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Measurement of jet fragmentation in PbPb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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The jet fragmentation function of inclusive jets with transverse momentum p_T above 100 GeV/c in PbPb collisions has been measured using reconstructed charged particles with p_T above 1 GeV/c in a cone of radius 0.3 around the jet axis. A data sample of PbPb collisions collected in 2011 at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}} = 2.76$ TeV corresponding to an integrated luminosity of 150 μb^{-1} is used. The results for PbPb collisions as a function of collision centrality and jet transverse momentum are compared to reference distributions based on pp data collected at the same center-of-mass energy in 2013, with an integrated luminosity of 5.3 pb^{-1}. A centrality-dependent modification of the fragmentation function is found. For the most central collisions, a significant enhancement is observed in the PbPb/pp fragmentation function ratio for charged particles with p_T less than 3 GeV/c. This enhancement is observed for all jet p_T bins studied.

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I. INTRODUCTION

High-energy collisions of heavy ions provide an important experimental tool to study the puzzles of confinement and chiral symmetry breaking in quantum chromodynamics (QCD), the theory of strong interactions. It is expected that a state of deconfined and chirally symmetric quarks and gluons, called the quark-gluon plasma (QGP), exists in the hot and dense QCD medium produced in heavy-ion collisions [1–4]. However, due to the complexity of multibody collision systems, finding clean experimental signatures of the QGP poses a challenge. In 1982, Björken first conjectured that high-energy partons produced in nucleus-nucleus collisions would lose energy as they traverse the QGP [5]. Since then, a variety of experimental observations, including the suppression of high-transverse-momentum (p_T) particles, have provided evidence for this conjecture. This suppression was first seen at the Relativistic Heavy Ion Collider (RHIC) [6,7] and later at the CERN Large Hadron Collider (LHC) (see, for example, Ref. [8] and references therein). In addition, the analysis of the first data from the CERN LHC provided more direct evidence of parton energy loss using the difference in p_T between back-to-back pairs of jets [9–11] and also jet-photon pairs [12]. Unbalanced dijet and jet-photon pairs were found to be much more prevalent in the most central PbPb collisions [10–12] compared to expectations in the absence of a hot and dense medium. Further theoretical QCD studies have been inspired by these observations using jets from the CERN LHC. On the other hand, it has been predicted that, in the presence of the strongly interacting medium produced in heavy-ion collisions, the partitioning of the parton energy into particles (the fragmentation function) may be modified and the yield of high-p_T particles suppressed [13–17]. Therefore, direct measurements of jet fragmentation in heavy-ion collisions are important in the quest for understanding QCD through medium-induced parton energy loss.

Studies of the detailed jet structure also have important practical consequences for other aspects of jet analyses, including the connection to the kinematics of the partons that produce jets. The longitudinal and transverse fragmentation properties of jets connect the perturbatively calculable production of high-p_T quarks and gluons with the hadronized final-state particles. The study of jet production requires reconstructing the jets using final-state particles. This reconstruction relies on hadronization models to quantify how the original jet energy is related to the energy determined by adding the energies of the individual particles. In addition, although the production cross section can be calculated perturbatively, there are corrections due to the nonperturbative hadronization process. Study of the fragmentation function provides an important experimental check on the validity of the assumed jet fragmentation in heavy-ion collisions. These results can also be used to directly connect jet observables to measurements of high-p_T particles.

The goal of this analysis is to measure the jet fragmentation function in heavy-ion collisions using reconstructed jets. This is in contrast to the parton fragmentation function measured in e^+e^- experiments, which is obtained relative to the initial parton momentum. In previous work [18], the higher p_T ($p_T > 4$ GeV/c) component of the fragmentation function was found to be qualitatively similar to that for jets in pp collisions, for which the medium is absent. The analysis described in this paper uses data from the 2011 PbPb run at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}} = 2.76$ TeV. This work expands on the previous results by measuring the fragmentation function for particles down to p_T of 1 GeV/c. Taking advantage of the higher integrated luminosity (150 μb for PbPb and 5.3 pb^{-1} for the pp reference data), the measurement is also carried out in more differential centrality bins, and as a function of jet p_T. This measurement complements the previously published observation of a modification of the transverse profile of the jet in PbPb [19], using the same 2011 and 2013 data.

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II. THE CMS DETECTOR

The centerpiece of the CMS detector is a superconducting solenoid, 12.5 m long with an internal diameter of 6 m, that provides a uniform magnetic field of 3.8 T. In the CMS coordinate system, the z axis points in the counterclockwise beam direction, the x axis points toward the center of the LHC ring, and the y axis points up, perpendicular to the plane of the LHC ring. The azimuthal angle ϕ is measured with respect to the x axis, and the polar angle θ is measured with respect to the z axis. Charged particles or charged particles reconstructed in the inner tracking system are characterized by their transverse momentum, $p_T = |\vec{p}|\,\sin\theta$, and pseudorapidity, $\eta = -\ln[\tan(\theta/2)]$. The inner tracking system is composed of a pixel detector with three barrel layers at radii between 4.4 and 10.2 cm and a silicon strip tracker with 10 barrel layers extending outward to a radius of 110 cm. Two endcap modules extend the acceptance of the tracking system up to $|\eta| = 2.5$. The momentum resolution for reconstructed tracks in the barrel region is about 1% at $p_T = 100$ GeV/c and up to 2% in the endcap at the same p_T.

The calorimeters inside the magnetic coil consist of a lead-tungstate crystal electromagnetic calorimeter (ECAL) and a brass-scintillator hadron calorimeter (HCAL) with coverage up to $|\eta| = 3$. Steel–quartz-fiber Cherenkov hadron forward (HF) calorimeters extend the coverage to $|\eta| = 5.2$. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke of the magnet. The calorimeter cells are grouped in projective towers of granularity $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ for the central rapidities ($|\eta| \leqslant 2$) considered in this paper. The energy scale in data agrees with that in the simulation to better than 1% in the barrel region ($|\eta| < 1.5$) and better than 3% in the endcap region ($1.3 < |\eta| < 3.0$) [20]. Hadron calorimeter cells in the $|\eta| < 3$ region are calibrated primarily with test-beam data and radioactive sources [21,22]. A detailed description of the CMS detector can be found in Ref. [23].

III. TRIGGER, EVENT SELECTION, AND CENTRALITY DETERMINATION

The CMS high-level trigger (HLT) system is used to select PbPb collision events containing high-p_T jets reconstructed from calorimeter towers. The trigger threshold applied to the jet transverse momentum is $p_T = 80$ GeV/c. For pp collisions, the threshold is 60 GeV/c. In addition to the online trigger decision, standard offline selection criteria are applied to remove backgrounds due to detector noise, beam gas collisions, beam scraping, and ultra-peripheral-collision events [11]. Events are further restricted to those with a reconstructed vertex which includes at least two tracks and has a z position within 15 cm of the detector center. Finally, an offline HF coincidence of at least three towers with energy greater than 3 GeV on each side of the interaction point is required. These event-quality requirements have only a small effect on the number of selected events and have a negligible impact on the jet analyses [11,12].

For the analysis of PbPb data, it is important to determine the collision centrality in each event, which is related to the overlap between the two colliding nuclei. Centrality is determined using the sum of transverse energy [energy times $\sin(\theta)$] reconstructed in the HF calorimeter (covering $2.9 < |\eta| < 5.2$). The HF transverse energy distribution is used to divide the event sample into percentiles of the total nucleus-nucleus hadronic interaction cross section. A detailed description of the centrality determination can be found in [11].

IV. MONTE CARLO SIMULATIONS

In this analysis, Monte Carlo (MC) simulations have been used primarily for evaluation of reconstruction performance, particularly in determination of tracking efficiency, and jet energy response and resolution. These studies mostly used QCD jet events simulated by the PYTHIA MC generator [24] (version 6.423, tune Z2) [25]. These simulated PYTHIA events are propagated through the CMS detector using the GEANT4 package [26] to simulate the detector response.

In order to account for the effect of the PbPb underlying event, the PYTHIA events are embedded into fully simulated PbPb events, generated by the HYDJET event generator [27] (version 1.8), which has been tuned to describe the centrality dependence of the hadron multiplicity, p_T spectra, and elliptic flow in minimum-bias PbPb data. The embedding is done by mixing the simulated digital information from PYTHIA and HYDJET.

V. RECONSTRUCTION

A. Jet reconstruction

For both pp and PbPb collisions, the analysis is based on jets reconstructed using the anti-k_T algorithm, with a distance parameter R of 0.3, utilizing particle-flow (PF) objects that combine tracking and calorimetric information [28,29]. The value of 0.3 for R, also used in previous CMS jet studies [11,12], was chosen to optimize the jet reconstruction efficiency and misidentification rate. In the PbPb data, the contribution of the underlying heavy-ion event is removed using an iterative pileup subtraction method [30].

Only events with a minimum jet $p_T > 100$ GeV/c, for which the trigger is more than 99% efficient, are selected. From this event sample, all of the PF jets above $p_T > 100$ GeV/c and also within $0.3 < |\eta| < 2$ are included in the analysis. Jets in the central region of $|\eta| < 0.3$ are excluded in order to avoid overlaps in the background-subtraction procedure (see Sec. VI B).

B. Charged-particle reconstruction

Charged particles are reconstructed in the following steps, which are similar to those used previously [8,19]. First, using a collection of pixel-only tracks required to have three hits in the pixel detector, the three-dimensional primary vertex position is estimated from extrapolations back to the beam spot region. Next, track candidates are built from triplet seeds, consisting of hits in three layers of the pixel barrel and endcap detectors. To reduce the random combinatorial background, only seeds pointing to a restricted region within 2 mm of the primary vertex and with a minimum p_T of 0.9 GeV/c are used. Further selections are made on the normalized goodness of the track fit (i.e., χ^2 per degree of freedom) and on the compatibility of the fitted triplet seeds with the primary vertex, before propagating the seed trajectories through the strip tracker to build fully reconstructed tracks. To improve the track reconstruction efficiency, two more iterations of the tracking are performed after removing hits unambiguously belonging to the tracks found in the first iteration. This procedure is based on the standard *pp* iterative tracking [31]. More efficient *pp*-based triplet track and pixel pair seedings are used in the second and third iterations, respectively. The tracks found in the later iterations are merged with the first-iteration tracks after removing any duplicate tracks, based on the fraction of shared hits. In all iterations, track quality criteria are applied to the final list of track candidates to reduce the reconstruction misidentification rate. The minimal p_T for tracks used in the analysis is 1 GeV/c.

A complete understanding of the tracking performance is of primary importance for this analysis. This was studied using jet events simulated with PYTHIA (tune Z2) embedded into a HYDJET 1.8 background. The track-by-track corrections for reconstruction efficiency and misidentified tracks are computed in bins of track η and p_T, neighboring jet p_T, and event centrality without any selection criteria imposed on the reconstructed jets.

The performance of the tracking algorithm depends on the local environment in which it operates. Therefore, the corrections are computed separately for the four centrality classes used in the analysis: 0%–10%, 10%–30%, 30%–50%, and 50%–100% (most central to most peripheral events). Due to the low multiplicity in the 50%–100% centrality, the correction is also used for the split 50%–70% and 70%–100% centrality bins, for the five centrality class results. At low p_T, the efficiency is ≈10% higher for the pure PYTHIA sample (i.e., *pp* multiplicity environment) than for the most central HYDJET-embedded PYTHIA (i.e., PbPb multiplicity environment), while at high p_T the difference is about 4%. The misidentification rate is small for all samples and ranges from 4% at 1 GeV/c to 2% at 120 GeV/c.

VI. ANALYSIS

A. Jet fragmentation function

The jet fragmentation function is measured by correlating reconstructed charged-particle tracks contained within the jet cones, with the axis of the respective jet [32]. As done in previous measurements at hadron colliders [33,34], the fragmentation function is presented as a function of the variables z and ξ, defined as

$$z = \frac{p_{\parallel}^{\mathrm{track}}}{p^{\mathrm{jet}}}, \quad \xi = \ln\frac{1}{z},$$

where $p_{\parallel}^{\mathrm{track}}$ is the momentum component of the track along the jet axis and p^{jet} is the magnitude of the jet momentum. All tracks in a cone of $\sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.3$ around the jet axis are included in the analysis. The fragmentation function, defined as $(1/N_{\mathrm{jet}})\ dN_{\mathrm{track}}/d\xi$, is normalized to the total number of jets (N_{jet}).

B. Underlying event subtraction

Due to the high level of underlying event activity coming from the heavy-ion collisions, tracks that are not associated with the jet fragmentation can be found within the jet cone. This uncorrelated background contribution to the fragmentation function is subtracted statistically using the so-called η-reflection method. The underlying event contribution is estimated by selecting charged particles that lie in a "background" jet cone obtained by reflecting the original jet cone around $\eta = 0$ while keeping the same ϕ coordinate. The background distribution is then subtracted from the raw distribution obtained from tracks in the jet cone. The use of this procedure is the reason why jets in the region $|\eta| < 0.3$ are excluded to avoid overlap between the signal jet region and the region used for background estimation.

C. Fragmentation function biases

The measured fragmentation function contains two sources of bias introduced by the jet reconstruction. The first bias results from jet reconstruction in the presence of a high-multiplicity background. As a result of the steeply falling jet spectrum, a significant fraction of reconstructed jets that just barely exceed the minimum p_T threshold come from the more abundant lower-energy jets enhanced by an upward fluctuation in the background. The second bias is caused by the jet reconstruction being correlated with the jet's fragmentation pattern. Jets which fragment harder, i.e., those that produce fewer particles but with higher average p_T, are easier to reconstruct and have a slightly higher energy scale.

Both biases are corrected for in the final analysis. The biases affect different parts of the fragmentation function and are assumed to be independent. The correction factors are individually derived based on the PYTHIA + HYDJET simulation. The first bias is corrected by comparing the estimated background in the reflected cone to the true background in the jet cone. A correction factor is then derived based on the ratio of the two and used to weight tracks in the background cone. The correction is computed as a function of track p_T and applied to events in the two highest analysis centrality classes where background tracks dominate over the signal tracks at low p_T. An important element of this MC-based technique is the fact that the tracks in the background cone have very similar fluctuations (i.e., similar variations in background energy) in the simulated heavy-ion events and in the data. The second bias is corrected by comparing the true fragmentation function of reconstructed jets in PYTHIA signal events and PYTHIA + HYDJET events. A ratio is derived based on the two and used to weight tracks in the *pp* jet cone so that the *pp* reference data can be consistently compared with PbPb. This correction is cross-checked by repeating the full analysis for different kinds of signal events with embedded jets, as described in Sec. VII.

D. Proton-proton reference data

In order to quantify any medium-related effects, the results are compared to reference distributions using the high-statistics jet data in *pp* collisions collected in 2013 at $\sqrt{s_{NN}} = 2.76$ TeV corresponding to an integrated luminosity of 5.3 ± 0.2 pb^{-1}. For a direct comparison between *pp* and PbPb collisions, the jet momentum resolution deterioration in PbPb events has to be taken into account. For this purpose, the reconstructed p_T of every jet in the *pp* data is smeared using a Gaussian distribution based on the quadratic difference of the jet momentum resolution in PbPb and *pp* data. The jet momentum resolutions are derived from the PbPb and *pp* MC simulations described in Sec. IV. In order to keep the jet kinematic constraints consistent, a reweighting factor, derived based on the ratio of the PbPb and the smeared *pp* jet p_T spectra, is applied to each *pp* jet. After the reweighting procedure, the resulting *pp* jet p_T distribution matches the one in PbPb in each centrality bin of the analysis.

VII. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties are primarily due to the tracking efficiency estimation, jet reconstruction, subtraction of the underlying background, and differences between MC simulations and data.

One systematic uncertainty arising from the tracking efficiency and rate of reconstructing misidentified (fake) tracks is estimated using the Monte Carlo simulations. This uncertainty is based on the comparison of the fragmentation function obtained by corrected, reconstructed tracks with those obtained using the generator-level particles. In both cases, the same (i.e., matched) reconstructed and generated jets are used. An additional 10% tracking efficiency uncertainty is assigned to account for the effects found in a study of the charge composition of reconstructed jets. Specifically, the observed charged fraction of a jet (as determined using the PF objects within the jet) decreases within the more central collisions with a 10% difference between central and peripheral heavy-ion data (the latter being very similar to *pp* data and the MC results). The difference in charge fraction between central and peripheral MC events is less than 2%. It is possible that this change is due to physics. However, to be conservative, a value of 10% is used as an estimate of a possible tracking inefficiency in high-multiplicity PbPb events that is possibly not reproduced by PYTHIA + HYDJET. The estimated uncertainty ranges from 0% for peripheral events to 10% for the most central events.

The fragmentation function is also sensitive to uncertainties in the jet reconstruction in two aspects: the smearing of jet energy due to resolution and the overall energy scale. In order to estimate the effects of the jet energy resolution, a fragmentation function is constructed from the same PbPb data but with the jet energy artificially modified by smearing with the additional jet energy resolution due to the underlying event. Comparison of the fragmentation function with and without modified jet energies is used to estimate the impact of these underlying event fluctuations. The full difference found between the two fragmentation functions is assigned as a systematic uncertainty. The uncertainty due to the jet energy scale is estimated by varying the energy of jets in the PbPb data by 5%. This factor is determined using a quadratic sum of the following three contributions. The uncertainty in the jet energy scale in *pp* data was found to be 2%–3% [35]. Comparing jet energies in reconstructed PYTHIA + HYDJET events to the generator-level values showed a variation of about 1%. As will be shown in Sec. VIII, the observed modification in the PbPb fragmentation function is largely characterized by an excess of particles with $p_T < 3$ GeV/c ($\langle p_T \rangle = 1.4$ GeV/c). The jet energy corrections used in the analysis are found using MC jets lacking these additional low-p_T particles. The impact of this effect was studied by inserting extra particles in the $1 < p_T < 2$ GeV/c range to the PYTHIA + HYDJET simulated jets. The ratio of reconstructed over generator-level fragmentation functions is found to vary by about 4% from the ratio found without extra embedded particles. The impact of the uncertainties due to the jet energy scale and resolution are different, since the scale uncertainty shifts all jet p_T values in the same direction, and the p_T shift due to resolution can be larger than that due to the scale uncertainty. The resulting changes in the fragmentation function depend on both the bin width in p_T^{jet} and the range of p_T^{track} that corresponds to a given bin in ξ. Thus, the fragmentation function uncertainties are a somewhat complex function of p_T^{jet} and ξ.

To estimate the uncertainty in the underlying-event background subtraction, the fragmentation function analysis is repeated with an alternative background subtraction using mixed events. This method estimates the background contribution to the fragmentation function using minimum-bias PbPb data. For each jet in a signal event, tracks around the (η,ϕ) position of the jet are taken from a separate minimum-bias event. The total p_T of these tracks constitutes the "mixed-event" background. The full difference between the two background-subtraction methods is quoted conservatively as the uncertainty in the fragmentation function due to background subtraction. Furthermore, due to the requirement of a minimum reconstructed jet energy, jets sitting on top of an upward background fluctuation are more likely to be selected. In MC events, it is known precisely which particles are from the underlying event and which are from the hard scattering signal, and therefore a correction for the impact of this effect on the default (η-reflected cone) background subtraction can be extracted. It is possible that the point-to-point underlying event fluctuations are slightly different between data and the MC. To account for this possibility, half of the size of the applied correction is quoted as a systematic uncertainty.

Finally, to estimate the effect of the signal jets in data having a different fragmentation pattern than jets in simulations, different types of signal jets are embedded into simulated heavy-ion events. Systematic uncertainties are quoted based on the difference between the reconstructed fragmentation functions with embedded gluon and quark jets.

The individual systematic uncertainties are added in quadrature to form the total systematic uncertainty. This is summarized in Table I. The quoted systematic uncertainty band is cross-checked by repeating the complete analysis with PYTHIA + HYDJET corrections applied to reconstructed events in which quenched jets generated using PYQUEN [27] are embedded. The reconstructed fragmentation function from

TABLE I. Summary of systematic uncertainties in jet fragmentation function analysis in bins of ξ for the 0%–10% centrality. The values indicate the typical values of the systematic uncertainties and the intervals indicate the range of systematic uncertainties for various ranges of ξ.

Item	Input/variation	$\xi < 1.5$			
Jet p_T range (GeV/c)		100–120	120–150	150–300	100–300
Jet energy resolution	10%–20% smearing	3.7%–6.7%	2%–6.2%	3.9%–6.9%	0.1%–0.7%
Jet energy scale	5% shift	9.3%–29%	8.5%–26%	7.9%–25%	8.9%–28%
Tracking efficiency	Nonclosure	0.1%–1.9%			
Tracking efficiency	Centrality variation	10%			
Background bias	50% of correction	<0.1%			
Background procedure	Difference between methods	1.9%–4.3%			
Gluon jet cross-check	Nonclosure	1.2%–3.9%			
Quark jet cross-check	Nonclosure	4.8%–9.8%			
Total		15%–28%	14%–37%	14%–20%	15%–31%
Item	Input/variation	$1.5 < \xi < 4$			
Jet p_T range (GeV/c)		100–120	120–150	150–300	100–300
Jet energy resolution	10%–20% smearing	0.1%–2.7%	1.1%–1.4%	0%–1.9%	0.1%–1.0%
Jet energy scale	5% shift	1.6%–4.8%	1.4%–4.4%	1.3%–4.1%	1.5%–4.6%
Tracking efficiency	Nonclosure	0.1%–0.7%			
Tracking efficiency	Centrality variation	10%			
Background bias	50% of correction	0%–3.3%			
Background procedure	Difference between methods	0%–2.7%			
Gluon jet cross-check	Nonclosure	3.8%–5.0%			
Quark jet cross-check	Nonclosure	0.2%–2.0%			
Total		11%–14%	11%–13%	11%–13%	11%–12%
Item	Input/variation	$4 < \xi < 5$			
Jet p_T range (GeV/c)		100–120	120–150	150–300	100–300
Jet energy resolution	10%–20% smearing	0.2%–0.6%	0.7%	1.0%–5.1%	1.7%–2.5%
Jet energy scale	5% shift	0.21%–2.9%	0.19%–2.7%	0.18%–2.5%	0.2%–2.8%
Tracking efficiency	Nonclosure	0.2%–1.6%			
Tracking efficiency	Centrality variation	10%			
Background bias	50% of correction	8.1%–8.8%			
Background procedure	Diff. between methods	3.8%–4.9%			
Gluon jet cross-check	Nonclosure	1.1%–4.2%			
Quark jet cross-check	Nonclosure	1.5%–4.5%			
Total		19%–26%	16%–17%	17%–23%	14%–16%

this study is consistent with the generator truth within the quoted systematic uncertainties.

VIII. RESULTS

Figure 1 shows the fragmentation function reconstructed in PbPb data and pp reference for $100 < p_T^{\mathrm{jet}} < 300$ GeV/c

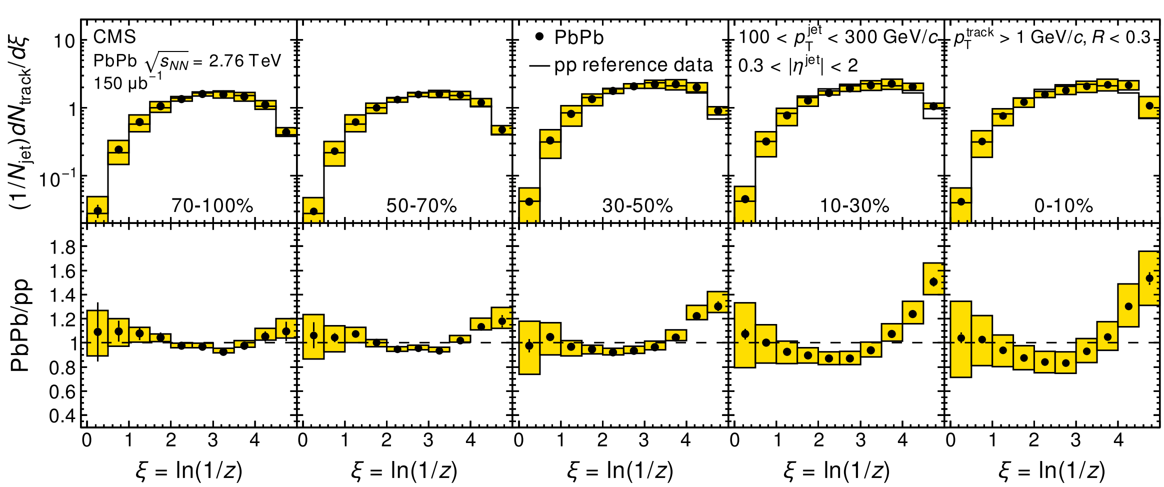

FIG. 1. (Color online) (Top) The PbPb fragmentation function in bins of centrality (increasing from left to right) overlaid with pp reference data. Jets have $100 < p_T < 300$ GeV/c, and tracks have $p_T > 1$ GeV/c. (Bottom) The ratio of each PbPb fragmentation function to its pp reference. Error bars are statistical, and boxes show the systematic uncertainty.

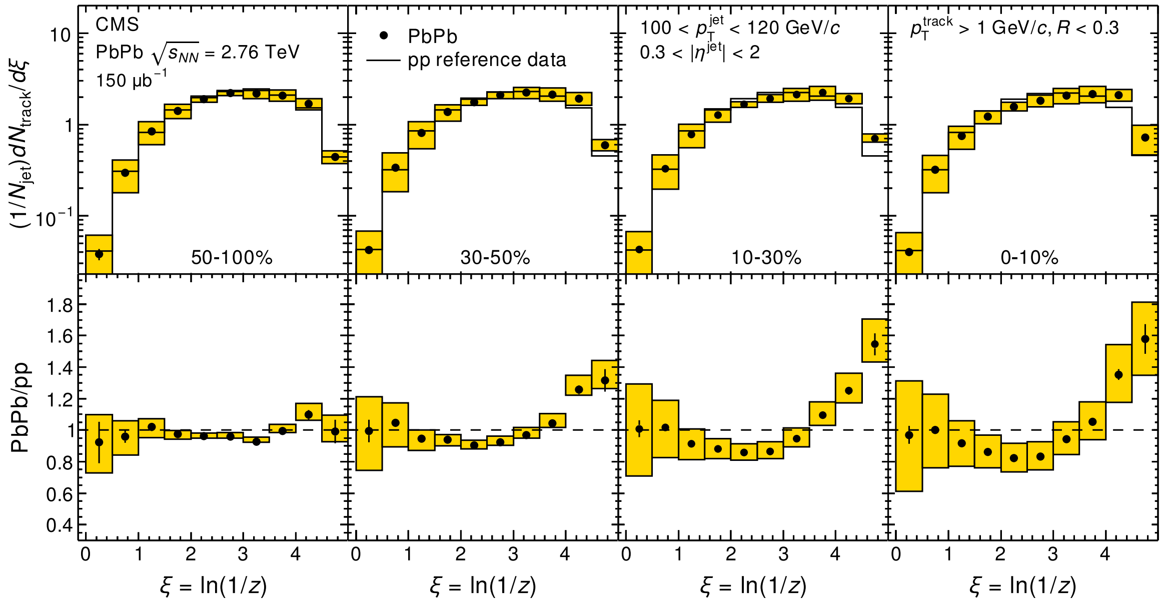

FIG. 2. (Color online) (Top) The PbPb fragmentation function in bins of centrality (increasing from left to right) overlaid with *pp* reference data. Jets have $100 < p_T < 120$ GeV/c, and tracks have $p_T > 1$ GeV/c. (Bottom) The ratio of each PbPb fragmentation function to its *pp* reference. Error bars are statistical, and boxes show the systematic uncertainty.

and tracks with p_T above 1 GeV/c within a radius of 0.3 relative to the corresponding jet axis. For the PbPb fragmentation function, the contribution from the underlying event is subtracted using the η reflection method. For the *pp* reference data, the corresponding jet distribution is first smeared with the additional PbPb jet resolution due to the underlying event, and then reweighted to match the jet p_T distribution in PbPb data. Figures 2–4 show the same fragmentation function differentially in jet p_T, for $100 < p_T^{jet} < 120$ GeV/c, $120 < p_T^{jet} < 150$ GeV/c, and $150 < p_T^{jet} < 300$ GeV/c, respectively. In the higher statistics Fig. 1, we retained the same 50%–70% and 70%–100% centrality binning from [19].

It is clear from the results in Figs. 1–4 that the modification of the fragmentation function of jets in PbPb compared to those in *pp* grows with increasingly central collision. In the 50%–100% bin, the ratio of PbPb/*pp* is almost flat at unity within the systematic uncertainties, which means no modification. However, a significant excess at high ξ (low track p_T) is

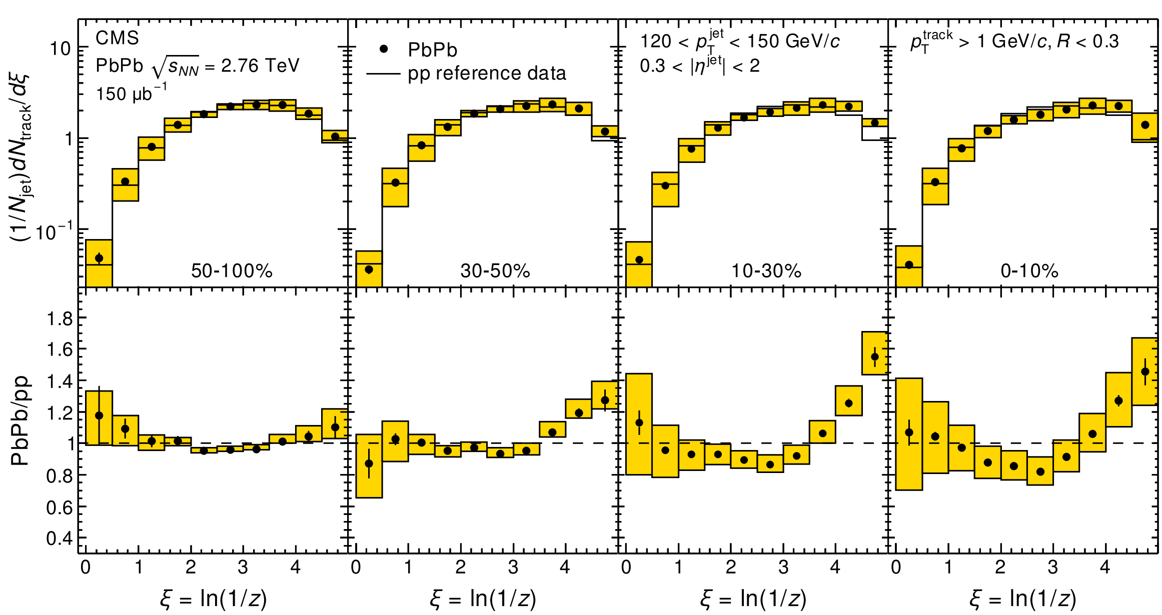

FIG. 3. (Color online) (Top) The PbPb fragmentation function in bins of centrality (increasing from left to right) overlaid with *pp* reference data. Jets have $120 < p_T < 150$ GeV/c, and tracks have $p_T > 1$ GeV/c. (Bottom) The ratio of each PbPb fragmentation function to its *pp* reference. Error bars are statistical, and boxes show the systematic uncertainty.

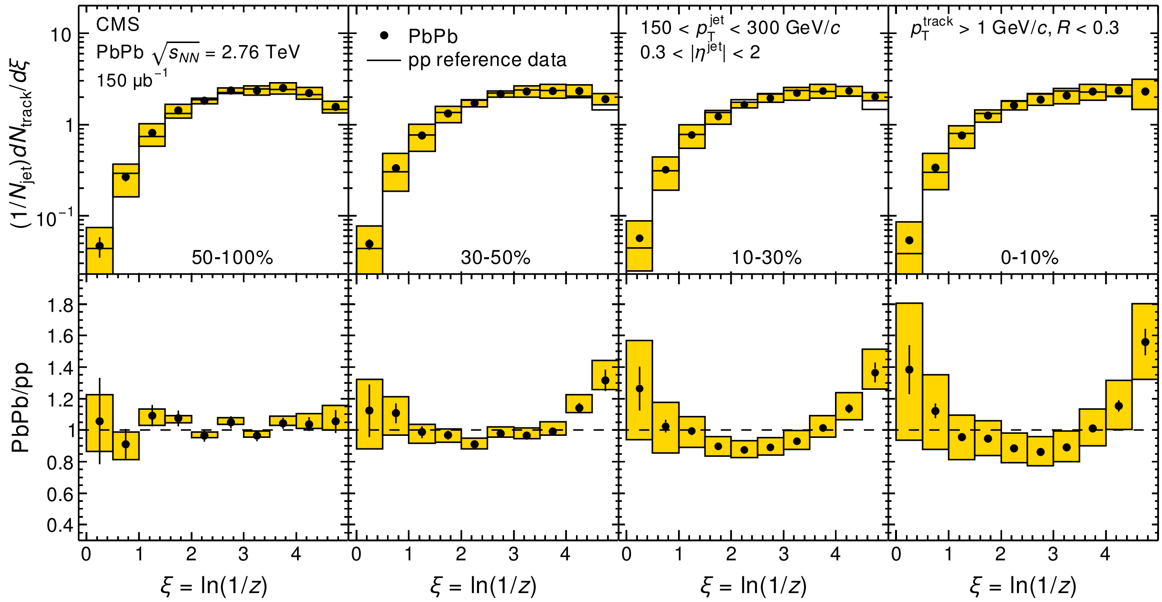

FIG. 4. (Color online) (Top) The PbPb fragmentation function in bins of centrality (increasing from left to right) overlaid with *pp* reference data. Jets have $150 < p_T < 300$ GeV/c, and tracks have $p_T > 1$ GeV/c. (Bottom) The ratio of each PbPb fragmentation function to its *pp* reference. Error bars are statistical, and boxes show the systematic uncertainty.

observed for more central events, combined with a depletion in the intermediate ξ. In the most central 0%–10% collisions and for the lowest charged-particle momenta studied, the PbPb/*pp* fragmentation function ratio rises to ∼1.5. This implies that for central collisions the spectrum of particles in a jet has an enhanced contribution of soft particles compared to that from *pp* collisions. No significant dependence of the modification on p_T^{jet} is observed within our current statistical and systematic uncertainties.

Possible sources of the observed modifications to the fragmentation function in central PbPb collisions include a change in the fraction of jets arising from either quarks or gluons, a change in the parton shower due to the medium [13–17], or the presence of particles resulting from the medium response. The fragmentation patterns of pure quarks and partons are predicted by PYTHIA to be significantly different. If traversing the medium has a bigger impact on gluons, as might be expected given their larger color charge compared to quarks, this change in the admixture of the two parton types would change the measured fragmentation function. The distinction between the second and third listed possibilities may or may not be valid depending on the specifics of the physical processes responsible for jet quenching. More detailed experimental and theoretical analysis will be required

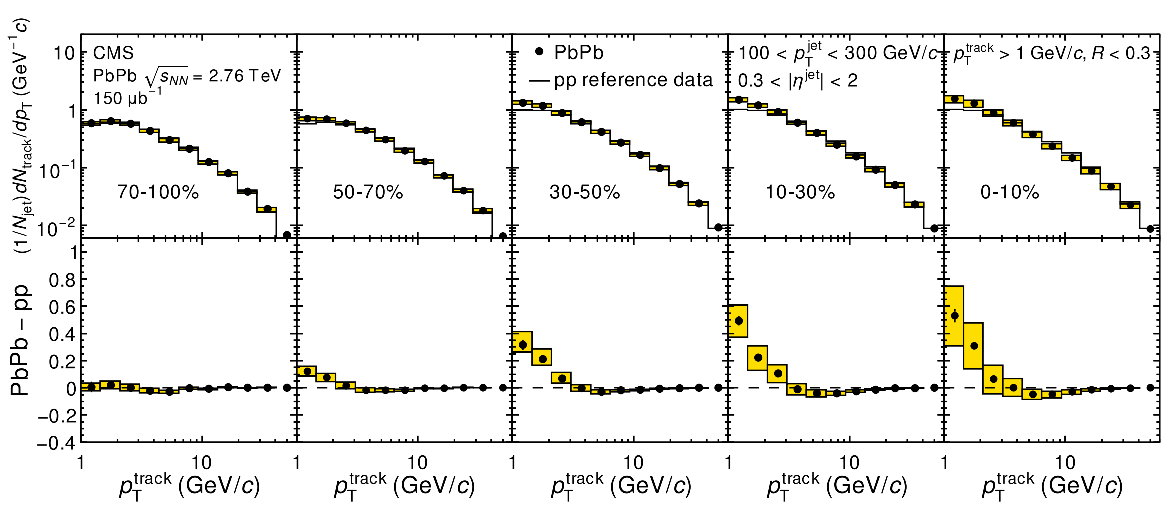

FIG. 5. (Color online) The spectrum of tracks inside the cone of jets with $100 < p_T^{jet} < 300$ GeV/c, as a function of track p_T, for PbPb (with increasing centrality from left to right) and *pp*. Both the PbPb and *pp* results are background subtracted, in the same manner as for the fragmentation function. The bottom panels show the difference of PbPb and *pp* spectra, demonstrating an excess of low-p_T tracks in the PbPb events.

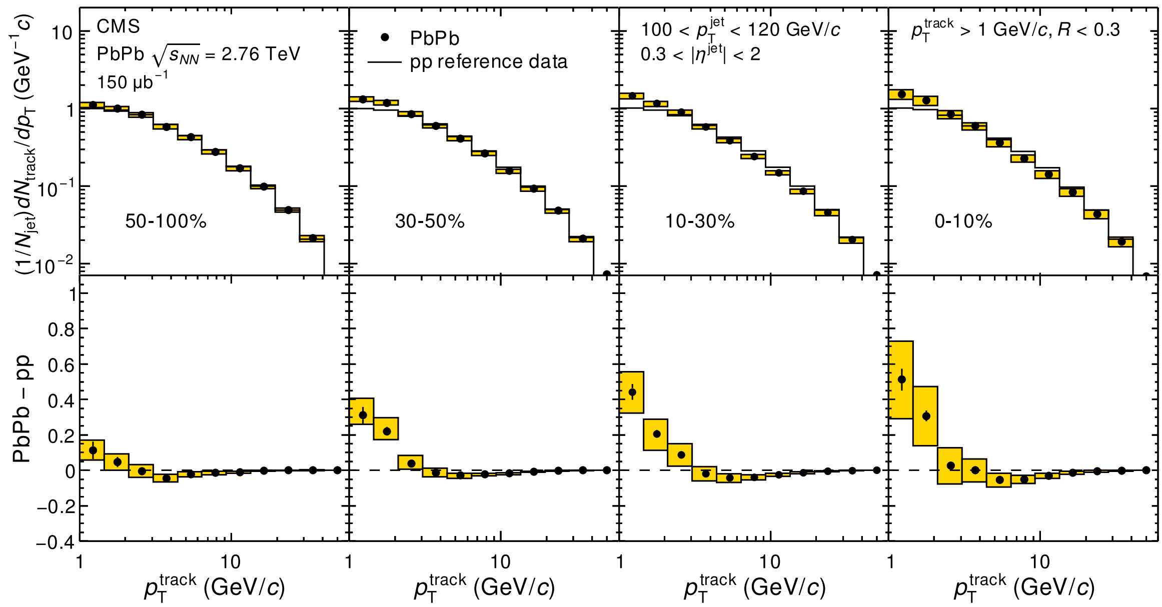

FIG. 6. (Color online) The spectrum of tracks inside the cone of jets with $100 < p_T^{jet} < 120$ GeV/c, as a function of track p_T, for PbPb (with increasing centrality from left to right) and pp. Both the PbPb and pp results are background subtracted, in the same manner as for the fragmentation function. The bottom panels show the difference of PbPb and pp spectra, demonstrating an excess of low-p_T tracks in the PbPb events.

to attempt to separate the influence of these, and possibly other, contributions to the observed effects.

One can further investigate in which track p_T ranges the fragmentation function exhibits an excess by examining the p_T spectra for tracks inside the jet cone. These distributions are obtained with the same background subtraction described above. Figure 5 shows the spectra of tracks in the jet cone compared to pp reference data. In order to quantify the excess of tracks at a given p_T, the bottom panels show the difference of the two distributions, pp subtracted from PbPb. Figures 6–8 show the same differentially in p_T^{jet}, for $100 < p_T^{jet} < 120$ GeV/c, $120 < p_T^{jet} < 150$ GeV/c, and $150 < p_T^{jet} < 300$ GeV/c, respectively. The excess that is observed at the high-ξ region of the fragmentation function

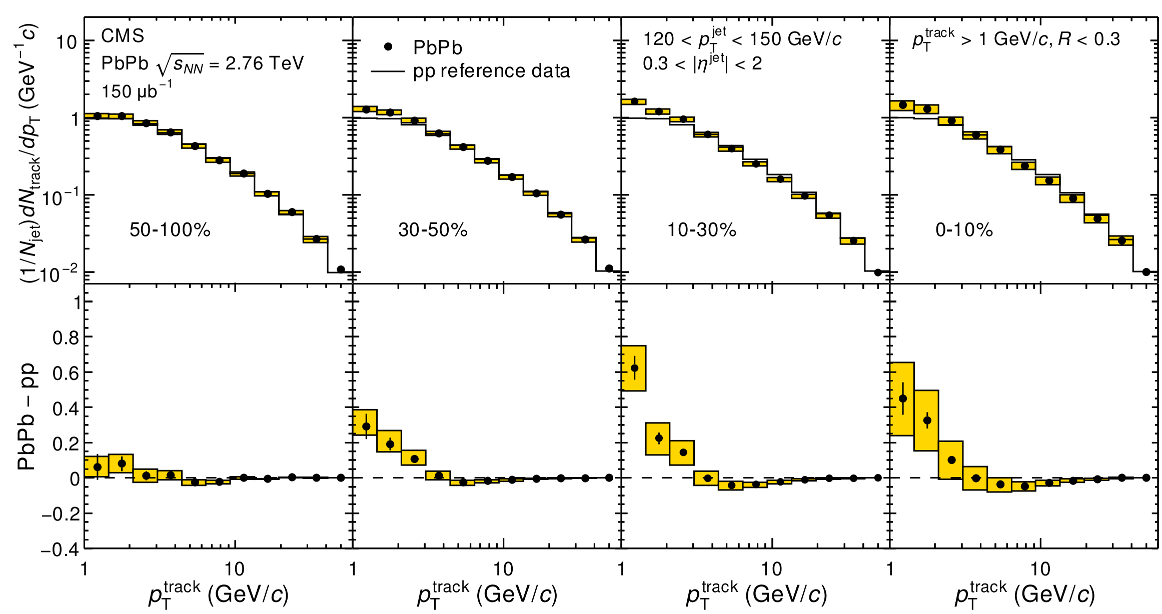

FIG. 7. (Color online) The spectrum of tracks inside the cone of jets with $120 < p_T^{jet} < 150$ GeV/c, as a function of track p_T, for PbPb (with increasing centrality from left to right) and pp. Both the PbPb and pp results are background subtracted, in the same manner as for the fragmentation function. The bottom panels show the difference of PbPb and pp spectra, demonstrating an excess of low-p_T tracks in the PbPb events.

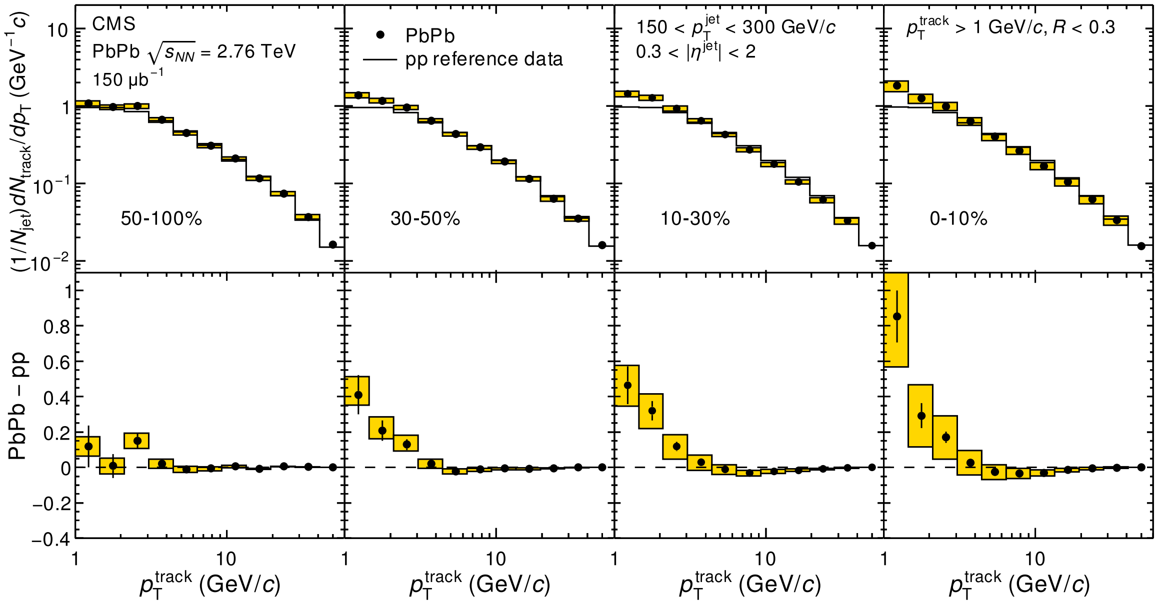

FIG. 8. (Color online) The spectrum of tracks inside the cone of jets with $150 < p_T^{jet} < 300$ GeV/c, as a function of track p_T, for PbPb (with increasing centrality from left to right) and pp. Both the PbPb and pp results are background subtracted, in the same manner as for the fragmentation function. The bottom panels show the difference of PbPb and pp spectra, demonstrating an excess of low-p_T tracks in the PbPb events.

is localized at low p_T for tracks (p_T below $\approx$3 GeV/c). No pronounced jet p_T dependence of this excess is observed within the current statistical and systematic uncertainties.

Figures 1–4 also show some evidence for a very weak suppression in the intermediate region, $\xi \approx 1.5$–3.0. This corresponds to the weak suppression seen in Figs. 5–8 around $p_T \approx 6$ GeV/c. Since summing the p_T of all included tracks cannot exceed the total jet p_T, it is impossible to have significantly more tracks in one p_T range without having fewer in another range. However, fewer tracks are required at high p_T to satisfy this summed-momentum restriction. While some depletion is observed, the uncertainties in the current results preclude a precise determination of the p_T range from which the excess low-p_T tracks originate.

IX. SUMMARY

The fragmentation function of inclusive jets in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV has been measured. Jets were reconstructed using the anti-k_T algorithm with a distance parameter of 0.3.

For the analysis, inclusive jets with $p_T^{jet} > 100$ GeV/c and $0.3 < |\eta_{jet}| < 2$ were reconstructed using particle-flow objects, which combine information from charged-particle tracking and calorimetry. The jet fragmentation function in a cone of 0.3 was obtained using charged particles with $p_T >$ 1 GeV/c and $|\eta| < 2.4$, and as a function of collision centrality for five centrality selections, 70%–100%, 50%–70%, 30%–50%, 10%–30%, and 0%–10%. The uncorrelated contribution from the underlying event to the charged-particle distribution in the cone was subtracted using an "η-reflected cone" method. The fragmentation function in PbPb collisions was compared to measurements with the same selection in pp collisions at the same center-of-mass energy. For this comparison, a jet momentum smearing and reweighting procedure was applied to obtain a proper pp-based reference.

For the 70%–100% most peripheral collisions, the fragmentation function in PbPb collisions agrees with that for the pp reference. For more central collisions, a significant modification of the fragmentation function in PbPb compared to pp in the intermediate- and high-ξ region develops. For charged particles in the region of 1–3 GeV/c, corresponding to ξ above about 3.5, a clear rise in the ratio of PbPb to pp is observed. In the intermediate-p_T range of fragmentation products, ξ between 2 and 3, evidence is seen for a small depletion in the ratio. In the most central 0%–10% collisions and for the lowest charged particle momenta studied, the PbPb/pp fragmentation function ratio rises to $\approx$1.6. For the current jet kinematic range, no significant variation of the modification with jet p_T is observed within the statistical and systematic uncertainties.

By including charged particles at lower p_T than the previous CMS measurement, a clear centrality-dependent modification of the inclusive jet fragmentation function in PbPb collisions is now revealed. As fragmentation at larger radii from the jet axis is dominated by low-p_T particles, this is consistent with the enhancement seen in Ref. [19]. The interplay between the modifications in the high-p_T and low-p_T parts of the fragmentation function provides constraints on models of medium-induced energy loss and opens up new avenues to understand the transport properties of the QGP.

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[1] E. V. Shuryak, Sov. Phys. JETP **47**, 212 (1978).
[2] J. C. Collins and M. J. Perry, Phys. Rev. Lett. **34**, 1353 (1975).
[3] N. Cabibbo and G. Parisi, Phys. Lett. B **59**, 67 (1975).
[4] B. A. Freedman and L. D. McLerran, Phys. Rev. D **16**, 1169 (1977).
[5] J. D. Björken, FERMILAB-PUB-82-059-THY, 1982.
[6] K. Adcox *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **88**, 022301 (2002).
[7] C. Adler *et al.* (STAR Collaboration), Phys. Rev. Lett. **89**, 202301 (2002).
[8] CMS Collaboration, Eur. Phys. J. C **72**, 1945 (2012).
[9] ATLAS Collaboration, Phys. Rev. Lett. **105**, 252303 (2010).
[10] CMS Collaboration, Phys. Rev. C **84**, 024906 (2011).
[11] CMS Collaboration, Phys. Lett. B **712**, 176 (2012).
[12] CMS Collaboration, Phys. Lett. B **718**, 773 (2013).
[13] X.-N. Wang and X. Guo, Nucl. Phys. A **696**, 788 (2001).
[14] T. Renk, Phys. Rev. C **78**, 034908 (2008).
[15] T. Renk, Phys. Rev. C **79**, 054906 (2009).
[16] N. Armesto, L. Cunqueiro, and C. A. Salgado, Eur. Phys. J. C **63**, 679 (2009).
[17] W.-T. Deng and X.-N. Wang, Phys. Rev. C **81**, 024902 (2010).
[18] CMS Collaboration, J. High Energy Phys. 10 (2012) 087.
[19] CMS Collaboration, Phys. Lett. B **730**, 243 (2014).
[20] CMS Collaboration, J. Instrum. **8**, P09009 (2013).
[21] CMS Collaboration, J. Instrum. **5**, T03012 (2010).

[22] S. Abdullin *et al.* (CMS Collaboration), Eur. Phys. J. C **60**, 359 (2009).
[23] CMS Collaboration, J. Instrum. **3**, S08004 (2008).
[24] T. Sjöstrand, S. Mrenna, and P. Skands, J. High Energy Phys. 05 (2006) 026.
[25] R. Field, arXiv:1010.3558 [hep-ph].
[26] S. Agostinelli *et al.* (GEANT4), Nucl. Instrum. Methods A **506**, 250 (2003).
[27] I. P. Lokhtin and A. M. Snigirev, Eur. Phys. J. C **45**, 211 (2006).
[28] CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009, http://cdsweb.cern.ch/record/1194487.
[29] CMS Collaboration, CMS Physics Analysis Summary CMS-PAS-PFT-10-002, 2010, http://cdsweb.cern.ch/record/1279341.
[30] O. Kodolova, I. Vardanian, A. Nikitenko, and A. Oulianov, Eur. Phys. J. C **50**, 117 (2007).
[31] CMS Collaboration, Eur. Phys. J. C **70**, 1165 (2010).
[32] T. Affolder *et al.* (CDF Collaboration), Phys. Rev. D **64**, 032001 (2001).
[33] F. Abe *et al.* (CDF Collaboration), Phys. Rev. Lett. **65**, 968 (1990).
[34] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **68**, 012003 (2003).
[35] CMS Collaboration, J. Instrum. **6**, P11002 (2011).

S. Chatrchyan,[1] V. Khachatryan,[1] A. M. Sirunyan,[1] A. Tumasyan,[1] W. Adam,[2] T. Bergauer,[2] M. Dragicevic,[2] J. Erö,[2] C. Fabjan,[2,a] M. Friedl,[2] R. Frühwirth,[2,a] V. M. Ghete,[2] C. Hartl,[2] N. Hörmann,[2] J. Hrubec,[2] M. Jeitler,[2,a] W. Kiesenhofer,[2] V. Knünz,[2] M. Krammer,[2,a] I. Krätschmer,[2] D. Liko,[2] I. Mikulec,[2] D. Rabady,[2,b] B. Rahbaran,[2] H. Rohringer,[2] R. Schöfbeck,[2] J. Strauss,[2] A. Taurok,[2] W. Treberer-Treberspurg,[2] W. Waltenberger,[2] C.-E. Wulz,[2,a] V. Mossolov,[3] N. Shumeiko,[3] J. Suarez Gonzalez,[3] S. Alderweireldt,[4] M. Bansal,[4] S. Bansal,[4] T. Cornelis,[4] E. A. De Wolf,[4] X. Janssen,[4] A. Knutsson,[4] S. Luyckx,[4] L. Mucibello,[4] S. Ochesanu,[4] B. Roland,[4] R. Rougny,[4] H. Van Haevermaet,[4] P. Van Mechelen,[4] N. Van Remortel,[4] A. Van Spilbeeck,[4] F. Blekman,[5] S. Blyweert,[5] J. D'Hondt,[5] N. Heracleous,[5] A. Kalogeropoulos,[5] J. Keaveney,[5] T. J. Kim,[5] S. Lowette,[5] M. Maes,[5] A. Olbrechts,[5] D. Strom,[5] S. Tavernier,[5] W. Van Doninck,[5] P. Van Mulders,[5] G. P. Van Onsem,[5] I. Villella,[5] C. Caillol,[6] B. Clerbaux,[6] G. De Lentdecker,[6] L. Favart,[6] A. P. R. Gay,[6] A. Léonard,[6] P. E. Marage,[6] A. Mohammadi,[6] L. Perniè,[6] T. Reis,[6] T. Seva,[6] L. Thomas,[6] C. Vander Velde,[6] P. Vanlaer,[6] J. Wang,[6] V. Adler,[7] K. Beernaert,[7] L. Benucci,[7] A. Cimmino,[7] S. Costantini,[7] S. Dildick,[7] G. Garcia,[7] B. Klein,[7] J. Lellouch,[7] J. Mccartin,[7] A. A. Ocampo Rios,[7] D. Ryckbosch,[7] S. Salva Diblen,[7] M. Sigamani,[7] N. Strobbe,[7] F. Thyssen,[7] M. Tytgat,[7] S. Walsh,[7] E. Yazgan,[7] N. Zaganidis,[7] S. Basegmez,[8] C. Beluffi,[8,c] G. Bruno,[8] R. Castello,[8] A. Caudron,[8] L. Ceard,[8] G. G. Da Silveira,[8] C. Delaere,[8] T. du Pree,[8] D. Favart,[8] L. Forthomme,[8] A. Giammanco,[8,d] J. Hollar,[8] P. Jez,[8] M. Komm,[8] V. Lemaitre,[8] J. Liao,[8] O. Militaru,[8] C. Nuttens,[8] D. Pagano,[8] A. Pin,[8] K. Piotrzkowski,[8] A. Popov,[8,e] L. Quertenmont,[8] M. Selvaggi,[8] M. Vidal Marono,[8] J. M. Vizan Garcia,[8] N. Beliy,[9] T. Caebergs,[9] E. Daubie,[9] G. H. Hammad,[9] G. A. Alves,[10] M. Correa Martins Junior,[10] T. Dos Reis Martins,[10] M. E. Pol,[10] M. H. G. Souza,[10] W. L. Aldá Júnior,[11] W. Carvalho,[11] J. Chinellato,[11,f] A. Custódio,[11] E. M. Da Costa,[11] D. De Jesus Damiao,[11] C. De Oliveira Martins,[11] S. Fonseca De Souza,[11] H. Malbouisson,[11] M. Malek,[11] D. Matos Figueiredo,[11] L. Mundim,[11] H. Nogima,[11] W. L. Prado Da Silva,[11] J. Santaolalla,[11] A. Santoro,[11] A. Sznajder,[11] E. J. Tonelli Manganote,[11,f] A. Vilela Pereira,[11] C. A. Bernardes,[12b] F. A. Dias,[12a,g] T. R. Fernandez Perez Tomei,[12a] E. M. Gregores,[12b] P. G. Mercadante,[12b] S. F. Novaes,[12a] Sandra S. Padula,[12a] V. Genchev,[13,b] P. Iaydjiev,[13,b] A. Marinov,[13] S. Piperov,[13] M. Rodozov,[13] G. Sultanov,[13] M. Vutova,[13] A. Dimitrov,[14] I. Glushkov,[14] R. Hadjiiska,[14] V. Kozhuharov,[14] L. Litov,[14] B. Pavlov,[14] P. Petkov,[14] J. G. Bian,[15] G. M. Chen,[15] H. S. Chen,[15] M. Chen,[15] R. Du,[15] C. H. Jiang,[15] D. Liang,[15] S. Liang,[15] X. Meng,[15] R. Plestina,[15,h] J. Tao,[15] X. Wang,[15] Z. Wang,[15] C. Asawatangtrakuldee,[16] Y. Ban,[16] Y. Guo,[16] Q. Li,[16] W. Li,[16] S. Liu,[16] Y. Mao,[16] S. J. Qian,[16] D. Wang,[16] L. Zhang,[16] W. Zou,[16] C. Avila,[17] C. A. Carrillo Montoya,[17] L. F. Chaparro Sierra,[17] C. Florez,[17] J. P. Gomez,[17] B. Gomez Moreno,[17] J. C. Sanabria,[17] N. Godinovic,[18] D. Lelas,[18] D. Polic,[18] I. Puljak,[18] Z. Antunovic,[19] M. Kovac,[19] V. Brigljevic,[20] K. Kadija,[20] J. Luetic,[20] D. Mekterovic,[20] S. Morovic,[20] L. Sudic,[20] A. Attikis,[21] G. Mavromanolakis,[21] J. Mousa,[21] C. Nicolaou,[21] F. Ptochos,[21] P. A. Razis,[21] M. Finger,[22] M. Finger Jr.,[22] A. A. Abdelalim,[23,i] Y. Assran,[23,j] S. Elgammal,[23,k] A. Ellithi Kamel,[23,l] M. A. Mahmoud,[23,m] A. Radi,[23,n] M. Kadastik,[24] M. Müntel,[24] M. Murumaa,[24] M. Raidal,[24] L. Rebane,[24] A. Tiko,[24] P. Eerola,[25] G. Fedi,[25] M. Voutilainen,[25] J. Härkönen,[26] V. Karimäki,[26] R. Kinnunen,[26] M. J. Kortelainen,[26] T. Lampén,[26] K. Lassila-Perini,[26] S. Lehti,[26] T. Lindén,[26] P. Luukka,[26] T. Mäenpää,[26] T. Peltola,[26] E. Tuominen,[26] J. Tuominiemi,[26] E. Tuovinen,[26] L. Wendland,[26] T. Tuuva,[27] M. Besancon,[28] F. Couderc,[28] M. Dejardin,[28] D. Denegri,[28] B. Fabbro,[28] J. L. Faure,[28] F. Ferri,[28] S. Ganjour,[28] A. Givernaud,[28] P. Gras,[28] G. Hamel de Monchenault,[28] P. Jarry,[28] E. Locci,[28] J. Malcles,[28] A. Nayak,[28] J. Rander,[28] A. Rosowsky,[28] M. Titov,[28] S. Baffioni,[29] F. Beaudette,[29] P. Busson,[29] C. Charlot,[29] N. Daci,[29] T. Dahms,[29] M. Dalchenko,[29] L. Dobrzynski,[29] A. Florent,[29] R. Granier de Cassagnac,[29] P. Miné,[29] C. Mironov,[29] I. N. Naranjo,[29] M. Nguyen,[29] C. Ochando,[29] P. Paganini,[29] D. Sabes,[29] R. Salerno,[29] J. B. Sauvan,[29] Y. Sirois,[29] C. Veelken,[29] Y. Yilmaz,[29] A. Zabi,[29] J.-L. Agram,[30,o] J. Andrea,[30] D. Bloch,[30] J.-M. Brom,[30] E. C. Chabert,[30] C. Collard,[30] E. Conte,[30,o] F. Drouhin,[30,o] J.-C. Fontaine,[30,o] D. Gelé,[30] U. Goerlach,[30] C. Goetzmann,[30] P. Juillot,[30] A.-C. Le Bihan,[30] P. Van Hove,[30] S. Gadrat,[31] S. Beauceron,[32] N. Beaupere,[32] G. Boudoul,[32] S. Brochet,[32] J. Chasserat,[32] R. Chierici,[32] D. Contardo,[32,b] P. Depasse,[32] H. El Mamouni,[32] J. Fan,[32] J. Fay,[32] S. Gascon,[32] M. Gouzevitch,[32] B. Ille,[32] T. Kurca,[32] M. Lethuillier,[32] L. Mirabito,[32] S. Perries,[32] J. D. Ruiz Alvarez,[32] L. Sgandurra,[32] V. Sordini,[32] M. Vander Donckt,[32] P. Verdier,[32] S. Viret,[32] H. Xiao,[32] Z. Tsamalaidze,[33,p] C. Autermann,[34] S. Beranek,[34]

M. Bontenackels,[34] B. Calpas,[34] M. Edelhoff,[34] L. Feld,[34] O. Hindrichs,[34] K. Klein,[34] A. Ostapchuk,[34] A. Perieanu,[34] F. Raupach,[34] J. Sammet,[34] S. Schael,[34] D. Sprenger,[34] H. Weber,[34] B. Wittmer,[34] V. Zhukov,[34,e] M. Ata,[35] J. Caudron,[35] E. Dietz-Laursonn,[35] D. Duchardt,[35] M. Erdmann,[35] R. Fischer,[35] A. Güth,[35] T. Hebbeker,[35] C. Heidemann,[35] K. Hoepfner,[35] D. Klingebiel,[35] S. Knutzen,[35] P. Kreuzer,[35] M. Merschmeyer,[35] A. Meyer,[35] M. Olschewski,[35] K. Padeken,[35] P. Papacz,[35] H. Reithler,[35] S. A. Schmitz,[35] L. Sonnenschein,[35] D. Teyssier,[35] S. Thüer,[35] M. Weber,[35] V. Cherepanov,[36] Y. Erdogan,[36] G. Flügge,[36] H. Geenen,[36] M. Geisler,[36] W. Haj Ahmad,[36] F. Hoehle,[36] B. Kargoll,[36] T. Kress,[36] Y. Kuessel,[36] J. Lingemann,[36,b] A. Nowack,[36] I. M. Nugent,[36] L. Perchalla,[36] O. Pooth,[36] A. Stahl,[36] I. Asin,[37] N. Bartosik,[37] J. Behr,[37] W. Behrenhoff,[37] U. Behrens,[37] A. J. 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