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Observation of medium-induced yield enhancement and acoplanarity broadening of low-p_T jets from measurements in pp and central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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Abstract

The ALICE Collaboration reports the measurement of semi-inclusive distributions of charged-particle jets recoiling from a high transverse momentum (high p_T) hadron trigger in proton–proton and central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. A data-driven statistical method is used to mitigate the large uncorrelated background in central Pb–Pb collisions. Recoil jet distributions are reported for jet resolution parameter $R = 0.2$, 0.4, and 0.5 in the range $7 < p_{T,jet} < 140$ GeV$/c$ and trigger–recoil jet azimuthal separation $\pi/2 < \Delta\varphi < \pi$. The measurements exhibit a marked medium-induced jet yield enhancement at low p_T and at large azimuthal deviation from $\Delta\varphi \sim \pi$. The enhancement is characterized by its dependence on $\Delta\varphi$, which has a slope that differs from zero by 4.7σ. Comparisons to model calculations incorporating different formulations of jet quenching are reported. These comparisons indicate that the observed yield enhancement arises from the response of the QGP medium to jet propagation.

*See Appendix A for the list of collaboration members

Matter at very high temperature forms a quark–gluon plasma (QGP), the state of matter in which quarks and gluons are not bound in colorless hadrons [1, 2]. A QGP filled the early Universe a few microseconds after the Big Bang, and is generated today in high-energy nuclear collisions at the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC) [3–7]. Measurements at RHIC and the LHC and their comparison to theoretical calculations show that the QGP flows with low specific shear viscosity [8]. Quantum chromodynamics (QCD) calculations on the lattice show that the effective number of QGP degrees of freedom is $\sim$15% lower than that of freely-interacting quarks and gluons, at temperatures well above the deconfinement transition temperature $\sim$ 150 MeV [9, 10]. However, understanding the origin of such emergent phenomena in terms of quasi-particle degrees of freedom remains elusive.

QCD jets arise from hard (high momentum-transfer Q^2) scattering of quarks and gluons (partons). The highly-virtual scattered partons radiate a gluon shower that hadronizes into a correlated spray of experimentally observable hadrons. Jet measurements in proton–proton (pp) collisions provide stringent tests of perturbative QCD (pQCD) calculations [11–13]. In nucleus–nucleus (A–A) collisions jets interact with the QGP, generating observable modifications to jet production and structure ("jet quenching") [14]. Comparison of jet quenching measurements and calculations provides unique insight into QGP dynamics and transport properties [15, 16].

Measurements of medium-induced jet angular deflection and substructure modification may elucidate microscopic QGP structure [17–19]. Jet scattering off of QGP quasi-particles is the partonic analog to Rutherford scattering off of atomic nuclei [20]. However, such measurements are challenging in heavy-ion collisions, due to large uncorrelated background. This is especially the case for jets with low transverse momentum ($p_{\mathrm{T,jet}}$), for which deflection effects may be sizable.

In this Letter the ALICE Collaboration reports measurements of the semi-inclusive distribution of charged-particle jets recoiling from a high-p_{T} hadron trigger [21, 22] in inelastic pp and in central Pb–Pb collisions at center-of-mass energy per nucleon–nucleon collision $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Uncorrelated jet yield in central Pb–Pb collisions is corrected using a statistical approach [22], which enables precise recoil jet measurements at low $p_{\mathrm{T,jet}}$ and large jet radius R, allowing for a comprehensive search for jet deflection effects over broad phase space.

Recoil jet yield distributions are measured as a function of $p_{\mathrm{T,jet}}$ and acoplanarity $\Delta\varphi$, the azimuthal separation of the trigger hadron and recoil jet, for jet resolution parameters $R = 0.2$, 0.4, and 0.5. Recoil jet measurements are reported as a function of $p_{\mathrm{T,jet}}$ for $7 < p_{\mathrm{T,jet}} < 140$ GeV/c within $|\Delta\varphi - \pi| < 0.6$ and as a function of $\Delta\varphi$ for $\pi/2 < \Delta\varphi < \pi$ within $10 < p_{\mathrm{T,jet}} < 100$ GeV/c. Theoretical calculations incorporating jet quenching are compared to the data. Analysis details and additional physics results are reported in a companion article [23].

The ALICE apparatus and its performance are described in Refs. [24, 25]. The data for pp collisions at $\sqrt{s} = 5.02$ TeV were recorded during the 2015 and 2017 LHC runs using a minimum bias (MB) trigger [23]. The data for Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV were recorded during the 2018 run using MB and centrality-enhanced triggers [23]. The Pb–Pb event population is selected for high event activity in the forward V0 detectors, corresponding to the 10% most-central fraction of the total Pb–Pb hadronic interaction cross section. After offline event selection, the analyzed dataset has 1.04B events for pp collisions and 89M events for central Pb–Pb collisions.

Charged-particle tracks are reconstructed from hits in the ALICE Inner Tracking System (ITS) and Time Projection Chamber (TPC). The response of these detectors was non-uniform in azimuth and varied between data-taking runs. Tracks are selected to account for such variations, resulting in uniform and stable tracking efficiency [23]. Tracks are accepted within pseudorapidity $|\eta| < 0.9$ and $p_{\mathrm{T}} > 0.15$ GeV/c.

The same analysis is carried out on pp and central Pb–Pb events. Events are selected based on the presence of a high-p_{T} charged-hadron trigger track within $p_{\mathrm{T,low}} < p_{\mathrm{T}} < p_{\mathrm{T,high}}$, denoted $\mathrm{TT}\{p_{\mathrm{T,low}}, p_{\mathrm{T,high}}\}$ ("Trigger Track," units in GeV/c). For events with multiple such tracks, one track is chosen randomly as the trigger. The p_{T}-dependence of the resulting TT distribution corresponds to that of inclusive charged-particle production. The analysis utilizes two TT classes, $\mathrm{TT}\{20,50\}$, denoted "signal", and $\mathrm{TT}\{5,7\}$, denoted "reference."

For TT-selected events, jet reconstruction with charged tracks is carried out in two passes, using the k_{T} and anti-k_{T} jet reconstruction algorithms and the p_{T} recombination scheme [26–28]. The jet acceptance is $|\eta_{\mathrm{jet}}| < 0.9 - R$ over the full azimuth, with additional selection on jet area to suppress unphysical jets [21]. Jets containing tracks with $p_{\mathrm{T}} > 100$ GeV/c are rejected; this rejection has negligible effect on the reported results. There is no other rejection of individual jet candidates.

The first reconstruction pass utilizes the k_{T} algorithm to estimate the event-wise median p_{T} density ρ [21, 29]. The signal and reference TT-selected event populations have different hard jet distributions, which influence the ρ distribution [22, 23]. Precise correction for uncorrelated background yield in central Pb–Pb collisions requires a shift in the reference-TT ρ distribution, determined by a data-driven procedure with sub-per mil precision [23]. This effect is negligible in pp collisions. The second reconstruction pass generates the jet population for physics analysis, utilizing the anti-k_{T} algorithm with $R = 0.2$, 0.4, and 0.5. The p_{T} of each second-pass jet is adjusted by a rough estimate of the background contribution ρA_{jet}, where A is the jet area. This estimate is refined by unfolding, discussed below.

Recoil jet distributions are normalized by the corresponding number of triggers and are semi-inclusive; absent of background they correspond to the production cross-section ratio for hadron–jet coincidences and inclusive hadrons [21] and are perturbatively calculable. The observable Δ_{recoil} is defined as the difference of such signal-TT and reference-TT distributions [21]:

$$\Delta_{\mathrm{recoil}}(p_{\mathrm{T,jet}}, \Delta\varphi) = \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T,jet}} \mathrm{d}\Delta\varphi}\bigg|_{p_{\mathrm{T}}^{\mathrm{trig}} \in \mathrm{TT_{sig}}} - c_{\mathrm{Ref}} \times \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T,jet}} \mathrm{d}\Delta\varphi}\bigg|_{p_{\mathrm{T}}^{\mathrm{trig}} \in \mathrm{TT_{ref}}} . \quad (1)$$

The scale factor c_{Ref} is extracted from data following the data-driven procedure described in Refs. [21, 23]. After scaling by c_{Ref}, the distribution of background jet yield that is uncorrelated with the trigger is identical in the two terms. The subtraction in Δ_{recoil} therefore provides precise correction for this background yield, enabling recoil jet measurements at low $p_{\mathrm{T,jet}}$ and large R.

Multiple hard partonic interactions (MPIs) in the same nuclear collision are independent and do not interfere [30]. MPIs which generate an uncorrelated trigger hadron and recoil jet in the same event constitute a significant background in the search for large-angle jet deflection, since the MPI-generated $\Delta\varphi$ distribution is uniform, masking any $\Delta\varphi$-dependent physical effect. However, Δ_{recoil} corrects the yield due to all uncorrelated sources, including MPIs, and no additional correction procedure to account for the MPI contribution is warranted in the analysis.

The measured Δ_{recoil} distribution is smeared in $p_{\mathrm{T,jet}}$ and $\Delta\varphi$ due to detector effects and residual background fluctuations [21, 22]. Correction for this smearing is carried out using iterative Bayesian unfolding [31] in one dimension ($p_{\mathrm{T,ch\ jet}}$) for measuring $\Delta_{\mathrm{recoil}}(p_{\mathrm{T,ch\ jet}})$, and in two dimensions ($p_{\mathrm{T,ch\ jet}}$,$\Delta\varphi$) for measuring $\Delta_{\mathrm{recoil}}(\Delta\varphi)$; see Ref. [23] for details and consistency checks. The largest systematic uncertainty in the corrected Δ_{recoil} distribution for pp collisions is due to tracking efficiency, while that for Pb–Pb collisions is due to the choice of prior used for unfolding.

The measurements are compared to theoretical model calculations incorporating jet quenching. All models generate hard processes using PYTHIA8 (Monash tune [32, 33]), but differ in the treatment of jet–medium interactions and QGP medium response. JEWEL [34, 35] calculates in-medium scattering using pQCD matrix elements. JETSCAPE [16] incorporates a virtuality-dependent interaction based on

MATTER [36, 37] and LBT [38, 39]. The Hybrid Model [40] describes weakly-coupled jet dynamics perturbatively, with strongly-coupled jet–medium interactions based on the AdS/CFT correspondence. JEWEL calculations optionally include medium response ("recoils on" or "recoils off"), where the "recoils on" calculation follows the "4MomSub" prescription [41]. The Hybrid Model likewise optionally includes medium response ("wake") and elastic scattering from discrete scattering centers [19]. Comparison is also made to a leading-order (LO) pQCD calculation with Sudakov resummation, in which medium-induced broadening is controlled by the jet transport coefficient $\hat{q}$ [42].

Figure 1, upper panels, show $\Delta_{\mathrm{recoil}}(p_{\mathrm{T,ch\ jet}})$, the $\Delta_{\mathrm{recoil}}(p_{\mathrm{T,ch\ jet}}, \Delta\varphi)$ distribution integrated over $|\Delta\varphi - \pi| < 0.6$, for $R = 0.2$, 0.4, and 0.5 in pp and central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The distributions cover $7 < p_{\mathrm{T,ch\ jet}} < 140$ GeV$/c$, including the lowest reported $p_{\mathrm{T,jet}}$ value for jet measurements in heavy-ion collisions at the LHC. The distributions are qualitatively similar, though with shape differences for $p_{\mathrm{T,ch\ jet}} \lesssim 30$ GeV$/c$.

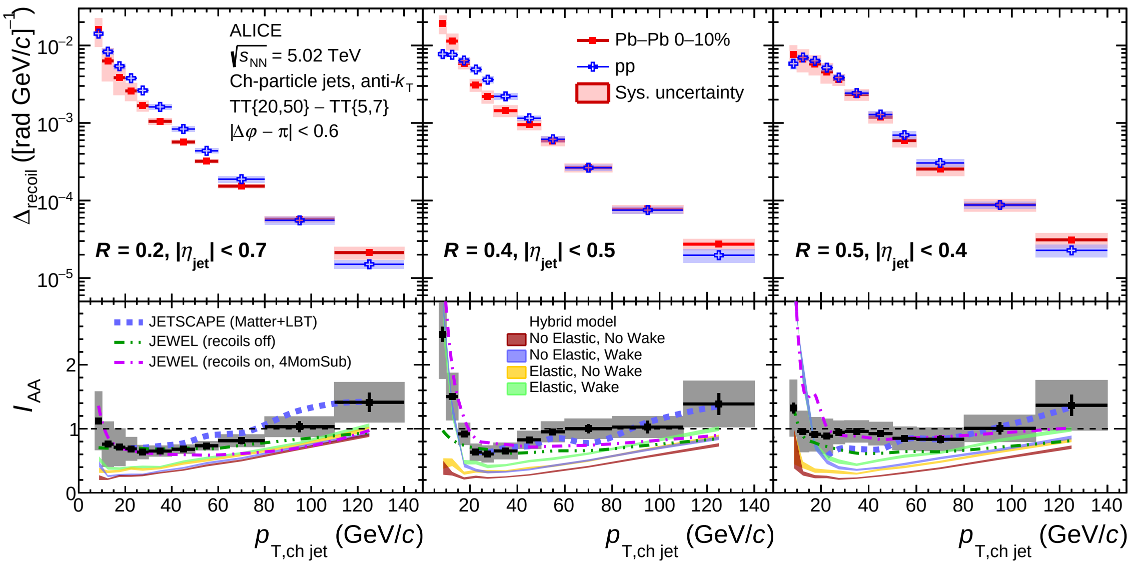

Figure 1: Distributions of recoil jets with $R = 0.2$, 0.4, and 0.5 in pp and central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Upper panels: corrected $\Delta_{\mathrm{recoil}}(p_{\mathrm{T,ch\ jet}})$ distributions. Lower panels: $I_{\mathrm{AA}}(p_{\mathrm{T,ch\ jet}})$ (see text). Also shown are calculations based on JETSCAPE [16], JEWEL [34, 35], and the Hybrid model [40] .

Figure 1, lower panels, show $I_{\mathrm{AA}}(p_{\mathrm{T,ch\ jet}})$, the ratio of the Pb–Pb and pp $\Delta_{\mathrm{recoil}}(p_{\mathrm{T,ch\ jet}})$ distributions. In the range $p_{\mathrm{T,ch\ jet}} < 20$ GeV$/c$, I_{AA} is consistent with or above unity for all R. For $20 < p_{\mathrm{T,ch\ jet}} \lesssim 60$ GeV$/c$, I_{AA} is below unity for $R = 0.2$ and 0.4, which is usually interpreted as medium-induced yield suppression due to energy loss [21]. The value of I_{AA} is consistent with or above unity at higher $p_{\mathrm{T,ch\ jet}}$ for $R = 0.2$ and 0.4, and at all $p_{\mathrm{T,ch\ jet}}$ for $R = 0.5$. It is shown in Ref. [43] that energy loss of the trigger-side jet can enhance I_{AA} and it is expected that jets with I_{AA} equal to or even above unity may still experience energy loss, consistent with inclusive jet measurements. It also suggests that increasing $I_{\mathrm{AA}}(p_{\mathrm{T,ch\ jet}})$ with increasing $p_{\mathrm{T,ch\ jet}}$ may indicate evolution in the geometric ("surface") bias of vertices which generate the observed high-p_{T} hadron triggers [23]. The $I_{\mathrm{AA}}(p_{\mathrm{T,ch\ jet}})$ distributions for $R = 0.2$ and 0.4 exhibit broad minima near $p_{\mathrm{T,ch\ jet}} \sim 20$–30 GeV$/c$; comparisons with models above and below this minimum are discussed separately.

In the range $p_{\mathrm{T,ch\ jet}} > 20$ GeV$/c$, for $R = 0.2$ and 0.4 JETSCAPE and the Hybrid Model (all options) exhibit a similar increase in $I_{\mathrm{AA}}(p_{\mathrm{T,ch\ jet}})$ with increasing $p_{\mathrm{T,ch\ jet}}$ as the data. JETSCAPE also reproduces the magnitude of $I_{\mathrm{AA}}(p_{\mathrm{T,ch\ jet}})$, while the Hybrid Model predicts a smaller value. JEWEL (recoils off) agrees with the measured $I_{\mathrm{AA}}(p_{\mathrm{T,ch\ jet}})$ up to 80 GeV$/c$ for $R = 0.2$ and up to 40 GeV$/c$ for $R = 0.4$, but underpredicts it at higher $p_{\mathrm{T,ch\ jet}}$. JEWEL (recoils on) similarly underpredicts the data in $p_{\mathrm{T,ch\ jet}} > 50$ GeV$/c$. For $R = 0.5$, JETSCAPE describes the data in $p_{\mathrm{T,ch\ jet}} > 50$ GeV$/c$, but underpredicts it below that range. JEWEL (recoils on) accurately describes the measured I_{AA} in $p_{\mathrm{T,ch\ jet}} > 20$ GeV$/c$ for $R = 0.5$, while JEWEL (recoils off) underpredicts it.

For $p_{\mathrm{T,ch\ jet}} < 20$ GeV$/c$, the data exhibit an increase in $I_{\mathrm{AA}}(p_{\mathrm{T,ch\ jet}})$ with decreasing $p_{\mathrm{T,ch\ jet}}$ for $R = 0.4$, with a less significant or negligible increase for $R = 0.2$ and 0.5. However, the difference in the magnitude of $I_{\mathrm{AA}}(p_{\mathrm{T,ch\ jet}})$ between different R jets is not significant within uncertainties. Notably, the Hybrid Model with wake-on (both with and without elastic scattering) and JEWEL (recoils on) reproduce the data for $R = 0.4$. This suggests that the increase in $I_{\mathrm{AA}}(p_{\mathrm{T,ch\ jet}})$ towards low $p_{\mathrm{T,ch\ jet}}$ may arise from medium response to interactions of higher-energy jets that are correlated with the trigger, although these models do less well at reproducing the low-$p_{\mathrm{T,ch\ jet}}$ $I_{\mathrm{AA}}(p_{\mathrm{T,ch\ jet}})$ for $R = 0.5$ jets, indicating that the redistribution of jet energy is not fully captured by models.

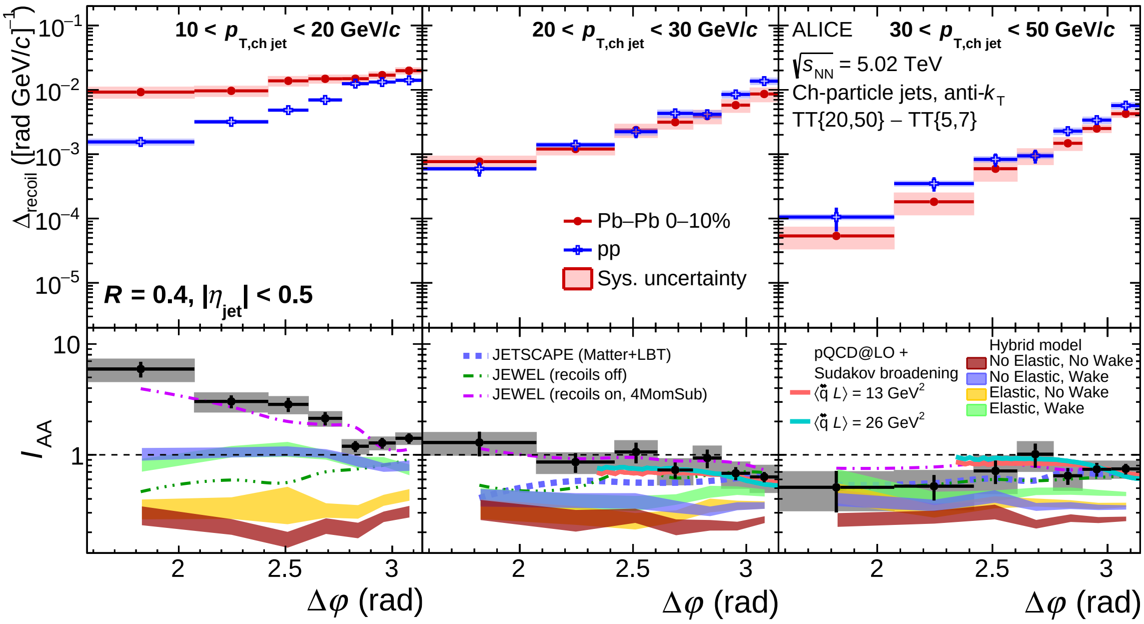

Figure 2: Upper panels: Corrected $\Delta_{\mathrm{recoil}}(\Delta\varphi)$ distributions for $R = 0.4$ in Pb–Pb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, for intervals in recoil $p_{\mathrm{T,ch\ jet}}$: [10,20] (left), [20,30] (middle), and [30,50] (right) GeV$/c$. Lower panels: $I_{\mathrm{AA}}(\Delta\varphi)$. Predictions from JETSCAPE [16], JEWEL [34, 35], and the LO pQCD calculation [42] are also shown.

Figure 2, upper panels, show $\Delta_{\mathrm{recoil}}(\Delta\varphi)$, the $\Delta_{\mathrm{recoil}}(p_{\mathrm{T,ch\ jet}}, \Delta\varphi)$ distribution projected onto $\Delta\varphi$ in intervals of $p_{\mathrm{T,ch\ jet}}$, for $R = 0.4$ in pp and central Pb–Pb collisions. The lower panels show their ratio, $I_{\mathrm{AA}}(\Delta\varphi)$. For $30 < p_{\mathrm{T,ch\ jet}} < 50$ GeV$/c$, medium-induced yield suppression ($I_{\mathrm{AA}}(\Delta\varphi) < 1$) is observed, largely independent of $\Delta\varphi$. For $20 < p_{\mathrm{T,ch\ jet}} < 30$ GeV$/c$, suppression is observed at $\Delta\varphi \sim \pi$, with a gradual but significant increase of $I_{\mathrm{AA}}(\Delta\varphi)$ at larger deviation from $\Delta\varphi \sim \pi$. Notably, for $10 < p_{\mathrm{T,ch\ jet}} < 20$ GeV$/c$, a marked medium-induced excess is observed ($I_{\mathrm{AA}}(\Delta\varphi) > 1$), which increases with increasing deviation from $\Delta\varphi \sim \pi$. A linear fit of this distribution in the range $0.5\pi < \Delta\varphi < 0.92\pi$, taking into account uncorrelated uncertainties only, has slope -40.5 ± 8.6, differing by 4.7σ from zero (which corresponds to no medium-induced modification). This is the first observation of strong acoplanarity broadening in the QGP.

The data in Fig. 1, middle panels, and in Fig. 2 are slices of the same two-dimensional distributions $\Delta_{\mathrm{recoil}}(p_{\mathrm{T,jet}}, \Delta\varphi)$. Note that $I_{\mathrm{AA}}(p_{\mathrm{T,ch\ jet}})$ is integrated over $|\Delta\varphi - \pi| < 0.6$, corresponding approximately to the rightmost four points in Fig. 2, which should be considered when comparing the figures.

Figure 2, lower panels, also show theoretical calculations. The LO pQCD calculation is consistent with data in $20 < p_{\mathrm{T,ch\ jet}} < 50$ GeV$/c$ and $2.4 < \Delta\varphi < \pi$ for $13 < \langle \hat{q}L \rangle < 26$ GeV^2, where L is the in-medium path length. JETSCAPE overpredicts the suppression in $20 < p_{\mathrm{T,ch\ jet}} < 30$ GeV$/c$, but agrees with data in $30 < p_{\mathrm{T,ch\ jet}} < 50$ GeV$/c$. JEWEL (recoils on) describes both the data shape and magnitude well for all $p_{\mathrm{T,ch\ jet}}$ intervals, including the significant broadening in $10 < p_{\mathrm{T,ch\ jet}} < 20$ GeV$/c$ that is not predicted by JEWEL (recoils off). None of the Hybrid Model variants describes the observed broadening at low $p_{\mathrm{T,ch\ jet}}$. These variants generate different magnitude of suppression but underestimate the measured value of I_{AA} in all $p_{\mathrm{T,ch\ jet}}$ bins. Only JEWEL (recoils on) correctly reproduces the marked azimuthal broadening at low $p_{\mathrm{T,ch\ jet}}$ seen in data.

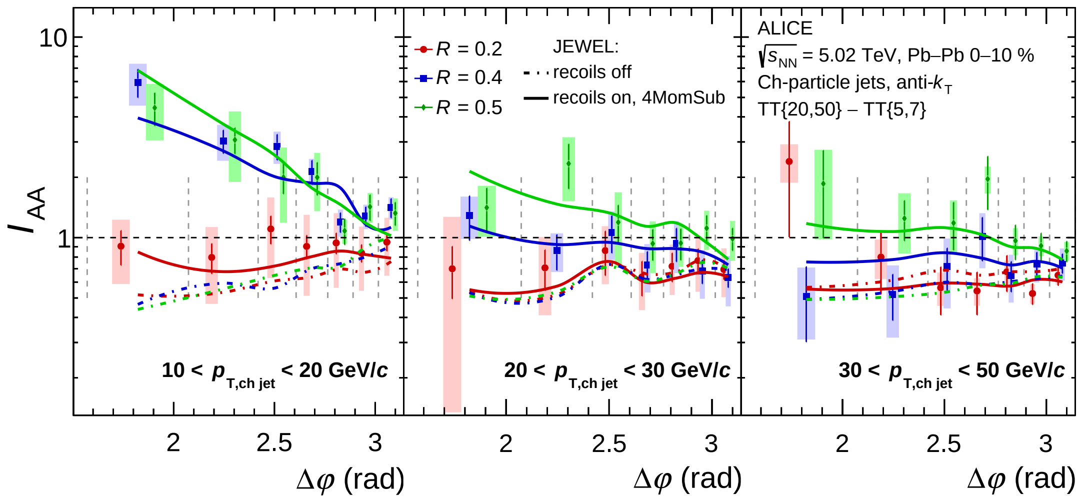

Figure 3: $I_{\mathrm{AA}}(\Delta\varphi)$ for $R = 0.2$, 0.4 and 0.5, for intervals in recoil $p_{\mathrm{T,ch\ jet}}$: [10,20], [20,30], and [30,50] GeV$/c$. The central points and systematic uncertainties are offset from the center of the $\Delta\varphi$ intervals for clarity. The vertical dashed gray lines represent the $\Delta\varphi$ interval edges. Predictions from JEWEL are also shown.

Figure 3 shows $I_{\mathrm{AA}}(\Delta\varphi)$ for $R = 0.2$, 0.4, and 0.5, for the $p_{\mathrm{T,ch\ jet}}$ intervals in Fig. 2. The medium-induced acoplanarity broadening in Fig. 2, left panel, is seen only in the range $10 < p_{\mathrm{T,ch\ jet}} < 20$ GeV$/c$, and only for $R = 0.4$ and 0.5 . The value of $I_{\mathrm{AA}}(\Delta\varphi)$ is either consistent with unity or suppressed at larger $p_{\mathrm{T,ch\ jet}}$ for $R = 0.4$ and 0.5, and for all measured $p_{\mathrm{T,ch\ jet}}$ for $R = 0.2$. The JEWEL (recoils on) calculation is likewise consistent within uncertainties with all of these data.

Figures 1, 2, and 3 present the first observation of medium-induced jet yield excess and acoplanarity broadening in the QGP. The broadening is significant in $10 < p_{\mathrm{T,ch\ jet}} < 20$ GeV$/c$ for $R = 0.4$ and 0.5 but is negligible for $R = 0.2$, and at larger $p_{\mathrm{T,ch\ jet}}$ for all R. This rapid transition in the acoplanarity distribution shape as a function $p_{\mathrm{T,ch\ jet}}$ and R is striking. Possible medium-induced acoplanarity broadening mechanisms include jet scattering from QGP quasi-particles; wake effects [44]; and jet splitting.

The latter two mechanisms do not generate perturbatively interpretable jets, with constituents that are softer in p_{T} and spatially more diffuse. In these scenarios, the rate to generate a correlated "jet" with $p_{\mathrm{T,ch\ jet}} > 10$ GeV$/c$ may scale approximately with the jet area, i.e. R^2, resulting in a strong R-dependence of the $I_{\mathrm{AA}}(\Delta\varphi)$ enhancement at low $p_{\mathrm{T,ch\ jet}}$, as observed. In contrast, a strong R-dependence of the $I_{\mathrm{AA}}(\Delta\varphi)$ enhancement is not a natural consequence of jet scattering from QGP quasi-particles, which should generate similar effects for $R = 0.2$, 0.4, and 0.5. The observed systematic dependence therefore disfavors in-medium jet scattering as the primary origin of in-medium acoplanarity broadening. Both JEWEL and the Hybrid model describe the observed low-$p_{\mathrm{T,ch\ jet}}$ behavior of $I_{\mathrm{AA}}(p_{\mathrm{T,ch\ jet}})$, only if jet–medium response is included. None of the models considered here successfully describe all available data.

In summary, measurements of semi-inclusive distributions of charged-particle jets recoiling from a high-p_{T} hadron trigger in pp and central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV have been reported over a broad kinematic range, including low $p_{\mathrm{T,jet}}$ and large R. A marked medium-induced enhancement in recoil jet acoplanarity is observed for the first time, but only at low $p_{\mathrm{T,jet}}$ for large R; this favors QGP wake effects or jet splitting as the underlying physical mechanism, and disfavors large-angle jet scattering.

Current model calculations incorporating jet quenching do not reproduce all of these observations. Further modeling developments, and their comparison to these and similar data, promise significant new understanding of the mechanisms governing energy transport and the dynamics of the QGP.

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A The ALICE Collaboration

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