

JET PRODUCTION AND MODIFICATION IN HEAVY-ION COLLISIONS WITH THE ATLAS DETECTOR*

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Jet production has been studied extensively in heavy-ion collisions to measure its modification in the presence of the quark–gluon plasma. Several recent measurements performed by the ATLAS experiment at the LHC are highlighted, including studies of the jet suppression as a function of jet radius and jet substructure. Additionally, results of the search for jet-induced wake are presented.

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1. Introduction

Jet production is extensively studied in ultra-relativistic heavy-ion (HI) collisions in order to understand the properties of the quark–gluon plasma (QGP) [1]. As the jets traversing the QGP medium interact with it, losing part of the original parton energy, this process may depend on the path length, parton shower shapes, jet substructure, or jet flavour [2, 3]. The outcome of this interaction is not easy to predict, and the models including it need input from the experiments.

This article focuses on the most recent results from the ATLAS [4] experiment at the LHC, obtained with 1.72 nb^{-1} of Pb+Pb and 255 pb^{-1} of pp data at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$. Their goals were to study how jet quenching depends on jet radius [5], how it depends on jet substructure [6], and to search for the presence of a jet-induced diffusion wake in the QGP [7].

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2. Jet-radius dependence of jet quenching

Studies of the jet quenching as a function of the jet radius (R) in heavy-ion collisions are an important step to understand the energy redistribution in the QGP, and could potentially reveal details of medium transport properties and jet fragmentation. Measurement of the dijet suppression was performed by the ATLAS experiment [5] to shed light on the differences in jet quenching for various jet radii. Jets were reconstructed with anti- k_T algorithm for five radii: $R = 0.2, 0.3, 0.4, 0.5, 0.6$. The minimum p_T of the leading jet ($p_{T,1}$) depended on R , being set to 100 GeV for 0.2, 0.3, and 0.4 jets, and to 158 GeV for 0.5 and 0.6 jets. The p_T of sub-leading jet ($p_{T,2}$) was required to satisfy the condition in the dijet momentum balance, $x_J = \frac{p_{T,2}}{p_{T,1}}$, to be $x_J < 0.32$. Only events with back-to-back ($\Delta\phi > 7\pi/8$) jets were selected. The absolutely normalized dijet momentum balance distributions were compared with pp cross sections normalized absolutely using the ratio

$$J_{AA} = \frac{1}{\langle T_{AA} \rangle N_{\text{evt}}^{AA}} \frac{dN_{\text{pair}}^{AA}}{dx_J} \bigg/ \left(\frac{1}{L_{pp}} \frac{dN_{\text{pair}}^{pp}}{dx_J} \right), \quad (1)$$

where $\langle T_{AA} \rangle$ is the mean nuclear thickness function, N_{evt}^{AA} is the total number of minimum-bias Pb+Pb events, N_{pair}^{AA} and N_{pair}^{pp} are dijet yields in Pb+Pb and pp collisions, respectively, and L_{pp} is the luminosity of the pp dataset.

The left panel of figure 1 shows comparison of the absolutely normalized x_J distributions in pp collisions and several centrality bins in Pb+Pb collisions. Balanced dijets (x_J close to unity) are suppressed, which is an

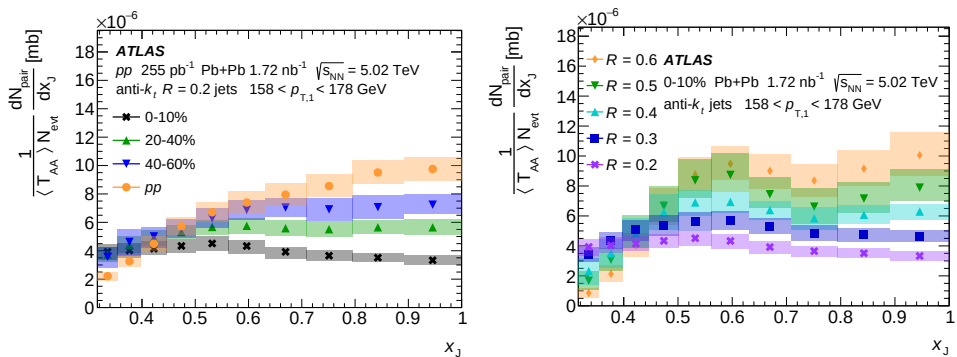


Fig. 1. The absolutely normalized x_J distributions for $R = 0.2$ jets in pp collisions and several centrality bins in Pb+Pb collisions (left) and for jet with various R in 0–10% central Pb+Pb collisions (right), all for leading jets with $158 < p_{T,1} < 178$ GeV. Jets are selected with $|y| < 2.1$ and $|\Delta\phi| > 7\pi/8$. The boxes correspond to systematic uncertainties and the bars to statistical uncertainties [5].

evidence of medium-induced energy loss. At the same time, there is an enhancement of imbalanced dijets. The right panel of figure 1 shows the absolutely normalized x_J distributions in 0–10% central Pb+Pb collisions, for leading jets with different radii. For small jet radii, more imbalanced jets are observed, the distribution peaks around 0.5, and the yield decreases at higher x_J . The effect is smaller for larger jets which suggests redistribution of jet momentum due to quenching in the QGP environment.

Studying the absolutely normalized x_J distributions in Pb+Pb data in relation to pp collisions, the larger J_{AA} is observed for larger jet radius, especially towards lower x_J , as presented in figure 2.

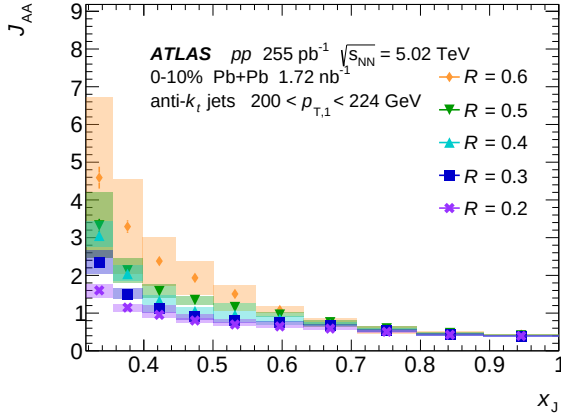


Fig. 2. The J_{AA} distributions in 0–10% central Pb+Pb collisions, for $200 < p_{T,1} < 224$ GeV. Jets are selected with $|y| < 2.1$ and $|\Delta\phi| > 7\pi/8$. The boxes correspond to systematic uncertainties and the bars to statistical uncertainties [5].

To quantify jet suppression, the di-jet R_{AA} , the pair nuclear modification factor, is defined as a function of $p_{T,1}$ as follows:

$$R_{AA}^{\text{pair}}(p_{T,1}) = \frac{\frac{1}{\langle T_{AA} \rangle N_{\text{evt}}^{AA}} \int_{0.32 \times p_{T,1}}^{p_{T,1}} \frac{d^2 N_{\text{pair}}^{AA}}{dp_{T,1} dp_{T,2}} dp_{T,2}}{\frac{1}{L_{pp}} \int_{0.32 \times p_{T,1}}^{p_{T,1}} \frac{d^2 N_{\text{pair}}^{pp}}{dp_{T,1} dp_{T,2}} dp_{T,2}}, \quad (2)$$

and as a function of $p_{T,2}$ with following equation:

$$R_{AA}^{\text{pair}}(p_{T,2}) = \frac{\frac{1}{\langle T_{AA} \rangle N_{\text{evt}}^{AA}} \int_{p_{T,2}}^{p_{T,2}/0.32} \frac{d^2 N_{\text{pair}}^{AA}}{dp_{T,1} dp_{T,2}} dp_{T,1}}{\frac{1}{L_{pp}} \int_{p_{T,2}}^{p_{T,2}/0.32} \frac{d^2 N_{\text{pair}}^{pp}}{dp_{T,1} dp_{T,2}} dp_{T,1}}. \quad (3)$$

The R_{AA}^{pair} distributions are shown as a function of leading and subleading jet p_T in the left and right panels of figure 3, respectively. Subleading

jets are generally more suppressed than leading jets, consistent with p_T -dependent medium interaction. A clear jet radius dependence can be noticed as suppression decreases with increasing R , which means that larger radius jets retain more energy within the jet cone. On the contrary, smaller R jets lose a larger fraction of energy outside the cone due to medium interactions. The R dependence of the jet pair nuclear modification factor is weaker for subleading jets.

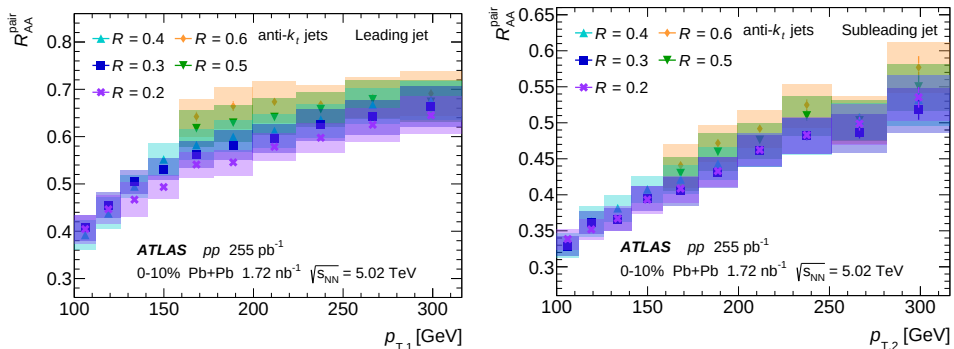


Fig. 3. The (left) leading and (right) subleading jet R_{AA}^{pair} distributions in dijets as a function of jet p_T in 0–10% central Pb+Pb collisions. Jets are selected with $|y| < 2.1$ and $|\Delta\phi| > 7\pi/8$. The boxes correspond to systematic uncertainties and the bars to statistical uncertainties [5].

3. Substructure dependence of jet quenching

Measurements of the jet substructure aim to answer the questions at what scale is the jet structure resolved by the medium and how does the jet with complex structure interact with the QGP medium. In the recent ATLAS measurement [6], the jet substructure was probed via charged-particle tracks.

In this measurement, the studied jets were $R = 1.0$ jets with $p_T > 200$ GeV. Jets were reclustered from $R = 0.2$ jets with $p_T > 35$ GeV and tracks with $p_T > 4$ GeV. Sub-jets were defined using the soft drop technique applied to tracks. The kinematics of the two sub-jets associated with the hardest splitting were used to determine two characteristic parameters defining the jet substructure: angular separation ($dR_{12} = \sqrt{(\Delta y_{12})^2 + (\Delta\phi_{12})^2}$) and splitting scale ($\sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \times dR_{12}$).

The jet modification factor R_{AA} is defined as

$$R_{AA} = \frac{1}{N_{\text{evt}}^{AA}} \frac{dN_{\text{jet}}^{AA}}{dp_T} \bigg/ \left(\langle T_{AA} \rangle \frac{d\sigma_{\text{jet}}^{pp}}{dp_T} \right), \quad (4)$$

where N_{jet}^{AA} is the jet yield in Pb+Pb collisions and σ_{jet}^{pp} is the cross-section in pp collisions. The R_{AA} is presented in figure 4 as a function of dR_{12} . It decreases with increasing dR_{12} between ~ 0.01 – 0.2 , showing more suppressed jets with wider internal separation. For $dR_{12} \geq 0.2$, suppression flattens, indicating no further dependence on wider substructure. Results are compared with measurements from Ref. [8] in the p_T interval 200–251 GeV ($R = 1.0$ jets with $R = 0.2$ constituents used to define sub-jets) and Ref. [9] in the p_T interval 200–315 GeV ($R = 0.4$ jets with charged-particle tracks matched to calorimeter energy clusters used to define sub-jets).

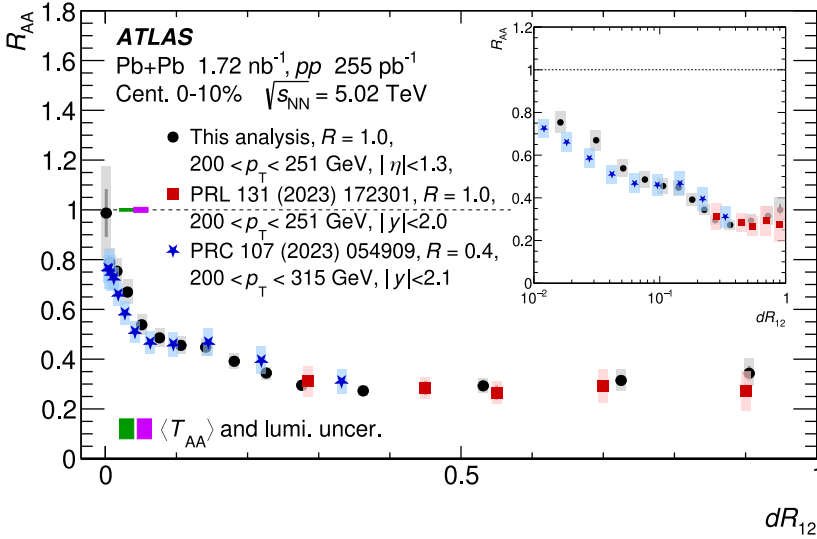


Fig. 4. The R_{AA} of $R = 1.0$ jets evaluated as a function of dR_{12} compared with measurements from Ref. [8] and Ref. [9]. The inset displays the same distributions using a logarithmic scale, highlighting features at lower dR_{12} values. The vertical bars on the data points indicate statistical uncertainties, while the shaded boxes indicate systematic uncertainties [6].

Furthermore, the R_{AA} dependence on $\sqrt{d_{12}}$ and jet p_T was studied, as shown on figure 5. The R_{AA} decreases steadily with increasing $\sqrt{d_{12}}$, indicating stronger quenching for jets with harder internal splittings (larger splitting scales). The right panel of figure 5, shows that the R_{AA} is largely independent of jet p_T within uncertainties.

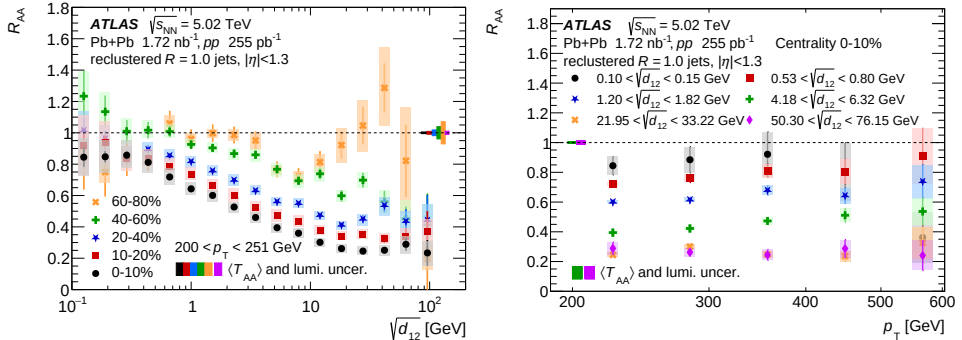


Fig. 5. Left: The R_{AA} of $R = 1.0$ jets evaluated as a function of $\sqrt{d_{12}}$ in five centrality bins and the p_T interval 200–251 GeV. Right: The R_{AA} of $R = 1.0$ jets in the most central 0–10% collisions evaluated as a function of jet p_T in six intervals of $\sqrt{d_{12}}$. The vertical bars on the data points indicate statistical uncertainties, while the shaded boxes indicate systematic uncertainties [6].

4. Search for jet-induced wake in QGP

As we have seen in the dijet asymmetry measurement, the suppression is smaller for larger jet radii, suggesting that the energy lost by the parton traversing the QGP is redistributed in the medium. According to predictions [10–12], energy lost by a parton could appear as an enhanced medium amplitude in the direction of the jet and a simultaneous depletion in the opposite direction. This collective low-momentum response of the quark–gluon plasma (QGP) to the energy lost by a high-energy parton is called a diffusion wake. Photon–jet events are chosen for the diffusion-wake search because the direct photon tags the initial parton direction with minimal bias, isolating medium effects. Selected events have high- p_T photon and back-to-back jet ($|\Delta\phi(\text{jet}, \text{photon})| > 3\pi/4$). The separation of the diffusion-wake signal from other correlated particle production contribution can be done by examining the correlation between the jet axis ($\eta_{\text{jet}}, \phi_{\text{jet}}$) and low- p_T tracks ($\eta_{\text{track}}, \phi_{\text{track}}$). The jet–track correlations are measured for charged particles with 0.5–2 GeV in the hemisphere opposite to the jet ($|\Delta\phi(\text{jet}, \text{track})| > \pi/2$) in three $x_{J\gamma} = \frac{p_T^{\text{jet}}}{p_T^{\gamma}}$ bins. The largest diffusion-wake signal is expected for the smallest $x_{J\gamma}$ bin, where the energy lost by jet is largest. The jet–track yield as a function of $|\Delta\eta(\text{jet}, \text{track})|$, normalized by the number of photon–jet pairs ($N^{\gamma-\text{jet}}$), Y_{corr} , is defined as

$$Y_{\text{corr}} = \frac{1}{N^{\gamma-\text{jet}}} \frac{d^2 N^{\text{jet-track}}}{d\Delta\eta d\Delta\phi}. \quad (5)$$

To reduce the impact of the background tracks, an event mixing technique is utilized, merging γ –jet signal pair with different minimum-bias events. The

ratio of Y_{corr} to the same quantity measured in mixed events (Y_{uncorr}) allows one to extract the relative amount of diffusion wake compared to the bulk medium. This quantity is shown in figure 6 for three $x_{J\gamma}$ bins. The ratios can be fitted with the following function:

$$a_0 + a_{\text{dw}} e^{-|\Delta\eta(\text{jet, track})|^2 / (2\sigma_{\text{dw}}^2)} . \quad (6)$$

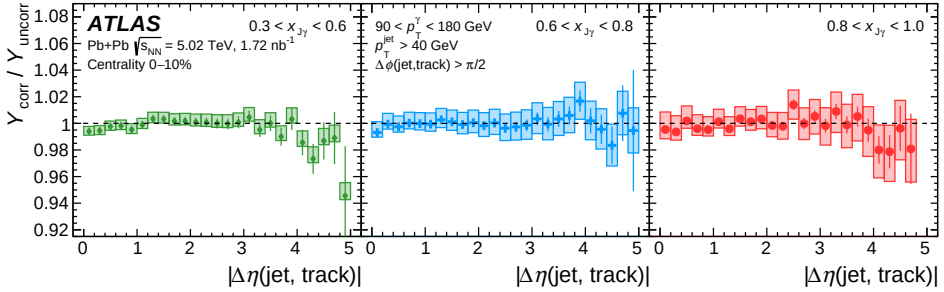


Fig. 6. The $Y_{\text{corr}}/Y_{\text{uncorr}}$ distributions are shown as a function of $|\Delta\eta(\text{jet, track})|$ for the Pb+Pb 0–10% centrality interval. Different panels represent different $x_{J\gamma}$ ranges ($0.3 < x_{J\gamma} < 0.6$, $0.6 < x_{J\gamma} < 0.8$, and $0.8 < x_{J\gamma} < 1.0$). The vertical bars indicate the statistical uncertainties. The total systematic uncertainties are shown as boxes in each $|\Delta\eta(\text{jet, track})|$ bin [7].

Figure 7 shows the most probable values of a_{dw} as well as the ± 1 and ± 2 standard deviation limits for the three $x_{J\gamma}$ bins. For all diffusion-wake widths σ_{dw}^2 and in all $x_{J\gamma}$ selections, the best-fit amplitudes are negative;

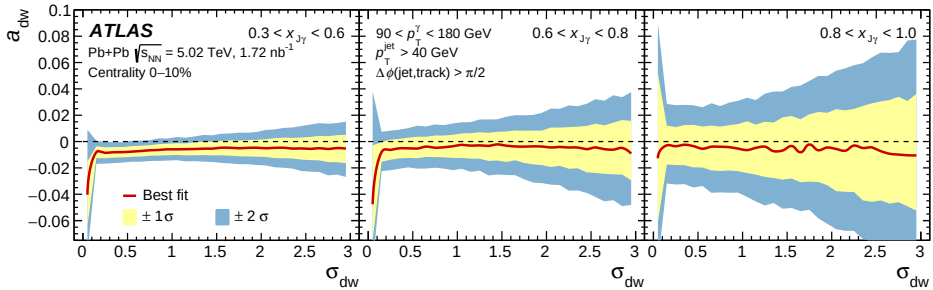


Fig. 7. The diffusion wake amplitude a_{dw} as a function of diffusion-wake width σ_{dw} from Gaussian fits for $Y_{\text{corr}}/Y_{\text{uncorr}}$. Different panels represent different $x_{J\gamma}$ ranges ($0.3 < x_{J\gamma} < 0.6$, $0.6 < x_{J\gamma} < 0.8$, and $0.8 < x_{J\gamma} < 1.0$). The red solid line is the most probable amplitude. The inner and outer shaded areas represent one ($\pm 1\sigma$) and two ($\pm 2\sigma$) standard deviation ranges, respectively [7].

however, all results are consistent with $a_{\text{dw}} = 0$, indicating no diffusion-wake signal within the current experimental sensitivity. Upper limits on the possible amplitude of the diffusion wake were set at the 95% confidence level.

5. Conclusion

Data from the ATLAS experiment at the LHC collectively indicate that partons strongly interact with the QGP, but the observable medium response is more complex than one might expect. Jet-radius-dependent dijet measurements demonstrate that increasing R recovers quenched energy, implying energy transport to large angles within the QGP. Large- R jet substructure reveals that jets with harder or wider splittings are more strongly suppressed, indicating medium resolution of the internal jet structure. Correlation studies in photon-jet events find no significant diffusion-wake signal, placing strong constraints on the magnitude of medium response predicted by theory.

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