Jet fragmentation and multijet studies in heavy ion collisions at ATLAS

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Abstract. We report on two measurements done by ATLAS in a context of exploring the jet quenching physics at LHC: the jet fragmentation measurement and the measurement of neighbouring jet production. Both of these measurements were done using the data collected in 2011 Pb+Pb run providing Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. These measurements are expected to provide an insight into the modifications of jets initiated by partons passing through hot and dense QCD matter created in heavy ion collisions.

1. Introduction
In this short report, we summarize two recent measurements done by ATLAS related to the jet quenching: the measurement of jet fragmentation [1] and the measurement of neighbouring jet production [2]. Both of these measurements are expected to improve our understanding of jet quenching. Jet quenching refers, collectively, to a set of possible modifications of parton showers by the quark-gluon plasma through interactions of the constituents of the shower with the colour charges in the plasma [3]. Shower constituents may be elastically or inelastically scattered resulting in both deflection and energy loss of the constituents of the shower. This modification of jet internal structure may be then detected as a modification of the jet fragmentation functions. If the parton shower is modified in its early stage when hard gluons are radiated, then rates of neighbouring jets may also be affected. The neighbouring jets originating from the same hard interaction propagate in approximately the same direction and should have similar path lengths in the medium. Therefore, measuring the neighbouring jet production may probe the differences in the quenching of two jets that do not result primarily from the difference in the path length.

2. Data selection
The measurements summarized in this report use the data collected in 2011 Pb+Pb run providing Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The data were selected using high-level trigger (HLT) seeded by a Level-1 minimum-bias trigger. The Level-1 trigger required a total transverse energy measured in the calorimeter greater than 10 GeV. The HLT jet trigger required a presence of underlying-event-subtracted jet with transverse energy greater than 20 GeV. The total integrated luminosity of data sample selected by the HLT trigger is $0.14 \text{nb}^{-1}$.

The measurement of neighbouring jets uses also the data selected by the minimum bias (MB) trigger. MB triggers use the zero degree calorimeter (ZDC) covering the pseudorapidity range of $|\eta| > 8.3$, the inner detector (ID) covering $|\eta| < 2.1$, and minimum-bias trigger scintillators
(MBTS) covering the pseudorapidity range of \(2.1 < |\eta| < 3.9\). The total integrated luminosity of data sample triggered by MB trigger is \(7 \mu b^{-1}\).

The reference Monte Carlo (MC) event sample was obtained by overlaying simulated PYTHIA \(^4\) \(pp\) hard-scattering events at \(\sqrt{s} = 2.76\) TeV onto 1.2 million minimum-bias Pb+Pb events recorded in 2011.

The centrality of Pb+Pb collisions was characterized by \(\Sigma E_{\text{FCal}}^T\), the total transverse energy measured in the forward calorimeters. The measurement of fragmentation functions was performed in seven centrality bins defined according to successive percentiles of the \(\Sigma E_{\text{FCal}}^T\) distribution ordered from the most central to the most peripheral collisions: 0–10%, 10–20%, 20–30%, 30–40%, 40–50%, 50–60%, and 60–80%. The measurement of neighbouring jet production was performed in four centrality bins, 0–10%, 10–20%, 20–40%, and 40–80%.

Jets were reconstructed using the anti-\(k_t\) jet finding algorithm \(^5\) with three different distance parameters, \(R = 0.2\), \(R = 0.3\), and \(R = 0.4\). The detailed description of the jet reconstruction and the algorithm for the UE subtraction can be found in Ref.\(^6\).

### 3. Fragmentation function measurement

The internal structure of the jet was characterized by measuring the transverse momentum \((p_{ch}^T)\) and longitudinal momentum fraction \((z \equiv p_{ch}^T \cos \Delta R / p_{jet}^T)\) distributions of charged particles with \(p_{ch}^T > 2\) GeV produced within an angular range \(\Delta R = 0.4\) of the reconstructed jet directions. Here, \(\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}\) where \(\Delta \phi\) (\(\Delta \eta\)) is the difference in azimuthal angles (pseudorapidities) between the charged particle and jet directions. Jets were required to have \(p_{jet}^T > 85, 92,\) and 100 GeV for \(R = 0.2, 0.3,\) and 0.4, respectively.

Two different sets of charged-particle fragmentation distributions were measured for each centrality bin and \(R\) value, the transverse momentum distribution\(^1\)

\[
D(p_T) \equiv \frac{1}{\varepsilon} \left( \frac{1}{N_{\text{jet}}} \frac{\Delta N_{\text{ch}}}{\Delta p_{ch}^T} - \frac{dN_{\text{UE}}^{\text{ch}}}{dp_{ch}^T} \right),
\]

and the fragmentation function,

\[
D(z) \equiv \frac{1}{\varepsilon} \left( \frac{1}{N_{\text{jet}}} \frac{\Delta N_{\text{ch}}}{\Delta z} - \frac{dN_{\text{UE}}^{\text{ch}}}{dp_{ch}^T} \bigg|_{p_{ch}^T = z p_{jet}^T} \right).
\]

Here \(N_{\text{jet}}\) represents the total number of jets in a given centrality bin, \(\Delta N_{\text{ch}}\) represents the number of measured charged particles within \(\Delta R = 0.4\) of the jets, \(1/\varepsilon\) stands for the tracking efficiency correction, and \(dN_{\text{ch}}^{\text{UE}} / dp_{ch}^T\) represents the background contribution coming from the underlying event (UE) which is subtracted. The background contribution,

\[
\frac{dN_{\text{ch}}^{\text{UE}}}{dp_{ch}^T} = \frac{1}{N_{\text{cone}}} \Delta N_{\text{ch}}^{\text{cone}}(p_{ch}^T, p_{jet}^T, \eta_{jet}) / \Delta p_{ch}^T,
\]

is evaluated for each jet radius separately in events having at least one jet above the jet \(p_T\) thresholds using \(N_{\text{cone}}\) cones of radius \(R = 0.4\) covering the full inner detector by a regular grid.

Any such cone having a charged particle with \(p_{ch}^T > 6\) GeV was assumed to be associated with a real jet in the event and was excluded from the UE background determination. The

\(^1\) Transverse momentum is defined with respect to the beam axis.
Figure 1. Ratios of unfolded $D(z)$ distributions for six bins in collision centrality to those in peripheral (60–80%) collisions, $D(z)_{\text{cent}}/D(z)_{60–80}$, for $R = 0.4$ jets. The error bars on the data points indicate statistical uncertainties while the yellow shaded bands indicate systematic uncertainties.

subtracted background was further corrected to account for proper pseudorapidity distribution of UE and for the elliptic flow.

Two corrections were performed to account for the impact of finite jet energy resolution on the measured distributions. First, the energy of each jet entering the evaluation of $D(p_T)$ and $D(z)$ was shifted to account for the mean effect of the “upfeeding” in a steeply falling jet $p_T$ spectrum produced by the finite jet energy resolution. Then, obtained measured distributions were unfolded to the truth level using SVD – a one-dimensional Singular Value Decomposition (SVD) method [8] implemented in RooUnfold [9] which removes also the effects of finite charged particle $p_T$ resolution.

The fragmentation functions are steeply falling distributions. To evaluate the centrality dependence of the fragmentation functions, ratios $R_{D(z)}$ were calculated of the $D(z)$ distributions for all centrality bins excluding the peripheral bin to the $D(z)$ measured in the peripheral, 60–80% centrality bin. The results of $R_{D(z)}$ ratios for $R = 0.4$ jets are shown in Fig. [1]. The ratios for all centralities show an enhanced yield of low $z$ fragments ($z \lesssim 0.04$) and a suppressed yield of fragments at intermediate $z$ values ($0.04 \lesssim z \lesssim 0.2$) in more central collisions relative to the 60–80% centrality bin. For the 0–10% centrality bin, the yield of fragments at $z = 0.02$ is enhanced relative to that in the 60–80% centrality bin by 25% while the yield at $z = 0.1$ is suppressed by about 10%. The yield at $z > 0.4$ is enhanced in central with respect to 60–80% peripheral collisions. The size of the observed modifications at low, intermediate, and high $z$ decreases gradually from central to peripheral collisions. The same effects are seen in the ratios of transverse momentum distributions, $R_{D(p_T)}$, as well. The same effects are seen also for $R = 0.3$ and $R = 0.2$ jets. The fluctuations in the UE are approximately 100% (30%) smaller for $R = 0.2$ ($R = 0.3$) jets than they are for $R = 0.4$ jets and, thus, jets reconstructed with smaller jet radii have significantly better jet energy resolution.

To further quantify the effects of the modifications, observed in Fig. [1] on the actual
distribution of fragments within the measured jets, the differences in fragmentation functions, $\Delta D(z) = D(z)|_{\text{cent}} - D(z)|_{\text{min}}$ were calculated and integrals of these distributions, $\int \Delta D(z)\,dz$ were evaluated over three $z$ ranges chosen to match the observations: 0.02–0.04, 0.04–0.2, and 0.4–1. The results indicate an increase in the number of particles with 0.02 < $z$ < 0.04 of less than one particle per jet in the 0–10% centrality bin relative to the 60–80% centrality bin. A decrease of about 1.5 particles per jet is observed for 0.04 < $z$ < 0.2. The differences between the integrals of the fragmentation functions over 0.4 < $z$ < 1 are not significant relative to the uncertainties. The results for $\int \Delta D(z)\,dz$ further indicate that in the most central collisions, a small fraction, < 2%, of the jet transverse momentum is carried by the excess particles in 0.02 < $z$ < 0.04 for central collisions, but that the depletion in fragment yield in 0.04 < $z$ < 0.2 accounts on average for about 14% of $p_T^{\text{jet}}$.

4. Neighbouring jet production

The rate of the neighbouring jets that accompany a test jet, $R_{\Delta R}$, is defined as

$$R_{\Delta R} = \frac{1}{dN_{\text{jet}}^{\text{test}}/dE_T^{\text{test}}} \sum_{i=1}^{N_{\text{jet}}^{\text{test}}} \frac{dN_{\text{nbr}}^{\text{jet},i}}{dE_T^{\text{test}}} (E_T^{\text{test}}, E_T^{\text{nbr},\text{min}}, \Delta R),$$

where $E_T^{\text{test}}$ and $E_T^{\text{nbr}}$ are the transverse energies of the test and neighbouring jet, respectively; $N_{\text{jet}}^{\text{test}}$ is the number of test jets in a given $E_T^{\text{test}}$ bin and $N_{\text{nbr}}^{\text{jet}}$ is number of neighbouring jets. The measurement of neighbouring jets uses $d$ instead of $R$ to label the distance parameter of jet finding algorithm in order to avoid a confusion with the main measured quantity. For each choice of $d$, neighbouring jets are considered if they lie within a specific annulus in $\Delta R$ away from the test jet: 0.5 < $\Delta R$ < 1.6, 0.6 < $\Delta R$ < 1.6, and 0.8 < $\Delta R$ < 1.6 for $d = 0.2$, $d = 0.3$, and $d = 0.4$ jets, respectively.

The $R_{\Delta R}$ measurement is performed differentially in collision centrality, transverse energy of the test jet, $E_T^{\text{test}}$, and transverse energy of the neighbouring jet, $E_T^{\text{nbr}}$. The raw $R_{\Delta R}$ distributions are corrected for a contribution from neighbouring jets that originate from different hard partonic interaction in the same Pb+Pb collision. The impact of the finite JER, reconstruction efficiency and position resolution on neighbouring jets is corrected for by applying bin-by-bin correction factors in transverse energy to the raw $R_{\Delta R}$ distributions that are derived from the MC data.

Fig. 2 shows the fully corrected $R_{\Delta R}$ distributions for $d = 0.4$ and $d = 0.2$ jets evaluated as a function of $E_T^{\text{test}}$. The distributions are shown for four centrality selections and three selections on minimum transverse energy of neighbouring jets, $E_T^{\text{nbr}} > 30$, 45, and 60 GeV. The $R_{\Delta R}$ distribution exhibits an increase with increasing $E_T^{\text{test}}$, which is consistent in shape with the previous measurement of the same quantity by D0 in p + p collisions [9]. Sizable differences between the four different centrality selections are observed for all three jet radii. The yield of neighbouring jets is suppressed as the centrality of the collision increases.

To further quantify the neighbouring jet yields, the per-test-jet normalized $E_T$ spectra of neighbouring jets were evaluated,

$$\frac{dR_{\Delta R}}{dE_T^{\text{nbr}}} = \frac{1}{dN_{\text{jet}}^{\text{test}}/dE_T^{\text{test}}} \sum_{i=1}^{N_{\text{jet}}^{\text{test}}} \frac{d^2N_{\text{nbr}}^{\text{jet},i}}{dE_T^{\text{test}} dE_T^{\text{nbr}}} (E_T^{\text{test},\text{min}}, E_T^{\text{nbr}}, \Delta R).$$

The trend of the suppression is less pronounced in these steeply falling spectra, thus the differences in the jet spectra evaluated as a function of centrality were quantified by fitting the spectra by a power-law functional form, $\propto 1/E_T^n$, and the power index has been extracted
for all three choices of jet radius and four centrality bins. The $E_T$ spectra measured in central and peripheral collisions differ in the power-law index by approximately two standard deviations for both $d = 0.4$ and $d = 0.3$ jets, suggesting that the $E_T$ spectra may be less steep in central than peripheral collisions.

To quantify the centrality dependence of the neighbouring jet yields, the ratio $\rho_{R_{\Delta R}}$ is calculated from $R_{\Delta R}$ measured in each centrality bin excluding the peripheral bin to $R_{\Delta R}$ measured in the 40–80% peripheral, bin. These ratios are evaluated for $d = 0.4$ jets which suffer the least from the statistical uncertainties which are still large. Nevertheless, several characteristic features can be observed. The $\rho_{R_{\Delta R}}$ does not exhibit any strong dependence on $E_T^{\text{jet}}$. The suppression factor $\rho_{R_{\Delta R}}$ of the most central collisions is at the level of $0.5 - 0.7$ for all three thresholds on $E_T^{\text{nbr}}$. The suppression becomes less pronounced with decreasing centrality. This is qualitatively consistent with the observation of the centrality dependent suppression of inclusive jet yields \[\text{[1]}.\] In that measurement, the suppression of the inclusive jet yields was evaluated in terms of the ratio $R_{\text{CP}}$ of inclusive jet yields in central to 60–80% peripheral collisions spanning the jet $p_T$ range of 40 – 200 GeV. Values of $R_{\text{CP}} \sim 0.5$ were measured in the 0–10% most central collisions and exhibited only a modest jet $p_T$ dependence. Contrary to a modest dependence of $\rho_{R_{\Delta R}}$ on the test jet $E_T$, the $\rho_{R_{\Delta R}}$ evaluated as a function of $E_T^{\text{nbr}}$ suggests a decrease of suppression with increasing $E_T^{\text{nbr}}$. Such a decrease of suppression with increasing $E_T^{\text{nbr}}$ may in fact be expected. The jet quenching is generally expected to depend on the initial parton energy, but if the parton splitting happens such that the two partons have similar energy, their quenching would likely be similar due to similar in-medium path-length traveled by the

**Figure 2.** $R_{\Delta R}$ distributions for $d = 0.4$ jets (upper) and $d = 0.2$ jets (lower) evaluated as a function of $E_T^{\text{jet}}$. The three different columns show $R_{\Delta R}$ distributions evaluated for three different thresholds on minimum neighbouring jet transverse energy, $E_T^{\text{nbr}} > 30, 45,$ and 60 GeV. The four different centrality bins are denoted by different markers in each plot. The shaded bands indicate systematic uncertainties, vertical errors represent statistical uncertainties. The data points for the 10–20%, 20–40%, and 40–80% centrality bins are shifted along the horizontal axis with respect to the 0–10% centrality bin for clarity.
two partons forming neighbouring jets. Thus, in the configuration of $E_T^{nbr} \approx E_T^{test}$ the per test jet normalization effectively removes the impact of the suppression.

5. Conclusions
In this short report, we have discussed two recent measurements by ATLAS, the jet fragmentation measurement and the measurement of neighbouring jet production. Significant changes in the jet fragmentation have been observed in central with respect to peripheral collisions, namely the enhancement of charged particle yields at low transverse momenta, depletion at intermediate transverse momenta, and an enhancement at high transverse momenta of charged particles.

The production of pairs of correlated jets was quantified using the rate of neighbouring jets that accompany a test jet, $R_{\Delta R}$, evaluated both as a function of test jet $E_T$ and neighbouring jet $E_T$. A significant dependence of $R_{\Delta R}$ on collision centrality has been observed in both cases, suggesting suppression of neighbouring jets which increases with increasing centrality of the collision reaching a factor of 0.5-0.7 suppression in central with respect to peripheral collisions.

This and other details investigated in these studies implies a complex behaviour of the jet modifications which should provide an important input for theoretical calculations aiming to describe the physics of jet quenching.

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References