for the 0–10% most central collisions. The correlation function was corrected for acceptance effects and background. The associated hadron yield was integrated on the near ($|\Delta\phi| < 0.7$) and away ($|\Delta\phi - \pi| < 1.1$) side. These integrated associated yields were evaluated for different $p_T$ intervals. To study medium effects on the measured associated yield, which is connected to the modification of the jet fragmentation function, the associated yield in pp collisions was compared to Pb–Pb collisions, at the same collision energy. Figure 1 shows the ratio of these two yields as a function of $p_T$ of the associated hadrons. The ratio is shown for the near side (left) and the away side (right). While there is a general enhancement of associated hadrons on the near side (the jet in which the $\pi^0$-trigger is produced) there is a more differential modification on the away side (the jet balancing the jet with the $\pi^0$-trigger). This enhancement of the near-side jet yield is not yet fully understood. It could be due to a modified fragmentation function, the medium response, or a different underlying parton sample that fragments. The away side, on the other hand, shows a depletion of high momentum particles and an enhancement of low momentum particles in the balancing jet. This picture is consistent with other measurements that show a transition of depletion to enhancement at a $p_T$ of the associated hadrons of about 3.5 GeV/c [17].

More properties of such correlation observables are currently studied in Pb–Pb and p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and will be available in the future for comparisons to the previously published results at the lower collision energy.
Figure 2. Ratio of the reconstructed jet mass for two collision systems: 0–10% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, and minimum bias p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results are shown for three jet-$p_T$ ranges. The measured ratios are compared to ratios of PYTHIA simulations at the two collision energies to illustrate the effect induced by the energy difference [3].

3. Jet mass measurements
ALICE has published the first jet mass measurement of charged jets produced in Pb–Pb and p–Pb collisions [3]. The jet mass is related to the virtuality of the parton that originates the jet shower [18]. There are several effects that may compete in modifying the virtuality of the parton traversing the hot and dense phase. The interaction of propagating partons with the hot nuclear matter might increase their virtuality, which in turn could increase the measured mass; energy loss experienced by the partons could decrease the mass; significant jet profile broadening could shift constituents out of the jet cone radius and thus decrease the mass; and the medium response to the jet could add particles to the jet which would increase the reconstructed jet mass [3].

The measurement was carried out for charged jets with resolution parameter of $R = 0.4$ and jet momenta of 60–120 GeV/$c$. The jets were constructed from particles with a track $p_T = 0.15$–100 GeV/$c$ and required at least one constituent with $p_T > 4$ GeV/$c$. The jets measured in the 0–10% most central Pb–Pb collisions were corrected for background contributions on a jet-by-jet basis and then unfolded back to the particle level. Jets measured in minimum bias p–Pb collisions were corrected for their small background contributions in the unfolding procedure.

The unfolded results of the jet mass in the two collision systems were compared to each other in three jet-$p_T$ intervals. Figure 2 shows the ratio of Pb–Pb to p–Pb data. Since the measurement is performed at two different collision energies this ratio is compared to the respective PYTHIA reference ratio to illustrate the effect induced by the energy difference. The difference in collision energies is expected to cause a slight shift of the ratio to lower jet masses; the observed ratio indicates a shift to lower masses beyond that expectation. In order to gain insight into which of the above-mentioned effects dominates the jet mass shift, a comparison to theoretical models is necessary. Figure 3 summarizes a comparison of the measured jet mass in Pb–Pb collisions to several theoretical predictions. It appears that the inclusion of the medium response in the models (JEWEL w. recoils and Q-PYTHIA) causes a significant shift of the jet mass to higher values, which is not confirmed by the experimental data. Surprisingly, PYTHIA, with its vacuum mass, describes the measurement best. It is obvious that more experimental results on the reconstructed jet mass at different jet radii and momenta are necessary in order to clarify the origin of this discrepancy.

Preliminary results from ATLAS on a related observable also show no significant medium
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1. Jet fragmentation function measured in Pb–Pb collisions

Figure 3. Distributions of the fully-corrected jet mass in 0–10% most central Pb–Pb collisions compared to predictions of PYTHIA simulations with the Perugia 2011 tune and predictions from JEWEL and Q-PYTHIA [3].

Effect on the measured jet mass [4]. ATLAS has measured the nuclear modification factor $R_{AA}$ in different jet $p_T$ bins as a function of $m/p_T$ (with $m$ being the jet mass). There is no obvious dependence of $R_{AA}$ on the jet mass in a given $p_T$ bin that would indicate a suppression of higher or lower masses in respect to pp collisions. For higher jet $p_T$ there might be an increased suppression for higher jet masses visible, which would also shift the average mass to lower values, as indicated by ALICE.

4. Jet substructure measurements of small-radius jets

To further study the modification of the jet fragmentation function and the medium recoil influence on reconstructed jet shapes, the ALICE collaboration has measured three additional jet shape observables [5]: the difference between leading and sub-leading track $p_T(LeSub)$, the momentum dispersion ($p_TD$), and the first radial moment or girth ($g$). They are defined as:

$$LeSub = p_{T,\text{lead track}} - p_{T,\text{sublead track}}, \quad p_TD = \sqrt{\frac{\sum_{i\in\text{jet}} p_{T,i}^2}{\sum_{i\in\text{jet}} p_{T,i}}}, \quad g = \sum_{i\in\text{jet}} \frac{p_{T,i}}{p_{T,jet}} \Delta R_{jet,i}. \quad (1)$$

$LeSub$, which measures a momentum difference between the two leading tracks, is sensitive to the hardness of the fragmentation process. The momentum dispersion is a measure for the quantity of jet fragments to which the original parton $p_T$ is distributed. In case the original parton $p_T$ is only distributed into very few jet constituents $p_TD$ will approximate 1; in case it is distributed to many jet constituents $p_TD$ will approach 0. The girth of very collimated jets or jets where one only finds very soft fragments at larger radii will have small values around 0 and jets with a very broad shower or hard fragments far away from the center will exhibit larger values of $g$.

These three jet shape variables were reconstructed in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and in pp collisions at $\sqrt{s} = 7$ TeV. The jet samples that were used to measure the jet shapes contained charged jets with $R = 0.2$ and $p_T^{ch,jet}$ of 40–60 GeV/c. The jets in the Pb–Pb data sample were corrected jet-by-jet for the contribution of the underlying event. The jets in both data sets were unfolded back to the particle level in a two-dimensional unfolding procedure. The jet shape measurement for the pp collision system is presented in Fig. 4. The data were compared to PYTHIA simulations which shows a good agreement to the vacuum jet shape distributions. Assuming no major collision energy dependence on the quality of description, this validates to use PYTHIA as a reference for the shapes measured in Pb–Pb collisions. Any major difference
of these measurements from PYTHIA simulations can thus be attributed to medium effects. Figure 5 presents the comparison of the fully corrected small-radius jet shapes, measured in Pb–Pb collisions, to PYTHIA simulations at the same collision energy. A significant difference of the jet shapes between data and simulation is observed. LeSub is overall well described by the vacuum distribution of PYTHIA. The $p_T D$ distribution is shifted to higher values as compared to the vacuum distribution indicating a harder fragmentation with fewer constituents in the jet. The $g$ distribution is shifted to lower values indicating a more collimated jet shower of jet cores in Pb–Pb collisions as compared to pp collisions.

![Figure 4](image1.png)

**Figure 4.** The jet shape distributions for small-radius jets of $R = 0.2$ and $p_T^{ch, jet} = 40–60$ GeV/c in minimum bias pp collisions with LeSub (left), $p_T D$ (middle), and $g$ (right). The lower panel shows the ratio to PYTHIA simulations with two different tunes [5].

![Figure 5](image2.png)

**Figure 5.** Jet shape distributions for small-radius jets of $R = 0.2$ and $p_T^{ch, jet} = 40–60$ GeV/c in 0–10% most central Pb–Pb collisions with LeSub (left), $p_T D$ (middle), and $g$ (right). The data are compared to PYTHIA simulations made with the Perugia 11 tune [5].
Overall, the fragmentation of jets reconstructed in Pb–Pb collisions appears to be more quark-like (harder, more collimated fragmentation) than gluon-like (wider, softer fragmenting jet) which could point to a survivor bias of quark jets being measured in Pb–Pb collisions.

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