Measurements of hard probes of the quark-gluon plasma with the ATLAS experiment at the LHC

Barbara Wosiek for the ATLAS Collaboration

H. Niewodniczański Institute of Nuclear Physics, Kraków, Poland

Abstract

ATLAS results on the production of high-transverse momentum probes in Pb+Pb and p+Pb collisions at the LHC are presented. The focus is on the jet measurements, which provide a useful tool to study the hot, dense and coloured matter created in ultra-relativistic heavy ion collisions. The ATLAS experiment has measured inclusive jet yields in pp and Pb+Pb collisions at √sNN = 2.76 TeV and in p+Pb collisions at √sNN = 5.02 TeV. The jet nuclear modification factor, RAA, is shown as a function of jet pT, rapidity and collision centrality. The RAA weakly increases with pT, shows no dependence on rapidity and smoothly decreases with the collision centrality. In 10% of the most central collisions, jet production is suppressed by a factor of two relative to pp yields scaled by the number of binary nucleon-nucleon collisions. Charged-particle fragmentation functions of jets are also measured and ratios of fragmentation functions between different centrality intervals show a centrality-dependent modification. The jet measurements in p+Pb collisions show jet enhancement in peripheral collisions and suppression in central collisions as compared to the scaled pp jet yields. These modifications are most pronounced at forward rapidities and at large jet transverse momenta. Jet production at forward rapidities shows a scaling in the total jet energy, suggesting that the modification of jet production in p+Pb collisions may depend on the kinematics of the initial hard parton-parton scattering.

Keywords: heavy-ion collisions, quark-gluon plasma, jet quenching

1. Introduction

In ultra-relativistic heavy ion collisions, a medium of the dense matter, composed of deconfined quarks and gluons, is produced. This medium is transparent to colour-neutral probes, such as electroweak bosons, but is opaque to coloured probes, such as high transverse momentum partons produced in hard scattering processes. Partons, propagating through the medium, lose energy either via the gluon radiation or by colliding with medium constituents. The resulting scattered partons fragment into streams of angularly correlated large–momentum particles, referred to as jets. The parton energy loss in the dense medium results in the suppression of jet yields in nuclear collisions as compared to the jet spectrum measured in pp collisions, the phenomenon known as the jet quenching. It also may lead to modifications of the jet fragmentation with respect to the fragmentation in the vacuum fragmentation.

A key observable in studying the medium modification of the high–pT probe, such as a jet, is the nuclear modification factor, RAA, defined as the ratio of the jet yield in Pb+Pb collisions to the yield measured in pp as:

\[ R_{AA} = \frac{1}{\langle T_{AA}\rangle} \frac{d^2N_{jet}^{AA}}{dydp_T}\mid_{cent} = \frac{1}{\langle N_{coll}\rangle} \frac{d^2N_{jet}^{pp}}{dydp_T}, \]

where the numerator denotes the per-event jet yield in a given centrality interval scaled by the average flux of nucleons for that centrality bin, \( \langle T_{AA}\rangle \), and the denominator is the jet cross-section measured in pp coll-

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1The list of members of the ATLAS Collaboration and acknowledgements can be found at the end of this issue.
sions at the same energy and jet $p_T$. The mean number of nucleon-nucleon collisions, $\langle N_{\text{coll}} \rangle$, is equal to $\langle T_{\text{AA}} \rangle \times \sigma_{\text{NN}}^{\text{inc}}$ calculated with a Glauber model \cite{1}. The jet production modification can also be studied using the central to peripheral ratio of jet yields, $R_{\text{CP}}$:

$$R_{\text{CP}} = \frac{\langle N_{\text{coll}}^{\text{P}} \rangle}{\langle N_{\text{coll}}^{\text{C}} \rangle} \cdot \frac{d^2N_{\text{jet}}}{dyd^2p_T},$$

(2)

where indexes C and P denote central and peripheral nucleus-nucleus collisions, respectively. Both, $R_{\text{AA}}$ and $R_{\text{CP}}$ measure deviations of jet yields from a simple hypothesis of incoherent superposition of binary nucleon-nucleon collisions, commonly referred to as factorization hypothesis of incoherent superposition of binary nucleon-nucleus collisions, respectively. Both, $R_{\text{AA}}$ and $R_{\text{CP}}$ measure deviations of jet yields from a simple hypothesis of incoherent superposition of binary nucleon-nucleon collisions, commonly referred to as factorization or geometric scaling, under which $R_{\text{AA}} = 1$ and $R_{\text{CP}} = 1$.

The geometric scaling hypothesis can be tested with measurements of probes insensitive to medium properties. Such a test provide electroweak bosons decaying into colour neutral particles. Indeed, the yields of photons as well as $W$ and $Z$ bosons decaying leptonically and measured in Pb+Pb collisions at the LHC scale, as expected, with the number of binary nucleon-nucleon collisions \cite{2,3,4}. This confirms that the geometric enhancement in the yield of the high-$p_T$ probe in more central collisions, which is due to the larger overlap, is correctly accounted for by scaling the per-event yield in a given centrality interval by the average per-collision flux of nucleons, $\langle T_{\text{AA}} \rangle$, or equivalently, the mean number of nucleon-nucleon collisions, $\langle N_{\text{coll}} \rangle$.

In these proceedings we report on the recent ATLAS measurement of inclusive jet production in Pb+Pb, $p+Pb$, and $pp$ collisions. The ATLAS detector \cite{5} is well designed to measure jets in the dense heavy-ion environment thanks to its high-resolution calorimeters covering the pseudorapidity interval $|\eta| < 5$. The data sets used in this analysis were recorded during the 2011 LHC Pb+Pb run at a collision energy of $\sqrt{s_{\text{NN}}} = 2.76$ TeV, the 2013 proton-proton run at the same centre-of-mass energy and the 2013 $p+Pb$ run at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The integrated luminosities of the analyzed data samples are of approximately 0.14 nb$^{-1}$, 4 pb$^{-1}$ and 28 nb$^{-1}$ for Pb+Pb, $pp$ and $p+Pb$ collisions, respectively. For data-taking, ATLAS used either a minimum bias or the jet trigger \cite{6}, providing high statistics samples of jets.

2. Inclusive jet spectra

The jets were reconstructed using the electromagnetic and hadronic calorimeters \cite{7} with the anti-$k_t$ algorithm with jet radius parameter $R = 0.4$. The contribution of the underlying event to each jet was subtracted on a jet-by-jet basis. The jet spectra were unfolded to account for the detector response and corrected for the trigger and reconstruction efficiency. PYTHIA dijets events were overlaid onto real data to evaluate the detector response and perform the unfolding.

The unfolded and efficiency corrected double differential cross-sections measured in $pp$ collisions at $\sqrt{s} = 2.76$ TeV are shown in Fig. 1 as a function of jet $p_T$ in five different ranges in jet rapidity \cite{9}. The $pp$ jet cross-sections are used to calculate nuclear modification factors for jets measured in Pb+Pb and $p+Pb$ collisions.

![Image of jet spectra](image-url)

Figure 1: The double differential jet cross-section in $pp$ collisions as a function of $p_T$ for different rapidity ranges \cite{9}. Error bars and shaded bands denote statistical and systematic uncertainties respectively. Each spectrum is scaled by an overall multiplicative factor for presentation purposes.

For Pb+Pb collisions the jet spectra are measured over the kinematic range $32 < p_T < 500$ GeV, $|y| < 2.1$ and as a function of the collision centrality \cite{9}. The centrality of Pb+Pb collisions is characterized by $\Sigma(E_T^{\text{Cal}})$, the total transverse energy measured in the ATLAS forward calorimeters covering $3.2 < |y| < 4.9$. The standard technique \cite{10} is used to define centrality classes in terms of percentiles of the $\Sigma(E_T^{\text{Cal}})$ distribution. A Glauber Monte Carlo model \cite{11} is employed to calculate $\langle T_{\text{AA}} \rangle$, $\langle N_{\text{coll}} \rangle$, and the average number of participating nucleons, $\langle N_{\text{part}} \rangle$, for each centrality class. Figure 2 shows the jet yields scaled by $\langle T_{\text{AA}} \rangle$ in different central-
The jet yield in Pb+Pb collisions is scaled by $\langle T_{AA} \rangle$ as a function of $p_T$ for different centrality bins. Error bars and shaded bands denote statistical and systematic uncertainties respectively. The dashed lines represent the $pp$ jet cross-section scaled by an overall multiplicative factor, the same as used for Pb+Pb jet yields.

Figure 3 shows the transverse momentum dependence of the jet $R_{AA}$ measured in three representative centrality bins and three ranges in rapidity. The wide coverage in the jet kinematics is seen.

3. Jet quenching in Pb+Pb collisions

Previous observations of the energy imbalance of dijets produced in central Pb+Pb collisions can be attributed to the jet quenching phenomenon. In addition, the measured $R_{CP}$ ratios indicate also that jet yields are suppressed in central relative to peripheral collisions. The comparison of jet yields in Pb+Pb collisions to $pp$ collisions using the jet $R_{AA}$ (see Eq. 1) can provide better understanding of the jet quenching effect. Figure 4 shows the transverse momentum dependence of the jet $R_{AA}$ measured in three representative centrality bins and three ranges in rapidity. The jet yields are suppressed by a factor of two in the most central 10% of collisions. In central collisions, a modest but significant increase of $R_{AA}$ with $p_T$ is observed. No dependence of $R_{AA}$ on rapidity is seen, as shown in the top panel of
The jet $R_{AA}$ as a function of $p_T$ for three different centrality bins and three intervals in $y$.[2] Error bars and boxes denote statistical and partially correlated in $p_T$-systematic uncertainties respectively. The uncertainties fully correlated in $p_T$ are indicated by shaded bands. The uncertainties on the luminosity and $\langle T_{AA}\rangle$ are indicated by shaded boxes centered at one.

Figure 5: The jet $R_{AA}$ as a function of rapidity for three different centrality bins in the selected range in $p_T$ (top) and as a function of $\langle N_{\text{part}}\rangle$ measured over $|y| < 2.1$ (bottom) [11]. Error bars denote statistical uncertainties while fully correlated and partially correlated systematic uncertainties are indicated in the top plot by boxes and shaded bands respectively. In the bottom plot the black lines indicate the point-to-point correlated ($T_{AA}$) uncertainties.

Fig 5. The bottom panel of Fig. 5 shows that $R_{AA}$ systematically decreases with centrality, characterised by $\langle N_{\text{part}}\rangle$, reaching a minimal value of 0.4 in 1% of the most central collisions.

4. Fragmentation of the quenched jets

The study of the internal structure of jets produced in ultra-relativistic heavy ion collisions provides additional information on the modification of parton showers in the created hot and dense medium. Here we report on the measurements of distributions of $z \equiv \frac{p_T^{\text{ch}} \cdot p_T^{\text{jet}}}{p_T^{\text{ch}} + p_T^{\text{jet}}}$, the longitudinal momentum fraction of charged jet constituents [13]. Figure 6 shows the unfolded distribution of the longitudinal momentum fraction, $D(z)$, measured in different centrality classes in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. A steep fall at $z \to 1$, characteristic of the jet fragmentation function, can be noted. To investigate the centrality dependence of the fragmentation function, the ratio $R_{D(z)}$ of the $D(z)$ distribution measured in different centrality classes to the same distribution measured in the peripheral cen-

Figure 6: Unfolded fragmentation function, $D(z)$, measured in different centrality classes [13]. The statistical uncertainties are smaller than the points, the systematic uncertainties are shown as shaded boxes. The lines connecting the central values of the measurements are shown to guide the eye.
trality class, 60–80%, is investigated. Figure 7 shows $R_{D(p \rightarrow p)}$ in six 10% centrality bins spanning the range 0–60%. For all collision centralities, an enhancement in the yield of low-$z$ fragments and depletion at intermediate $z$ values is observed. These modifications are the strongest in 10% of the most central collisions and are gradually reduced with decreasing centrality. At large $z$ values, close to unity, the large statistical and systematic uncertainties preclude a definite statement. However, $R_{D(p \rightarrow p)}$ exceeds one with a significance of about 1σ in contrast to predictions of strong reduction in the yield of large-$z$ fragments from radiative energy loss models [15, 16].

Figure 7: Ratios of the $D(z)$ distributions measured in six centrality intervals to the distribution measured in peripheral 60–80% centrality class [14]. Statistical and systematic uncertainties are shown by error bars and shaded boxes respectively.

5. Jet production modification in $p+Pb$ collisions

In $p+Pb$ collisions no significant jet quenching is expected owing to the absence of the hot and dense partonic medium. However, studies of the nuclear modification factor in $p+Pb$ collisions are important to establish a baseline reference for the interpretation of $Pb+Pb$ results. The $pp$ data at the same energy as that of $p+Pb$ collisions, $\sqrt{s} = 5.02$ TeV, are not available. Therefore, the reference $pp$ jet production cross-section at this energy is constructed based on the interpolation between the 2.76 TeV and 7 TeV $pp$ cross-sections using the $xT$-scaling [17, 11]. Due to the large uncertainties in the energy scale and $xT$ interpolation for the $pp$ data at large rapidities, the reference 5.02 TeV $pp$ spectra are derived only for $-2.1 < y* < 2.8$ [11]. In this rapidity range, the jet $R_{Pb}$ can be calculated. Figure 8 shows the transverse momentum dependence of the nuclear modification factor in eight rapidity bins for jets produced in 0–90% $p+Pb$ collisions. In the covered rapidity bins, the inclusive jet $R_{Pb}$ is consistent with unity, within the systematic uncertainties of the measurement, or shows a marginal enhancement of the order of 10%. The data are compared in Fig. 8 with the NLO pQCD calculation of $R_{Pb}$, obtained using the EPS09 parameterisation of nuclear parton distribution functions [18]. The measurements are systematically slightly higher than the calculations, although, within the systematic uncertainties, the general consistency of data and calculations can be concluded. It follows from the above that the $p+Pb$ jet production, averaged over all accessible collision centralities, shows no significant modification relative to $pp$ data.

Figure 8: Transverse momentum dependence of the jet $R_{Pb}$ measured in different rapidity intervals in $\sqrt{s_{NN}} = 5.02$ TeV $p+Pb$ collisions averaged over all centralities [11]. Statistical and systematic uncertainties are shown by error bars and boxes respectively. Shaded bands represent the NLO pQCD calculations using the modified parton distribution functions [19].

Centrality dependence of the jet production in $p+Pb$ collisions is studied using $R_{Pb}$ and $R_{CP}$ evaluated in different classes of the collision centrality, which is de-
fined with the help of $\Sigma E_T^{\text{Pb}}$. Figure 9 shows the $R_{p\text{Pb}}$ in central (0–10%), mid-central (20–30%) and peripheral (60–90%) collisions in all accessible rapidity bins. Jet yields are suppressed in central collisions and enhanced in peripheral collisions as compared to $p\bar{p}$ data. The observation of the near-ideal $N_{\text{coll}}$ scaling of the $R_{p\text{Pb}}$ averaged over all collision centralities (see Fig. 8) results from this variation of $R_{p\text{Pb}}$ with centrality. The deviations from the geometric scaling (i.e. expected scaling with $N_{\text{coll}}$) increase with $p_T$ and are dominant at forward rapidities. At $y^* < 0$ and low $p_T$, the geometric scaling is restored.

The central-to-peripheral ratio, $R_{CP}$, is evaluated in different rapidity intervals and in three centrality classes in $\sqrt{s_{\text{NN}}} = 5.02$ TeV $p+\text{Pb}$ collisions [11]. Statistical and systematic uncertainties are shown by error bars and boxes respectively. The uncertainties on the $pp$ luminosity and $(T_{\text{PbPb}})$ are indicated by shaded boxes centered at one.

A gradually increasing suppression of jets with $y^*$ in the forward rapidity hemisphere may result from the jet kinematics. To test this hypothesis, the $R_{p\text{Pb}}$ in each forward rapidity bin is replotted using the quantity $p_T \times \cosh ((y^*))$, where $(y^*)$ is the centre of the rapidity bin. This quantity approximates the total energy of the jet. Figure 10 shows the $R_{p\text{Pb}}$ as a function of $p_T \times \cosh ((y^*))$ for 0–10% of the most central collisions (left plot) and peripheral 60–90% of collisions (right plot) measured in four bins of forward rapidities. The approximate rapidity-independent trends can be seen, although in central collisions the $R_{p\text{Pb}}$ decreases with $p_T \times \cosh ((y^*))$ while an increase is observed in peripheral collisions.

The $R_{CP}$ for 0–10% of the most central collisions is plotted against $p_T \times \cosh ((y^*))$ for all studied rapidity class used as a reference [11]. Statistical and systematic uncertainties are shown by error bars and boxes respectively. The uncertainties on ratios of $(N_{\text{coll}})$ are indicated by shaded boxes centered at one.

The $R_{CP}$ for 0–10% of the most central collisions is plotted against $p_T \times \cosh ((y^*))$ for all studied rapidity ranges in Fig. 11. Interestingly, at forward and mid-rapidities ($y^* > -0.3$) the $R_{CP}$ measured in different rapidity bins follows the same, almost linear in logarithm of $p_T \times \cosh ((y^*))$, dependence on the jet total energy. This single trend exhibited by $R_{CP}$ is a consequence of
opposite trends seen in $R_{p\text{p}}$ measured in central and peripheral collisions. At backward rapidities ($y^* < -0.3$) this trend is not observed. For other collision centralities, the same trends are observed with a centrality-dependent slope in $R_{\text{CP}}$ versus $\ln p_T \times \cosh((y^*))$.

6. Summary and discussion

These proceedings present the ATLAS measurements of the inclusive jet production in the LHC $\sqrt{s_{\text{NN}}} = 2.76$ TeV Pb+Pb and $\sqrt{s_{\text{NN}}} = 5.02$ TeV $p+\text{Pb}$ collisions. Unfolded, double differential jet spectra are measured over a broad kinematic range in the jet transverse momentum and rapidity. Centrality dependence of jet yields is studied using the reference $pp$ jet cross-sections and the central-to-peripheral ratio of the jet yields. The modifications of the jet yields with respect to the geometric scaling with the number of binary nucleon-nucleon collisions are observed.

The jet nuclear modification factor, $R_{\text{AA}}$, measured in Pb+Pb collisions shows suppression of jet yields as compared to the $pp$ reference data. This suppression monotonically increases with increasing centrality and shows a weak dependence on the jet $p_T$, consistent with the theoretical prediction from Ref. [19]. The $R_{\text{AA}}$ is found to be independent of jet rapidity, over the range $|y| < 2.1$, for all collision centralities and jet transverse momenta. This may indicate that the two effects, the steeper $p_T$ spectrum at forward rapidities and potentially smaller energy loss of quark jets, dominating the forward $y$ region, compensate each other.

The measurements of charged-particle fragmentation functions of the quenched jets in Pb+Pb collisions show medium-dependent modifications, which smoothly evolve with the collision centrality. The central-to-peripheral ratio of distributions of the longitudinal momentum fraction shows an enhancement in the yield of low-$z$ fragments, suppression of fragments with the intermediate $z$ values and a weak enhancement of large-$z$ fragments. The latter observation, which seems to contradict the theoretical expectations, may be partially attributed to the fact, that in this analysis the quenched jets are used as a reference while model predictions refer to the suppression of large-$z$ fragments with respect to the vacuum-produced jets.

For $p+\text{Pb}$ collisions, the measured jet yields are consistent with the expected geometric scaling, but only for collisions averaged over all centralities. When studied as a function of the collision centrality, the jet yields are strongly modified, showing an enhancement in peripheral collisions and suppression in central collisions. These modifications are amplified at high transverse momenta and in the forward rapidity regions. In addition, at forward rapidities, the jet nuclear modification factors are found to scale with the total jet energy. These observations may imply either a large change in the impact parameter-dependent number of the hard-scattered partons or a correlation between the kinematics of the hard scattering process and the soft interactions which are the basis for the centrality determination, or the combination of both.

The presented results provide valuable constrains on the theoretical description of jet quenching in ultra-relativistic nuclear collisions.

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References