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Measurement of inclusive jet charged-particle fragmentation functions in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector

ATLAS Collaboration *

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A B S T R A C T

Measurements of charged-particle fragmentation functions of jets produced in ultra-relativistic nuclear collisions can provide insight into the modification of parton showers in the hot, dense medium created in the collisions. ATLAS has measured jets in $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions at the LHC using a data set recorded in 2011 with an integrated luminosity of 0.14 nb$^{-1}$. Jets were reconstructed using the anti-$k_t$ algorithm with distance parameter values $R = 0.2, 0.3, 0.4$. Distributions of charged-particle transverse momentum and longitudinal momentum fraction are reported for seven bins in collision centrality for $R = 0.4$ jets with $p_T^\text{ch} > 100$ GeV. Commensurate minimum $p_T$ values are used for the other radii. Ratios of fragment distributions in each centrality bin to those measured in the most peripheral bin are presented. These ratios show a reduction of fragment yield in central collisions relative to peripheral collisions at intermediate $z$ values, $0.04 \leq z \leq 0.2$, and an enhancement in fragment yield for $z \lesssim 0.04$. A smaller, less significant enhancement is observed at large $z$ and large $p_T$ in central collisions.

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1. Introduction

Collisions between lead nuclei at the LHC are thought to produce a quark–gluon plasma (QGP), a form of strongly interacting matter in which quarks and gluons become locally deconfined. One predicted consequence of QGP formation is the “quenching” of jets generated in hard-scattering processes during the initial stages of the nuclear collisions [1]. Jet quenching refers, collectively, to a set of possible modifications of parton showers by the QGP through interactions of the constituents of the shower with the colour charges in the plasma [2,3]. In particular, quarks and gluons in the shower may be elastically or inelastically scattered resulting in both deflection and energy loss of the constituents of the shower. The deflection and the extra radiation associated with inelastic processes may broaden the parton shower and eject partons out of an experimental jet cone [4–9]. As a result, jet quenching can potentially both soften the spectrum of the momentum of hadrons inside the jet and reduce the total energy of the reconstructed jet. A complete characterization of the effects of jet quenching therefore requires measurements of both the single-jet suppression and the jet fragmentation distributions.

Observations of modified dijet asymmetry distributions [10–12], modified balance-jet transverse momentum ($p_T$) distributions in $\gamma + \text{jet}$ events [13], and suppressed inclusive jet yield in Pb+Pb collisions at the LHC [14,15] are consistent with theoretical calculations of jet quenching. However, it has been argued that those measurements do not sufficiently discriminate between calculations that make different assumptions regarding the relative importance of the contributions described above [16]. Based on the above arguments, theoretical analyses are incomplete without experimental constraints on the theoretical description of jet fragmentation distributions.

This Letter presents measurements of charged-particle jet fragmentation functions in $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions using 0.14 nb$^{-1}$ of data recorded in 2011. The jets used in the measurements were reconstructed with the anti-$k_t$ [17] algorithm using distance parameter values $R = 0.2, 0.3, 0.4$. Results are presented for the charged-particle transverse momentum ($p_T^\text{ch}$) and longitudinal momentum fraction ($z \equiv p_T^\text{ch} \cdot z^{\text{jet}} / p_T^{\text{jet}}$) distributions,

$$D(p_T) \equiv \frac{1}{N_{\text{jet}}} \frac{dN_{\text{ch}}}{dp_T^\text{ch}}, \quad (1)$$

$$D(z) \equiv \frac{1}{N_{\text{jet}}} \frac{dN_{\text{ch}}}{dz}, \quad (2)$$

of charged particles with $p_T^\text{ch} > 2$ GeV produced within an angular range $\Delta R = 0.4$ of the reconstructed jet directions for jets with $p_T^{\text{jet}} > 85$, 92, and 100 GeV for $R = 0.2$, 0.3, and 0.4, respectively. Here, $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$ where $\Delta \phi$ ($\Delta \eta$) is the difference in azimuthal angles (pseudorapidities) between the charged particles.
particle and jet directions. The $p_T^{\text{jet}}$ thresholds for the three $R$ values were chosen to match the $R$-dependence of the measured transverse momentum of a typical jet. For simplicity, the terms “fragmentation functions” are used to describe the distributions defined in Eq. (2) with the understanding that $D(z)$ is different from a theoretical fragmentation function, $D(z, Q^2)$, calculated using unquenched jet energies and with no restriction on the angles of particles with respect to the jet axis. Earlier measurements by CMS of jet fragmentation functions [18] in Pb+Pb collisions at the LHC show no significant modification, but the uncertainties on that measurement were not sufficient to exclude modifications at the level of $\sim 10\%$. CMS recently released a new result [19] using higher statistics data from 2011 that show fragmentation function modifications which are consistent with the results presented in this Letter.

### 2. Experimental setup

The measurements presented in this Letter were performed using the ATLAS calorimeter, inner detector, muon spectrometer, trigger, and data acquisition systems [20]. The ATLAS calorimeter system consists of a 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 and has a $\Delta Y \times \Delta \phi$ granularity of $0.1 \times 0.1$ for $|\eta| < 2.5$ and $0.2 \times 0.2$ for $2.5 < |\eta| < 4.9$. The EM calorimeters are segmented longitudinally in shower depth into three compartments with 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 middle sampling layer, which typically has the largest energy deposit in EM showers, has a granularity of $0.025 \times 0.025$ over $|\eta| < 2.5$.

The inner detector [21] measures charged particles within the pseudorapidity interval $|\eta| < 2.5$ using a combination of silicon pixel detectors, silicon microstrip detectors (SCT), and a strawtube transition radiation tracker (TRT), all immersed in a 2 T axial magnetic field. All three detectors are composed of a barrel and two symmetrically placed end-cap sections. The pixel detector is composed of 3 layers of sensors with nominal feature size $50 \mu \text{m} \times 400 \mu \text{m}$. The SCT barrel section contains 4 layers of modules with $80 \mu \text{m}$ pitch sensors on both sides, while each end-cap consists of nine layers of double-sided modules with radial strips having a mean pitch of $80 \mu \text{m}$. 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 straw interlaced with fibres in the barrel (end-cap). Charged particles with $p_T^{\text{ch}} > 0.5 \text{ GeV}$ typically traverse three layers of pixel sensors, four layers of double-sided SCT sensors, and, in the case of $|\eta| < 2.0$, 36 TRT straws.

Minimum bias Pb+Pb collisions were identified using measurements from the zero degree calorimeters (ZDCs) and the minimum-bias trigger scintillator (MBTS) counters [20]. The ZDCs are located symmetrically at $z = \pm 140 \text{ m}$ and cover $|\eta| > 8.3$.

In Pb+Pb collisions the ZDCs measure primarily “spectator” neutrons, which originate from the incident nuclei and do not interact hadronically. The MBTS detects charged particles over $2.1 < |\eta| < 3.9$ using two counters placed at $z = \pm 3.6 \text{ m}$. MBTS counters are divided into 16 modules with 8 different positions in azimuth and covering 2 different $|\eta|$ intervals. Each counter provides measurement of both the pulse heights and arrival times of ionization energy deposits.

Events used in this analysis were selected for recording by a combination of Level-1 minimum-bias and High Level Trigger (HLT) jet triggers. The Level-1 trigger required a total transverse energy measured in the calorimeter of greater than 10 GeV. The HLT jet trigger ran the offline Pb+Pb jet reconstruction algorithm, described below, for $R = 0.2$ jets except for the application of the final hadronic energy scale correction. The HLT trigger selected events containing an $R = 0.2$ jet with transverse energy $E_T > 20 \text{ GeV}$.

### 3. Event selection and data sets

This analysis uses a total integrated luminosity of $0.14 \text{ nb}^{-1}$ of Pb+Pb collisions recorded by ATLAS in 2011. Events selected by the HLT jet trigger were required to have a reconstructed primary vertex and a time difference between hits in the two sides of the MBTS detector of less than 3 ns. The primary vertices were reconstructed from charged-particle tracks with $p_T^{\text{ch}} > 0.5 \text{ GeV}$. The tracks were reconstructed from hits in the inner detector using the ATLAS track reconstruction algorithm described in Ref. [22] with settings optimized for the high hit density in heavy-ion collisions [23]. A total of 14.2 million events passed the described selections.

The centrality of Pb+Pb collisions was characterized by $\sum E_T^{\text{Cal}}$, the total transverse energy measured in the forward calorimeters [23]. Jet fragmentation functions were measured in seven centrality bins defined according to successive percentiles of the $\sum E_T^{\text{Cal}}$ distribution ordered from the most central to the most peripheral collisions: $0$–$10\%$, $10$–$20\%$, $20$–$30\%$, $30$–$40\%$, $40$–$50\%$, $50$–$60\%$, and $60$–$80\%$. The percentiles were defined after correcting the $\sum E_T^{\text{Cal}}$ distribution for a 2% minimum-bias trigger inefficiency that affects the most peripheral events which are not included in this analysis.

The performance of the ATLAS detector and offline analysis in measuring jets and charged particles in the environment of Pb+Pb collisions was evaluated using a large Monte Carlo (MC) event sample obtained by overlaying simulated [24] PYTHIA [25] pp hard-scattering events at $\sqrt{s} = 2.76 \text{ TeV}$ onto 1.2 million minimum-bias Pb+Pb events recorded in 2011. The same number of PYTHIA events was produced for each of five intervals of $p_T$, the transverse momentum of outgoing partons in the $2 \to 2$ hard-scattering, with boundaries 17, 35, 70, 140, 280, and $560 \text{ GeV}$. The detector response to the PYTHIA events was simulated using Geant4 [26], and the simulated hits were combined with the data from the minimum-bias Pb+Pb events to produce 1.2 million overlaid events for each $p_T$ interval.

### 4. Jet and charged-particle analysis

Charged particles included in the fragmentation measurements were required to have at least two hits in the pixel detector, including a hit in the first pixel layer if the track trajectory makes such a hit expected, and seven hits in the silicon microstrip detector. In addition, the transverse ($d_0$) and longitudinal ($z_0 \sin \theta$) impact parameters of the tracks measured with respect to the primary vertex were required to satisfy $|d_0|/\sigma_{d_0} < 3$ and $|z_0 \sin \theta|/\sigma_{z_0} < 3$, where $\sigma_{d_0}$ and $\sigma_{z_0}$ are uncertainties on $d_0$ and $z_0 \sin \theta$, respectively, obtained from the track-fit covariance matrix.
Jets were reconstructed using the techniques described in Ref. [14], which are briefly summarized here.

The anti-$k_T$ algorithm was first run in four-momentum recombination mode, on $\Delta R = 0.1 \times 0.1$ logical towers and for three values of the anti-$k_T$ distance parameter, $R = 0.2, 0.3$, and 0.4. The tower kinematics were obtained by summing electromagnetic-scale energies of calorimeter cells within the tower boundaries. Then, an iterative procedure was used to estimate a layer- and $\eta$-dependent underlying event (UE) energy density while excluding actual jets from that estimate. The UE energy was subtracted from each calorimeter cell within the towers included in the reconstructed jet. The correction takes into account a $\cos2\phi$ modulation of the calorimeter response due to elliptic flow of the medium [23] which is estimated by measurement of the amplitude of that modulation in the calorimeter. The final jet kinematics were calculated via a four-momentum sum of all (assumed massless) cells contained within the jets using subtracted $E_T$ values. A correction was applied to the reconstructed jet to account for jets not excluded or only partially excluded from the UE estimate. Then, a final jet $\eta$- and $E_T$-dependent hadronic energy scale calibration factor was applied.

After the reconstruction, additional selections were applied for the purposes of this analysis. "UE jets" generated by fluctuations in the underlying event, were removed using techniques described in Ref. [14].

To prevent neighbouring jets from distorting the measurement of the fragmentation functions, jets were required to be isolated. The isolation cut required that there be no other jet within $\Delta R = 1$ having $p_T > p_T^{iso}$ where $p_T^{iso}$, the isolation threshold, is set to half of the analysis threshold for each $R$ value, $p_T^{iso} = 42.5, 46$, and $50$ GeV for $R = 0.2, 0.3$, and 0.4, respectively. To prevent muons from semileptonic heavy-flavour decays from influencing the measured fragmentation functions, all jets with reconstructed muons having $p_T > 4$ GeV within a cone of size $\Delta R = 0.4$ were excluded from the analysis. To prevent inactive regions in the calorimeters from producing artificial high $z$ fragments, jets were required to have more than 90% of their energy contained within fully functional regions of the calorimeter. Finally, all jets included in the analysis were required to match HLT jets reconstructed with transverse momenta greater than the trigger threshold of 20 GeV. The HLT jets were found to be fully efficient for the jet kinematic selection used in this analysis. Table 1 shows the impact of the cuts on the number of measured jets in central (0–10%) and peripheral (60–80%) collisions. All these cuts together retain more than 96% of all jets.

### Table 1

| Cut description | $N_{jet}$ | $0$–$10\%$ | $60$–$80\%$ |
|----------------|----------|-------------|-------------|
| All jets       | 41 191   | 2579        |             |
| UE jet rejection | 41 116 | 2570        |             |
| Isolation      | 40 986   | 2554        |             |
| Muon rejection | 40 525   | 2523        |             |
| Inactive area exclusion | 39 548 | 2458        |             |
| Trigger jet match | 39 548 | 2458        |             |

5. Jet and track reconstruction performance

The performance of the ATLAS detector and analysis procedures in measuring jets was evaluated from the MC sample using the procedures described in Ref. [14]. Reconstructed MC jets were matched to “truth” jets obtained by separately running the anti-$k_T$ algorithm on the final-state PYTHIA particles for the three jet $R$ values used in this analysis. For the jet fragmentation measurements, the most important aspect of the jet performance is the jet energy resolution (JER). For jet energies $>100$ GeV, the JER in central (0–10%) collisions for $R = 0.4$ jets has comparable contributions from UE fluctuations and “intrinsic” resolution of the calorimetric jet measurement. For peripheral collisions and $R = 0.2$ jets, the intrinsic calorimeter resolution dominates the JER. The value of JER evaluated for jets with $p_T = 100$ GeV in 0–10% collisions is 0.18, 0.15, and 0.13 for $R = 0.4$, $R = 0.3$, and $R = 0.2$ jets, respectively.

The combination of the finite JER and the steeply falling $p_T$ spectrum produces a net migration of jets from lower $p_T$ to higher $p_T$ values (hereafter referred to as “upfeeding”) such that a jet reconstructed with a given $p_T^{rec}$ corresponds, on average, to a lower truth-jet $p_T$, $p_T^{true}$. The relationship between $p_T^{true}$ and $p_T^{rec}$ was evaluated from the MC data set for the different centrality bins and three $R$ values used in this analysis. For the jet $p_T^{rec}$ values used in this analysis, that relationship is well described by a linear dependence,

$$p_T^{true} = \alpha p_T^{rec} + \beta. \quad (3)$$

Sample values for $\alpha$ and $\beta$ and the resulting $\langle p_T^{true} \rangle$ values for $R = 0.2$ and $R = 0.4$ jets in peripheral and central collisions are listed in Table 2. The extracted relationships between $p_T^{true}$ and $\langle p_T^{true} \rangle$ will be used in the fragmentation analysis to correct for the average shift in the measured jet energy.

MC studies indicate that the efficiency for PYTHIA jets to be reconstructed and to pass UE jet rejection exceeds 98% for $p_T^{jet} > 60$ GeV in the 0–10% centrality bin. For kinematic selection of jets used in this study, the jet reconstruction was fully efficient.

The efficiency for reconstructing charged particles within jets in Pb+Pb collisions was evaluated using the MC sample. Fig. 1 shows comparisons of distributions of four important track-quality variables between data and MC simulation for reconstructed tracks over a narrow $p_T^{ch}$ interval, $5 < p_T^{ch} < 7$ GeV, to minimize the impact of differences in MC and data charged-particle $p_T^{ch}$ distributions. The ratios of the data to MC distributions also shown in the figure indicate better than 1% agreement in the $\eta$ dependence of the average number of pixel and SCT hits associated with the tracks. The distributions of $d_0$ and $\cos\theta$ agree to $<10\%$ except in the tails of the distributions, which contribute a negligible fraction of the distribution. For the purpose of evaluating the track reconstruction performance and for the evaluation of response matrices that are used in the unfolding (described below), the reference “truth” particles were taken from the set of final-state PYTHIA charged particles. These were matched to re-

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1. Final-state PYTHIA particles are defined as all generated particles with lifetimes longer than $0.3 \cdot 10^{-10}$ s originating from the primary interaction or from subsequent decay of particles with shorter lifetimes.
constructed charged particles using associations between detector hits and truth tracks recorded by the ATLAS Geant4 simulations. Truth particles for which no matching reconstructed particle was found were considered lost due to inefficiency.

The charged-particle reconstruction efficiency, $\varepsilon(\pT, \eta)$, was evaluated separately in each of the seven centrality bins used in this analysis for truth particles within $\Delta R = 0.4$ of $R = 0.4$ truth jets having $pT^{\text{true}} > 100$ GeV. Fig. 2 shows the efficiency as a function of truth-particle $pT$ averaged over $|\eta| < 1$ (top) and $1 < |\eta| < 2.5$ (bottom) for the 0–10% and 60–80% centrality bins. For $pT < 8$ GeV, $\varepsilon(\pT, \eta)$ was directly evaluated using fine bins in $pT$ and $\eta$. For $pT > 8$ GeV the $pT$ dependence of the efficiencies were parameterized separately in the two pseudorapidity intervals shown in Fig. 2 using a functional form that describes trends at low $pT$ as well as at high $pT$. An example of the resulting parameterizations is shown by the solid curves in Fig. 2. A centrality-dependent systematic uncertainty in the parameterized efficiencies, shown by the shaded bands in Fig. 2, was evaluated based on both the uncertainties in the parameterization and on observed variations of the efficiency with $pT$, which largely result from loss of hits in the SCT at higher detector occupancy. Thus, the systematic uncertainty in the 60–80% centrality bin is small because no significant variation of the efficiency is observed at low detector occupancy, while the uncertainties are largest for the 0–10% centrality bin with the largest detector occupancies.

The efficiencies shown in Fig. 2 decrease by about 12% between the $|\eta| < 1$ interval covered by the SCT barrel and the $1 < |\eta| < 2.5$ interval covered primarily by the SCT end-cap. More significant localized drops in efficiency of about 20% are observed over $1 < |\eta| < 1.2$ and $2.3 < |\eta| < 2.5$ corresponding to the transition between the SCT barrel and end-cap and the detector edge respectively. To account for this and other localized variations of the high $pT$ reconstruction efficiency with pseudorapidity, the parameterizations in Fig. 2 for $pT > 8$ GeV are multiplied by an $\eta$-dependent factor evaluated in intervals of 0.1 units to produce $\varepsilon(\pT, \eta)$.

6. Fragmentation functions and unfolding

Jets used for the fragmentation measurements presented here were required to have $pT^{\text{jet}} > 85$, 92 and 100 GeV for $R = 0.2$, 0.3, and 0.4 jets, respectively. The jet thresholds for $R = 0.3$ and $R = 0.2$ jets represent the typical energy measured with the smaller jet radii for an $R = 0.4$ jet with $pT = 100$ GeV. Jets were also required to have either $0 < |\eta| < 1$ or $1.2 < |\eta| < 1.9$. The restriction of the measurement to $|\eta| < 1.9$ avoids the region at the detector edge with reduced efficiency ($|\eta| > 2.3$). The exclusion of the range $1 < |\eta| < 1.2$ removes from the measurement jets whose large-$z$ fragments, which are typically collinear with the jet axis, would be detected in the lower-efficiency $\eta$ region spanning the gap between SCT barrel and end-cap. While this exclusion does
with a real jet in the event and was excluded from the UE background determination. The threshold of 6 GeV was chosen to be high enough to avoid bias of the UE $p_T^{\text{ch}}$ distribution.

The resulting per-jet UE charged-particle yields, $\frac{dN_{\text{ch}}^{\text{UE}}}{dp_T^{\text{ch}}}$ were evaluated over $2 < p_T^{\text{ch}} < 6$ GeV as a function of $p_T^{\text{ch}}$, $R$, and $|\eta|$, averaged over all cones in all events within a given centrality bin according to:

$$\frac{dN_{\text{ch}}^{\text{UE}}}{dp_T^{\text{ch}}} = \frac{1}{N_{\text{cone}}} \frac{\Delta N_{\text{cone}}^{\text{ch}}(p_T^{\text{ch}}, R, |\eta|)}{\Delta p_T^{\text{ch}}}.$$  

(5)

Here $N_{\text{cone}}$ represents the number of background cones having a jet of a given radius above the corresponding $p_T^{\text{jet}}$ threshold, and $\Delta N_{\text{cone}}^{\text{ch}}$ represents the number of charged particles in a given $p_T^{\text{ch}}$ bin in all such cones evaluated for jets with a given $p_T^{\text{jet}}$ and $|\eta|$. Not shown in Eq. (5) is a correction factor that was applied to each background cone to correct for the difference in the average UE-particle yield at a given $p_T^{\text{ch}}$ between the $\eta$ position of the cone and $|\eta|$, and a separate correction factor to account for the difference in the elliptic flow modulation at the $\phi$ position of the UE cone and $\phi$. That correction was based on a parameterization of the $p_T^{\text{ch}}$ and centrality dependence of previously measured elliptic flow coefficients, $v_2$ [23].

By evaluating the UE contribution only from events containing jets included in the analysis, the background automatically has the correct distribution of centralities within a given centrality bin. The $dN_{\text{ch}}^{\text{UE}}/dp_T^{\text{ch}}$ is observed to be independent of $p_T^{\text{jet}}$ both in the data and MC simulation. That observation excludes the possibility that the upfeeding of jets in $p_T^{\text{ch}}$ due to the finite JER could induce a dependence of the UE on jet $p_T$. However, such upfeeding was observed to induce in the MC events a $p_T^{\text{jet}}$-independent, but centrality-dependent mismatch between the extracted $dN_{\text{ch}}^{\text{UE}}/dp_T^{\text{ch}}$ and the actual UE contribution to reconstructed jets. That mismatch was found to result from intrinsic correlations between the charged-particle density in the UE and the MC $p_T^{\text{jet}}$ error, $\Delta p_T^{\text{jet}} = p_T^{\text{jet,rec}} - p_T^{\text{jet,true}}$. In particular, jets with positive (negative) $\Delta p_T^{\text{jet}}$ are found to have an UE contribution larger (smaller) than jets with $\Delta p_T^{\text{jet}} \sim 0$. Due to the net upfeeding on the falling jet spectrum, the selection of jets above a given $p_T^{\text{jet}}$ threshold causes the UE contribution to be larger than that estimated from the above-described procedure. The average fractional mismatch in the estimated UE background was found to be independent of $p_T^{\text{ch}}$ and to vary with centrality by factors between 1.04–1.08, 1.07–1.10, and 1.12–1.15 for $R = 0.2$, 0.3, and 0.4, respectively. The measured $dN_{\text{ch}}^{\text{UE}}/dp_T^{\text{ch}}$ values in the data were corrected by these same factors before being subtracted.

Two different sets of charged-particle fragmentation distributions were measured for each centrality bin and $R$ value:

$$D^{\text{meas}}(p_T) = \frac{1}{N_{\text{jet}}} \frac{1}{\Delta p_T^{\text{ch}}} \frac{\Delta N_{\text{ch}}^{\text{ch}}(p_T^{\text{ch}}, R, |\eta|)}{\Delta p_T^{\text{ch}}} - \frac{dN_{\text{ch}}^{\text{UE}}}{dp_T^{\text{ch}}},$$  

(6)

and

$$D^{\text{meas}}(z) = \frac{1}{N_{\text{jet}}} \frac{1}{\Delta p_T^{\text{ch}}} \frac{\Delta N_{\text{ch}}^{\text{ch}}(p_T^{\text{ch}}, R, |\eta|)}{\Delta p_T^{\text{ch}}} - \frac{dN_{\text{ch}}^{\text{UE}}}{dp_T^{\text{ch}}} \left(\frac{1}{\Delta z} \frac{dN_{\text{ch}}^{\text{UE}}}{dp_T^{\text{ch}}} \right),$$  

(7)

where $N_{\text{jet}}$ represents the total number of jets passing the above-described selection cuts in a given centrality bin, and $\Delta N_{\text{ch}}^{\text{ch}}$ represents the number of measured charged particles within $\Delta R = 0.4$ of the jets in given bins of $p_T^{\text{ch}}$, and $z$, respectively. The efficiency correction, $1/\varepsilon$, was applied on a per-particle basis using the parameterized MC efficiency, $\varepsilon(p_T, \eta)$, assuming $p_T^{\text{true}} = p_T^{\text{rec}}$. While

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4 The $\Delta R$ is a boost-invariant replacement for the polar angle $\theta$. 

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**Fig. 2.** Charged-particle reconstruction efficiency as a function of truth $p_T$, for 0–10% (red) and 60–80% (blue) centrality bins in the region $|\eta| < 1$ (top) and $1 < |\eta| < 2.5$ (bottom). The $p_T$ values for the 0–10% points are shifted for clarity. The solid curves show parameterizations of efficiencies. The shaded bands show the systematic uncertainty in the parameterized efficiencies (see text). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
that assumption is not strictly valid, the efficiency varies sufficiently slowly with \( p_T^{\text{true}} \) that the error introduced by this assumption is \( \lesssim 1\% \) everywhere.

The measured \( D^{\text{meas}}(z) \) distributions for \( R = 0.4 \) jets in the 0–10\% and 60–80\% centrality bins are shown in the top left panel in Fig. 3. The top middle panel shows the ratio of \( D^{\text{meas}}(z) \) between central (0–10\%) and peripheral (60–80\%) collisions, \( D_{\text{Di}}^{\text{meas}}(z) \equiv D^{\text{meas}}(z)_{0-10}/D^{\text{meas}}(z)_{60-80} \). For comparison, the \( D^{\text{meas}}(z) \) ratio is shown on the top right panel for \( R = 0.2 \) jets. Similar plots are shown in Fig. 4 but for \( D^{\text{meas}}(p_T) \). The \( D^{\text{meas}}(z) \) ratios for both \( R = 0.2 \) and \( R = 0.4 \) indicate an enhanced fragment yield at low \( z \), \( z \lesssim 0.04 \), in jets in the 0–10\% centrality bin compared to jets in the 60–80\% centrality bin and a suppressed yield of fragments with \( z \sim 0.1 \). Similar results are observed in the \( D^{\text{meas}}(p_T) \) ratios over the corresponding \( p_T \) ranges. The \( R = 0.2 \) \( D^{\text{meas}}(p_T) \) and the \( R = 0.2 \) and \( R = 0.4 \) \( D^{\text{meas}}(p_T) \) ratios rise above one for \( z \gtrsim 0.2 \) or \( p_T \gtrsim 25 \) GeV. However, the ratios differ from one by only 1–2\% (stat). No such variations of the \( D^{\text{meas}}(z) \) and \( D^{\text{meas}}(p_T) \) distributions with centrality as seen in the data are observed in the MC simulation. The central-to-peripheral ratios of MC \( D^{\text{meas}}(z) \) and \( D^{\text{meas}}(p_T) \) distributions for \( R = 0.4 \) and \( R = 0.2 \) jets (not shown) are within 3\% of one for all \( z \) and \( p_T \).

The \( D^{\text{meas}}(p_T) \) and \( D^{\text{meas}}(z) \) distributions were unfolded using a one-dimensional Singular Value Decomposition (SVD) method [27] implemented in RooUnfold [28] to remove the effects of charged particle and jet \( p_T \) resolution. The SVD method implements a regularized matrix-based unfolding that attempts to "invert" the equation \( b = Ax \), where \( x \) is a true spectrum, \( b \) is an observed spectrum, and \( A \) is the "response matrix" that describes the transformation of \( x \) to \( b \). For \( D(p_T) \), the unfolding accounts only for the charged-particle \( p_T \) resolution and uses a response matrix derived from the MC data set that describes the distri-
bution of reconstructed $p_T^{\text{ch}}$ as a function of MC truth $p_T^{\text{ch}}$. The response matrix $A(p_T^{\text{true}}, p_T^{\text{true}})$ is filled using the procedures described in Section 5. The $D(z)$ unfolding simultaneously accounts for both charged particle and jet resolution using a response matrix $A(z^{\text{rec}}, z^{\text{true}})$ with $z^{\text{true}}$ ($z^{\text{rec}}$) calculated using purely truth (fully reconstructed) quantities. A cross-check was performed for the $D(z)$ unfolding that included only the jet energy resolution to ensure that the combination of the two sources of resolution in the one-dimensional unfolding did not distort the result. Because the $D^{\text{meas}}(z)$ and $D^{\text{meas}}(p_T)$ distributions were already corrected for the charged-particle reconstruction efficiency, the response matrices were only populated with truth particles for which a reconstructed particle was obtained and each entry was corrected for reconstruction efficiency so as to not distort the shape of the true distributions.

To ensure that statistical fluctuations in the MC $p_T^{\text{true}}$ or $z^{\text{true}}$ distributions do not distort the unfolding, those distributions were smoothed by fitting them to appropriate functional forms. The truth $D(p_T)$ distributions were fit to polynomials in $\ln(p_T)$. The truth $D(z)$ distributions were parameterized using an extension of a standard functional form [29],

$$D(z) = a \cdot z^d (1 + c - z)^{d} \cdot (1 + b \cdot (1 - z)^{d}),$$

(8)

where $a, b, c, d$ were free parameters of the fit. The non-standard additional parameter “c” was added to improve the description of the truth distribution at large $z$. When filling the truth spectra and response matrices, the entries were weighted to match the truth spectra to the fit functions.

The SVD unfolding was performed using a regularization parameter obtained from the ninth singular value ($k = 9$) of the unfolding matrix. Systematic uncertainties in the unfolding due to regularization were evaluated by varying $k$ over the range 5–12 for which the unfolding was observed to be neither significantly biased by regularization nor unstable. The statistical uncertainties in the unfolded spectra were obtained using the pseudo-experiment method [27]. The largest absolute uncertainty obtained over 5 ≤ $k$ ≤ 12 was taken to be the statistical uncertainty in the unfolded result.

Unfolded fragmentation functions, $D(z)$, are shown in the top left panel in Fig. 3 and compared to the corresponding $D^{\text{meas}}(z)$ distributions for $R = 0.4$ jets in central (0–10%) and peripheral (60–80%) collisions. Similar results for $D(p_T)$ are shown in Fig. 4. For both figures, the ratios of unfolded to measured distributions are shown in the bottom left panel with the ratio for 0–10% centrality bin offset by $+1$. Those ratios show that the unfolding has minimal impact on the fragmentation functions in both peripheral and central collisions. Only the largest $z$ point in the 0–10% bin changes by more than 20%.

The middle and top right panels in Fig. 3 (Fig. 4) show for $R = 0.4$ and $R = 0.2$ jets, respectively, the ratios of unfolded $D(z)$ ($D(p_T)$) distributions, $R_{D(z)} = D(z)_{0/40/60} / D(z)_{0/40/80}$ ($R_{D(p_T)} = D(p_T)_{0/40/60} / D(p_T)_{0/40/80}$), compared to the ratios before unfolding. The unfolding reduces the $D(z)$ ratio slightly at low $z$ but otherwise leaves the shapes unchanged. To evaluate the impact of the unfolding on the difference between central and peripheral fragmentation functions, the middle and bottom right panels in Fig. 3 (Fig. 4) show the ratio of $R^{\text{meas}}(z)_{D(p_T)}$ to $R^{\text{meas}}(z)_{D(p_T)}$. Except for the lowest $z$ point, the ratio is consistent with one over the entire $z$ range. Thus, the features observed in $R^{\text{meas}}(z)_{D(p_T)}$ namely the enhancement at low $z$ ($p_T$) in central collisions relative to peripheral collisions, the suppression at intermediate $z$ ($p_T$), and the rise above one at large $z$ ($p_T$) are robust with respect to the effects of the charged particle and jet $p_T$ resolution.

7. Systematic uncertainties

Systematic uncertainties in the unfolded $D(z)$ and $D(p_T)$ distributions can arise due to uncertainties in the jet energy scale and jet energy resolution, from systematic uncertainties in the unfolding procedure including uncertainties in the shape of the truth distributions, uncertainties in the charged particle reconstruction, and from the UE subtraction procedure.

The systematic uncertainty due to the jet energy scale (JES) has two contributions, an absolute JES uncertainty and an uncertainty in the variation of the JES from peripheral to more central collisions. The absolute JES uncertainty was determined by shifting the transverse momentum of the reconstructed jets according to the evaluation of the jet energy scale uncertainty in Ref. [30]. The typical size of the JES uncertainty for jets used in this study is 2%. The shift in the JES has negligible impact on the ratios between central and peripheral events of $D(p_T)$ and $D(z)$ distributions whereas it has a clear impact on the $D(p_T)$ and $D(z)$ distributions. At high $p_T$ or $z$ the resulting uncertainty reaches 15%. The evaluation of centrality-dependent uncertainty on JES uses the estimates from Ref. [14]. The centrality-dependent JES uncertainty is largest for the most central collisions where it reaches 15%. The evaluation of the jet energy resolution (JER) uncertainty follows the procedure applied in proton–proton jet measurements [31]. The typical size of JER uncertainty for jets used in the study is less than 2%. This uncertainty is centrality independent since the dijets in MC are overlaid to real data. The resulting combined systematic uncertainty from JER and centrality-dependent JES on the ratios reaches 6% at high $p_T$ and 10% at high $z$ and it has a similar size in the case of $D(p_T)$ or $D(z)$ distributions as in the case of their ratios.

The systematic uncertainty associated with the unfolding is connected with the sensitivity of the unfolding procedure to the choice of regularization parameter and to the parameterization of the truth distribution. The uncertainty due to the choice of regularization parameter was evaluated by varying $k$ over the range 5–12. The typical systematic uncertainty is found to be smaller than 3% or 2% for the $D(z)$ or $D(p_T)$, respectively. The systematic uncertainty due to the parameterization of the truth distribution was determined from the statistical uncertainties of the fits to these distributions. This systematic uncertainty is below 1% or 2% for the $D(z)$ or $D(p_T)$, respectively.

The estimate of systematic uncertainty due to the tracking efficiency follows methods of the inclusive charged particle measurement [23]. The uncertainty is quantified using the error of the fit of tracking efficiency and by varying the tracking selection criteria. In the intermediate-$p_T$ region the systematic uncertainty is less than 2%. In the low and high $p_T$ region the systematic uncertainty is larger, but less than 8%.

An independent evaluation of potential systematic uncertainties in the central-to-peripheral ratios of $D(z)$ and $D(p_T)$, due to all aspects of the analysis, was obtained by evaluating the deviation from unity of the MC central (0–10%) to peripheral (60–80%) ratios of the fragmentation functions. Since there is no jet quenching employed in MC simulation, the ratios are expected not to show any deviation from unity. No deviation from unity is indeed observed, the largest localized deviation is ≤ 4%. To quantify the deviations from unity, the MC $R_{D(z)}$ and $R_{D(p_T)}$ ratios were fit by piece-wise continuous functions composed of linear functions defined over the $z$ ($p_T$) ranges $z = 0.02–0.06$ ($p_T = 2–6$ GeV), $z = 0.06–0.3$ ($p_T = 6–30$ GeV), and $z = 0.3$ ($p_T > 30$ GeV) with parameters constrained such that the linear functions match at the boundaries. The resulting fits are used as estimates of the systematic uncertainties on all measured $R_{D(z)}$ and $R_{D(p_T)}$ Ratios reported in Section 8. This systematic uncertainty is certainly correlated with and may overlap with other systematic uncertainties described above.
8. Results

The unfolded fragmentation functions, $D(z)$ and $D(p_T)$, for $R = 0.4$ jets are shown in Fig. 5 for the seven centrality bins included in the analysis with the distributions for different centralities multiplied by successive values of two for presentation purposes. The shaded error bands indicate systematic uncertainties as discussed in the previous section. The $D(p_T)$ and $D(z)$ distributions have similar shapes that are characteristic of fragmentation functions with a steep drop at the endpoint.

To evaluate the centrality dependence of the fragmentation functions, ratios were calculated of the $R = 0.4$ $D(z)$ distributions for all centrality bins excluding the peripheral bin to the $D(z)$ measured in the peripheral, 60–80% centrality bin. The results are shown in Fig. 6. The ratios for all centralities show an enhanced yield of low $z$ fragments and a suppressed yield of fragments at
mediate, and smaller distributions collisions.

About 60–80% centrality, the enhancement in the fragmentation functions at large z or $p_T$ in central collisions is more significant for the smaller jet sizes.

**9. Discussion**

To quantify the effects of the modifications observed in Fig. 8 on the actual distribution of fragments within the measured jets, the differences in fragmentation functions, $\Delta D(z) = D(z)_{\text{cent}} - D(z)_{60-80}$ were calculated and integrals of these distributions, $\int \Delta D(z) dz$ taken over three z ranges chosen to match the observations: 0.02–0.04, 0.04–0.2, and 0.4–1. The last interval was chosen to focus on the region where $R_{D(z)} > 1$. The results are given in Tables 3 and 4 for $R = 0.3$ and $R = 0.2$ jets, respectively. Similar results were obtained for $R = 0.4$ jets but with larger uncertainties. The results presented in the tables indicate an increase in the number of particles with $0.02 < z < 0.04$ of less than one particle per jet in the 0–10% centrality bin relative to the 60–80% centrality bin. A decrease of about 1.5 particles per jet is observed for $0.04 < z < 0.2$. The differences between the integrals of the fragmentation functions over $0.4 < z < 1$ are not significant relative to the uncertainties. The results for $\int \Delta D(z) dz$ shown in the two tables indicate that in the most central collisions a small fraction, <2%, of the jet transverse momentum is carried by the excess particles in $0.02 < z < 0.04$ for central collisions, but that the depletion in fragment yield in $0.04 < z < 0.2$ accounts on average for about 14% of $p_T^\text{jet}$.

To better evaluate the significance of the increase in $R_{D(z)}$ and $R_{D(p_T)}$ above one at large $z$ or $p_T$, average $R_{D(z)}$ and $R_{D(p_T)}$ ratios were calculated by summing the central and peripheral $D(z)$ or $D(p_T)$ distributions over different regions corresponding to the last n points in the measured distributions, $n = 2–6$. For each resulting average ratio, $\bar{R}_{D(z)}$ or $\bar{R}_{D(p_T)}$, the significance of the deviation from one was evaluated as $(\bar{R}_{D(z)} - 1)/\sigma(\bar{R}_{D(z)})$ or $(\bar{R}_{D(p_T)} - 1)/\sigma(\bar{R}_{D(p_T)})$ where $\sigma$ represents the combined

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**Fig. 7.** Ratios of unfolded $D(p_T)$ distributions for six bins in collision centrality to those in peripheral (60–80%) collisions, $D(p_T)_{60-80}/D(p_T)_{0-10}$ for $R = 0.4$ jets. The error bars on the data points indicate statistical uncertainties while the yellow shaded bands indicate systematic uncertainties. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Fig. 8. Ratios of unfolded fragmentation functions, $D(z)$ (top) and $D(p_T)$ (bottom), for central (0–10%) collisions to those in peripheral (60–80%) collisions for $R = 0.2$ (left) and $R = 0.3$ (right) jets. The fragmentation functions were evaluated using charged hadrons within $\Delta R = 0.4$ of the jet axis. The error bars on the data points indicate statistical uncertainties while the yellow shaded bands indicate systematic uncertainties. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Differences of $D(z)$ distributions in different centralities with respect to peripheral events for $R = 0.3$ jets. The errors represent combined statistical and systematic uncertainties.

| Centrality | $z = 0.02–0.04$ | $z = 0.04–0.2$ | $z = 0.4–1.0$ |
|------------|-----------------|-----------------|-----------------|
|            | $\langle \Delta D(z) \rangle_z$ | $\langle z \Delta D(z) \rangle_z$ | $\langle \Delta D(z) \rangle_z$ | $\langle z \Delta D(z) \rangle_z$ |
| 0–10%      | 0.79$_{-0.25}^{+0.19}$ | 0.020$_{-0.007}^{+0.005}$ | -1.7$_{-0.6}^{+0.6}$ | -0.14$_{-0.06}^{+0.04}$ | 0.00$_{-0.04}^{+0.05}$ | 0.033$_{-0.021}^{+0.026}$ |
| 10–20%     | 0.66$_{-0.18}^{+0.17}$ | 0.016$_{-0.005}^{+0.005}$ | -1.6$_{-0.6}^{+0.6}$ | -0.12$_{-0.06}^{+0.05}$ | 0.05$_{-0.04}^{+0.05}$ | 0.029$_{-0.021}^{+0.024}$ |
| 20–30%     | 0.52$_{-0.18}^{+0.13}$ | 0.013$_{-0.004}^{+0.005}$ | -1.3$_{-0.6}^{+0.6}$ | -0.12$_{-0.04}^{+0.04}$ | 0.04$_{-0.04}^{+0.05}$ | 0.025$_{-0.021}^{+0.024}$ |
| 30–40%     | 0.39$_{-0.17}^{+0.12}$ | 0.009$_{-0.004}^{+0.005}$ | -1.3$_{-0.7}^{+0.6}$ | -0.10$_{-0.05}^{+0.04}$ | 0.06$_{-0.04}^{+0.05}$ | 0.036$_{-0.021}^{+0.019}$ |
| 40–50%     | 0.38$_{-0.15}^{+0.11}$ | 0.009$_{-0.004}^{+0.004}$ | -0.6$_{-0.8}^{+0.6}$ | -0.07$_{-0.06}^{+0.04}$ | -0.01$_{-0.04}^{+0.04}$ | -0.005$_{-0.021}^{+0.024}$ |
| 50–60%     | 0.28$_{-0.21}^{+0.15}$ | 0.006$_{-0.004}^{+0.006}$ | -1.2$_{-0.7}^{+0.6}$ | -0.08$_{-0.06}^{+0.04}$ | 0.04$_{-0.04}^{+0.05}$ | 0.025$_{-0.021}^{+0.024}$ |

Table 4
Differences of $D(z)$ distributions in different centralities with respect to peripheral events for $R = 0.2$ jets. The errors represent combined statistical and systematic uncertainties.

| Centrality | $z = 0.02–0.04$ | $z = 0.04–0.2$ | $z = 0.4–1.0$ |
|------------|-----------------|-----------------|-----------------|
|            | $\langle \Delta D(z) \rangle_z$ | $\langle z \Delta D(z) \rangle_z$ | $\langle \Delta D(z) \rangle_z$ | $\langle z \Delta D(z) \rangle_z$ |
| 0–10%      | 0.65$_{-0.20}^{+0.21}$ | 0.017$_{-0.005}^{+0.006}$ | -1.7$_{-0.6}^{+0.6}$ | -0.14$_{-0.06}^{+0.04}$ | 0.07$_{-0.04}^{+0.05}$ | 0.037$_{-0.022}^{+0.030}$ |
| 10–20%     | 0.69$_{-0.16}^{+0.16}$ | 0.016$_{-0.005}^{+0.005}$ | -1.6$_{-0.7}^{+0.6}$ | -0.13$_{-0.05}^{+0.04}$ | 0.08$_{-0.04}^{+0.05}$ | 0.046$_{-0.025}^{+0.029}$ |
| 20–30%     | 0.48$_{-0.14}^{+0.11}$ | 0.013$_{-0.004}^{+0.003}$ | -1.6$_{-0.5}^{+0.6}$ | -0.13$_{-0.04}^{+0.04}$ | 0.04$_{-0.04}^{+0.05}$ | 0.026$_{-0.024}^{+0.029}$ |
| 30–40%     | 0.44$_{-0.15}^{+0.11}$ | 0.011$_{-0.004}^{+0.003}$ | -1.4$_{-0.7}^{+0.6}$ | -0.11$_{-0.05}^{+0.05}$ | 0.07$_{-0.05}^{+0.04}$ | 0.044$_{-0.028}^{+0.029}$ |
| 40–50%     | 0.33$_{-0.14}^{+0.09}$ | 0.009$_{-0.004}^{+0.003}$ | -1.0$_{-0.8}^{+0.6}$ | -0.05$_{-0.06}^{+0.04}$ | -0.03$_{-0.04}^{+0.05}$ | -0.011$_{-0.020}^{+0.024}$ |
| 50–60%     | 0.27$_{-0.18}^{+0.12}$ | 0.007$_{-0.005}^{+0.005}$ | -1.0$_{-0.7}^{+0.6}$ | -0.07$_{-0.06}^{+0.04}$ | 0.04$_{-0.04}^{+0.05}$ | 0.027$_{-0.025}^{+0.029}$ |
statistical and systematic uncertainty. Because there is significant cancellation of systematic uncertainties in the ratios, this analysis provides a more sensitive evaluation of the significance of the large-$z$ excess. For $R = 0.4$ jets the combined $R_{D_{(2)}}(R_{D_{(pT)}})$ differs from one by approximately $1\sigma$ ($1.5\sigma$) for any of the $n$ values. For $R = 0.2$ jets, $R_{D_{(2)}}$ differs from 1 by approximately $1.5\sigma$ for all $n$ values, while $R_{D_{(pT)}}$ differs from one by $2\sigma$ for $n = 3–6$ corresponding to $p_T > 47.5$ GeV through $p_T > 20$ GeV. The greater significance of the deviations of the $R = 0.2$ $R_{D_{(pT)}}$ relative to the $R = 0.2$ $R_{D_{(2)}}$ and the $R = 0.4$ $R_{D_{(2)}}$ and $R_{D_{(pT)}}$ can be attributed to the reduced role of the jet energy resolution in influencing the measurement of the central-to-peripheral ratios for large hadron momenta.

Theoretical predictions for medium modifications of fragmentation functions based on radiative energy loss [32–35] have generally predicted substantial reduction in the yield of high $p_T$, or large-$z$ fragments and an enhancement at low $p_T$ or low $z$. The predicted reduction at large $z$ generally results from the radiative energy loss of the leading partons in the shower and the resulting redistribution of the jet energy to lower $z$ hadrons. Instead of a reduction, an enhanced yield of high-$z$ fragments is seen in the data. However, the difference between observed behaviour at large $z$ and expectations from theoretical calculations may be at least partially attributed to the fact that the fragmentation functions presented in this paper were evaluated with respect to the energies of quenched jets. In contrast, theoretical analyses of the fragmentation functions of quenched jets are typically evaluated in terms of the initial, unquenched jet energies. However, some recent theoretical analyses [36,37] of jet fragmentation functions using quenched jet energies have shown that jet quenching calculations can reproduce the general features observed in the results presented in this Letter. In addition to direct modifications of the fragmentation function due to quenching, the quenching may indirectly alter the fragmentation function of inclusive jets by altering the relative fraction of quarks and gluons.

The simultaneous effects of quenching on the hadron constituents of jets and the measured jet energies may explain a relative increase of experimental fragmentation functions in central collisions at large $z$ as suggested by the data. Jets that fragment to large-$z$ hadrons may lose less energy than typical jets due to reduced formation or colour-neutralization time [38]. Thus, the fragmentation function measured for inclusive jets may have a higher proportion of jets with large-$z$ hadrons. The results in Ref. [36] indicate such an effect that is qualitatively similar to the data.

10. Conclusions

This Letter has presented measurements by ATLAS of charged-particle fragmentation functions in jets produced in $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions at the LHC. The measurements were performed using a data set recorded in 2011 with an integrated luminosity of 0.14 nb$^{-1}$. Jets were reconstructed with the anti-$k_T$ algorithm for distance parameters $R = 0.2, 0.3, 0.4$, and the contributions of the underlying event to the jet kinematics and the jet fragment distributions were subtracted. Jet fragments were measured within an angular range $\Delta R = 0.4$ from the jet axes for all three jet sizes. Distributions of per-jet charged-particle transverse momentum, $D(p_T)$, and longitudinal momentum fraction, $D(z)$, were presented for seven bins in collision centrality for jet $p_T > 85, 92,$ and 100 GeV, respectively, for $R = 0.2$, $R = 0.3$, and $R = 0.4$ jets. Ratios of fragmentation functions in the different centrality bins to the 60–80% bin were presented and used to evaluate the medium modifications of jet fragmentation. Those ratios show an enhancement in fragment yield in central collisions for $z < 0.04$, a reduction in fragment yield for $0.04 < z < 0.2$ and an enhancement in the fragment yield for $z > 0.4$. The modifications decrease monotonically with decreasing collision centrality from 0–10% to 50–60%. A similar set of modifications is observed in the $D(p_T)$ distributions over corresponding $p_T$ ranges.

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G. Aad 84, B. Abbott 112, J. Abdallah 152, S. Abdellaoui 116, O. Abdo 11, R. Aben 106, B. Abi 113, M. Abolins 89, O.S. AbouZeid 159, H. Abramowicz 154, H. Abreu 153, R. Abreu 30, Y. Abulaiti 147a,147b, B.S. Acharya 165a,165b, a, L. Adamczyk 38a, D.L. Adams 25, J. Adelman 177, S. Adomeit 99, T. Adye 130, T. Agatonovic-Jovin 13a, J.A. Aguilar-Saavedra 125a,125b, M. Agustoni 17, S.P. Ahlen 22, F. Ahmadov 64, b, G. Aielli 134a,134b, H. Akersbedi 147a,147b, T.P.A. Akesson 80, G. Akimoto 156, A.V. Akimov 95, G.L. Alberghini 20a,20b, J. Albert 170, S. Albbrand 55, M.J. Alconada Verzini 70, M. Aleksa 30, I.N. Aleksandrov 64, C. Alexà 26a, G. Alexander 134, G. Alexander 147a,147b, T. Alexopoulos 10, M. Albrecht 147a,147b, G. Alimonti 90a, L. Aliko 84, J. Allison 31, B.M.M. Allbrooke 18, L.J. Allison 94, P.P. Allport 73, J. Almond 83, A. Alloisio 36, F. Alonso 70, F. Alpigiani 75, A. Altheimer 103a,103b, B. Alvarez Gonzalez 89, M.G. Alviggi 103a,103b, K. Amako 65, Y. Amaral Coutinho 24a, C. Amelung 23, D. Amidei 58, S.P. Amor Dos Santos 125a,125c, A. Amorim 125a,125b, S. Amorosio 48, N. Amrani 154, G. Amundsen 23, C. Anastopoulos 140, L.S. Ancu 49, N. Andari 30, T. Andeen 35, C.F. Anders 58b, G. Anders 30, K.J. Anderson 31, A. Andrea 90a,90b, V. Andrei 58a, X.S. Anduaga 70, S. Angelidakis 3, I. Angelozzi 106, P. Anger 44, A. Angenard 35, F. Anghinolfi 30, A.V. Anisenkov 108, N. Anjos 125a, A. Annoy 47, A. Antonelli 47, A. Antonov 97, J. Antos 145b, F. Anuoli 133a, M. Aoki 65, L. Aperio Bella 18, R. Apollc 119, G. Arabidze 89, I. Aracena 144, Y. Arai 65, J.P. Arcoleo 125a, T.H. Arce 45, J-F. Argen 94, S. Argyropoulos 42, M. Arik 19a, A.J. Armbruster 30, O. Arneaz 30, V. Arnal 81, H. Arnold 48, M. Arratia 28, O. Arslan 21, A. Artamonov 96, G. Arttoni 23, S. Asa 156, N. Asbah 42, A. Ashkenazi 134, B. Asman 147a,147b, L. Asquith 6, K. Assamagan 25, R. Astalos 145a, M. Atkinson 166, N.B. Atlay 142, B. Auerbach 8, K. Augsten 127, M. Aurousseau 125a, G. Avolio 30, A. Azuelos 94, d, Y. Azuma 156, M.A. Baak 30, A. Baas 58a, C. Bacci 135a,135b, H. Bachacou 137, K. Bachas 155, M. Backes 139, M. Backhaus 30, J.P. Backes Mayes 144, E. Badesco 26a, P. Bagiacchi 133a,133b, P. Bagnaia 133a,133b, Y. Bai 33a, T. Bain 35, J.T. Baines 130, O.K. Baker 177, P. Balek 128, F. Balli 137, E. Banas 39, Sw. Banerjee 174, A.A.E. Bannoura 176, V. Bansal 170, H.S. Bansil 18, L. Barak 173, S.P. Baranow 95, E.L. Barberi 87, D. Barberis 90a,50b, D. Barberis 90a, M. Barbero 84, T. Barillari 100, M. Barisoni 76, T. Barklow 144, N. Barlow 28, B.M. Barnett 130, R.M. Barnett 15, Z. Barovska 5, A. Baroncelli 135a, G. Barone 49, A.J. Barri 119, F. Barreiro 81, J. Barrio Geimarras da Costa 57, R. Bartoldus 144, A.E. Barton 71, P. Bartos 145a, V. Bartosch 150, A. Bassalat 116, A. Basye 166, R.L. Bates 53, J.R. Batley 28, M. Battaglia 138, M. Battistini 30, F. Bauer 137, H.S. Bawa 144, T. Beau 79, P.H. Beauchemin 162, R. Becchere 123a,123b, P. Bechtel 21, H.P. Beck 17, K. Becker 147a,147b, S. Becker 99, M. Beckingam 171, C. Becott 116, A. Beddall 19c, A. Beddall 19d, S. Bedikan 177, V.A. Bednyakov 64, C.P. Bee 149, L.J. Beemster 106, T.A. Beemster 176, M. Begel 25, K. Behr 119, C. Belanger-Champagne 86, P.J. Bell 49, W.H. Bell 49, G. Bella 154, L. Bellagamba 20, A. Bellerive 29, M. Bellomo 85, K. Belotitsky 97, O. Beltramello 30, O. Benay 154, D. Benchekroun 136a, K. Bendtz 147a,147b, N. Benekov 166, Y. Benhammou 154, E. Benhar Naccioli 49, J.A. Benitez Garcia 160b, D.P. Benjamin 45, J.R. Bensinger 23, K. Benslama 131, S. Bentvelsen 106, D. Berge 106, E. Bergeaas Kuutmann 16, N. Berger 3, F. Berghaus 171, P. Beringer 15, C. Bernard 22, P. Bernat 77, C. Bernius 78, F.U. Bernlochner 170, T. Berry 76, P. Berta 84, G. Bertolli 147a,147b, F. Bertolucci 123a,123b, D. Bertsche 112, M.J. Besana 90a, G.J. Besjes 105, O. Bessidskaia 147a,147b, M.F. Bessner 42, N. Besson 137, C. Betancour 48, S. Bethke 100, W. Bhimji 46, R.M. Bianchi 124, L. Bianchini 23, M. Bianco 30, O. Biebel 99, S.P. Bieniek 77, K. Bierwagen 54, J. Biesiada 15, M. Bigielli 135a, J. Bilbao De Mendizabal 49, H. Bilokon 47, M. Bindi 154, S. Binet 116, A. Bingul 19e, C. Bini 133a,133b, C.W. Black 151, J.E. Black 144, K.M. Black 22, D. Blackburn 139, R.E. Blair 5, J.-B. Blanchard 137, T. Blazej 145a, I. Bloch 42, C. Bloker 23, W. Blum 82, F. Blumenschein 34, G.J. Bobbink 106, V.S. Bobrovnichenko 108, S.S. Bocchetta 80, A. Bocci 45, C. Bock 99, C.R. Boddy 119, M. Boehmer 48, T.T. Boek 176, J.A. Bogaerts 30.
R. Ueno 29, M. Ughetto 84, M. Ugland 14, M. Uhlenbrock 21, F. Ukegawa 161, G. Unal 30, A. Undrus 25, G. Unel 164, F.C. Ungaro 48, Y. Unno 65, D. Urbaniec 35, P. Urruqio 87, G. Usai 8, A. Usanov 61, L. Vacavant 84, V. Vacek 127, B. Vachon 86, N. Valencic 106, S. Valentinetti 20a,20b, A. Valero 168, L. Valery 34, S. Valkar 128, E. Valladolid Gallego 168, S. Vallorcisa 49, J.A. Valls Ferrer 168, W. Van Den Wollenberg 106, P.C. Van Der Deijl 106, R. van der Geer 106, H. van der Graaf 106, R. Van Der Leeuw 106, D. van der Ster 30, N. van Eldik 30, P. van Gemmeren 6, J. Van Nieukoop 143, I. van Vulpen 106, M.C. van Woerden 30, M. Vanadia 133a,133b, W. Vandelli 30, R. Vanucci 121, A. Vaniachine 6, P. Vankov 42, F. Vannucci 79, G.vardanyan 178, R. Vare 133a, E.W. Varnes 7, T. Varol 85, D. Varouchas 79, A. Vartapetian 8, K.E. Varvell 151, F. Vazeille 34, T. Vazquez Schroeder 54, J. Veatch 7, F. Veloso 125a,125c, S. Veneziano 133a, A. Ventura, D. Ventura 85, M. Venturi 170, N. Venturi 155, A. Venturini 23, V. Vercesi 120b, M. Verducci 133a,133b, W. Verkerke 106, J.C. Vermeulen 106, A. Vest 44, M.C. Vetterli 143, O. Viazlo 80, I. Vichou 166, T. Vickey 146c, O.E. Vickey Boeriu 146c, G.H.A. Viehhaufer 119, S. Vieh 169, R. Vigne 30, M. Villa 20a,20b, M. Villaplana Perez 90a,90b, E. Vilucchi 47, V.B. Vinogradov 64, J. Virzi 15, I. Vivarelli 150, F. Vives Vaque 3, S. Vlachos 10, D. Vladoiu 99, M. Vlasak 127, A. Vogel 21, M. Vogel 32a, P. Vokac 127, G. Volpi 123a,123b, M. Volpi 87, H. von der Schmitt 100, H. von Radziewski 48, E. von Toerne 21, V. Vorobel 128, K. Vorobeiev 97, M. Vos 168, R. Voss 30, J.H. Vossebeld 73, N. Vranjes 137, M. Vranjes Milosavljevic 106, V. Vrba 126, M. Vreeswijk 106, T. Vu Anh 48, R. Vuillermet 30, I. Vukotic 31, Z. Vykdyal 127, P. Wagner 21, W. Wagner 176, H. Wahlberg 70, S. Wahrmund 44, J. Wakabayashi 102, J. Walder 71, R. Walker 99, W. Walkowiak 142, R. Wall 177, P. Waller 73, B. Walsh 177, C. Wang 152a, M. Wang 45, F. Wang 174, H. Wang 15, H. Wang 40, J. Wang 42, J. Wang 33a, K. Wang 86, R. Wang 104, S.M. Wang 152, T. Wang 21, X. Wang 177, C. Wanotayaroj 115, A. Warburton 86, C.P. Ward 28, D.R. Wardrobe 77, M. Warsinsky 48, A. Washbrook 46, C. Wasicki 42, P.M. Watkins 18, A.T. Watson 18, I.J. Watson 151, M.F. Watson 18, G. Watts 139, S. Watts 83, B.M. Waugh 77, S. Webb 83, M.S. Weber 17, S.W. Weber 175, J.S. Weidert 31, A.R. Weidinger 119, P. Weigel 100, B. Weichert 60, J. Weingarten 54, C. Weiser 48, H. Weits 106, P.S. Wells 30, T. Wenau 25, D. Wendland 16, Z. Weng 152a, T. Wengler 30, S. Wenig 30, N. Wermes 21, M. Werner 48, P. Werner 30, M. Wessels 58a, J. Wetter 162, K. Whalen 29, A. White 6, M.J. White 1, R. White 32b, W-M. Yao 15, X. Yao 33a, W-M. Yao 15, Y. Yasu 65, E. Yatsenko 42, K.H. Yau Wong 21, J. Ye 40, S. Ye 25, A.L. Yen 57, E. Yildirim 42, M. Yilmaz 4b, R. Yoyoosofimya 124, K. Yorita 172, R. Yoshida 6, K. Yoshihara 156, C. Young 144, C.J.S. Young 30, S. Youssef 42, D.R. Yu 15, J. Yu 8, J.M. Yu 88, J. Yu 113, L. Yuan 66, A. Yurkewicz 107, I. Yusuf 28,8a, B. Zabinski 39, R. Zaidan 62, A.M. Zaitsev 129, A. Zaman 149, S. Zambito 23, L. Zanello 133a,133b, D. Zanzi 100, C. Zeitnitz 176, M. Zeman 127, A. Zemla 38a, K. Zengel 23, O. Zenin 129, T. Zenjii 145a, D. Zerwas 116, G. Zevi della Porta 57, D. Zhang 88, F. Zhang 174, H. Zhang 89, J. Zhang 6, L. Zhang 152, X. Zhang 33d, Z. Zhang 116, Z. Zhao 33b, A. Zhemchugov 7, J. Zhong 88, B. Zhou 88, L. Zhou 35, N. Zhou 164, C.G. Zhu 33d, H. Zhu 33a, J. Zhu 88, Y. Zhu 33b, X. Zhuang 33a, K. Zhukov 95, A. Zibeli 175, D. Ziemska 60, N.I. Zimine 64, C. Zimmermann 82, R. Zimmermann 21, S. Zimmermann 21, S. Zimmermann 48, Z. Zinonos 54, M. Ziolkowski 142, G. Zobernig 174, A. Zoccoli 20a,20b, M. zur Nedden 16, G. Zurzolo 103a,103b, V. Zutshi 107, L. Zwalinski 30.

1 Department of Physics, University of Adelaide, Adelaide, Australia
2 Physics Service, SUNY Albany, Albany, NY, United States
3 Department of Physics, University of Alberta, Edmonton, AB, Canada
4 (a) Department of Physics, Ankara University, Ankara; (b) Department of Physics, Gazi University, Ankara; (c) Division of Physics, TOBB University of Economics and Technology, Ankara;
5 (a) Atomic Energy Authority, Ankara, Turkey
6 High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States
7 ATLAS Collaboration / Physics Letters B 739 (2014) 320–342
