Correlations of High- p_T Hadrons and Jets in ALICE[†]

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Abstract: There are two prominent experimental signatures of quark–gluon plasma creation in ultra-relativistic heavy-ion collisions: the jet quenching phenomenon and the azimuthal-momentum space-anisotropy of final-state particle emission. Recently, the latter signature was also observed in lighter collision systems such as p–Pb or pp. This raises a natural question of whether in these systems, the observed collectivity is also accompanied by jet quenching. In this paper, we overview ALICE measurements of the jet quenching phenomenon studied using semi-inclusive distributions of track-based jets recoiling from a high-transverse momentum (p_T) hadron trigger in Pb–Pb and p–Pb collisions at LHC energies. The constructed coincidence observable, the per trigger normalized yield of associated recoil jets, is corrected for the complex uncorrelated jet background, including multi-partonic interactions, using a data-driven statistical subtraction method. In the p–Pb data, the observable was measured in events with different underlying event activity and was utilized to set an upper limit on the average medium-induced out-of-cone energy transport for jets with resolution parameter $R = 0.4$. The associated jet momentum shift was found to be less than $0.4 \text{ GeV}/c$ at 90% confidence.

Keywords: jet quenching; QGP; event activity; small systems

1. Introduction

Ultra-relativistic heavy-ion collisions are used to probe the properties of strongly interacting matter in the regime of extremely high-energy densities and temperatures and vanishing baryochemical potential [1]. Lattice quantum chromodynamics calculations predict that under such conditions, the hadron gas phase undergoes a transition to the state called quark–gluon plasma (QGP) [2]. In this phase, quarks and gluons are released from their confinement in hadrons. The transition has a smooth cross-over character and happens at a temperature of about 150 MeV [3].

A collision of heavy ions creates a rapidly evolving dynamical system where the QGP phase lasts only a short instant. As the collision zone expands and cools, quarks and gluons merge together, giving a rise to a multitude of hadrons that further interact among each other until the kinematic freeze-out is reached [1]. When particles from the collision reach our detector, the QGP does not exist anymore; therefore, properties of the QGP can be investigated indirectly only. Among different experimental observables that are studied in this context, two of them are believed to be directly associated with the production of the QGP in heavy-ion collisions: the large azimuthal-momentum space-anisotropy of produced particles [4,5] and the jet quenching phenomenon [6,7]. The first observable is connected with the time evolution of the initial spatial anisotropy of the collision zone, which results in an azimuthal-momentum space-anisotropy of produced particles. Hydrodynamic calculations, which model this process, show that the magnitude of the observed flow is compatible with QGP behaving like a nearly perfect liquid with a very small shear-viscosity to entropy-density ratio [8].

The jet quenching phenomenon is manifested by a marked reduction of energy of high- p_T hadrons and jets that traversed the QGP medium. Their yield measured in heavy-ion collisions is suppressed

when compared to the yield that would be expected from a superposition of the corresponding number of independent pp collisions.

Jets are intuitively understood as collimated sprays of particles that are produced by the fragmentation of highly virtual partons. The exact definition of a jet is done with jet reconstruction algorithms [9]. These algorithms were designed to recover energy of the original parton by summing up momenta of final-state particles. In elementary collisions, the production of jets is well-described with the perturbative quantum chromodynamics [10]. In heavy-ion collisions, highly virtual partons that fragment to jets are produced by hard scatterings that happen before the QGP is formed. The parton shower thus gets modified while these partons traverse the medium [11]. Based on the observed modification, medium properties can be inferred. Jets are thus considered well-suited probes of the produced QGP.

Jets in heavy-ion collisions are accompanied by an intensive underlying event. A jet reconstruction algorithm therefore often clusters together just soft particles from the underlying event and creates a so-called combinatorial background jet. One way to suppress the contribution of these artificial jets is to require the presence of a high- p_T constituent within the reconstructed jet [12]. This condition, however, imposes a fragmentation bias on the reconstructed jets and can essentially affect the selected jet sample. As we will see in the following section, hadron-jet coincidence measurements offer a way to overcome this problem [13]. They allow the removal of the contribution of combinatorial background jets, including the contribution from multi-parton interactions, without imposing the fragmentation bias on analyzed jets. The method is data-driven and uses statistical subtraction. It is suitable also for jets having large R and low p_T .

2. Hadron-Jet Coincidence Measurements in Pb–Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

A principle of hadron-jet coincidence measurements will be explained based on the analysis of Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV recorded by ALICE in 2011. The same analysis procedure will be then applied to the data from p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV from 2013. Further details about both data sets and analyses can be found in the original papers [14,15].

ALICE is one of the four big experiments working at the Large Hadron Collider at CERN. The ALICE apparatus is described in detail elsewhere [16]. Let us note that track reconstruction is based on position measurements performed by a six-layer silicon tracker called the Inner Tracking System [17], which surrounds the interaction point, and the Time Projection Chamber [18]. Both detectors have full azimuthal coverage, and tracks can be efficiently reconstructed in the pseudorapidity range $|\eta_{\text{track}}| < 0.9$. Both detectors are placed in a 0.5 T solenoidal magnetic field, which ensures reasonable transverse momentum resolution for tracks in the range $0.15 < p_{T,\text{track}} < 100$ GeV/c.

Track-based jets are reconstructed from charged tracks with $0.15 < p_{T,\text{track}} < 100$ GeV/c using the infrared and collinear safe anti- k_T algorithm [19] as implemented in the FastJet package [20]. Reconstructed jets have a resolution parameter of $R = 0.4$ and are assembled using the boost-invariant p_T -recombination scheme. Pseudorapidity of jets is constrained by a fiducial cut $|\eta_{\text{jet}}| < 0.5$ to remove jets whose jet cone overlaps with borders of the ALICE acceptance. The reconstructed transverse momentum of jets, $p_{T,\text{jet}}^{\text{raw,ch}}$, is corrected for the mean underlying event contribution on an event-by-event basis by subtracting a product of the mean underlying event density ρ and jet area A_{jet} ,

$$p_{T,\text{jet}}^{\text{reco,ch}} = p_{T,\text{jet}}^{\text{raw,ch}} - \rho \cdot A_{\text{jet}}. \quad (1)$$

Here, the mean underlying event density is estimated by the standard area-based approach [21] as

$$\rho = \text{median}_{k_T \text{ jets}} \frac{p_{T,\text{jet}}^{\text{ch}}}{A_{\text{jet}}}, \quad (2)$$

which is calculated based on a sample of reconstructed k_T track-based jets with $R = 0.4$.

In hadron-jet coincidence measurements, we analyze events that contain a high- p_T track, the so-called trigger track or TT. The presence of a high- p_T particle unambiguously selects events with a hard scattering. The trigger track p_T is required to be in some chosen range $X < p_{T,\text{trig}} < Y \text{ GeV}/c$, which is denoted $\text{TT}\{X,Y\}$ throughout the text. If multiple TT candidates are found, one of them is chosen at random. Jets, which are to be analyzed, are selected to be nearly back-to-back in azimuth w.r.t. to TT,

$$|\varphi_{\text{TT}} - \varphi_{\text{jet}}| < \pi - 0.6 \text{ rad} \quad (3)$$

where φ_{TT} and φ_{jet} denote azimuthal angles of TT and recoiling jets. Figure 1 shows the per trigger normalized transverse momentum spectra of recoil jets associated with two exclusive trigger track p_T bins $\text{TT}\{8,9\}$ and $\text{TT}\{20,50\}$ in the 0–10% centrality bin of Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$. Note that both spectra exhibit a remarkable similarity in the region $p_{T,\text{jet}}^{\text{reco, ch}} \lesssim 0$, where their shape does not depend on the transverse momentum of TT. Jets populating this region are predominantly combinatorial background jets, which are accidentally associated with TT. On the other hand, in the region $p_{T,\text{jet}}^{\text{reco, ch}} > 0$, both spectra differ. Since the presence of a $\text{TT}\{20,50\}$ hadron biases the four-momentum transfer in the associated hard scattering to higher values, the corresponding recoil jet spectrum is harder. The spectrum in the region $p_{T,\text{jet}}^{\text{reco, ch}} > 0$ also has, however, the component coming from combinatorial background jets. Based on the situation in the region $p_{T,\text{jet}}^{\text{reco, ch}} \lesssim 0$, it is assumed that this component is independent of TT p_T . Thus, it will be canceled when both spectra are subtracted.

$$\Delta_{\text{recoil}} = \frac{1}{N_{\text{trig}}} \cdot \frac{d^2 N_{\text{jet}}}{dp_{T,\text{jet}}^{\text{ch}} d\eta_{\text{jet}}} \Big|_{\text{TT}\{20,50\}} - \frac{1}{N_{\text{trig}}} \cdot \frac{d^2 N_{\text{jet}}}{dp_{T,\text{jet}}^{\text{ch}} d\eta_{\text{jet}}} \Big|_{\text{TT}\{8,9\}}. \quad (4)$$

Here N_{trig} denotes the number of TT in a given TT bin. Let us point out that on the theory side, the per trigger normalized yield of recoil jets can be expressed in terms of a cross section to produce a high- p_T hadron and a cross section to produce a high- p_T hadron together with a jet.

$$\frac{1}{N_{\text{trig}}} \cdot \frac{d^2 N_{\text{jet}}}{dp_{T,\text{jet}}^{\text{ch}} d\eta_{\text{jet}}} \Big|_{p_{T,\text{trig}} \in \text{TT}} = \frac{1}{\sigma_{h+X}} \cdot \frac{d^2 \sigma_{h+\text{jet}+X}}{dp_{T,\text{jet}}^{\text{ch}} d\eta_{\text{jet}}} \Big|_{p_{T,h} \in \text{TT}}. \quad (5)$$

The measured Δ_{recoil} spectrum was further corrected for jet reconstruction inefficiency and jet energy scale smearing due to instrumental effects and local underlying event fluctuations. The relation between the measured jet spectrum and the true jet spectrum was assumed to be linear, and the combined effect of the instrumental effects and local background fluctuations on the true jet spectrum was described by means of a response matrix. Regularized inversion of this matrix and the corresponding solution for the true spectrum was found by means of Bayesian unfolding [22,23]. The fully corrected Δ_{recoil} spectrum for anti- k_T jets with $R = 0.2, 0.4$, and 0.5 is shown in the right-hand side panel of Figure 1.

The medium-induced modification of the recoil jet spectrum was quantified by means of a ratio

$$\Delta I_{\text{AA}} = \frac{\Delta_{\text{recoil}}^{\text{Pb-Pb}}}{\Delta_{\text{recoil}}^{\text{PYTHIA}}}, \quad (6)$$

where $\Delta_{\text{recoil}}^{\text{Pb-Pb}}$ denotes the fully corrected Δ_{recoil} spectrum measured in Pb–Pb collisions and $\Delta_{\text{recoil}}^{\text{PYTHIA}}$ is a reference Δ_{recoil} spectrum obtained from the PYTHIA 6 Perugia 2010 [24] simulation of pp collisions at the same center-of-mass energy per nucleon–nucleon collision; see Figure 2. Statistics of the measured pp $\sqrt{s} = 2.76 \text{ TeV}$ data by ALICE was found to be insufficient for this analysis. Nevertheless, for pp collisions at $\sqrt{s} = 7 \text{ TeV}$, the PYTHIA Δ_{recoil} spectrum reproduces the measured data very well [14]. The ΔI_{AA} ratio is found to be below unity, which shows that the studied sample of recoil jets was affected by jet quenching. Similar suppression was also found for track-based anti- k_T jets having $R = 0.2$ and $R = 0.5$ [14].

Figure 1. (a) Per trigger normalized transverse momentum spectra of recoil jets associated with trigger track p_T bins TT{8,9} and TT{20,50} measured in the 0–10% centrality bin of Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. (b) Fully corrected Δ_{recoil} distributions for track-based anti- k_T jets with $R = 0.2, 0.4$, and 0.5 . Systematic uncertainties in the data are shown by boxes. Taken from [14].

Figure 2. Ratio of Δ_{recoil} spectra obtained from the 0–10% centrality bin of Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and from the PYTHIA 6 Perugia 2010 simulation of pp collisions at $\sqrt{s} = 2.76$ TeV. Systematic uncertainties in the data are shown by boxes. Taken from [14].

3. Searches for Jet Quenching in p–Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

In past, the PHENIX collaboration has searched for jet quenching in d–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [25]. PHENIX measured a nuclear modification factor of inclusive anti- k_T jets with $R = 0.3$. The nuclear modification factor was calculated as

$$R_{\text{dAu}} = \frac{dN_{\text{jets}}^{\text{d-Au}}/dp_{T,\text{jet}}}{T_{\text{dAu}} \cdot d\sigma_{\text{pp}}/dp_{T,\text{jet}}}, \quad (7)$$

where T_{dAu} is the nuclear overlap function for a given centrality bin of deuteron–gold, $d\sigma_{\text{pp}}/dp_{T,\text{jet}}$ is the inclusive cross section for jets in pp collisions at the same nucleon–nucleon center-of-mass energy and $dN_{\text{jets}}^{\text{d-Au}}/dp_{T,\text{jet}}$ is the measured spectrum of jets for a given centrality in d–Au. PHENIX found that R_{dAu} is compatible with unity for minimum bias events. However, once they sorted measured events in centrality classes, they found significant enhancement for peripheral events and suppression for central events. The behavior of R_{dAu} for peripheral events was surprising since peripheral events were expected to be similar to pp. The similar ordering of the nuclear suppression factor for jets was seen also by ATLAS in peripheral and central p–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [26]. The interpretation

of these results in terms of medium-induced modification of jet production is problematic, since the calculation of the nuclear overlap function does not take into account conservation laws, which play an important role in small systems [27], e.g., momentum conservation. The detection of a high- p_T jet at midrapidity affects measurement of event activity or “centrality” in forward rapidity, and the assigned event geometry can be biased.

Hadron-jet coincidence observables have the advantage that they can be used to identify jet quenching without the need to know the corresponding nuclear overlap function [15]. If there were no medium-induced modifications of jet production in p–Pb, cross sections appearing on the right-hand side of (5) could be expressed in terms of the corresponding pp cross sections and the nuclear overlap functions T_{pPb} ,

$$\frac{1}{\sigma_{h+X}^{p-Pb}} \cdot \left. \frac{d^2\sigma_{h+jet+X}^{p-Pb}}{dp_{T,jet}^{ch} d\eta_{jet}} \right|_{p_{T,h} \in TT} = \frac{1}{T_{pPb} \cdot \sigma_{h+X}^{pp}} \cdot \left. \frac{T_{pPb} \cdot d^2\sigma_{h+jet+X}^{pp}}{dp_{T,jet}^{ch} d\eta_{jet}} \right|_{p_{T,h} \in TT}. \quad (8)$$

Since the nuclear overlap function term appears in the numerator and denominator, they cancel. It is thus not necessary to know the relation between the measured event activity and the collision geometry.

Analysis of Δ_{recoil} spectra in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is analogous to what was done in Pb–Pb. In p–Pb, event activity was measured by two forward detectors, the neutron zero degree calorimeter (ZNA) and the V0A scintillator array. Figure 3 shows the per trigger normalized yield of recoil jets associated with the chosen trigger track p_T bins TT{6,7} and TT{12,50} in 20% of p–Pb events with the largest event activity in the ZNA. The resulting raw Δ_{recoil} distribution is shown by open circles.

Figure 3. (a) Per trigger normalized transverse momentum spectra of recoil jets associated with trigger track p_T bins TT{6,7} and TT{12,50} measured in the 0–20% neutron zero degree calorimeter (ZNA) centrality bin of p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. (b) Fully corrected Δ_{recoil} distributions for track-based anti- k_T jets with $R = 0.4$. Systematic uncertainties in the data are shown by boxes. Taken from [15].

The right-hand side panel of Figure 3 shows the fully corrected Δ_{recoil} spectra obtained for minimum bias p–Pb events, for 20% of events that had the largest event activity in the ZNA, and for 50% of events that had the lowest event activity in the ZNA. Medium-induced modification of the spectrum was studied by means of the ratio of the Δ_{recoil} spectra measured for the high and low event activity; see Figure 4. The data are compatible with unity and do not exhibit a visible jet-quenching effect. Furthermore, we used these data to provide a limit on the magnitude of medium-induced energy transport to large angles out of the $R = 0.4$ jet cone. The fully corrected Δ_{recoil} spectra have an exponential shape (Figure 3). Under the assumption that higher energy density in events with

higher event activity would cause a horizontal shift of the Δ_{recoil} spectrum, we can parameterize the Δ_{recoil} spectra measured for low- and high-event activity as $\Delta_{\text{recoil}}|_{0-20\%} = a \cdot \exp(-p_{T,\text{jet}}^{\text{ch}}/b)$ and $\Delta_{\text{recoil}}|_{50-100\%} = a \cdot \exp((-p_{T,\text{jet}}^{\text{ch}} + \bar{s})/b)$, respectively. Here, a and b are constants, and $\bar{s}$ is the spectrum shift. The corresponding ratio is then $\Delta_{\text{recoil}}|_{0-20\%}/\Delta_{\text{recoil}}|_{50-100\%} = \exp(-\bar{s}/b)$. The ratio is independent of jet p_T and can be used to extract $\bar{s}$ provided that the ratio and the slope parameter b are extracted from data. Thus from the data in Figures 3 and 4, the following estimates for the spectrum shift were obtained [15]: $\bar{s} = (-0.12 \pm 0.35_{\text{stat}} \pm 0.03_{\text{syst}})$ GeV/ c for events where event activity was measured by ZNA, and $\bar{s} = (-0.06 \pm 0.34_{\text{stat}} \pm 0.02_{\text{syst}})$ GeV/ c for events where event activity was measured by V0A. Both values are consistent with zero within uncertainties.

The measured $\bar{s}$ values were further used to set a one-sided 90% confidence upper limit on the medium-induced charged energy transport out of the jet cone of $R = 0.4$ for jets with $15 < p_{T,\text{jet}}^{\text{ch}} < 50$ GeV/ c . In events with high V0A or high ZNA activity, the medium-induced charged energy transport is less than 0.4 GeV/ c at 90% confidence. This limit is shown by the red line in Figure 4.

In summary, observables that are based on correlations of high- p_T hadrons with jets provide a powerful tool to probe properties of the medium created in heavy-ion collisions. This approach makes it possible to cope with a large underlying event and does not induce fragmentation bias on the studied jet sample. It is also well-suited for jet quenching studies in small systems since their interpretation does not depend on models that relate collision geometry with event activity.

Figure 4. Ratio of fully corrected Δ_{recoil} spectra measured in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV in events having different event activity biases. Event activity was measured by ZNA (a) and V0A (b). Systematic uncertainties in the data are shown by boxes. The red line shows a value of the ratio for the situation when medium-induced charged energy transport out of the $R = 0.4$ jet cone would be $\bar{s} = -0.4$ GeV/ c . Taken from [15].

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