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Measurement of jet fragmentation in 5.02 TeV proton–lead and proton–proton collisions with the ATLAS detector

The ATLAS Collaboration ⋆

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Abstract

A measurement of the fragmentation functions of jets into charged particles in $p+\mathrm{Pb}$ collisions and pp collisions is presented. The analysis utilizes 28 nb^{-1} of $p+\mathrm{Pb}$ data and 26 pb^{-1} of pp data, both at $\sqrt{s_{\mathrm{NN}}}=5.02$ TeV, collected in 2013 and 2015, respectively, with the ATLAS detector at the LHC. The measurement is reported in the centre-of-mass frame of the nucleon–nucleon system for jets in the rapidity range $|y^*|<1.6$ and with transverse momentum $45<p_{\mathrm{T}}<260$ GeV. Results are presented both as a function of the charged-particle transverse momentum and as a function of the longitudinal momentum fraction of the particle with respect to the jet. The pp fragmentation functions are compared with results from Monte Carlo event generators and two theoretical models. The ratios of the $p+\mathrm{Pb}$ to pp fragmentation functions are found to be consistent with unity.

Keywords: Relativistic heavy-ion collisions; Jets; Fragmentation into hadrons

1. Introduction

Heavy-ion collisions at the Large Hadron Collider (LHC) are performed in order to produce and study the quark–gluon plasma (QGP), a phase of strongly interacting matter which emerges at very high energy densities; a recent review can be found in Ref. [1]. Measurements of jets and jet properties in heavy-ion collisions are sensitive to the properties of the QGP. In order to quantify jet modifications in heavy-ion collisions, proton–proton (pp) collisions are often used as a

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reference system. Using this reference, rates of jet production in Pb + Pb collisions are observed to be reduced compared to that expected from the rates in pp collisions, appropriately scaled to account for the nuclear thickness in Pb + Pb collisions [2,3]. Charged-particle fragmentation functions are also observed to be modified in Pb + Pb collisions compared to pp collisions [4–6]. Both of these effects are interpreted as arising predominantly from the modification of the parton showering process in the final stages of the collision.

In addition to final-state differences emerging from the presence of the hot and dense matter, jet production in Pb + Pb collisions may also differ from that in pp collisions due to effects arising from the presence of the large nucleus. For example, nucleons bound in a nucleus are expected to have a modified structure compared to the free nucleon [7], and partons may lose energy in the nuclear environment before scattering [8]. Proton–nucleus collisions are used to differentiate between initial- and final-state effects in Pb + Pb collisions. The inclusive jet production rate in proton–lead (p + Pb) collisions at 5.02 TeV was measured [9–11] at the LHC and found to be only slightly modified after normalization by the nuclear thickness function. Measurements made at the Relativistic Heavy Ion Collider with deuteron–gold collisions yield similar results [12] (interestingly, Refs. [9,12] observe a centrality dependence to inclusive jet production). High transverse momentum (p_{T}) charged hadrons originate from the fragmentation of jets and provide a complementary observable to that of jet production. The CMS Collaboration observed a small excess in the charged-particle spectrum measured in p + Pb collisions for $p_{\mathrm{T}} > 20$ GeV particles compared to that expected from pp collisions [13]. Measurements of charged-particle fragmentation functions for jets in different p_{T} intervals in p + Pb and pp collisions are crucial for connecting the jet and charged-particle results. Therefore, the measurements reported here are necessary both to establish a reference for jet fragmentation measurements in Pb + Pb collisions and to determine any modifications to jet fragmentation in p + Pb collisions due to the presence of a large nucleus.

In recent years many of the features of Pb + Pb collisions which were interpreted as final state effects due to hot nuclear matter were also observed in p + Pb collisions at the LHC and in d + Au collisions at RHIC. These features include long-range hadron correlations [14–17] and a centrality-dependent reduction in the quarkonia yields [18–21]. There is considerable debate about whether these features arise from the same source as in Pb + Pb collisions [22] or from other effects such as initial state gluon saturation [23]. Measurements of jets in p + Pb collisions showed no effects that would be attributable to hot nuclear matter, however additional measurements of jet properties in these collisions could help to constrain the source of the modifications observed in other observables.

In this paper, the jet momentum structure in pp and p + Pb collisions is studied using the distributions of charged particles associated with jets which have a transverse momentum $p_{\mathrm{T}}^{\mathrm{jet}}$ in the range 45 to 260 GeV. Jets are reconstructed with the anti-k_t algorithm [24] using a radius parameter $R = 0.4$. Charged particles are assigned to jets via an angular matching $\Delta R < 0.4$,[1] where ΔR is the angular distance between the jet axis and the charged-particle position. Results on the fragmentation functions are presented both as a function of the ratio between the

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Rapidity is defined as $y = 0.5 \ln \frac{E+p_z}{E-p_z}$ where E and p_z are the energy and the component of the momentum along the beam direction. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

component of the particle transverse momentum parallel to the jet direction, and the jet p_{T}, $z \equiv p_{\mathrm{T}} \cos \Delta R \,/\, p_{\mathrm{T}}^{\mathrm{jet}}$,[2] and as a function of the charged-particle transverse momentum with respect to the beam direction, p_{T}:

$$D(z) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}z}, \tag{1}$$

and

$$D(p_{\mathrm{T}}) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}p_{\mathrm{T}}}. \tag{2}$$

The quantity N_{ch} is the number of charged particles and N_{jet} is the number of jets under consideration. The fragmentation functions are per-jet normalized.

The fragmentation functions are compared in p + Pb and pp collisions at a centre-of-mass energy of 5.02 TeV. In order to quantify any difference between p + Pb and pp collisions, the ratios of the fragmentation functions are measured:

$$R_{D(z)} \equiv \frac{D(z)_{p\mathrm{Pb}}}{D(z)_{pp}}. \tag{3}$$

In Pb + Pb collisions, such measurements are also presented as a function of charged-particle p_{T} [4,6] to explore the absolute p_{T} scale of the modifications and to reduce jet-related uncertainties. Thus, in addition to the more commonly used fragmentation functions as a function of z, this paper also presents the analogous distributions and their ratios as a function of charged particle p_{T}:

$$R_{D(p_{\mathrm{T}})} \equiv \frac{D(p_{\mathrm{T}})_{p\mathrm{Pb}}}{D(p_{\mathrm{T}})_{pp}}. \tag{4}$$

2. Experimental set-up

The measurements presented here are performed using the ATLAS calorimeter, inner detector, trigger, and data acquisition systems [25]. The calorimeter system consists of a sampling liquid argon (LAr) electromagnetic (EM) calorimeter covering $|\eta| < 3.2$, a steel–scintillator sampling hadronic calorimeter covering $|\eta| < 1.7$, a LAr hadronic calorimeter covering $1.5 < |\eta| < 3.2$, and two LAr forward calorimeters (FCal) covering $3.2 < |\eta| < 4.9$. The hadronic calorimeter has three sampling layers longitudinal in shower depth. The EM calorimeters are segmented longitudinally in shower depth into three layers plus an additional pre-sampler layer. The EM calorimeter has a granularity that varies with layer and pseudorapidity, but which is generally much finer than that of the hadronic calorimeter. The minimum-bias trigger scintillators (MBTS) [25] detect charged particles over $2.1 < |\eta| < 3.9$ using two segmented counters placed at $z = \pm 3.6$ m. Each counter provides measurements of both the pulse heights and the arrival times of ionization energy deposits.

A two-level trigger system was used to select the p + Pb and pp collisions analysed here. The first, the hardware-based trigger stage Level-1, is implemented with custom electronics. The second level is the software-based High Level Trigger (HLT). Jet events were selected by the HLT with Level-1 seeds from jet, minimum-bias, and total-energy triggers. The total-energy trigger

[2] The ΔR is an approximation of the opening angle $\sqrt{(\Delta\theta)^2 + (\Delta\phi)^2}$.

required a total transverse energy measured in the calorimeter of greater than 5 GeV. The HLT jet trigger operated a jet reconstruction algorithm similar to that applied in the offline analysis and selected events containing jets with transverse energy thresholds ranging from 20 GeV to 75 GeV in $p+\mathrm{Pb}$ collisions and up to 85 GeV in pp collisions. In both the pp and $p+\mathrm{Pb}$ collisions, the highest-threshold jet trigger sampled the full delivered luminosity. Minimum-bias $p+\mathrm{Pb}$ events were required to have at least one hit in a counter on each side of the MBTS detector at the Level-1 trigger.

The inner detector measures charged-particle tracks within the pseudorapidity interval $|\eta|<2.5$ using a combination of silicon pixel detectors, silicon microstrip detectors (SCT), and a straw-tube transition radiation tracker (TRT), all immersed in a 2 T axial magnetic field [25]. Each of the three detectors is composed of a barrel and two symmetric end-cap sections. The pixel detector is composed of three layers of sensors with a nominal pixel size of 50 μm × 400 μm. Following the $p+\mathrm{Pb}$ data-taking and prior to the 5 TeV pp data-taking an additional silicon tracking layer, the "insertable B-layer" (IBL) [26], was installed closer to the interaction point than the other three layers. The SCT barrel section contains four layers of modules with 80 μm pitch sensors on both sides, and each end-cap consists of nine layers of double-sided modules with radial strips having a mean pitch of 80 μm. The two sides of each SCT layer in both the barrel and the end-caps have a relative stereo angle of 40 mrad. The TRT contains up to 73 (160) layers of staggered straws interleaved with fibres in the barrel (end-cap).

3. Event selection and data sets

The $p+\mathrm{Pb}$ data used in this analysis were recorded in 2013. The LHC was configured with a 4 TeV proton beam and a 1.57 TeV per nucleon Pb beam producing collisions with $\sqrt{s_{\mathrm{NN}}}=5.02$ TeV and a rapidity shift of the centre-of-mass frame, $\Delta y=0.465$, relative to the laboratory frame. The data collection was split into two periods with opposite beam configurations. The first period consists of approximately 55% of the integrated luminosity with the Pb beam travelling toward positive rapidity and the proton beam to negative rapidity. The remaining data were taken with the beams of protons and Pb nuclei swapped. The total $p+\mathrm{Pb}$ integrated luminosity is 28 nb^{-1}. Approximately 26 pb^{-1} of $\sqrt{s}=5.02$ TeV pp data from 2015 was used. The instantaneous luminosity conditions provided by the LHC resulted in an average number of $p+\mathrm{Pb}$ interactions per bunch crossing of 0.03. During pp data-taking, the average number of interactions per bunch crossing varied from 0.6 to 1.3.

The $p+\mathrm{Pb}$ events selected are required to have a reconstructed vertex, at least one hit in each MBTS detector, and a time difference measured between the two MBTS sides of less than 10 ns. The pp events used in this analysis are required to have a reconstructed vertex; no requirement on the signal in the MBTS detector is imposed. In $p+\mathrm{Pb}$ collisions the event centrality is determined by the FCal in the Pb-going direction as in Ref. [9]. The $p+\mathrm{Pb}$ events used here belong to the 0–90% centrality interval.

The performance of the ATLAS detector and offline analysis in measuring fragmentation functions in $p+\mathrm{Pb}$ collisions is evaluated using a sample of Monte Carlo (MC) events obtained by overlaying simulated hard-scattering pp events generated with PYTHIA version 6.423 (PYTHIA6) [27] onto minimum-bias $p+\mathrm{Pb}$ events recorded during the same data-taking period. A sample consisting of 2.4×10^{7} pp events is generated with PYTHIA6 using parameter values from the AUET2B tune [28] and the CTEQ6L1 parton distribution function (PDF) set [29], at $\sqrt{s}=5.02$ TeV and with a rapidity shift equivalent to that in the $p+\mathrm{Pb}$ collisions is used in the overlay procedure. About half of the events are simulated with one beam configuration

and the second half with the other. The detector response is simulated using GEANT4 [30,31], and the simulated hits are combined with those from the data event. An additional sample of 2.6×10^7 pp hard-scattering events simulated with PYTHIA version 8.212 (PYTHIA8) [32] at $\sqrt{s} = 5.02$ TeV with the A14 tune [33] and NNPDF23LO PDF set [34] is used to evaluate the performance for measuring fragmentation functions in the 2015 pp data. Finally, fragmentation functions at generator-level evaluated from 1.5×10^7 5.02 TeV pp events [35] generated with HERWIG++ using the UEEE5 tune [36] and the CTEQ6L1 PDFs [29] are compared to the fragmentation function measured in 5.02 TeV pp data.

4. Jet and track selection

Jets are reconstructed with the same heavy-ion jet reconstruction algorithm used in previous measurements in $p+\text{Pb}$ collisions [9]. The anti-k_t algorithm [24] is first run in four-momentum recombination mode using as input the signal in $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ calorimeter towers with the anti-k_t radius parameter R set to 0.4 and 0.2 ($R = 0.4$ jets are used for the main analysis and the $R = 0.2$ jets are used to improve the jet position resolution as discussed below). The energies in the towers are obtained by summing the energies of calorimeter cells at the electromagnetic energy scale within the tower boundaries. Then, an iterative procedure is used to estimate the layer- and η-dependent underlying event (UE) transverse energy density, while excluding the regions populated by jets. The UE transverse energy is subtracted from each calorimeter cell and the four-momentum of the jet is updated accordingly. Then, a jet η- and p_{T}-dependent correction factor derived from the simulation samples is applied to correct the jet momentum for the calorimeter response. Additionally, the jet energies were corrected by a multiplicative factor derived in *in situ* studies of the transverse momentum balance of jets recoiling against photons, Z bosons, and jets in other regions of the calorimeter [37,38]. This *in situ* calibration, which typically differed from unity by a few percent, accounts for differences between the simulated detector response and data.

Jets are required to have jet centre-of-mass rapidity, $|y^*_{\text{jet}}| < 1.6$,[3] which is the largest symmetric overlap between the two collision systems for which there is full charged-particle tracking coverage within a jet cone of size $R = 0.4$. To prevent neighbouring jets from distorting the measurement of the fragmentation functions, jets are rejected if there is another jet with higher p_{T}within a distance $\delta R = 1.0$, where δR is the distance between the two jet axes. To reduce the effects of the broadening of the jet position measurement due to the UE, for $R = 0.4$ jets, the jet direction is taken from that of the closest matching $R = 0.2$ jet within $\delta R = 0.3$ when such a matching jet is found (this procedure has been previously used in Ref. [5]). All jets included in the analysis are required to have p_{T} sufficiently large for the jet trigger efficiency to be higher than 99%. Reconstructed jets which consist only of isolated high-p_{T} electrons [39] from electroweak bosons are excluded from this analysis.

The MC samples are used to evaluate the jet reconstruction performance and to correct the measured distributions for detector effects. The $p+\text{Pb}$ jet reconstruction performance is described in Ref. [9]; the jet reconstruction performance in pp collisions is found to be similar to that in $p+\text{Pb}$ collisions. In the MC samples, the kinematics of the particle-level jets are re-

[3] The jet centre-of-mass rapidity y^*_{jet} is defined as $y^*_{\text{jet}} \equiv y_{\text{jet}} - \Delta y$ where y_{jet} is the jet rapidity in the ATLAS rest frame and Δy is the rapidity shift of the centre-of-mass frame.

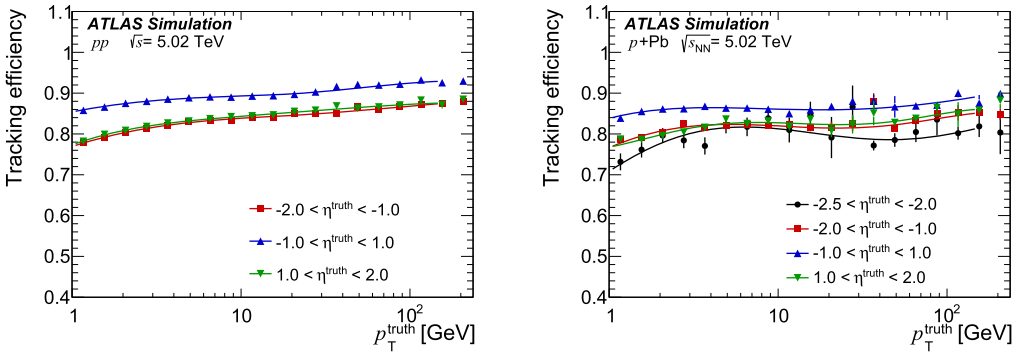

Fig. 1. Tracking efficiency as a function the primary particle momentum at generation level, $p_{\mathrm{T}}^{\mathrm{truth}}$, in pp collisions (left) and in $p+\mathrm{Pb}$ collisions for one of the two beam configurations (right). The different sets of points show the primary particle pseudorapidity, η^{truth}, intervals in which the track reconstruction efficiency has been performed. The different η^{truth} intervals in pp and $p+\mathrm{Pb}$ plots reflect the different regions of the tracking system used in the two cases due to the boosted $p+\mathrm{Pb}$ system. The solid curves show parameterizations of efficiencies.

constructed from primary particles[4] with the anti-k_t algorithm with radius parameter $R=0.4$. In these studies, particle-level jets are matched to reconstructed jets with a $\Delta R<0.2$.

Tracks used in the analysis of $p+\mathrm{Pb}$ collisions are required to have at least one hit in the pixel detector and at least six hits in the SCT. Tracks used in the analysis of pp collisions are required to have at least 9 or 11 total silicon hits for $|\eta|<1.65$ or $|\eta|>1.65$, respectively, including both the pixel layers and the SCT. This includes a hit in the first (first or second) pixel layer if expected from the track trajectory for the $p+\mathrm{Pb}$ (pp) data. All tracks used in this analysis are required to have $p_{\mathrm{T}}>1$ GeV. In order to suppress the contribution of secondary particles, the distance of closest approach of the track to the primary vertex is required to be less than 1.5 mm along the beam axis and less than a value which varies from approximately 0.6 mm at $p_{\mathrm{T}}=1$ GeV to approximately 0.2 mm at $p_{\mathrm{T}}=20$ GeV in the transverse plane.

The efficiency for reconstructing charged particles within jets in $p+\mathrm{Pb}$ and pp collisions is evaluated using PYTHIA6 and PYTHIA8 MC samples, respectively, and is computed by matching the reconstructed tracks to generator-level primary particles. The association is done based on contributions of generator-level particles to the hits in the detector layers. A reconstructed track is matched to a generator-level particle if it contains hits produced primarily by this particle [31]. The efficiencies are determined separately for the two $p+\mathrm{Pb}$ running configurations because the η regions of the detector used for the track measurement are different for the two beam configurations. The charged-particle reconstruction efficiencies as a function of the primary particle's transverse momentum, $p_{\mathrm{T}}^{\mathrm{truth}}$, in coarse η^{truth} intervals, are shown in Fig. 1 in pp and $p+\mathrm{Pb}$ collisions. The $p_{\mathrm{T}}^{\mathrm{truth}}$ dependence of the efficiencies is parameterized using a fifth-order polynomial in $\log(p_{\mathrm{T}}^{\mathrm{truth}})$ which describes the efficiency behaviour in the range of particle $p_{\mathrm{T}}^{\mathrm{truth}}$ from 1.0 to 150 GeV. The tracking efficiency is observed to be constant above 150 GeV and a constant efficiency value is used for particles with $p_{\mathrm{T}}^{\mathrm{truth}}>150$ GeV due to the limited size of the MC samples in that phase space region. To account for finer scale variations of the tracking efficiency with pseudorapidity, the parameterizations are multiplied by an η-dependent scale factor

[4] Primary particles are defined as particles with a mean lifetime $\tau>0.3\times10^{-10}$ s either directly produced in pp interactions or from subsequent decays of particles with a shorter lifetime. All other particles are considered to be secondary.

evaluated in η^{truth} intervals of 0.1 units in coarse $p_{\text{T}}^{\text{truth}}$ intervals. The dependence of the charged-particle efficiency on $p_{\text{T}}^{\text{jet}}$ is found to be negligible for the $p_{\text{T}}^{\text{jet}}$ selections used here. The measured $D(z)$ and $D(p_{\text{T}})$ distributions are corrected for the contribution of reconstructed "fake" tracks which cannot be matched to a generated primary particle in the MC samples produced without minimum bias interactions overlaid and the residual contribution of tracks matched to secondary particles. The fraction of secondary and fake tracks is found to be below 2% of the tracks that pass the selection in any track and jet kinematic region. The contribution from these tracks to the fragmentation functions is subtracted from the measured fragmentation functions in both the pp and $p+\text{Pb}$ collisions.

5. Analysis procedure

Reconstructed charged particle tracks are associated with a reconstructed jet if they fall within $\Delta R = 0.4$ of the jet axis. For each of these particles the momentum fraction, z, is calculated. The measured fragmentation functions are constructed as:

$$D(z)_{\text{meas}} \equiv \frac{1}{N_{\text{jet}}} \frac{1}{\varepsilon(\eta,\, p_{\text{T}})} \frac{\Delta N_{\text{ch}}(z)}{\Delta z} \tag{5}$$

and

$$D(p_{\text{T}})_{\text{meas}} \equiv \frac{1}{N_{\text{jet}}} \frac{1}{\varepsilon(\eta,\, p_{\text{T}})} \frac{\Delta N_{\text{ch}}(p_{\text{T}})}{\Delta p_{\text{T}}}, \tag{6}$$

where $\varepsilon(\eta,\, p_{\text{T}})$ is the track reconstruction efficiency, and N_{jet} is the total number of jets in a given $p_{\text{T}}^{\text{jet}}$ bin. The quantities $\Delta N_{\text{ch}}(z)$ and $\Delta N_{\text{ch}}(p_{\text{T}})$ are the numbers of associated tracks within the given z or p_{T} range, respectively. The efficiency correction is applied on a track-by-track basis, assuming $p_{\text{T}} = p_{\text{T}}^{\text{truth}}$. While that assumption is not strictly valid, the efficiency varies sufficiently slowly with $p_{\text{T}}^{\text{truth}}$ that the error introduced by this assumption is negligible.

In $p+\text{Pb}$ collisions the UE contribution to the fragmentation functions from charged particles not associated with the jet constitutes a background that needs to be subtracted. It originates in soft interactions that accompany the hard process in the same $p+\text{Pb}$ collision and depends on charged-particle p_{T} and η. This background is determined event by event for each measured jet by using a grid of $\Delta R = 0.4$ cones that span the full coverage of the inner detector. The cones have a fixed distance between their centres chosen such that the coverage of the inner detector is maximized while the cones do not overlap each other. Any such cone containing a charged particle with $p_{\text{T}} > 3.5$ GeV is assumed to be associated with a real jet and is excluded from the UE contribution. The 3.5 GeV threshold is derived from studies of UE contribution in MC samples. The estimated contribution from UE particles in each cone is corrected to account for differences in the average UE particle yield at a given p_{T} between the η position of the cone and the η position of the jet. The correction is based on a parameterization of the p_{T} and η dependence of charged-particle yields in minimum-bias collisions. The resulting UE contribution is evaluated for charged particles in the transverse momentum interval of $1 < p_{\text{T}} < 3.5$ GeV and averaged over all cones. The UE contribution is further corrected for the correlation between the actual UE yield within the jet cone and the jet energy resolution discussed in Ref. [5]. This effect is corrected by a multiplicative correction factor, dependent on the track p_{T} (or z) and the jet p_{T}. The correction is estimated in MC samples as the ratio of the UE contribution calculated from tracks within the area of a jet that do not have an associated generator-level particle to the UE contribution estimated by the cone method. Corrected UE contributions are then subtracted from

measured distributions. The maximum size of the UE contribution is 20% for the lowest track p_{T} (or z). The UE from the cone method is compared to an alternative UE estimation and the difference is found to be negligible. The subtracted UE contribution has no azimuthal variation in $p+\mathrm{Pb}$ collisions and no UE subtraction is performed for the pp measurement due to negligible UE contribution (less than 2% over the entire kinematic range measured).

The measured $D(z)$ and $D(p_{\mathrm{T}})$ distributions are corrected for detector effects by means of a two-dimensional Bayesian unfolding procedure [40] using the RooUnfold package [41]. The unfolding procedure removes the effect of bin migration due to the jet energy and the track momentum resolutions. Using the MC samples, four-dimensional response matrices are created using the particle-level and reconstructed $p_{\mathrm{T}}^{\mathrm{jet}}$, and generator-level and reconstructed track $p_{\mathrm{T}}(z)$. Separate unfolding matrices are constructed for the $p+\mathrm{Pb}$ and pp data. An independent bin-by-bin unfolding procedure is used to correct the measured $p_{\mathrm{T}}^{\mathrm{jet}}$ spectra, which is used to normalize the unfolded fragmentation functions by the number of jets. The response matrices are reweighted such that the shapes of the measured fragmentation functions and jet spectra in the simulation match those in the data. The number of iterations in the Bayesian unfolding is selected to be the minimum number for which the relative change in the fragmentation function at $z=0.1$ is smaller than 0.2% per additional iteration in all $p_{\mathrm{T}}^{\mathrm{jet}}$ bins. This condition ensures the stability of the unfolding and minimizes statistical fluctuations due to the unfolding in the high z and p_{T} regions. The resulting number of iterations is driven by the low $p_{\mathrm{T}}^{\mathrm{jet}}$ intervals, which require the most iterations to converge. The systematic uncertainty due to the unfolding is typically much larger than the impact of the stability requirement, especially for the lowest $p_{\mathrm{T}}^{\mathrm{jet}}$ values used in this analysis (discussed in Section 6). Following this criterion, 14 iterations are used for both the $p+\mathrm{Pb}$ and pp data sets. The analysis procedure is tested by dividing the MC event sample in half and using one half to generate response matrices with which the other half is unfolded. Good recovery of the generator-level distributions is observed for the unfolded events and the deviations from perfect closure are incorporated into the systematic uncertainties.

6. Systematic uncertainties

The systematic uncertainties in the measurement of the fragmentation functions and their ratios are described in this section. The following sources of systematic uncertainty in the measurement of the fragmentation functions and their ratios are considered: the jet energy scale (JES), the jet energy resolution (JER), the dependence of the unfolded results on the choice of the starting MC distributions, the residual non-closure of the unfolding and the tracking-related uncertainties. For each variation reflecting a systematic uncertainty the fragmentation functions are re-evaluated and the difference between the varied and nominal fragmentation functions is used as an estimate of the uncertainty. The systematic uncertainties in the $D(z)$ and $D(p_{\mathrm{T}})$ measurements in both collision systems are summarized in Figs. 2 and 3, respectively, for two different jet p_{T} bins. The systematic uncertainties from each source are taken as uncorrelated and combined in quadrature to obtain the total systematic uncertainty.

The JES uncertainty is determined from *in situ* studies of the calorimeter response [37,42,43], and studies of the relative energy-scale difference between the jet reconstruction procedure in heavy-ion collisions and the procedure used in pp collisions [44]. The impact of the JES uncertainty on the measured distributions is evaluated by constructing new response matrices where all reconstructed jet transverse momenta are shifted by ±1 standard deviation ($\pm1\sigma$) of the JES uncertainty. The data are then unfolded with these matrices. Each component that contributes

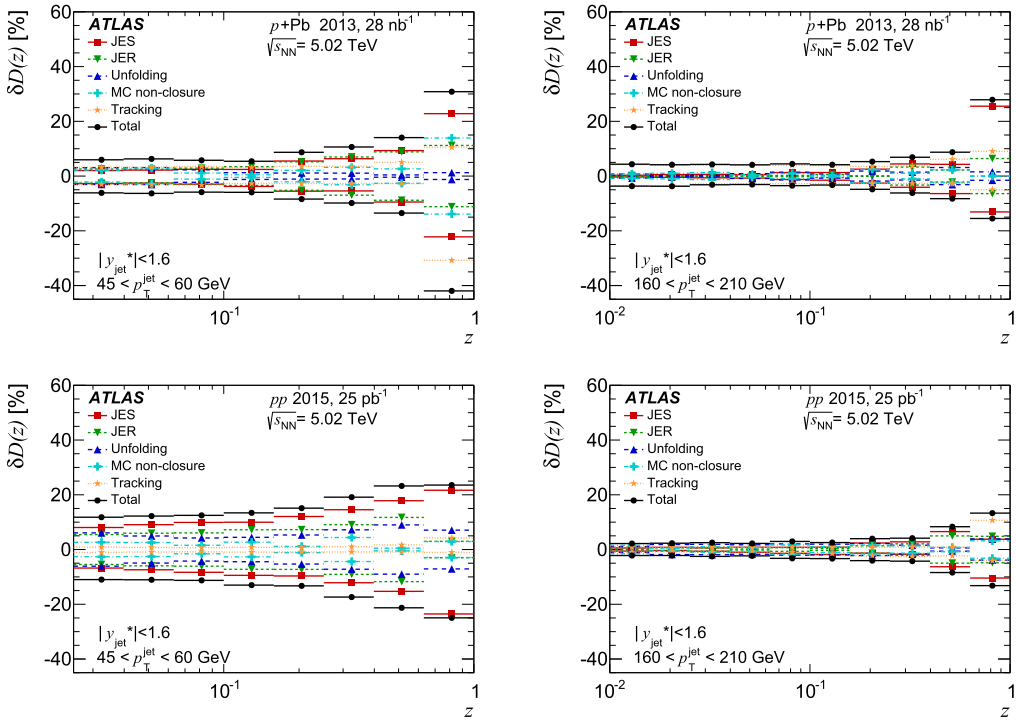

Fig. 2. Summary of the systematic uncertainties in the fragmentation function, $D(z)$, in $p+\mathrm{Pb}$ collisions (top) and pp collisions (bottom) for jets in the 45–60 GeV $p_{\mathrm{T}}^{\mathrm{jet}}$ interval (left) and in the 160–210 GeV $p_{\mathrm{T}}^{\mathrm{jet}}$ interval (right). The systematic uncertainties due to JES, JER, unfolding, MC non-closure and tracking are shown along with the total systematic uncertainty from all sources.

to the JES uncertainty is varied separately. In total, 45 and 51 independent systematic components constitute the full JES uncertainty in the analysis of $p+\mathrm{Pb}$ and pp collisions, respectively. These components are uncorrelated among each other within the data set and fully correlated across p_{T} and η. The JES uncertainty increases with increasing z and particle p_{T} at fixed $p_{\mathrm{T}}^{\mathrm{jet}}$ and decreases with increasing $p_{\mathrm{T}}^{\mathrm{jet}}$.

The uncertainty in the fragmentation functions due to the JER is estimated by repeating the unfolding procedure with modified response matrices, where the resolution of the reconstructed jet $p_{\mathrm{T}}^{\mathrm{jet}}$ is broadened by Gaussian smearing. The smearing factor is evaluated using an *in situ* technique involving studies of dijet energy balance [45,46]. The systematic uncertainty due to the JER increases with increasing z and particle p_{T} at fixed $p_{\mathrm{T}}^{\mathrm{jet}}$ and decreases with increasing $p_{\mathrm{T}}^{\mathrm{jet}}$.

The unfolding uncertainty is estimated by generating the response matrices from the MC distributions without reweighting to match the shapes of the reconstructed data in $p_{\mathrm{T}}^{\mathrm{jet}}$ and $D(z)$ or $D(p_{\mathrm{T}})$. Conservatively, an additional uncertainty to account for possible residual limitations in the analysis procedure was assigned by evaluating the non-closure of the unfolded distributions in simulations, as described in Section 5. The magnitude of both of these uncertainties is typically below 5% except for the highest z and track p_{T} bins.

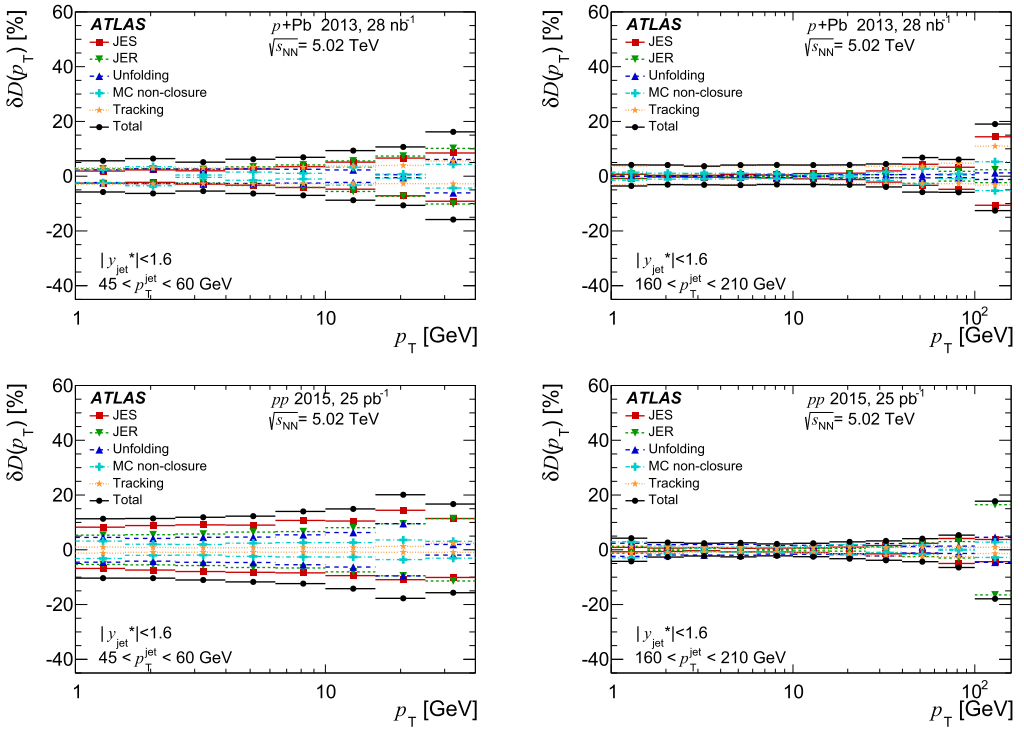

Fig. 3. Summary of the systematic uncertainties in the fragmentation function, $D(p_{\mathrm{T}})$, in $p+\mathrm{Pb}$ collisions (top) and pp collisions (bottom) for jets in the 45–60 GeV $p_{\mathrm{T}}^{\mathrm{jet}}$ interval (left) and in the 160–210 GeV $p_{\mathrm{T}}^{\mathrm{jet}}$ interval (right). The systematic uncertainties due to JES, JER, unfolding, MC non-closure and tracking are shown along with the total systematic uncertainty from all sources.

The uncertainties related to the track reconstruction and selection originate from several sources. Uncertainties related to the rate of secondary and fake tracks, the material description in the simulation, and the track's transverse momentum were obtained from studies in data and simulation described in Ref. [47]. The systematic uncertainty in the secondary-track and fake-track rate is 30% in pp collisions and 50% in $p+\mathrm{Pb}$. The contamination by secondary and fake tracks is at most 2%, the resulting uncertainty in the fragmentation functions is at most 1%. The sensitivity of the tracking efficiency to the description of the inactive material in the MC samples is evaluated by varying the material description. This uncertainty is between 0.5 and 2% (depending on track η) in the track p_{T} range used in the analysis. Uncertainty in the tracking efficiency due to the high local track density in the cores of jets is 0.4% [48] for all $p_{\mathrm{T}}^{\mathrm{jet}}$ selections in this analysis. The uncertainty due to the track selection criteria is evaluated by repeating the analysis with an additional requirement on the significance of the distance of closest approach of the track to the primary vertex. This uncertainty affects both the track reconstruction efficiency and the rate of secondary and fake tracks. The resulting uncertainty typically varies from 1% at low track p_{T} and low z to 5% at high track p_{T} and high z. The systematic uncertainties in the fragmentation functions due to the parameterization of the efficiency corrections is less than 1%. An additional uncertainty takes into account a possible residual misalignment of the tracking detectors in pp data-taking. The alignment in this data was checked *in situ* with $Z \to \mu^+\mu^-$

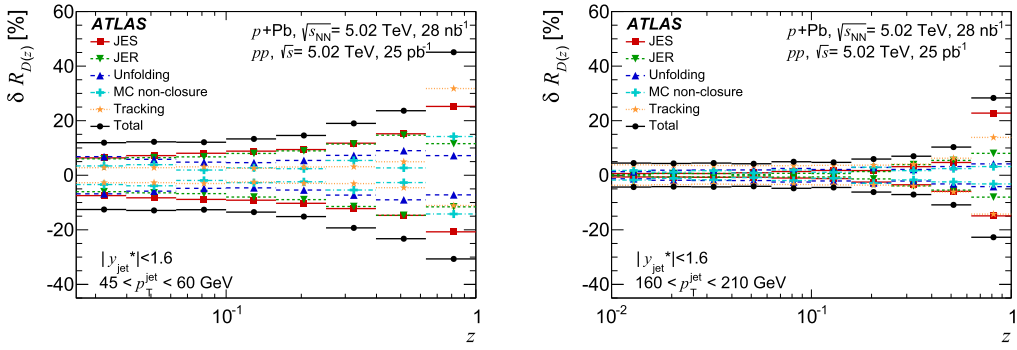

Fig. 4. Summary of the systematic uncertainties for $R_{D(z)}$ ratios, for jets in the 45–60 GeV p_{T} interval (left) and in the 160–210 GeV p_{T} interval (right). The systematic uncertainties due to JES, JER, unfolding, MC non-closure and tracking are shown along with the total systematic uncertainty from all sources.

events, and thus a track-p_{T}dependent uncertainty arises from the finite size of this sample. The resulting uncertainties in the fragmentation functions are typically smaller than 1% except at large z where they are as large as 4%. Finally, the track-to-particle matching requirements are varied. This variation affects the track reconstruction efficiency, the track momentum resolution, and the rate of secondary and fake tracks. The resulting uncertainties in the fragmentation functions are smaller than 1%. After deriving new response matrices and efficiency corrections, the resulting systematic uncertainty in the fragmentation functions is found to be less than 0.5%. The tracking uncertainties shown in Figs. 2 and 3 include all the above explained track-related systematic uncertainties added in quadrature.

The correlations between the various systematic components in the two collision systems are considered when taking the ratios of $p+\mathrm{Pb}$ to pp fragmentation functions. For the JES uncertainty, each source of uncertainty is classified as either correlated or uncorrelated between the two systems depending on its origin. The JER, unfolding and MC non-closure uncertainties are taken to be uncorrelated. For the tracking-related uncertainties the variation in the selection requirements, tracking in dense environments, secondary-track and fake-track rates, and parameterization of the efficiency corrections are taken as uncorrelated. The first three of these are conservatively considered as uncorrelated because the tracking system was augmented with the IBL and the tracking algorithm changed between the $p+\mathrm{Pb}$ and pp data-taking periods. The uncertainties due to the track-to-particle matching and the inactive material in the MC samples are taken as correlated between $p+\mathrm{Pb}$ and pp collisions. For the correlated uncertainties the ratios are re-evaluated applying the variation to both collision systems; the resulting variations of the ratios from their central values is used as the correlated systematic uncertainty. The total systematic uncertainties in the $R_{D(z)}$ and $R_{D(p_{\mathrm{T}})}$ distributions are shown in Figs. 4 and 5, respectively, for two $p_{\mathrm{T}}^{\mathrm{jet}}$ intervals.

7. Results

The $D(z)$ and $D(p_{\mathrm{T}})$ distributions in both collision systems are shown in Figs. 6 and 7, respectively. Fig. 8 compares the $D(z)$ distribution in pp collisions at 5.02 TeV to the predictions from three event generators (PYTHIA6, PYTHIA8, and HERWIG++) using the parameter-value tunes and PDF sets described in Section 3 for the six $p_{\mathrm{T}}^{\mathrm{jet}}$ intervals. The PYTHIA8 generator

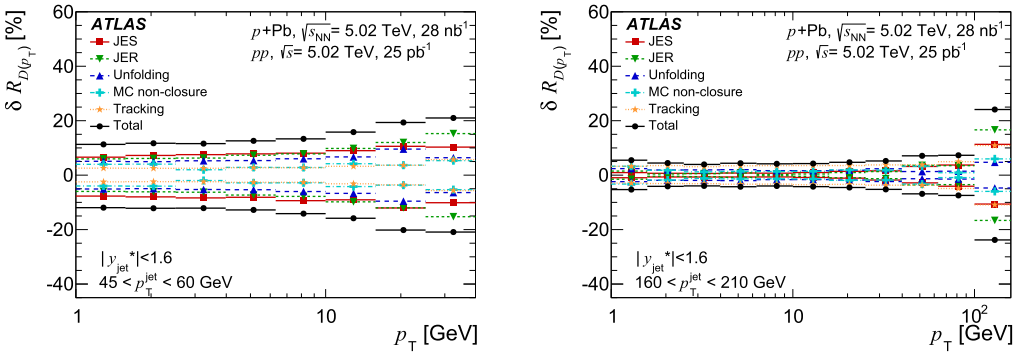

Fig. 5. Summary of the systematic uncertainties for $R_{D(p_{\mathrm{T}})}$ ratios, for jets in the 45–60 GeV p_{T} interval (left) and in the 160–210 GeV p_{T} interval (right). The systematic uncertainties due to JES, JER, unfolding, MC non-closure and tracking are shown along with the total systematic uncertainty from all sources.

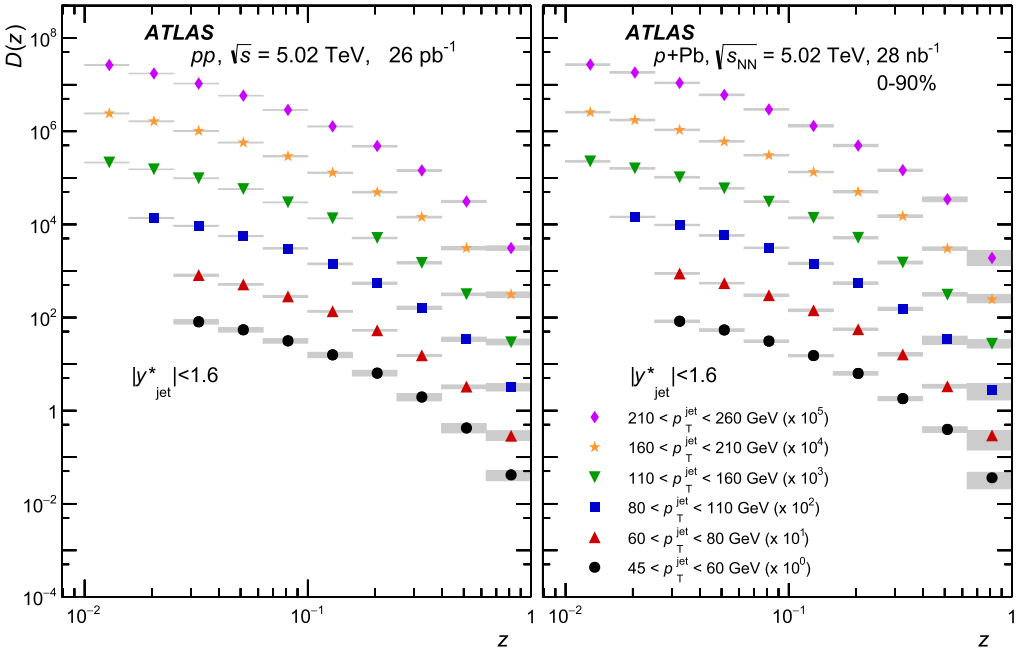

Fig. 6. Fragmentation functions as a function of the charged particle z in pp (left) and $p+\mathrm{Pb}$ collisions (right) for the $p_{\mathrm{T}}^{\mathrm{jet}}$ intervals used in this analysis. The fragmentation functions in both collision systems are offset by multiplicative factors for clarity as noted in the legend. The statistical uncertainties are shown as error bars and the systematic uncertainties are shown as shaded boxes. In many cases the statistical uncertainties are smaller than the marker size.

provides the best description of the data, generally agreeing within about 5 to 10% over the kinematic range used here. PYTHIA6 agrees within approximately 25% when compared to the data and HERWIG++ agrees within approximately 20% except for the highest z region, where there are some larger deviations. Similar agreement with PYTHIA6 and HERWIG++ generators with different tunes than used in this analysis was reported by ATLAS in the measurement of

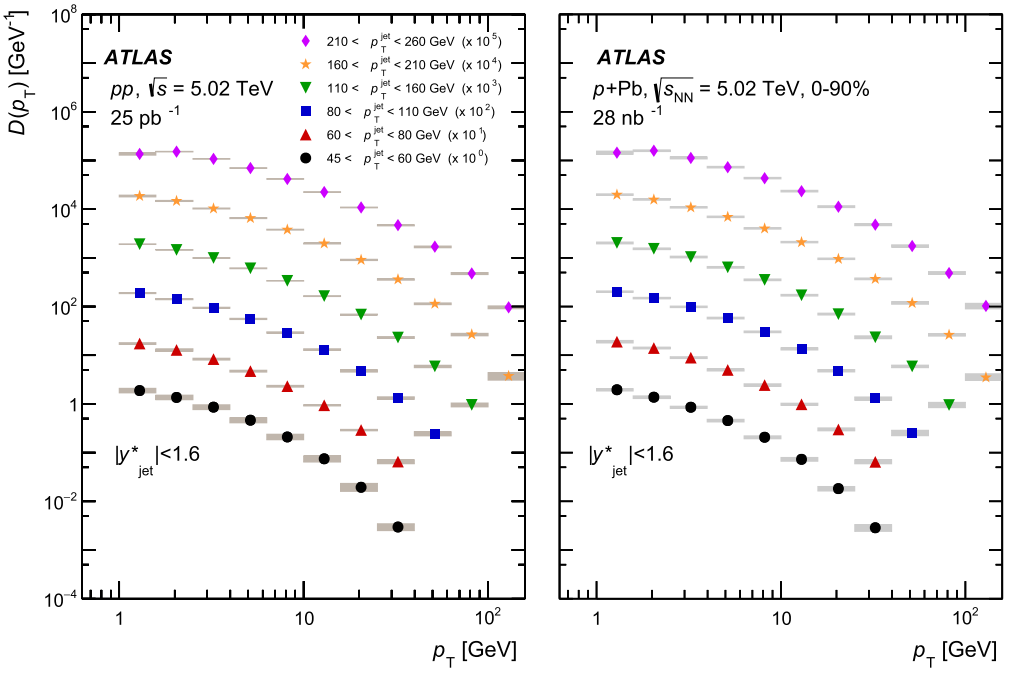

Fig. 7. Fragmentation functions as a function of the charged particle p_{T} in pp (left) and $p+\mathrm{Pb}$ collisions (right) for the $p_{\mathrm{T}}^{\mathrm{jet}}$ intervals used in this analysis. The fragmentation functions in both collision systems are offset by multiplicative factors for clarity as noted in the legend. The statistical uncertainties are shown as error bars and the systematic uncertainties are shown as shaded boxes. In many cases the statistical uncertainties are smaller than the marker size.

fragmentation functions in 7 TeV pp collisions [49]. The tunes of PYTHIA6 and PYTHIA8 used here include the results from that measurement.

Fig. 9 shows the pp fragmentation functions compared to two theoretical calculations. These predictions use a slightly different definition of z compared to the definition used in this measurement. This can introduce a difference between the fragmentation functions of approximately 1%. The calculation in Refs. [50,51] provides fragmentation functions with next-to-leading-order (NLO) accuracy as well as a resummation of logarithms in the jet cone size. The calculation in Ref. [52] is at NLO and uses the approximation that the jet cone is narrow. For the parton-to-charged-hadron fragmentation functions, both calculations use DSS07 fragmentation functions [53]. The uncertainties in the theoretical calculation are not estimated, including the uncertainty in DSS07, which is common to both calculations. The calculations are systematically higher than the data and generally agree within 20–30%. Larger deviations are observed at the low and high z regions. The DSS07 fragmentation functions have a minimum z of 0.05 and the calculations use extrapolated fragmentation functions in the region below $z = 0.05$.

Figs. 10 and 11 show the ratios of fragmentation functions in $p+\mathrm{Pb}$ collisions to those in pp collisions, as a function of z and p_{T} respectively for $p_{\mathrm{T}}^{\mathrm{jet}}$ from 45 to 260 GeV. Over the kinematic range selected here, the $R_{D(z)}$ and $R_{D(p_{\mathrm{T}})}$ distributions show deviations from unity of up to approximately 5% (up to 10% for 60–80 GeV jet selections) for $z < 0.1$ and $p_{\mathrm{T}} < 10$ GeV. The deviations are larger than the reported systematic uncertainties by at most a couple of percent and always less than 1.5σ of the systematic uncertainties. At higher z and

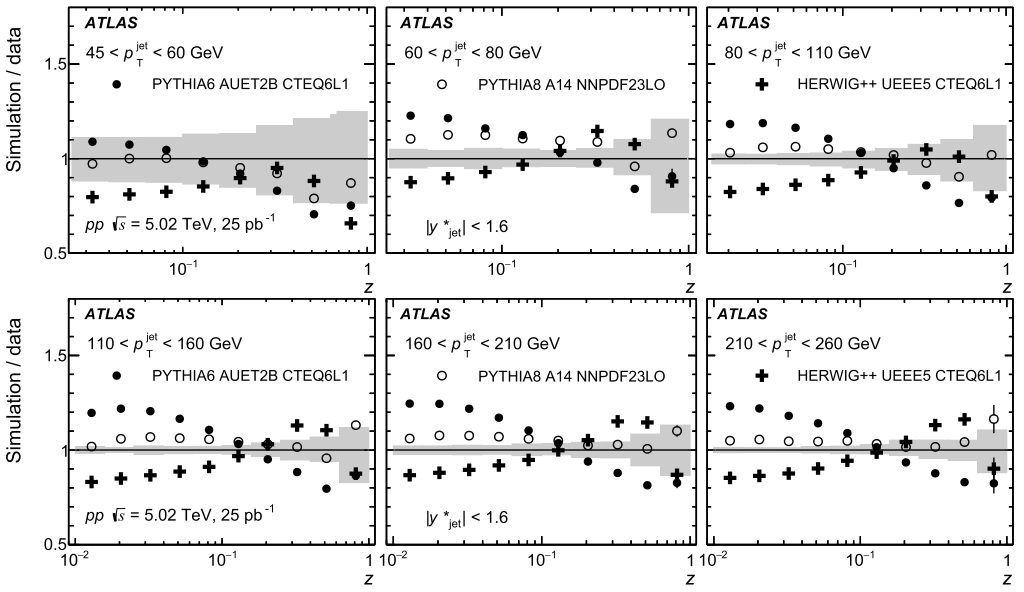

Fig. 8. Ratios of the particle-level $D(z)$ distributions from PYTHIA6, PYTHIA8, and HERWIG++ to the unfolded pp data for the six $p_{\mathrm{T}}^{\mathrm{jet}}$ intervals used in this analysis. The statistical uncertainties are shown as error bars and the systematic uncertainties in the data are shown as the shaded region around unity. In many cases the statistical uncertainties are smaller than the marker size.

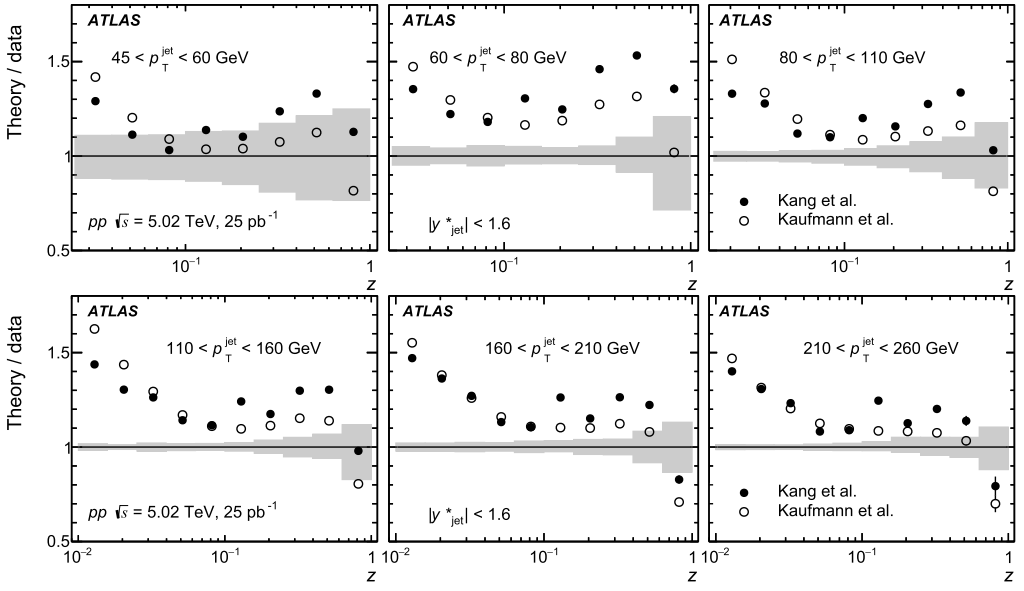

Fig. 9. Ratios of theoretical calculations from Refs. [50,51] (solid points) and Ref. [52] (open points) to the unfolded pp $D(z)$ distributions for the six $p_{\mathrm{T}}^{\mathrm{jet}}$ intervals used in this analysis. The statistical uncertainties are shown as error bars and the systematic uncertainties in the data are shown as the shaded region around unity. The uncertainties in the theoretical calculations are not shown.

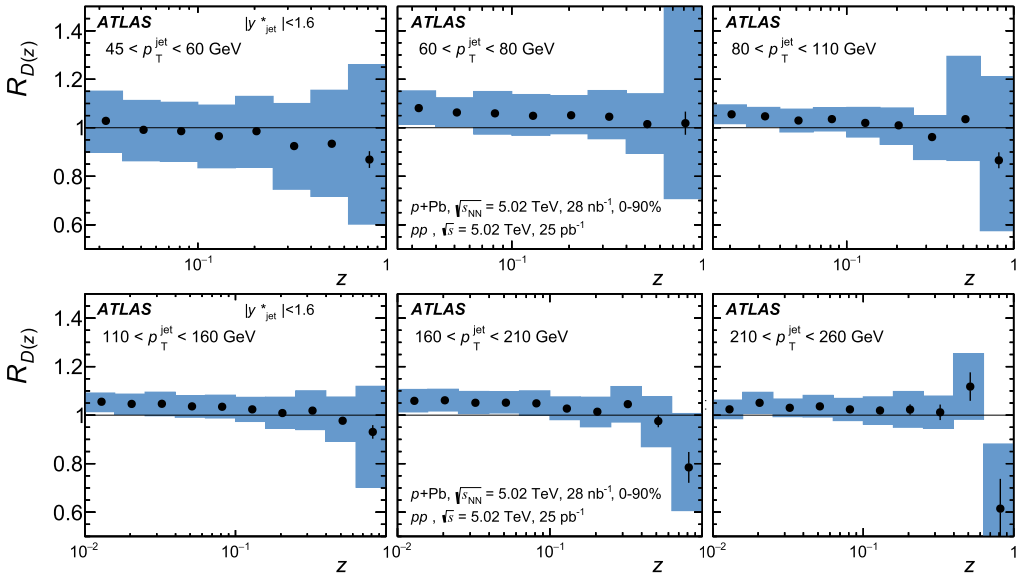

Fig. 10. Ratios of fragmentation functions as a function of the charged particle z in $p+\mathrm{Pb}$ collisions to those in pp collisions for the six $p_{\mathrm{T}}^{\mathrm{jet}}$ intervals. The statistical uncertainties are shown as error bars and the total systematic uncertainties are shown as shaded boxes.

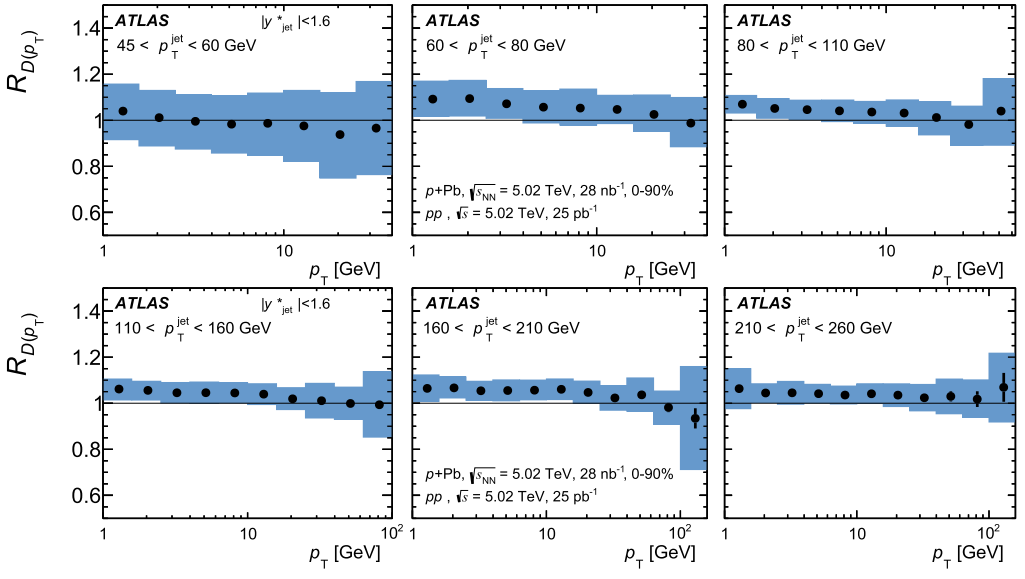

Fig. 11. Ratios of fragmentation functions as a function of the charged particle p_{T} in $p+\mathrm{Pb}$ collisions to those in pp collisions for the six $p_{\mathrm{T}}^{\mathrm{jet}}$ intervals. The statistical uncertainties are shown as error bars and the total systematic uncertainties are shown as shaded boxes.

p_{T} values the ratios are consistent with unity. At the highest z points for the 160–210 GeV and 210–260 GeV jet selections, deviations from unity of approximately 0.9σ and 1.3σ of combined statistical and systematic uncertainties, respectively, are observed. This is not observed in the $D(p_{\mathrm{T}})$ distributions. In most $p_{\mathrm{T}}^{\mathrm{jet}}$ bins there is a slight decrease of the central values of $R_{D(z)}$ and $R_{D(p_{\mathrm{T}})}$ with increasing z and p_{T}; however the size of the effect is smaller than the systematic uncertainties.

8. Summary

This paper presents the first measurement of the jet charged-particle fragmentation functions in a $p+\mathrm{A}$ collisions system. The jet charged-particle fragmentation functions are reported for $|y^*_{\mathrm{jet}}| < 1.6$ and $p_{\mathrm{T}}^{\mathrm{jet}}$ from 45 to 260 GeV in $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV $p+\mathrm{Pb}$ and pp collisions with the ATLAS detector at the LHC. The measurement utilizes 28 nb^{-1} of $p+\mathrm{Pb}$ data and 26 pb^{-1} of pp data. The pp fragmentation functions are compared to predictions from the PYTHIA6, PYTHIA8 and HERWIG++ generators. The generators show deviations from the pp data of up to approximately 25%, depending on z and the choice of generator. PYTHIA8 with the A14 tune and NNPDF23LO PDF set matches the data most closely. The pp $D(z)$ distributions are also compared to two theoretical calculations based on next-to-leading-order QCD and DSS07 fragmentation functions. The calculations are systematically higher than the data and agree generally within 20–30%, with larger deviations at small and large values of z. These measurements help constrain jet fragmentation in pp collisions. The ratios of fragmentation functions in $p+\mathrm{Pb}$ collisions to those in pp collisions show no evidence for modification of jet fragmentation in $p+\mathrm{Pb}$ collisions. This measurement provides new constraints on the modifications to jets in $p+\mathrm{Pb}$ collisions at the LHC and is directly relevant to the current investigations into the properties of small collision systems. Finally, these measurements of jet fragmentation functions for different intervals of jet transverse momentum provide necessary baseline measurements for quantifying the effects of the quark-gluon plasma in Pb + Pb collisions.

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