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Medium-induced modification of groomed and ungroomed jet mass and angularities in Pb–Pb collisions at $\sqrt{s_{\mathbf{NN}}} = 5.02$ TeV

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Abstract

The ALICE Collaboration presents a new suite of jet substructure measurements in Pb–Pb and pp collisions at a center-of-mass energy per nucleon pair $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. These measurements provide access to the internal structure of jets via the momentum and angle of their constituents, probing how the quark–gluon plasma modifies jets, an effect known as jet quenching. Jet grooming additionally removes soft wide-angle radiation to enhance perturbative accuracy and reduce experimental uncertainties. We report the groomed and ungroomed jet mass m_{jet} and jet angularities $\lambda_{\alpha}^{\kappa}$ using $\kappa = 1$ and $\alpha > 0$. Charged-particle jets are reconstructed at midrapidity using the anti-k_{T} algorithm with resolution parameter $R = 0.2$. A narrowing of the jet mass and angularity distributions in Pb–Pb collisions with respect to pp is observed and is enhanced for groomed results, confirming modification of the jet core. By using consistent jet definitions and kinematic cuts between the mass and angularities for the first time, previous inconsistencies in the interpretation of quenching measurements are resolved, rectifying a hurdle for understanding how jet quenching arises from first principles and highlighting the importance of a well-controlled baseline. These results are compared with a variety of theoretical models of jet quenching, providing constraints on jet energy-loss mechanisms in the quark–gluon plasma.

*See Appendix A for the list of collaboration members

1 Introduction

Collisions of ultra-relativistic heavy ions at the Large Hadron Collider (LHC) allow the study of bulk properties in quantum chromodynamics (QCD) at high temperature and density. These collisions produce a strongly-interacting state of matter called the quark–gluon plasma (QGP) [1, 2] where quarks and gluons are deconfined from nucleons. The hard scattering of two partons from these collisions forms collimated sprays of particles called jets. As they traverse the QGP, the partonic jets lose energy to the medium and their internal structure is modified, an effect known as jet quenching [3–7]. Consequently, jets can probe the structure and evolution of the QGP, and provide information about QGP transport properties, degrees of freedom, and the mechanisms for energy loss, as a function of momentum scale.

Jet substructure observables, which characterize the angular and transverse momentum distributions of the particles which constitute jets, can quantify these QGP quenching effects [8, 9]. For example, the jet invariant mass, $m_{\text{jet}} \equiv \sqrt{E_{\text{jet}}^2 - p_{\text{jet}}^2}$, where E_{jet} is the jet energy and p_{jet} its total momentum, has seen extensive experimental [10–20] and theoretical [21–24] study in recent years. The generalized jet angularities [25–29] are another class of such observables, defined as

$$\lambda_\alpha^\kappa \equiv \sum_{i \in \text{jet}} \left(\frac{p_{\text{T},i}}{p_{\text{T, jet}}} \right)^\kappa \left(\frac{\Delta R_i}{R} \right)^\alpha, \tag{1}$$

where i runs over constituents in the jet, p_{T} designates transverse momentum, R is the jet resolution parameter, and $\Delta R_i \equiv \sqrt{(y_{\text{jet}} - y_i)^2 + (\varphi_{\text{jet}} - \varphi_i)^2}$ gives the distance between the jet axis and its ith constituent in the rapidity (y) – azimuthal angle (φ) plane. The continuous parameters α and κ define the specific observable, where the $\kappa = 1$ and $\alpha > 0$ configurations are infrared and collinear (IRC) safe [30].

Both m_{jet} and λ_α^κ characterize the jet radial energy profile, with a direct theoretical relation between them,

$$\lambda_2^1 = \left(\frac{m_{\text{jet}}}{p_{\text{T, jet}} R} \right)^2 + \mathscr{O}[(\lambda_2^1)^2], \tag{2}$$

where λ_2^1 is also called the jet thrust [31], and the last term contains higher-order corrections in m_{jet} [32]. The jet thrust is also related to the jet girth [33], $g = \lambda_1^1 R$, with a smaller angular weighting α. The ALICE collaboration measured g and m_{jet} in Pb–Pb collisions during LHC Run 1 at nucleon–nucleon center-of-mass energy $\sqrt{s_{\text{NN}}} = 2.76$ TeV, and compared the results to Monte Carlo models of pp collisions [11, 34]. Significant quenching modification was observed for g, while no significant modification was seen for m_{jet}. Since g and m_{jet} are theoretically related, this discrepancy was unexpected. These measurements differed in their ranges of $p_{\text{T, jet}}$, associated with quenching strength and nonperturbative dependence, as well as the angular weighting α, associated with momentum broadening, which both could account for the discrepancy.

This letter presents angularities for the 10% most central Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. A recent measurement of IRC-safe angularities in pp collisions at identical center-of-mass energy is used as a no-quenching baseline [35]. We preserve the notation $\lambda_\alpha \equiv \lambda_\alpha^1$ from this measurement, and compare these angularities with new measurements of m_{jet} using the same pp and Pb–Pb collision data, using equivalent R for the first time to address the girth–mass inconsistency. The results are reported for background-subtracted charged-particle jets with transverse momenta of $40 < p_{\text{T}}^{\text{ch jet}} < 60$ GeV/c.

Soft drop grooming [36] is employed to remove soft wide-angle radiation from jets, minimizing the nonperturbative dependence of m_{jet} and λ_α. Systematically varying $p_{\text{T, jet}}$, α, R, and grooming for each observable provides coherent constraints on models of jet quenching.

2 Experimental setup and datasets

A description of the ALICE detector and its performance is given in Refs. [37, 38]. The pp data were collected in 2017 at $\sqrt{s} = 5.02$ TeV during Run 2 of the CERN LHC [39] using a minimum-bias trigger, which requires a coincidence of hits in two forward V0 scintillator detectors [40]. The Pb–Pb data were collected during 2018 at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, using high-multiplicity events in the V0 detectors to trigger on the 10% most central collisions (0–10% centrality class) [41]. The event selection includes a primary-vertex selection and the removal of beam-induced background events and pileup [42]. The pp data sample contains 870 million events and corresponds to an integrated luminosity of 18.0 ± 0.4 nb^{-1} [43]. The 0-10% centrality Pb–Pb data sample contains 91.2 million events, corresponding to an integrated luminosity of 0.119 ± 0.003 nb^{-1} [44].

Charged-particle tracks are reconstructed using information from both the Time Projection Chamber (TPC) [45] and the Inner Tracking System (ITS) [46], using both global tracks and complementary tracks. Global tracks are required to include at least one hit in the silicon pixel detector (SPD), comprising the two innermost layers of the ITS, and to satisfy a number of quality criteria [47]. Complementary tracks do not contain any hits in the SPD, but otherwise satisfy the tracking criteria, and are refit using the primary vertex of the event to constrain their trajectory. Including complementary tracks ensures approximately uniform azimuthal acceptance, while preserving similar p_{T} resolution to tracks with SPD hits. Tracks with $0.15 < p_{\mathrm{T}} < 100$ GeV/c are accepted over the pseudorapidity range $|\eta| < 0.9$. The accepted tracks exhibit a momentum resolution ranging from about 1% at track $p_{\mathrm{T}} = 1$ GeV/c to 4% at track $p_{\mathrm{T}} = 50$ GeV/c.

3 Analysis method

Jets are reconstructed from charged-particle tracks with FastJet 3.3.3 [48] using the anti-k_{T} algorithm [49] with E-scheme recombination and resolution parameter $R = 0.2$. This small value of R reduces contamination from combinatorial jets at low $p_{\mathrm{T}}^{\mathrm{ch\,jet}}$ in Pb–Pb data, thereby increasing overlap with the measured vacuum baseline [35]. Despite track-based observables being collinear-unsafe [50], they offer greater momentum and angular precision than calorimeter-based observables. The $\pi^{\pm}$-meson mass is assumed for all jet constituents, and the jet pseudorapidity η_{jet} is required to be within the fiducial volume of the TPC, $|\eta_{\mathrm{jet}}| < 0.9 - R$. For pp collisions, all reconstructed jets in the range $5 < p_{\mathrm{T}}^{\mathrm{ch\,jet}} < 200$ GeV/c are analyzed. In heavy-ion collisions, jets are influenced by a large background from the underlying event (UE) [51], owing to the large number of soft, thermally-produced particles from the QGP. To reduce this thermal background, the event-by-event constituent subtraction method is used [52], which adds “ghosts” to the event over the entire acceptance. These ghosts, whose small transverse momentum is calculated from the average background density, are then combined with real local particles within a maximum recombination distance $R_{\mathrm{max}} = 0.1$. When combined, the softer (lower p_{T}) particle of the pair is removed from the event, while its p_{T} and mass is subtracted from that of the harder particle. After background subtraction, the measured range is truncated to $40 < p_{\mathrm{T}}^{\mathrm{ch\,jet}} < 200$ GeV/c before applying corrections.

Jets are groomed using soft drop [36], which reclusters the jet into an angularly-ordered tree using the Cambridge/Aachen algorithm [53] before iterating along the hardest branch and trimming away soft, wide-angle radiation at each splitting until the soft drop condition is satisfied, $p_{\mathrm{T,min}}/(p_{\mathrm{T,min}} + p_{\mathrm{T,max}}) > z_{\mathrm{cut}}(\Delta R/R)^{\beta}$, where $p_{\mathrm{T,i}}$ are the transverse momenta of the branches and z_{cut} and β are user parameters, which are set to 0.2 and 0, respectively. These settings require the jet to have a splitting where the softer branch carries 20% or more of the total transverse momentum of the splitting (i.e., $z_{\mathrm{cut}} = 0.2$) independent of the angle of the splitting (i.e., $\beta = 0$), which improves the efficiency of tagging the first hard splitting in the large background of Pb–Pb collisions [54].

The reconstructed jet mass and jet angularity distributions are affected by tracking inefficiency, particle interactions with detector material, and finite track p_{T} resolution. Moreover, the background subtraction procedure in Pb–Pb collisions only corrects for the average UE, and remaining background fluctuations smear the reconstructed distributions. To account for these effects, pp events are simulated with the PYTHIA 8 generator using the Monash 2013 tune [55] and passed through a setup of the ALICE detector using GEANT3 [56] to account for the particle transport through the detector material. For the Pb–Pb analysis, the PYTHIA 8 simulations including GEANT3 reconstruction (detector level) are embedded into reconstructed Pb–Pb data events (combined level). Background subtraction and jet reconstruction are performed on the combined-level events, identical to the data analysis. Jets are matched geometrically between the detector (in pp) or combined (in Pb–Pb) level to the jets reconstructed from the PYTHIA 8 simulation without detector effects (truth-level), with these jet matches required to be unique. In Pb–Pb, the matched combined-level jet must contain tracks from the detector-level jet amounting to at least 50% of the p_{T} of the detector-level jet. These requirements allow for a reliable estimation of background effects and fluctuations on the observables.

A four-dimensional response matrix (RM) describing the detector and background response in $p_{\mathrm{T}}^{\mathrm{ch\,jet}}$ and λ_α or m_{jet} is constructed from the jets matched between detector-level (combined-level) and generator-level and used in a two-dimensional unfolding with the iterative Bayesian unfolding algorithm [57] as implemented in RooUnfold [58]. The number of iterations through the unfolding was optimized by ensuring good closure of the unfolding procedure at the earliest iteration, with values ranging from 5 to 15 depending on the collision system and $p_{\mathrm{T}}^{\mathrm{ch\,jet}}$ interval. More details on the background subtraction and jet matching can be found in Ref. [59].

4 Systematic uncertainties

The systematic uncertainties for the observables reported in this paper are estimated from the uncertainty on the tracking efficiency, the unfolding, and the dependence on the event generator used in the simulations. In Pb–Pb, additional uncertainties arise from the estimation of the thermal background and the background subtraction procedure. Variations to the analysis procedure (described below) are performed to estimate these uncertainties, with the relative variation between unfolded distributions obtained with the default and modified procedures taken as the relative systematic uncertainty. The total systematic uncertainty is then taken as the quadratic sum of all contributions. The procedure is the same with and without grooming.

The systematic uncertainty due to the tracking efficiency uncertainty is evaluated using random rejection of tracks before jet finding. The tracking efficiency uncertainty is estimated to be 3% in pp and 3–5% in Pb–Pb collisions, depending on track p_{T}, based on variations in the track selection criteria and on the ITS–TPC track-matching efficiency uncertainty. The RM is recreated after randomly rejecting the fraction of tracks equal to the corresponding uncertainty, and the results are unfolded. The systematic uncertainty arising from the unfolding regularization is evaluated by varying the number of unfolding iterations by ±2 units, altering the shape of the prior distribution, changing the detector-level observable binning, and truncating the lower and upper bounds in the detector-level charged-particle jet transverse momentum $p_{\mathrm{T,det}}^{\mathrm{ch\,jet}}$ range by 5 and 80 GeV/c, respectively. The systematic uncertainty due to the model dependence of the generator used to construct the response matrix is estimated by comparing results obtained via unfolding with RMs generated using PYTHIA 8 [55] and HERWIG 7 [60, 61] for the pp and Pb–Pb analyses, and also JEWEL [62] for the Pb–Pb analysis. The systematic uncertainty introduced by the background subtraction in Pb–Pb collisions using the constituent subtraction procedure is estimated by varying $R_{\max}$ from “under-subtraction” ($R_{\max} = 0.05$) to “over-subtraction” ($R_{\max} = 0.5$), around the nominal value of $R_{\max} = 0.1$. The uncertainty due to residual contamination from the uncorrelated thermal background produced by the QGP is estimated by embedding combined-level MC jets into a simulated thermal background and applying the analysis procedure, with any non-closure observed in the unfolding taken as a systematic uncertainty. The total relative systematic uncertainty ranges from 2% to 26% for λ_α and 3% to 30% for m_{jet}, with larger values in the tails of the λ_α and m_{jet} distributions and lower $p_{\mathrm{T}}^{\mathrm{ch\,jet}}$

intervals. See Ref. [59] for more details about the systematic uncertainties used in this measurement.

5 Results

In this letter we report the m_{jet} and λ_α distributions in the charged-jet transverse momentum interval $40 < p_{\text{T}}^{\text{ch jet}} < 60$ GeV/c in inclusive pp and central (0–10%) Pb–Pb collisions; additional $p_{\text{T}}^{\text{ch jet}}$ ranges from 60 to 150 GeV/c are reported in Ref. [59]. The inclusive jet angularities from Ref. [35], measured in pp collisions at $\sqrt{s} = 5.02$ TeV, are used as a baseline for these Pb–Pb results. The distributions are reported both with and without soft drop grooming (using the parameters $z_{\text{cut}} = 0.2$ and $\beta = 0$) as normalized differential cross sections,

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\lambda_\alpha} \equiv \frac{1}{N_{\text{jets}}}\frac{\mathrm{d}N_{\text{jets}}}{\mathrm{d}\lambda_\alpha} \text{ (ungroomed),} \quad \text{or} \quad \frac{1}{\sigma_{\text{inc}}}\frac{\mathrm{d}\sigma}{\mathrm{d}\lambda_{\alpha,\text{g}}} \equiv \frac{1}{N_{\text{jets}}}\frac{\mathrm{d}N_{\text{gr jets}}}{\mathrm{d}\lambda_{\alpha,\text{g}}} \text{ (groomed),} \tag{3}$$

where N_{jets} is the number of inclusive (ungroomed) jets within a given $p_{\text{T}}^{\text{ch jet}}$ range and σ is the corresponding cross section. For the groomed case, some jets (including all single-particle jets) are removed by the grooming procedure, and therefore the cross section is explicitly normalized by the number of inclusive (ungroomed) jets; for the ungroomed case, $\sigma = \sigma_{\text{inc}}$. The analog of Eq. 3 also applies for m_{jet}.

Figure 1 shows the ungroomed m_{jet} and groomed $m_{\text{jet,g}}$ distributions for $40 < p_{\text{T}}^{\text{ch jet}} < 60$ GeV/c, while the ungroomed λ_α distributions are shown in Fig. 2 and the groomed λ_α distributions are displayed in Fig. 3. The distributions from Pb–Pb collisions are compared to pp data and several models, with Pb–Pb/pp ratios displayed in the bottom panels. The relative uncertainties are assumed to be uncorrelated between collision systems, and theoretical error bands are purely statistical. The ratios suggest an enhancement at small values of angularity and mass and a corresponding suppression at large values, consistent with jet "narrowing," i.e. the transverse momentum becoming more collimated along the jet axis; systematic uncertainties, however, are significant, especially for ungroomed m_{jet}.

Quenching modification of the ungroomed jet girth (λ_1), as quantified in the Pb–Pb/pp ratio, is smaller than when using a MC simulated pp baseline generated with PYTHIA 8, where both tails of the ratio are modified by an approximate factor of 2 [34]. This difference is explained by an approximate 20% difference between the central values of the pp data and PYTHIA 8 simulation in the tails of the distribution [59]. This difference, which enhanced the observed quenching effects in Ref. [34], highlights the importance of measuring a proper vacuum baseline for jet quenching. Modification of the jet thrust λ_2 is more significant than m_{jet}, despite the theoretical relation given in Eq. 2.

Comparisons to various theoretical calculations are shown. JETSCAPE [63] uses a medium-modified parton shower described by MATTER [64] for the high-virtuality phase and Linear Boltzmann Transport (LBT) [65] for the low-virtuality phase. Higher-Twist parton energy loss calculations [66] use POWHEG [67] + PYTHIA 6 as a vacuum baseline; as the partons traverse the QGP, they probabilistically emit medium-induced gluon radiation following the $\hat{q}$-dependent Higher-Twist formalism [68–71]. Finally, the Hybrid model [72] allows partons produced by a vacuum shower to undergo medium interactions according to a strongly-coupled AdS/CFT-based model. Two variations are given, where partons do or do not interact via in-medium elastic Molière scattering [73], which scatters particles at large angles and broadens both m_{jet} and λ_α. Individual comparisons of groomed and ungroomed m_{jet} and λ_α distributions between pp and Pb–Pb data and model predictions are reported in Ref. [59].

Models show general agreement with the measured Pb–Pb/pp ratios within uncertainties. However, data disfavors the Hybrid model with in-medium elastic scattering at large m_{jet} (2.3σ difference in the last bin) but slightly favors it at large λ_α ($\alpha = 2$ exhibits a 0.94σ difference in the last bin, as compared to 1.8σ for no elastic scattering). While Eq. 2 relates m_{jet} and λ_2 directly to one another, model comparisons show differing behavior within this kinematic regime. Since the distributions are positive definite and obey square proportionality following Eq. 2, large corrections to this equation must apply at these

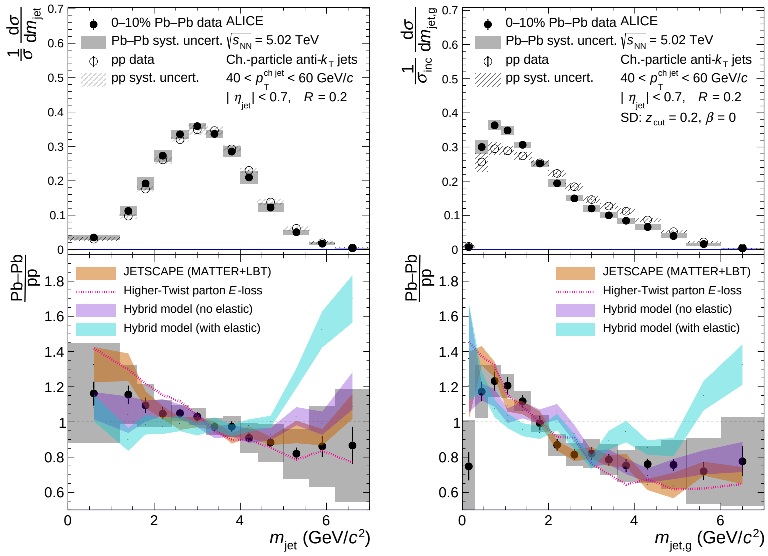

Figure 1: ALICE measurements of ungroomed $m_{\rm jet}$ (left) and groomed $m_{\rm jet,g}$(right) using $R = 0.2$ charged-particle jets with $40 < p_{\rm T}^{\rm ch\,jet} < 60$ GeV/c in pp and Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV compared to models. The bottom panel shows the ratio of Pb–Pb distributions to pp, which quantifies the substructure modifications from quenching.

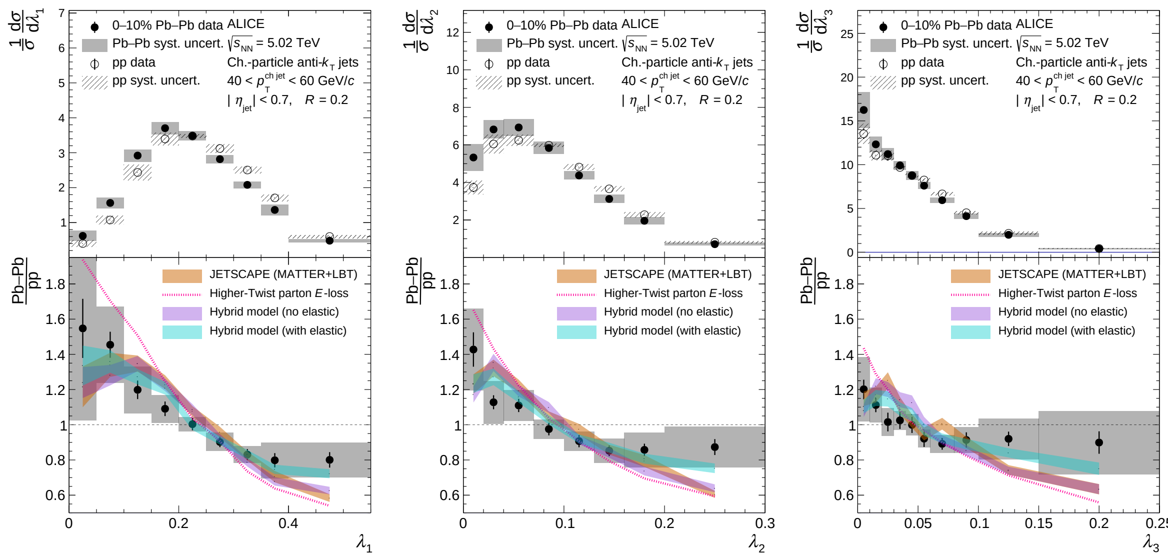

Figure 2: ALICE measurements of ungroomed λ_α for $\alpha = 1$ ('girth,' left), $\alpha = 2$ ('thrust,' center), and $\alpha = 3$ (right) using $R = 0.2$ charged-particle jets with $40 < p_{\rm T}^{\rm ch\,jet} < 60$ GeV/c in pp and Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV compared to models. The bottom panel shows the ratio of Pb–Pb distributions to pp, which quantifies the substructure modifications from quenching.

values of $p_{\rm T}^{\rm ch\,jet}$. These could include nonperturbative effects such as hadronization as well as higher-order correction terms $\mathscr{O}[(\lambda_2)^2]$, which both could be significant at these smaller values of $p_{\rm T}^{\rm ch\,jet}$ where the strong coupling α_S is large. Therefore, despite the close mathematical relationship, the observables remain different. Underlying physical differences also exist, as jet mass is sensitive to quark masses, whereas the IRC-safe jet angularities are more sensitive to the angular profile of jet fragmentation. The behavioral discrepancies between the measured distributions originate from these physical differences of the observables themselves, which clarifies the girth–mass discrepancy observed between earlier measurements. This observation highlights the importance of making broad measurements of quenched

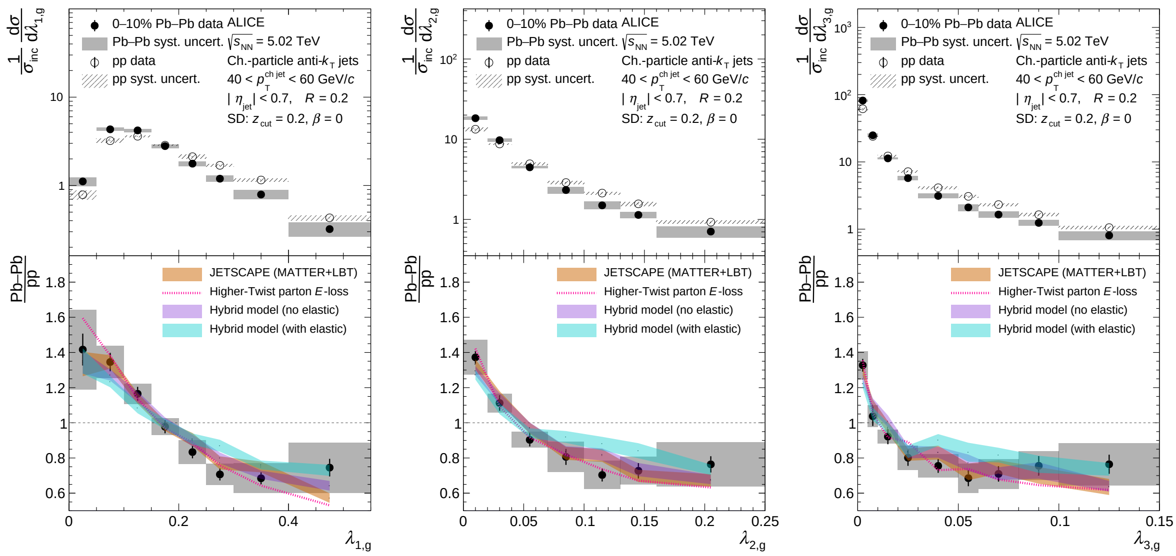

Figure 3: ALICE measurements of groomed $\lambda_{\alpha,\mathrm{g}}$ for $\alpha = 1$ ('girth,' left), $\alpha = 2$ ('thrust,' center), and $\alpha = 3$ (right) using $R = 0.2$ charged-particle jets with $40 < p_{\mathrm{T}}^{\mathrm{ch\,jet}} < 60$ GeV/c in pp and Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV compared to models. The bottom panel shows the ratio of Pb–Pb distributions to pp, which quantifies the substructure modifications from quenching. These ratios are visibly enhanced as compared to the ungroomed distributions shown in Fig. 2, signifying a strongly quenched jet core.

jet substructure, as closely-related observables can provide significantly different probes of underlying physical phenomena.

Increasing the value of α in Fig. 2 correspondingly increases the weight of wide-angle jet constituents, which are more affected by nonperturbative processes [32, 35]. Less narrowing is observed with increased α for the ungroomed λ_α, revealing a strongly quenched jet core. This conclusion is supported by a significant enhancement in the narrowing effect of λ_α for jets groomed with soft drop, comparing Figs. 2 and 3. Removing soft, wide angle jet constituents substantially modifies the shapes of the groomed distributions, with the distributions of $m_{\mathrm{jet,g}}$ and $\lambda_{\alpha,\mathrm{g}}$ peaking at lower values than m_{jet} and λ_α. Soft drop grooming also reduces systematic uncertainties via limiting the effects from tracking inefficiency and generator dependence. Nevertheless, most models describe the groomed observables better than the ungroomed ones, despite the smaller uncertainties of the groomed results, as grooming reduces the influence of soft, wide-angle radiation thus improving theoretical control.

6 Conclusions

In this letter, measurements of jet mass and angularities in pp and Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV are presented. The medium-induced jet modifications in Pb–Pb collisions are explored both with and without grooming. These results depict a consistent picture of narrowing as jets traverse the QGP, which is dominated by a collinearized jet core. By measuring both m_{jet} and jet thrust (λ_2) using the same jets, and by also measuring the appropriate pp baseline, we reexamine the inconsistency between the girth and mass distributions raised by earlier measurements, which showed conflicting quenching behavior in these related observables. Fundamental differences are found between these observables at low $p_{\mathrm{T}}^{\mathrm{ch\,jet}}$ ($40 < p_{\mathrm{T}}^{\mathrm{ch\,jet}} < 60$ GeV/c) also in the analysis presented in this letter. This indicates that the mass–thrust relation (Eq. 2) must depend on significant higher-order corrections or on nonperturbative physics at low $p_{\mathrm{T}}^{\mathrm{ch\,jet}}$, where the strong coupling α_S is large.

The data generally agree with models including in-medium energy loss. The jet mass prefers no in-medium elastic Molière scattering (within the Hybrid model), but the jet angularities slightly prefer if this process is included. Future studies are needed to understand these model discrepancies. Theory comparisons also reveal that a pp baseline is essential for evaluating quenching behavior of jet substructure and should always be measured to fully profit from heavy-ion runs at the LHC. Compared to previous measurements using a MC simulated pp baseline, the quenching effects are smaller.

While jet grooming has been used in many recent measurements, the phase space of groomed observables remains mostly unexplored. Using grooming to reduce experimental uncertainties while selecting observables which probe effects such as in-medium color coherence will be essential to illuminate medium structure and the origins of jet quenching. Grooming can also be used to reduce nonperturbative effects, providing a handle to isolate these mechanisms in the QGP.

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