Measurement of the Groomed Jet Radius and Momentum Splitting Fraction in pp and Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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This article presents groomed jet substructure measurements in pp and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE detector. The soft drop grooming algorithm provides access to the hard parton splittings inside a jet by removing soft wide-angle radiation. We report the groomed jet momentum splitting fraction, z_g, and the (scaled) groomed jet radius, θ_g. Charged-particle jets are reconstructed at midrapidity using the anti-k_T algorithm with resolution parameters $R = 0.2$ and $R = 0.4$. In heavy-ion collisions, the large underlying event poses a challenge for the reconstruction of groomed jet observables, since fluctuations in the background can cause groomed parton splittings to be misidentified. By using strong grooming conditions to reduce this background, we report these observables fully corrected for detector effects and background fluctuations for the first time. A narrowing of the θ_g distribution in Pb-Pb collisions compared to pp collisions is seen, which provides direct evidence of the modification of the angular structure of jets in the quark-gluon plasma. No significant modification of the z_g distribution in Pb-Pb collisions compared to pp collisions is observed. These results are compared with a variety of theoretical models of jet quenching, and provide constraints on jet energy-loss mechanisms and coherence effects in the quark-gluon plasma.

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Introduction.—Ultrarelativistic heavy-ion collisions at the Large Hadron Collider (LHC) are used to study the high temperature deconfined phase of strongly interacting matter known as the quark-gluon plasma (QGP) [1–5]. Highly energetic jets created early in the collisions interact with the QGP medium and through those interactions they can lose energy and their internal structure can be modified. This process, known as jet quenching, can be used to reveal the physical properties of the QGP itself such as its transport coefficients and the quasiparticle nature of its degrees of freedom as a function of scale [6–9]. Experimentally, jet quenching is evaluated by comparing jet measurements in heavy-ion collisions to analogous measurements in pp collisions [10–18]. Notably, measurements of the jet angularity [16] and jet transverse profile [18], which are sensitive to a combination of the angular and momentum space structure of jets, suggest a narrowing of the jet core in heavy-ion collisions. Nonetheless, up to now, no direct modification of the intrajet angular distribution alone has been measured.

Jet grooming algorithms provide access to the hard (high-momentum transfer) parton splittings inside a jet by removing soft wide-angle radiation [19–21]. Access to the hard splittings isolates substructures that are well-controlled in perturbative QCD (PQCD), which in heavy-ion collisions may help constrain various jet quenching effects such as energy loss, transverse-momentum broadening, and color coherence. Measurements of groomed jet observables in heavy-ion collisions have been performed by the ALICE and CMS Collaborations [22–24], and opened a new avenue in the study of jet substructure in heavy-ion collisions.

The soft drop (SD) [19–21] grooming algorithm identifies a single splitting by first reconstructing a jet with the anti-k_{T} algorithm and then reclustering the constituents of the jet using the Cambridge-Aachen (CA) algorithm [25] in order to follow the angular ordering of the QCD parton shower. The splitting is selected from within the history of the reclustering with a grooming condition, $z > z_{\mathrm{cut}}\theta^{\beta}$, where β and z_{cut} are tunable parameters, z is the fraction of transverse momentum (p_T) carried by the subleading (lowest p_T) prong,

$$z \equiv \frac{p_{T,\mathrm{subleading}}}{p_{T,\mathrm{leading}} + p_{T,\mathrm{subleading}}}, \tag{1}$$

and θ is the relative angular distance between the leading and subleading prong,

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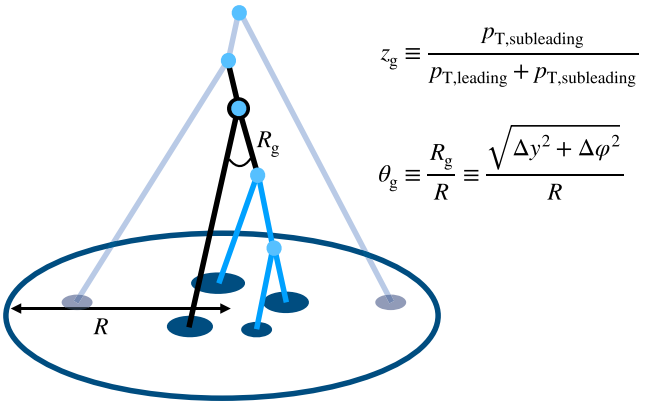

FIG. 1. Graphical representation of the angularly ordered Cambridge-Aachen reclustering of jet constituents and subsequent soft drop grooming procedure [19], with the identified splitting denoted in black and the splittings that were groomed away in light blue.

$$\theta \equiv \frac{\sqrt{\Delta y^2 + \Delta\varphi^2}}{R}, \tag{2}$$

where Δy and $\Delta\varphi$ are the distances measured in rapidity and azimuthal angle, respectively, and R is the jet resolution parameter. The groomed splitting is then characterized by two relevant kinematic observables: the groomed momentum fraction, z_g, and the (scaled) groomed jet radius, θ_g, which are the values of z and θ of Eqs. (1) and (2) for the identified splitting, as shown in Fig. 1.

In pp collisions, measurements of the θ_g and z_g distributions were performed at RHIC and the LHC [23,26–29]. At high-transverse momentum p_T, the data are described within uncertainties by PQCD predictions [30].

In heavy-ion collisions, it was proposed that θ_g may be sensitive to several important jet-quenching physics mechanisms: the relative suppression of gluon vs quark jets, transverse-momentum broadening, and the ability of the medium to resolve a color dipole as two independent color charges [31,32]. Uncertainty principle arguments suggest that wider splittings are formed earlier in vacuum than narrower splittings ($t_f \sim 1/\theta_g{}^2$ where t_f is the splitting formation time). In heavy-ion collisions, this would result in wider splittings traversing a longer path in the medium on average. Complementary to θ_g, it has been argued that z_g may be sensitive to the modification of the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi splitting function in the QGP, the breaking of color coherence, and the response of the medium to the jet [33–36]. By measuring both θ_g and z_g simultaneously, and thereby both the angular and momentum scales of the hard substructure of jets, these jet quenching mechanisms can be further constrained.

Up to now, no measurement of θ_g has been performed in heavy-ion collisions. Previous measurements of the z_g distribution by the CMS [22] and ALICE Collaborations [23] indicated significant modification with respect to pp collisions. However, these results were not corrected for background and detector effects, and are difficult to compare directly to theoretical calculations [37]. In this Letter, we report the first fully corrected measurement of groomed substructure observables in heavy-ion collisions, allowing for a rigorous comparison with theoretical calculations.

Experimental setup and datasets.—A description of the ALICE detector and its performance can be found in Refs. [38,39]. The pp data set used in this analysis was collected in 2017 during LHC Run 2 at $\sqrt{s} = 5.02$ TeV using a minimum-bias (MB) trigger defined by the coincidence of the signals from two scintillator arrays in the forward region (V0 detectors) [40]. The Pb-Pb dataset was collected in 2018 at $\sqrt{s_{NN}} = 5.02$ TeV. Central and semicentral triggers that select events in the 0%–10% and 30%–50% centrality intervals based on the multiplicity of produced particles in the forward V0 detectors, were used [41,42]. The event selection includes a primary-vertex selection and the removal of beam-induced background events and pileup [10]. After these selections, the pp data sample contains 870 million events and corresponds to an integrated luminosity of 18.0 ± 0.4 nb^{-1} [43]. The Pb-Pb data sample contains 92 million events in central collisions and 90 million events in semicentral collisions, corresponding to an integrated luminosity of 0.12 nb^{-1} and 0.06 nb^{-1}, respectively.

This analysis uses charged-particle tracks reconstructed using information from both the Time Projection Chamber (TPC) [44] and the Inner Tracking System (ITS) [45]. While track-based observables are collinear unsafe [46–48], they can be measured with greater precision than calorimeter-based observables and recent measurements have demonstrated that for the groomed jet observables considered here, track-based distributions are compatible with the corresponding collinear-safe distributions [49]. Tracks with $0.15 < p_T < 100$ GeV/c were accepted over pseudorapidity range $|\eta| < 0.9$. Further details about the track selection are described in Ref. [50]. The accepted tracks exhibit approximately uniform azimuthal acceptance and momentum resolution $\sigma(p_T)/p_T$ ranging from about 1% at track $p_T = 1$ GeV/c to 4% at track $p_T = 50$ GeV/c.

Analysis method.—Jets were reconstructed from charged-particle tracks with FastJet3.2.1 [51] using the anti-k_T algorithm with E-scheme recombination for resolution parameters $R = 0.2$ and 0.4 [52,53]. The pion mass is assumed for all jet constituents. Jets in heavy-ion collisions have a large uncorrelated background contribution due to fluctuations in the underlying event (UE) [54]. The event-by-event constituent subtraction method was used, which corrects the overall jet p_T and its substructure simultaneously by subtracting UE energy constituent by constituent [55,56]. A maximum recombination distance

$R_{\mathrm{max}} = 0.25$ was used. After background subtraction, the measured range is $40 < p_{T,\mathrm{ch\,jet}} < 120$ GeV/c. The jet axis is required to be within the fiducial volume of the TPC, $|\eta_{\mathrm{jet}}| < 0.9 - R$, where η_{jet} is the jet pseudorapidity.

Local background fluctuations in a heavy-ion collision environment can result in an incorrect splitting (unrelated to the hard scattering) being identified by the grooming algorithm. In order to address this issue, the measurement was performed by applying a strong grooming condition, $z_{\mathrm{cut}} = 0.2$ (with $\beta = 0$), which better mitigates these effects as compared to softer grooming conditions (e.g., $z_{\mathrm{cut}} = 0.1$) [37]. To further reduce the mistagging effects, we report measurements with either a small resolution parameter ($R = 0.2$ in central collisions) or with more peripheral collisions (30%–50% for $R = 0.4$).

The rate of prong mistagging from residual background effects was evaluated by embedding jets simulated with the PYTHIA8 event generator [57] into measured Pb-Pb data and following the procedure in Ref. [37]. The residual background contribution ranges from approximately 5% up to 15% at lower p_T, in more central events, and at larger R. This level of background contamination is small enough to allow the results to be unfolded for detector effects and background fluctuations. The impact of the residual background contribution remains one of the main sources of systematic uncertainty [50].

The reconstructed $p_{T,\mathrm{ch\,jet}}$, θ_g, and z_g distributions were corrected for effects related to the tracking inefficiency, particle-material interactions, and track p_T resolution. Moreover, in Pb-Pb collisions, background fluctuations significantly smear the reconstructed distributions of θ_g and z_g. To account for these effects, events were simulated with the PYTHIA8 generator using the Monash 2013 tune [57] and the GEANT3 model [58] for the particle transport in the ALICE detectors' material. For the Pb-Pb data, we embedded the simulated events into measured Pb-Pb data to mimic the background effects. A four-dimensional response matrix describing the detector and background response in $p_{T,\mathrm{ch\,jet}}$ and θ_g or z_g was constructed and used in the two-dimensional unfolding in $p_{T,\mathrm{ch\,jet}}$, θ_g, or z_g using the iterative Bayesian unfolding algorithm [59,60].

Systematic uncertainties.—The largest systematic uncertainties in this measurement originate from the tracking inefficiency, the unfolding procedure, residual mistagged prongs, and the background subtraction procedure. The total systematic uncertainty is calculated as the quadratic sum of all of the individual systematic uncertainties described below.

The systematic uncertainty due to the uncertainty of the tracking efficiency is evaluated using random rejection of additional tracks in jet finding according to the estimated tracking efficiency uncertainty of 4%, based on variations in the track selection criteria and on the ITS-TPC track-matching efficiency uncertainty. The systematic uncertainty arising from the unfolding regularization procedure is evaluated by varying the number of unfolding iterations by ± 2 units, scaling the prior distribution, varying the binning, and varying the lower bound in the detector-level charged-particle jet transverse momentum $p_{T,\mathrm{det}}^{\mathrm{ch\,jet}}$ range by 5 GeV/c. The systematic uncertainty due to the model-dependence of the generator used to construct the response matrix is estimated by comparing results obtained with PYTHIA [57], HERWIG [61], and JEWEL [62]. The systematic uncertainty due to the bias introduced by the constituent subtraction procedure is estimated by varying R_{max} from "undersubtraction" ($R_{\mathrm{max}} = 0.05$) to "oversubtraction" ($R_{\mathrm{max}} = 0.7$), around the nominal value of $R_{\mathrm{max}} = 0.25$. The systematic uncertainty due to a possible residual contamination of mistagged splittings after unfolding is estimated with a closure test. The total relative systematic uncertainty ranges from 3%–24% for θ_g and 4%–10% for z_g. See Ref. [50] for more details about the systematic uncertainties used in this measurement.

Results.—We report the θ_g and z_g distributions in the $p_{T,\mathrm{ch\,jet}}$ interval between 60 and 80 GeV/c for $z_{\mathrm{cut}} = 0.2$ in central (0%–10%, $R = 0.2$) and semicentral (30%–50%, $R = 0.4$) Pb-Pb collisions. The distributions are reported as normalized differential cross sections,

$$\frac{1}{\sigma_{\mathrm{jet,inc}}}\frac{d\sigma}{dz_g} = \frac{1}{N_{\mathrm{jet,inc}}}\frac{dN}{dz_g}, \tag{3}$$

where N is the number of jets passing the SD condition with a given $p_{T,\mathrm{ch\,jet}}$, $N_{\mathrm{jet,inc}}$ is the number of inclusive jets, and $\sigma, \sigma_{\mathrm{jet,inc}}$ are the corresponding cross sections. The analog of Eq. (3) also applies for θ_g.

The z_g and θ_g distributions are shown in Figs. 2 and 3, respectively. The distributions from Pb-Pb collisions are compared with the corresponding distributions from pp collisions, with their ratios displayed in the bottom panels. The relative uncertainties are assumed to be uncorrelated between pp and Pb-Pb collisions, and are added in quadrature in the ratio. In Pb-Pb collisions the precision of the measurements decreases as the jet resolution parameter is increased or the centrality is decreased, as the prong mistagging probability decreases with centrality and with decreasing R.

The fraction of jets that do not contain a splitting which passes the SD condition (f_{tagged}) differs by at most 1% between Pb-Pb and pp collisions. Therefore, any modifications in Pb-Pb compared to pp collisions can change the shape of the distribution, but keep the integral approximately the same.

The z_g distributions in Pb-Pb and pp collisions are consistent within experimental uncertainties for all jet momenta, jet resolution parameters, and centralities measured.

The situation is remarkably different when comparing the groomed jet radius, θ_g, in both systems. For $R = 0.2$ in

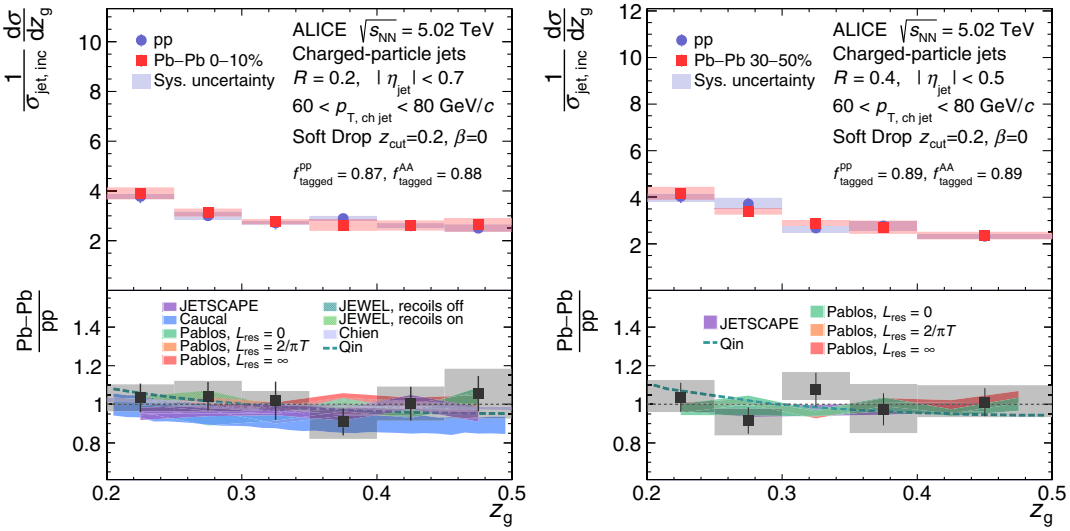

FIG. 2. Unfolded z_g distributions for charged-particle jets in pp collisions compared to those in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with $z_{cut} = 0.2$ for 0%–10% centrality for $R = 0.2$ (left) and 30%–50% centrality for $R = 0.4$ (right). The distributions are normalized to the inclusive jet cross section in the $60 < p_{T,ch\,jet} < 80$ GeV/c interval, and f_{tagged} indicates the fraction of splittings that were tagged to pass the SD condition in the selected $p_{T,ch\,jet}$ interval. The ratios in the bottom panel are compared to the following theoretical predictions: JETSCAPE [63], JEWEL [62,64], Caucal *et al.* [34,65], Chien *et al.* [33], Qin *et al.* [35], and Pablos *et al.* [36,66,67]. Further details can be found in Ref. [50].

central collisions, the data suggests a narrowing of the Pb-Pb distribution relative to the pp distribution is observed. This narrowing persists even in semicentral Pb-Pb collisions for $R = 0.4$ where quenching effects are expected to be less than in central collisions.

We compare the ratio of the measurements in pp and Pb-Pb collisions with several theoretical implementations of jet quenching:

(i) JETSCAPE [63] consists of a medium-modified parton shower with the MATTER model [68] controlling

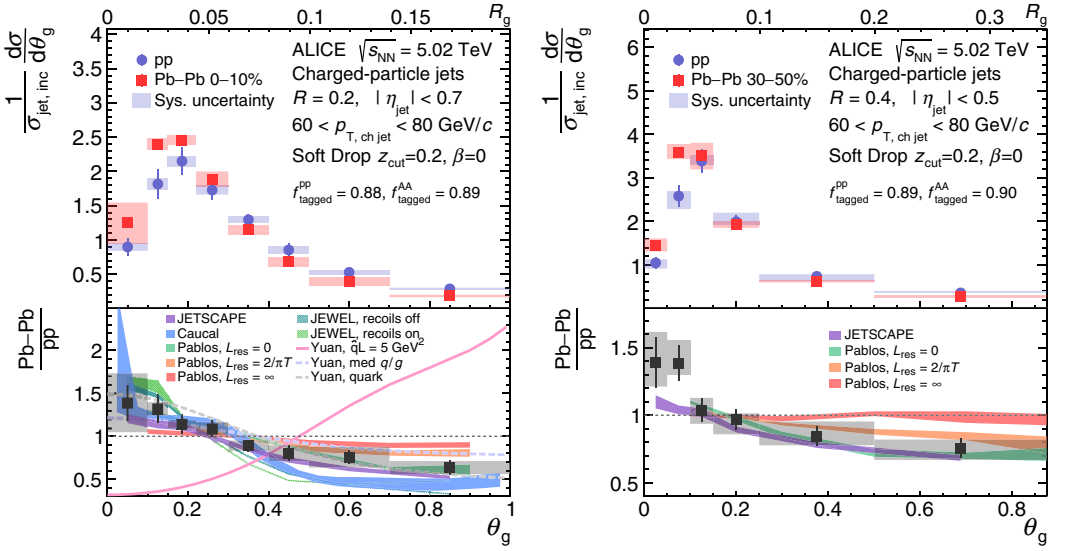

FIG. 3. Unfolded θ_g distributions for charged-particle jets in pp collisions compared to those in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with $z_{cut} = 0.2$ for 0%–10% centrality for $R = 0.2$ (left) and 30%–50% centrality for $R = 0.4$ (right). The distributions are normalized to the inclusive jet cross section in the $60 < p_{T,ch\,jet} < 80$ GeV/c interval, and f_{tagged} indicates the fraction of splittings that were tagged to pass the SD condition in the selected $p_{T,ch\,jet}$ interval. The ratios in the bottom panel are compared to the following theoretical predictions: JETSCAPE [63], JEWEL [62,64], Caucal *et al.* [34,65], Pablos *et al.* [36,66,67], and Yuan *et al.* [31]. Further details can be found in Ref. [50].

the high-virtuality phase and the Linear Boltzmann Transport (LBT) model describing the low-virtuality phase [69]. The version of JETSCAPE used for this calculation employs a jet transport coefficient, $\hat{q}$, that includes dependence on parton virtuality, in addition to dependence on the local temperature and running of the parton-medium coupling.

(ii) JEWEL [62,64] consists of a Monte Carlo implementation of Baier-Dokshitzer-Mueller-Peigne-Schiff-Zakharov-based medium-induced gluon radiation in a medium modeled with a Bjorken expansion. We consider the impact of medium recoil by including calculations both with and without recoils enabled [70].

(iii) Caucal *et al.* [34,65] implements a PQCD parton shower with incoherent interactions including both factorized vacuum and medium-induced emissions in a static brick medium.

(iv) Chien *et al.* [33] (for z_g only) applies Soft Collinear Effective Theory with Glauber gluon interactions.

(v) Qin *et al.* [35] (for z_g only) applies the higher twist formalism with coherent energy loss.

(vi) Pablos *et al.* [36,66,67] consists of partons produced by a vacuum shower that interact with the medium according to a strongly coupled AdS/CFT-based model. The parameter L_{res} describes the degree to which the medium can resolve the jet angular structure, where $L_{\mathrm{res}} = 0$ corresponds to full resolution of all jet constituents (fully incoherent), $L_{\mathrm{res}} = \infty$ corresponds to fully coherent energy loss, and $L_{\mathrm{res}} = 2/\pi T$ is an intermediate case, where T is the local medium temperature.

(vii) Yuan *et al.* [31] (for θ_g only) "med q/g" and "quark" consist of medium-modified quark-gluon fractions without any additional effects, where the quark-gluon fractions in the med q/g case are extracted in Ref. [71] with a relative suppression factor of approximately four between gluon jets and quark jets. The calculation labeled "$\hat{q}L$" includes an implementation of transverse-momentum broadening.

The Pb-Pb–to–pp ratios of the z_g distributions are consistent with all theoretical predictions considered. The predicted modifications, which have been constrained by previous measurements [22,23], are small, and the differences between them are yet smaller than the current uncertainty of the data. Nevertheless, these new measurements are the first direct comparisons of predictions to fully corrected data, and limit the possible in-medium modifications of the momentum structure of hard splittings to be less than 10–20% depending on the centrality, jet R, and the grooming settings considered.

Despite employing different microscopic implementations of the jet-medium interactions, the majority of the models capture the qualitative feature of the narrowing seen in the θ_g distributions. The theoretical models can be grouped according to three distinct mechanisms by which θ_g is modified: incoherent energy loss, coherent energy loss, and transverse broadening. The measurements are consistent with models implementing (transverse) incoherent interaction of the jet shower constituents with the medium. This is illustrated by calculations of Pablos *et al.* where the data favor the incoherent energy loss ($L_{\mathrm{res}} = 0$) and is also supported by Caucal *et al.*, JEWEL, and JETSCAPE. On the other hand, the Yuan *et al.* calculation with medium-modified "quark-gluon" fractions indicates that the data could be explained by the stronger suppression of gluon showers, which are on average broader, with fully coherent energy loss. These two physics mechanisms—the degree of incoherent energy loss, and the relative quark-gluon suppression—both lead to a suppression of wide-angle splittings. The prediction by Yuan *et al.* $\hat{q}L$ exhibits the opposite trend compared to the data, demonstrating that there is no strong transverse broadening in the hard substructure.

The presented measurements indicate that the medium has a significant resolving power for splittings with a particular dependence on the angular (or coherence) scale, promoting narrow structures or filtering out wider jets altogether.

Conclusions.—We reported the groomed jet momentum fraction, z_g, and the (scaled) groomed jet radius, θ_g, of charged-particle jets measured in pp and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE detector. By using stronger grooming conditions in the SD grooming algorithm, we suppressed contamination of mistagged splittings from the underlying event, and unfolded the final distributions for detector and background fluctuation effects. This allows for the first time the direct comparison of groomed jet measurements in heavy-ion collisions with theoretical predictions of jet quenching in the QGP. The z_g distributions are consistent with no modification in Pb-Pb collisions compared to pp collisions. The θ_g distributions are narrower in Pb-Pb collisions compared to pp collisions, which is the first direct experimental evidence for the modification of the angular scale of groomed jets in heavy-ion collisions.

These new results demonstrate sensitivity to the microscopic structure of the QGP, including its angular resolving power. This marks an important step towards quantitative understanding of the properties of the QGP, and provides a new path for novel differential jet substructure measurements to further elucidate the microscopic nature of the QGP.

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