Centrality and rapidity dependence of inclusive jet production in $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV p+Pb collisions with the ATLAS detector

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Abstract

Measurements of reconstructed jets in high-energy proton-nucleus collisions over a wide rapidity and transverse momentum range are a fundamental probe of the partonic structure of nuclei. Inclusive jet production is sensitive to the modification of parton distribution functions (PDF) in the high-density nuclear environment. Furthermore, any modification of jet production in p+A collisions has implications for understanding the strong suppression seen in central A+A collisions. The latest results on inclusive jet production in 29/nb of proton-lead collisions at 5.02 TeV with the ATLAS detector at the LHC are presented. The centrality of p+Pb events is characterized through the sum of the transverse energy in the Pb-going forward calorimeter. In minimum bias p+Pb collisions, the jet yields are seen to be consistent with calculations incorporating nuclear PDF effects. However, the jet yields in central and peripheral p+Pb collisions are found to be strongly suppressed and enhanced, respectively, relative to geometric expectations. Furthermore, the modifications at forward rapidities are seen to be consistent with a scaling in the total jet energy, suggesting that the modifications may depend on the initial kinematics of the hard parton-parton scattering.

Keywords: heavy ion physics, nuclear parton distribution functions, proton–nucleus collisions, centrality

1. Introduction

Measurements of inclusive jet production in proton-nucleus (p+A) collisions are expected to probe the partonic structure of the nucleus and its possible modification in the high partonic density environment [1]. More generally, they test the putative factorization between hard and soft processes in collisions involving nuclei and, at high-x, may reveal novel features of the proton wavefunction [2]. Measurements of hadron and jet production in d+Au collisions at RHIC have observed violations of factorization, but only at low p_{T} and forward rapidity or high p_{T} and mid-rapidity [3]. The large acceptance of the LHC detectors can access a kinematic range which includes both regions.

In these proceedings, measurements of the centrality dependence of inclusive jet production in $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV p+Pb collisions as a function of jet transverse momentum (p_{T}) and center of mass rapidity[2] (y^*) by the ATLAS detector at the LHC [4] are presented. The data are described in more detail in [5]. The centrality dependence of the per event jet yield, $(1/N_{\mathrm{evt}})(\mathrm{d}^2N_{\mathrm{jet}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*)$, is investigated through the nuclear modification factor,

$$R_{\mathrm{pPb}} = \left.(1/N_{\mathrm{evt}})(\mathrm{d}^2N_{\mathrm{jet}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*)\right|_{\mathrm{cent}} \Big/ \; T_{\mathrm{pA}} \cdot (\mathrm{d}^2\sigma^{pp}_{\mathrm{jet}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*) \tag{1}$$

where T_{pA} is the mean nuclear thickness seen by the proton in events of the given centrality class and $d^2\sigma^{pp}_{\mathrm{jet}}/dp_{\mathrm{T}}dy^*$ is the pp jet cross-section at the same $\sqrt{s}$. The modifications are also explored through the central-to-peripheral ratio,

[1] A list of members of the ATLAS Collaboration and acknowledgements can be found at the end of this issue.

[2] In this work, $y^*, \eta > 0$ and $y^*, \eta < 0$ correspond to the downstream proton (forward) and nucleus (backward) directions, respectively.

$$R_{\mathrm{CP}}^{\mathrm{cent}} = (1/R_{\mathrm{coll}})\ (1/N_{\mathrm{evt}})(\mathrm{d}^2 N_{\mathrm{jet}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*)\Big|_{\mathrm{cent}} \Big/ \ (1/N_{\mathrm{evt}})(\mathrm{d}^2 N_{\mathrm{jet}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y^*)\Big|_{\mathrm{peri}} \quad (2)$$

where R_{coll} is the ratio of the mean number of colliding nucleons $\langle N_{\mathrm{coll}} \rangle$ in the two centrality selections.

The R_{CP} and R_{pPb} measure deviations in the jet yield from the geometric expectation of an incoherent superposition of an equivalent number of nucleon-nucleon collisions (under which $R_{\mathrm{CP}} = 1$ and $R_{\mathrm{pPb}} = 1$).

2. Data selection, centrality definition and jet reconstruction

The data used in this work comprise 28.9 nb^{-1} of p+Pb data at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV and 4.0 pb^{-1} pf pp data at $\sqrt{s} = 2.76$ TeV delivered by the LHC in early 2013. Both data sets were recorded using a combination of minimum bias and high level jet triggers, with the minimum bias sample used to understand the performance of the trigger. The minimum bias trigger conditions for p+Pb collisions were the presence at least one hit in each side of the minimum bias trigger scintillator (MBTS) detector. Offline, p+Pb events were also required to have a reconstructed vertex. Furthermore, events consistent with diffractive excitation of the proton (defined by the absence of calorimeter clusters in the Pb-going forward calorimeter) and in-time pileup (defined by the presence of more than one reconstructed vertex with $\Sigma p_{\mathrm{T}} > 6$ GeV of associated tracks) were rejected. In pp collisions, the presence of hits in the inner detector was used as the minimum bias trigger, and in the offline analysis only a reconstructed vertex was required.

The centrality of p+Pb events was characterized through the sum of the total transverse energy in the Pb-going forward calorimeter, situated at $-4.9 < \eta < -3.1$, using the same procedure developed in the ATLAS measurement of the charged particle multiplicity in p+Pb [6]. A Monte Carlo (MC) Glauber simulation with nucleon-nucleon inelastic cross-section $\sigma_{\mathrm{NN}} = 70$ mb was used to simulate the geometry of inelastic p+Pb collisions and calculate the probability distribution of the number of participating nucleons N_{part}. Extensions to the wounded nucleon (WN) model and input from `PYTHIA` simulations of pp collisions were used to model the N_{part}-dependent signal in the forward calorimeter. The best fit to the data was used to extract the mean nuclear thickness function T_{pA} and mean number of nucleon-nucleon collisions $\langle N_{\mathrm{coll}} \rangle$ in each centrality interval.

Jets were reconstructed according to a procedure adapted from that used in Pb+Pb collisions, which utilizes an iterative estimation and subtraction of the soft heavy ion underlying event (UE) pedestal underneath jets. ATLAS calorimeter cells were collected into $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ calorimeter towers at the electromagnetic scale. The UE contribution was estimated separately in each $\Delta\eta = 0.1$ interval and each calorimeter layer, with regions of activity consistent with jets excluded from the background determination. Jets were reconstructed using the anti-k_{t} algorithm with $R = 0.4$ on the UE-subtracted towers. The final set of jets were corrected for any inadvertent inclusion of jets into the UE estimate, and were corrected to the full hadronic scale through a calibration derived from MC simulation, described below. Finally, a small residual correction, derived from *in situ* studies of the energy balance between jets and objects with an independently derived energy scale such as photons or Z bosons, was applied. This reconstruction procedure was used identically in p+Pb and pp collisions, and in data and MC. Offline jets matched to the online jet triggers described above were selected for use in the analysis. To avoid any corrections for the trigger efficiency, each jet p_{T} interval was populated exclusively by the highest-luminosity trigger which was > 99% efficient in the interval.

3. Monte Carlo simulation, performance and corrections

The performance of the jet reconstruction procedure in p+Pb collisions was evaluated with an MC simulation consisting of $\sqrt{s} = 5.02$ TeV `PYTHIA` pp hard scattering events overlaid onto minimum bias p+Pb events recorded during the 2013 run, with the detector response fully simulated using GEANT4. Separate samples of 18 million events were generated for each p+Pb beam orientation, with the center of mass rapidity boost with respect to the lab frame in the `PYTHIA` pp event matching that in the data in each case. Furthermore, the centrality of the p+Pb event was determined before overlay, allowing the performance and corrections to be derived in a fully centrality-dependent way. In all centralities, the reconstruction efficiency was determined to be > 99% for $p_{\mathrm{T}} > 25$ GeV jets.

The performance was quantified through the mean and RMS of the fractional deviation of the reconstructed jet p_{T} from the truth jet p_{T}, $p_{\mathrm{T}}^{\mathrm{reco}}/p_{\mathrm{T}}^{\mathrm{truth}} - 1$, called the jet energy scale (JES) closure and resolution (JER), respectively. The JES closure was better than 2% for all $p_{\mathrm{T}} > 25$ GeV jets and better than 1% for all $p_{\mathrm{T}} > 100$ GeV jets. At low p_{T}, the JES and JER exhibit a weak centrality dependence of up to 1% in the JES closure and 2% in the JER in the most

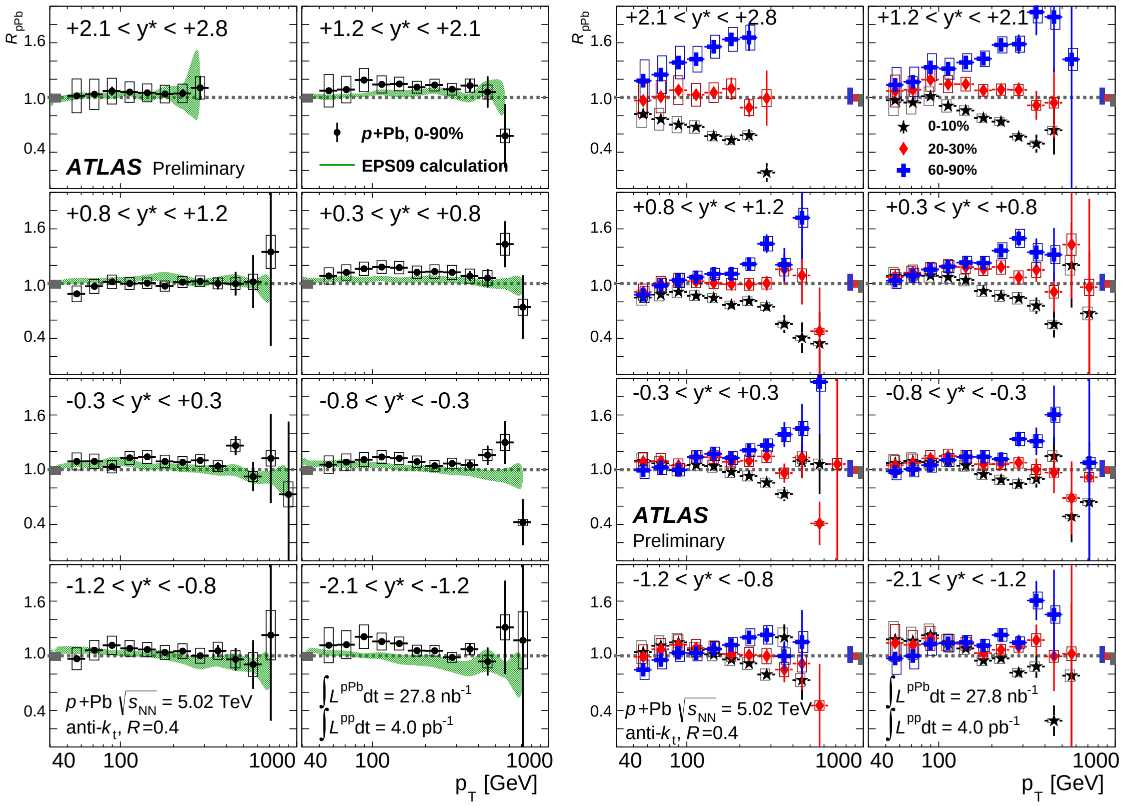

Figure 1. Nuclear modification factor R_{pPb} as a function of jet p_{T}, with each panel at a different jet y^{*} range. The vertical error bars and boxes represent total statistical and systematic uncertainties, respectively. The shaded boxes on the left (left panel) and right (right panel) sides of the horizontal axis at $R_{\mathrm{pPb}} = 1$ correspond to the systematic uncertainty on the geometric parameters and luminosity. *Left:* R_{pPb} for 0–90% p+Pb events, compared to a pQCD calculation incorporating the EPS09 nPDF set. *Right:* R_{pPb} for the most central 0–10% (black stars), mid-peripheral 20–30% (red diamonds) and peripheral 60–90% (blue crosses) events.

central events relative to the most peripheral. The performance was also quantified in $\sqrt{s}$ = 2.76 TeV pp collisions using a separate sample of 9 million PYTHIA hard scattering events at that energy. In pp collisions, the JES closure is better than 1% in all p_{T} and y^{*} intervals studied.

To correct for the migration between p_{T} intervals induced by any residual JES non-closure and the finite JER, a set of "bin-by-bin" correction factors were applied to the detector level jet yields. The correction factors were determined separately for each p+Pb centrality and for pp by comparing the number of truth and reconstructed jets in a given p_{T} interval, after reweighing the truth spectrum to match what is observed in the data. The corrections are 10%-30% in most of the p_{T} intervals. Since the R_{pPb} and R_{CP} are ratios of spectra measured and corrected in very similar ways, the corrections typically cancel to a large extent between the numerator and denominator. Similarly, the resulting systematic uncertainties on the nuclear modification factors are modest.

4. Nuclear modification factors for jets

After correcting for detector effects as described above, the jet cross-section at $\sqrt{s}$ = 2.76 TeV is interpolated to the desired reference energy of $\sqrt{s}$ = 5.02 TeV through a previous ATLAS measurement of the x_{T} (= $2p_{\mathrm{T}}/\sqrt{s}$) scaling of jet production between $\sqrt{s}$ = 2.76 TeV and $\sqrt{s}$ = 7 TeV [7]. Since the x_{T} interpolation uses only ATLAS data with a consistent anti-k_t cone size, the resulting uncertainties on the R_{pPb} associated with this procedure are modest.

The left panel of Figure 1 shows the R_{Pb} for 0–90% events and a pQCD-based calculation which includes nuclear modifications to the PDFs as incorporated in the EPS09 set [1]. In all rapidity intervals studied, the R_{pPb} is consistent

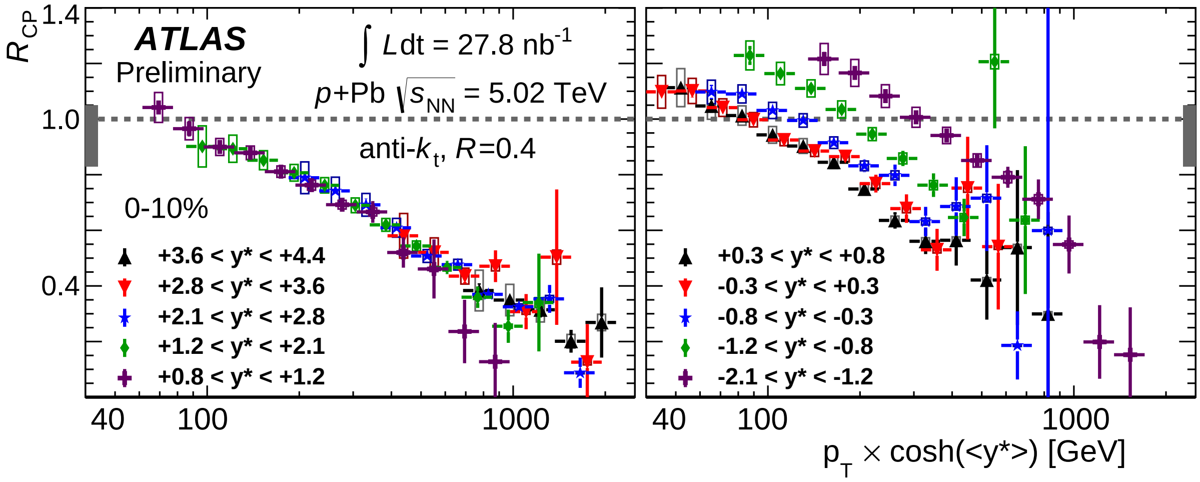

Figure 2. Nuclear modification factor R_{CP} for the most central to most peripheral selection, 0–10%/60–90% plotted as a function of the approximate total jet energy $p_{\mathrm{T}} \times \cosh(\langle y^* \rangle)$. Each series shows a different selection on the jet rapidity y^*, with the left and right panels showing the five most forward and backward selections, respectively. The vertical error bars and boxes represent total statistical and systematic uncertainties, respectively. The shaded boxes on the left and right sides of the horizontal axis at $R_{\mathrm{CP}} = 1$ correspond to the systematic uncertainty on the geometric parameters.

with a slight p_{T}-dependent enhancement above unity, in line with the expectations from EPS09. The right panel of Figure 1 shows the centrality-dependent R_{pPb}. At low p_{T} and at backwards rapidities, the R_{pPb} is generally consistent with the geometric expectation. However, at higher p_{T} and more forward rapidities, the R_{pPb} features strong deviations in the jet yield from the geometric expectation. The jet yield is suppressed in central collisions and enhanced in peripheral collisions. Furthermore, the modifications are systematically larger at higher p_{T} and more forward rapidities.

To explore the kinematic dependence of the modifications, the data were plotted as a function of the approximate total jet energy, $p_{\mathrm{T}} \times \cosh(\langle y^* \rangle)$, where $\langle y^* \rangle$ is the midpoint of the rapidity bin. Figure 2 shows the 0–10%/60–90% R_{CP} at all rapidities studied as a function of $p_{\mathrm{T}} \times \cosh(\langle y^* \rangle)$. When plotted this way, the R_{CP} for rapidities in the range $0.8 < y^* < 4.4$ can be seen to follow a single trend that is a function of $p_{\mathrm{T}} \times \cosh(\langle y^* \rangle)$ alone. This scaling in the total energy holds until approximately mid-rapidity, but does not hold for backwards rapidities ($y^* < -0.3$).

5. Conclusion

These proceedings present a measurement of inclusive jet production in p+Pb collisions at 5.02 TeV with the ATLAS detector. The jet yield in minimum bias collisions is found to be in line with the expectation from the modest modification of nuclear parton distribution functions over a wide kinematic range. Centrality-selected yields are also presented, using the transverse energy in the Pb-going forward calorimeter to characterize the event centrality. The centrality dependent jet yields are strongly modified, with a suppression (enhancement) in central (peripheral) events. Furthermore, the modifications at forward rapidities are found to obey a scaling relation in the total jet energy, suggesting that the mechanism responsible for the observed effects may depend in a simple way on the underlying parton-parton kinematics, such as the fractional longitudinal momentum of the parton originating in the proton x_p.

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