EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Measurement of the angle between jet axes in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

ALICE Collaboration*

Abstract

This letter presents the first measurement of the angle between different jet axes (denoted as ΔR_{axis}) in Pb–Pb collisions. The measurement is carried out in the 0–10% most-central events at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Jets are assembled by clustering charged particles at midrapidity using the anti-k_{T} algorithm with resolution parameters $R = 0.2$ and 0.4 and transverse momenta in the intervals $40 < p_{\mathrm{T}}^{\mathrm{ch\,jet}} < 140$ GeV/c and $80 < p_{\mathrm{T}}^{\mathrm{ch\,jet}} < 140$ GeV/c, respectively. Measurements at these low transverse momenta enhance the sensitivity to quark–gluon plasma (QGP) effects. A comparison to models implementing various mechanisms of jet energy loss in the QGP shows that the observed narrowing of the Pb–Pb distribution relative to pp can be explained if quark-initiated jets are more likely to emerge from the medium than gluon-initiated jets. These new measurements discard intra-jet p_{T} broadening as described in a model calculation with the BDMPS formalism as the main mechanism of energy loss in the QGP. The data are sensitive to the angular scale at which the QGP can resolve two independent splittings, favoring mechanisms that incorporate incoherent energy loss.

*See Appendix A for the list of collaboration members

The strongly interacting, deconfined state of matter of our universe a few microseconds after the Big Bang can be recreated in ultrarelativistic heavy-ion collisions at the Large Hadron Collider (LHC) [1, 2]. Studying the microscopic structure of this quark–gluon plasma (QGP) can elucidate the physics of many-body strongly coupled systems [3]. Because droplets of QGP created at colliders are small and short-lived, studying interactions within those droplets requires auto-generated probes. In this study, jets of energetic hadrons, which arise from high-momentum-transfer (hard) collisions between quarks and gluons (partons) in the incoming nuclei, are used. These hard-scattered particles produce showers of secondary partons, which give rise to jets of multiple correlated hadrons (see Fig. 1, left).
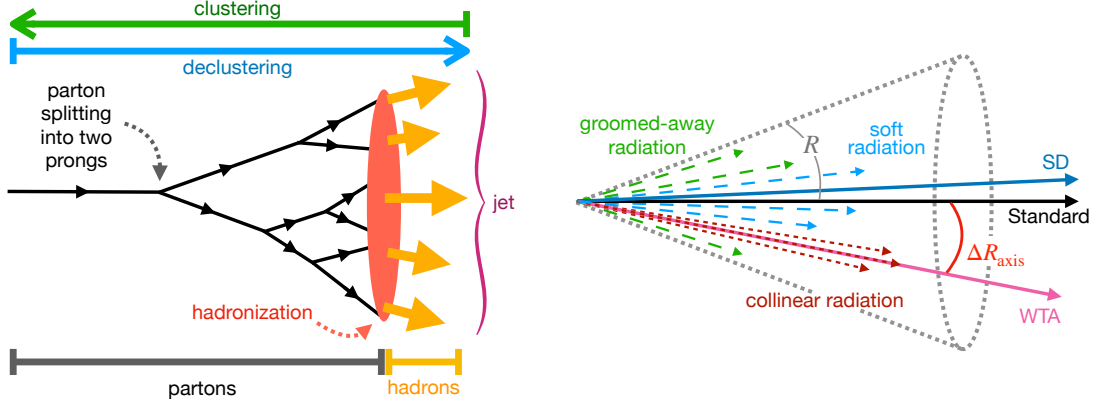

Figure 1: Left: schematic of how energetic partons split or fragment into lower-energy prongs or branches of partons down to a scale in which hadrons emerge. An algorithm can be run over final-state hadrons to cluster them into jets. An inverse declustering algorithm can be used to recursively explore the jet substructure. Right: schematic showing that different jet axes (solid arrows) can be selected from a jet to construct the ΔR_{axis} observable. The Standard axis (represented by a black arrow) is constrained by all the jet constituents (represented by dashed arrows). The SD axis (represented by a dark blue arrow) is determined by the particles left in the jet after grooming (blue and dark red arrows). Finally, the WTA axis (represented by a pink arrow) tends to be aligned with the most energetic constituent.

When traversing the QGP, jets interact with the medium, lose energy, and are modified relative to their structure in elementary (e.g., ee or pp) collisions. Thus, measuring the substructure of jets can provide sensitivity to different scales within the jet modification process. The direction of a jet in rapidity (y) and azimuth (φ), referred to as the jet axis, is affected by transverse modification of the partonic shower, with varying sensitivity to soft radiation, depending on how the axis is defined [4].

This letter presents the first measurement in heavy-ion collisions of the angle between pairs of jet axes, ΔR_{axis} (see Fig. 1, right). This observable shows how well the QGP resolves the angular structure of the parton shower [4] and is defined as

$$\Delta R_{axis} \equiv \sqrt{(y_{axis,1} - y_{axis,2})^2 + (\varphi_{axis,1} - \varphi_{axis,2})^2}, \tag{1}$$

where $y_{axis,i}$ and $\varphi_{axis,i}$ are the rapidity and azimuthal coordinates of the axes, respectively. The axes considered in this analysis are:

– "Standard": coordinates in y–φ of the 4-vector resulting from clustering jets with the anti-k_T algorithm [5] using the E recombination scheme (two branches combined into one by adding their 4-momenta). In this case, all jet constituents including soft (low-transverse-momentum) and hard radiation contribute to the axis.

– "Soft Drop" (SD): coordinates in y–φ of jet after soft wide-angle radiation is removed using the Soft Drop grooming procedure [6] with the Cambridge–Aachen (C/A) reclustering algorithm [7,

2

8]. The procedure stops when a splitting is found that satisfies the condition

$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{\Delta R_{1,2}}{R} \right)^{\beta}, \qquad (2)$$

where $p_{T,i}$ are the transverse momenta of each of the two branches in the splitting, $\Delta R_{1,2}$ is the distance between them in the y–φ plane, R is the jet resolution parameter, and z_{cut} and β are user-set parameters.

– "Winner-Takes-All" (WTA): coordinates in y–φ of jet after reclustering its constituents using the C/A algorithm and the WTA p_T recombination scheme [9], which combines two jet branches into one by giving the merged branch the total p_T of the two sub-branches and the direction of the hardest sub-branch. The WTA axis is often consistent with the direction of the hardest constituent of the jet and is insensitive to soft radiation at the leading power of the observable [4].

Measurements of ΔR_{axis} are sensitive to medium-induced effects. For example, an increase in the relative fraction of quark- vs. gluon-initiated jets due to medium-induced radiative energy loss can narrow the angular distribution, while multiple scattering of the hard-scattered parton off medium partons can broaden it [10]. Reference 11 reported a net narrowing of the distribution in Pb–Pb collisions, quantitatively consistent with the former. This can be expected if the broadening was primarily in the wide-angle radiation that grooming removes from the jet. This is tested by looking for broadening effects in an ungroomed angular observable, such as the angle between the Standard and WTA axes.

Measurements of ΔR_{axis} are also sensitive to the wake created by a jet imparting some of its momentum to the QGP. This wake is often referred to as medium response [12] and is expected to dominate at large angles from the Standard axis. Consequently, progressively increasing the grooming intensity, while simultaneously varying the jet resolution parameter R can uncover the medium response effect. Comparing experimental results with different models is expected to disentangle medium response and medium-induced large-angle radiation.

The medium resolution length, L_{res}, is a property of the QGP proportional to the inverse of its local temperature [13]. It characterizes the minimum separation distance at which two color charges within the same jet interact independently with the QGP. Certain groomed substructure observables are sensitive to this scale [14]. In this analysis, the sensitivity of ΔR_{axis} to L_{res} is investigated.

The measured ΔR_{axis} distributions in pp collisions at $\sqrt{s} = 5.02$ TeV reported in Ref. 15 are used as the reference for QGP-induced effects reported here. Perturbative QCD calculations [4] were found to agree with the measurements in pp collisions within the experimental uncertainties, demonstrating good theoretical control of the observables. The data were collected in 2018 from Pb–Pb collisions at a center-of-mass energy per nucleon–nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE detector [2]. A detailed description of the detector and its performance can be found in Refs. 16 and 17. A trigger based on the charged-particle multiplicity in the forward region [18] was used to select events in the 0–10% centrality class [19, 20]. The events were required to have a reconstructed primary vertex within ± 10 cm of the nominal interaction point in the longitudinal direction. Beam-induced background events were removed using two Zero Degree Calorimeters and pileup effects were removed by discarding events that contained multiple reconstructed vertices [21]. These selection criteria yield a data sample with 92 million events, corresponding to an integrated luminosity of ≈ 0.12 nb^{-1}.

Charged-particle tracks reconstructed in the Inner Tracking System (ITS) [22] and Time Projection Chamber (TPC) [23] used in the analysis were required to have a transverse momentum $p_T > 0.15$ GeV/c and a pseudorapidity $|\eta| < 0.9$. See the supplemental materials [24] for details. The detector performance was estimated by propagating simulated events through a GEANT 3 [25] model of the ALICE detector. The transverse-momentum resolution $\sigma(p_T)/p_T$ increases linearly from $\approx 1\%$ at $p_T = 1$ GeV/c to $\approx 4\%$

at $p_{\mathrm{T}} = 50$ GeV/c [17]. The tracking efficiency rapidly increases from $\approx 65\%$ at $p_{\mathrm{T}} = 0.15$ GeV/c to $\approx 85\%$ at $p_{\mathrm{T}} = 1$ GeV/c, and remains above $\approx 75\%$ at higher p_{T}. The large uncorrelated background from the underlying event (UE) [26] in high-multiplicity heavy-ion collisions is subtracted before jet finding using the event-wide constituent subtraction procedure from Refs. 27 and 28. The parameters used are $\alpha = 0$, $A_{\mathrm{g}} = 0.01$, and $\Delta R^{\mathrm{max}} = 0.1$ (0.25) when the track sample is used to cluster jets of $R = 0.2$ (0.4).

Tracks included in jet clustering are assigned the charged-pion mass. Charged-particle jets are clustered with the anti-k_{T} algorithm, the E recombination scheme, and resolution parameters $R = 0.2$ and 0.4, using FastJet [29]. Jets containing a track with $p_{\mathrm{T}} > 100$ GeV/c and jets with their Standard axis not pointing inside the fiducial volume of the TPC ($|\eta_{\mathrm{jet}}| < 0.9 - R$) are discarded.

The measured distributions are unfolded to correct for detector effects as well as residual UE fluctuations using an iterative Bayesian procedure [30, 31]. The procedure uses a 4D response matrix (RM) that captures the correspondence between ΔR_{axis} and jet transverse momentum ($p_{\mathrm{T}}^{\mathrm{ch\,jet}}$) at the generator and detector levels. The generator-level component of the RM is modeled using generated PYTHIA 8 [32] Monash 2013 [33] events. The detector-level component of the RM is modeled by propagating those events through a GEANT 3 [25] model of the ALICE detector and embedding the smeared events into measured Pb–Pb events.

Systematic uncertainties arise from the tracking inefficiency, unfolding procedure, unfolding model dependence, UE subtraction procedure, and residual effects from combinatorial jets. The tracking-inefficiency uncertainty is determined by repeating the analysis with an RM based on a track sample with 4% of all tracks randomly rejected. This number corresponds to the uncertainty in the tracking efficiency, determined by varying the track selection parameters and ITS–TPC matching criteria.

The unfolding-procedure uncertainty is determined by extending the lower and upper bounds of the $p_{\mathrm{T}}^{\mathrm{ch\,jet}}$ spectrum by 5 GeV/c, changing the detector-level ΔR_{axis} binning, changing the number of unfolding iterations, and scaling the prior distribution. The four categories of variations are carried out individually and combined into an unfolding uncertainty using their standard deviation. The uncertainty from the model dependence in the unfolding is determined by repeating the analysis with response matrices based on different event generators including Herwig 7 [34] and JEWEL [35] with and without the inclusion of medium partons recoiling after interactions with the jet.

Potential bias introduced by the event-wide UE subtraction [27, 28] is quantified as the maximum difference between the nominal result and the results obtained by repeating the procedure with parameters $\Delta R^{\mathrm{max}} = 0.05$ (0.1), which lead to an under-subtraction, and $\Delta R^{\mathrm{max}} = 0.5$ (0.7), which lead to an over-subtraction of the background, for jets of $R = 0.2$ (0.4). Deviations between the generator-level and unfolded distributions due to residual combinatorial jets are determined with a closure test. PYTHIA 8 events are embedded into background events with no jets and analyzed identically to the measured data. Deviations between the unfolded and PYTHIA 8 generator-level spectra are assigned as the uncertainty.

The systematic uncertainties are added in quadrature. The total systematic uncertainty is in the range of 2–61% depending on ΔR_{axis} and $p_{\mathrm{T}}^{\mathrm{ch\,jet}}$. The large variation comes primarily from the background subtraction procedure at low $p_{\mathrm{T}}^{\mathrm{ch\,jet}}$ (where background effects are largest). It is small at low values of ΔR_{axis}, and smoothly grows in the tails of the distributions. See the supplemental materials [24] for details. The measured distributions are normalized to the total number of jets in a given $p_{\mathrm{T}}^{\mathrm{ch\,jet}}$ interval, N, which is equivalent to reporting the self-normalized cross section:

$$\frac{1}{N(p_{\mathrm{T}}^{\mathrm{ch\,jet}})}\frac{\mathrm{d}N}{\mathrm{d}\Delta R_{\mathrm{axis}}}\left(p_{\mathrm{T}}^{\mathrm{ch\,jet}}\right) \equiv \frac{1}{\sigma(p_{\mathrm{T}}^{\mathrm{ch\,jet}})}\frac{\mathrm{d}\sigma}{\mathrm{d}\Delta R_{\mathrm{axis}}}\left(p_{\mathrm{T}}^{\mathrm{ch\,jet}}\right). \tag{3}$$

This normalization choice causes the Pb–Pb/pp ratios to go above unity at low ΔR_{axis}. In an absolute cross section measurement, the ratio would be below unity as a result of jet suppression in heavy-ion

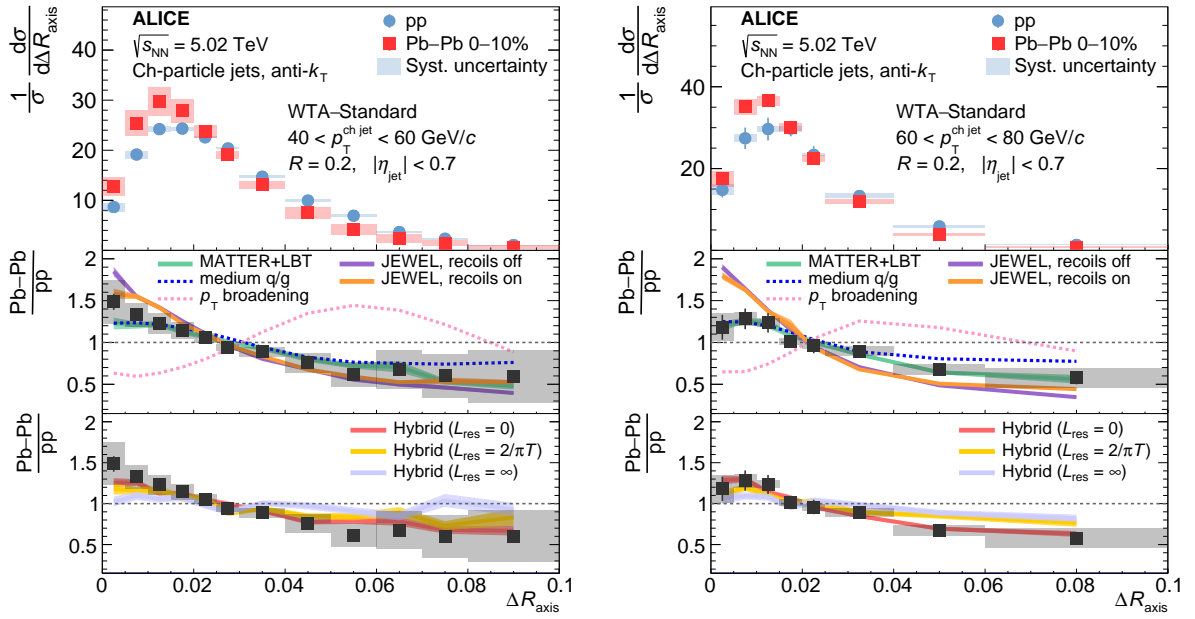**Figure 2:** Top panels: fully corrected Pb–Pb and pp $\Delta R_{axis}^{WTA-Standard}$ distributions in the $p_T^{ch\,jet}$ intervals $[40, 60]$ (left), and $[60, 80]$ (right) GeV/c for jets of $R = 0.2$. The pp baseline is taken from Ref. 15. Central and bottom panels: measured Pb–Pb/pp ratio in black, as well as predictions from a selection of jet quenching models.

collisions. The suppression factor was measured in Ref. 36. Thus, only the shape and not the absolute scale of the ΔR_{axis} spectra is reported.

The measured WTA–Standard distributions are shown in Fig. 2 for $R = 0.2$ jets in the $p_T^{ch\,jet}$ ranges $[40, 60]$ and $[60, 80]$ GeV/c. The top panels show ΔR_{axis} spectra from Pb–Pb and pp collisions. The vertical error bars represent the statistical uncertainties and the rectangles represent the total systematic uncertainties. The central and bottom panels show the Pb–Pb/pp ratio, with all uncertainties assumed uncorrelated and added in quadrature when calculating the ratio. The equivalent results for other $p_T^{ch\,jet}$ ranges, jet resolution parameters, and grooming settings are included in the supplemental materials [24].

The data are compared with several jet quenching models. These models have different implementations of the microscopic properties of the medium, its evolution, and the jet–medium interaction. The **JEWEL** event generator [35] models the medium with a boost-invariant longitudinally expanding ideal quark–gluon gas [37]. Parameters from Ref. 38, which are adequate for the kinematics of this measurement, are used. The medium partons recoiling after interacting with jet constituents can be discarded from the event (recoils off) or allowed to hadronize together with the jet (recoils on). **"MATTER+LBT"** is from the JETSCAPE event generator [39, 40], implementing an in-medium parton shower with interactions of high- (low-) virtuality partons with the medium described by the MATTER [41] (Linear Boltzmann Transport [42]) model. The curve labeled **"medium q/g"** corresponds to a phenomenological model in which the only difference between the Pb–Pb and pp results comes from a modification of the fraction of quarks and gluons that initiate the jets [43, 44], highlighting that these two jet populations lose energy differently in the medium. The **"p_T broadening"** calculation adds to the previous model a p_T broadening caused by incoherent multiple scatterings with the medium partons [10] following the BDMPS approach [45–47]. This calculation uses a mean square momentum transfer coefficient between the jet and medium constituents $\langle \hat{q}L \rangle = 5$ GeV^2. **"Hybrid"** is from the hybrid model [48], which describes the weakly coupled jet showering process using the DGLAP formalism and the strongly coupled interaction between the jet constituents and medium partons via holographic calculations of energy loss based on AdS/CFT. The case $L_{res} = 0$ corresponds to fully incoherent energy loss, where the medium is able to resolve the splitting immediately after the parton fragments, resulting in higher energy loss [13].
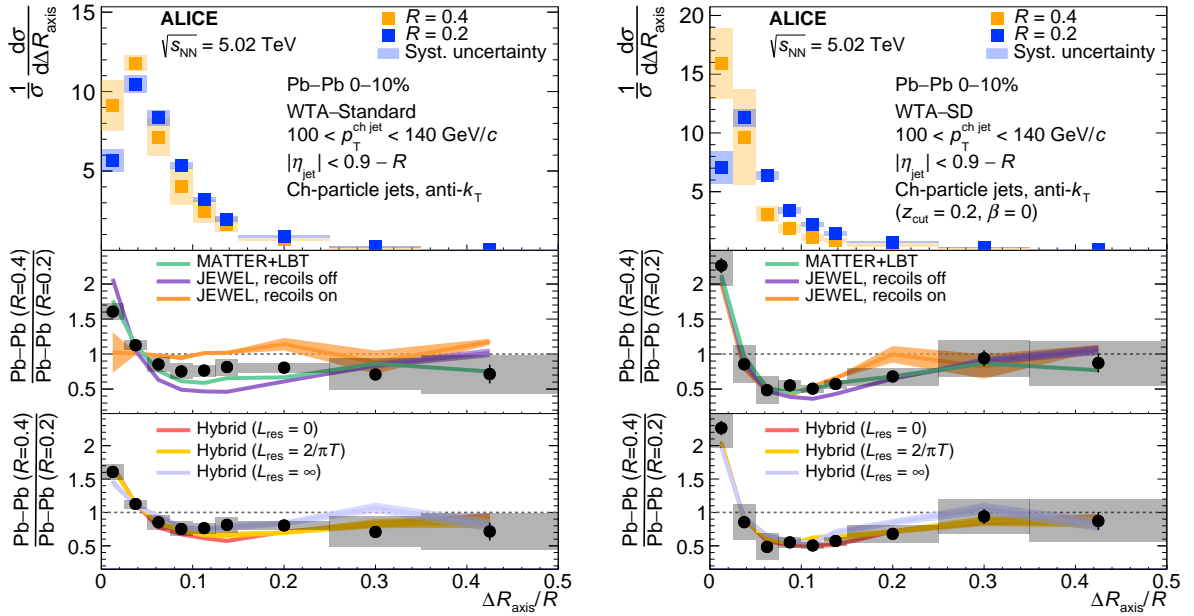
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Figure 3: Top panels: fully corrected Pb–Pb $\Delta R_{axis}^{WTA-Standard}/R$ (left), and $\Delta R_{axis}^{WTA-SD}/R$ with ($z_{cut} = 0.2, \beta = 0$) (right) distributions in the $p_T^{ch\,jet}$ interval $[100, 140]$ GeV/c. Central and bottom panels: measured Pb–Pb($R = 0.4$)/Pb–Pb($R = 0.2$) ratio in black, as well as predictions from a selection of jet quenching models.

The case $L_{res} = \infty$ corresponds to fully coherent energy loss, where the medium is not able to resolve splittings, and the energy loss is lower. The intermediate case $L_{res} = 2/\pi T$, where T is the medium local temperature, is also included. All "Hybrid" curves include medium-response effects from Ref. 49.

The measured $R = 0.2$ distributions are narrower than those measured in pp collisions. Results with $R = 0.4$, presented in the supplemental materials [24], are consistent with this narrowing, but also with no modification within statistical and systematic uncertainties. The narrowing may be due to a selection bias, as jets selected using $p_T^{ch\,jet}$ (rather than the initial momentum before the jet-medium interactions, which is not accessible experimentally) tend to lose little energy in the QGP [50]. Similarly, the experimental result is also consistent with a quark-enhanced mixture of jets surviving the interaction with the medium relative to the vacuum case, as expected since gluon-initiated jets couple more strongly to partons of the QGP and thus lose more energy [11, 43, 51]. The MATTER+LBT model overall describes the data for all considered kinematical regions.

In contrast with $R = 0.2$, for larger R there are significant differences in JEWEL predictions with and without recoils. This is expected, as the medium response populates larger angles away from the Standard jet axis. However, grooming reduces the sensitivity to the medium response. The Hybrid model does not predict a significant effect from the medium response. See the supplemental materials [24] for details. The inclusion of other models in which the medium response can be turned on and off (e.g. Co-LBT [52, 53]) could help clarify the sensitivity of ΔR_{axis} to the properties and magnitude of this effect. Narrowing of the distributions relative to those measured in pp collisions for jets of $R = 0.2$ is qualitatively predicted by all models except for "p_T broadening". This excludes the hypothesis that intra-jet p_T broadening manifests in the groomed radiation in previous measurements [11].

The data are closest to incoherent energy loss of jets in the Hybrid model ($L_{res} = 0$). The fully coherent case ($L_{res} = \infty$) predicts significantly less narrowing. Fully incoherent energy loss better reproduces the data than the intermediate case of $L_{res} = 2/\pi T$. In holographic calculations of the Debye screening length, the intermediate case is expected to be closer to the true medium resolution scale [13].

The precision of the data at higher $p_T^{ch\,jet}$ is limited by the integrated luminosity of the pp dataset, which

only allows for an extraction of the Pb–Pb/pp results up to 100 GeV/c. However, in heavy-ion collisions, larger $p_T^{\text{ch jet}}$ can be studied through the ratio of $(R = 0.4)/(R = 0.2)$ spectra, where the systematic uncertainties partially cancel. This kinematic range is also important for future comparisons with results from other experiments which cannot access the low-p_T regime of this measurement. The ratio is reported as a function of the jet angular scale $\Delta R_{\text{axis}}/R$ that, by construction, is independent of R. Figure 3 shows the ratio for $p_T^{\text{ch jet}} \in [100, 140]$ GeV/c together with theoretical predictions. The ungroomed WTA–Standard result is challenging to models, as can be seen in Fig. 3 (left). Grooming improves the agreement between the models and the data (see Fig. 3 (right)), suggesting that the ungroomed result captures significantly more of the non-perturbative aspects of jet quenching.

Comparing $\Delta R_{\text{axis}}^{\text{WTA}-\text{Standard}}$ to $\Delta R_{\text{axis}}^{\text{WTA}-\text{SD}}$ with different grooming settings shows that grooming does not significantly impact the experimental results. This is similar to pp collisions, where the Standard and SD axes were found more aligned with each other than either of them with the WTA axis. While the Standard axis is influenced by the soft wide-angle radiation groomed away in the SD-axis case, it is dominated by the hard radiation that remains in the SD case.

In summary, the first measurement of the angle between the WTA and Standard or Soft Drop groomed charged-particle jet axes in Pb–Pb collisions is reported. The measurement was carried out using 0–10% most-central collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE detector and for $p_T^{\text{ch jet}} \in [40, 140]$ ([80,140]) GeV/c for jets of $R = 0.2$ (0.4).

Narrowing of the ΔR_{axis} distribution relative to the vacuum case is found. The narrowing may be explained if the Pb–Pb distribution is dominated by quark-initiated jets, since gluon-initiated jets are expected to interact more with the medium. This is consistent with the prediction from the "medium q/g" model. The measurement disfavors intra-jet p_T broadening, as implemented in Ref. 10.

The ΔR_{axis} observables exhibit sensitivity to the medium resolution length. The measurement favors incoherent energy loss of jets, where the medium resolves a splitting immediately after it happens, regardless of the angular separation between the prongs. Future measurements of ΔR_{axis} in photon- or Z-boson-tagged jets could provide a way to experimentally vary the fraction of quark- vs. gluon-initiated jets.

Acknowledgements

References

[1] W. Busza, K. Rajagopal, and W. van der Schee, "Heavy Ion Collisions: The Big Picture, and the Big Questions", *Ann. Rev. Nucl. Part. Sci.* **68** (2018) 339–376, arXiv:1802.04801 [hep-ph].

[2] **ALICE** Collaboration, "The ALICE experiment – A journey through QCD", arXiv:2211.04384 [nucl-ex].

[3] B. V. Jacak and B. Müller, "The exploration of hot nuclear matter", *Science* **337** (2012) 310–314.

[4] P. Cal, D. Neill, F. Ringer, and W. J. Waalewijn, "Calculating the angle between jet axes", *JHEP* **04** (2020) 211, arXiv:1911.06840 [hep-ph].

[5] M. Cacciari, G. P. Salam, and G. Soyez, "The anti-k_t jet clustering algorithm", *JHEP* **04** (2008) 063, arXiv:0802.1189 [hep-ph].

[6] A. J. Larkoski, S. Marzani, G. Soyez, and J. Thaler, "Soft Drop", *JHEP* **05** (2014) 146, `arXiv:1402.2657 [hep-ph]`.

[7] Y. L. Dokshitzer, G. D. Leder, S. Moretti, and B. R. Webber, "Better jet clustering algorithms", *JHEP* **08** (1997) 001, `arXiv:hep-ph/9707323`.

[8] M. Wobisch and T. Wengler, "Hadronization corrections to jet cross-sections in deep inelastic scattering", in *Workshop on Monte Carlo Generators for HERA Physics (Plenary Starting Meeting)*, pp. 270–279. 4, 1998. `arXiv:hep-ph/9907280`.

[9] D. Bertolini, T. Chan, and J. Thaler, "Jet Observables Without Jet Algorithms", *JHEP* **04** (2014) 013, `arXiv:1310.7584 [hep-ph]`.

[10] F. Ringer, B.-W. Xiao, and F. Yuan, "Can we observe jet P_T-broadening in heavy-ion collisions at the LHC?", *Phys. Lett. B* **808** (2020) 135634, `arXiv:1907.12541 [hep-ph]`.

[11] **ALICE** Collaboration, S. Acharya *et al.*, "Measurement of the groomed jet radius and momentum splitting fraction in pp and Pb−Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV", *Phys. Rev. Lett.* **128** (2022) 102001, `arXiv:2107.12984 [nucl-ex]`.

[12] G. Milhano, U. A. Wiedemann, and K. C. Zapp, "Sensitivity of jet substructure to jet-induced medium response", *Phys. Lett. B* **779** (2018) 409–413, `arXiv:1707.04142 [hep-ph]`.

[13] Z. Hulcher, D. Pablos, and K. Rajagopal, "Resolution Effects in the Hybrid Strong/Weak Coupling Model", *JHEP* **03** (2018) 010, `arXiv:1707.05245 [hep-ph]`.

[14] J. Casalderrey-Solana, J. G. Milhano, D. Pablos, and K. Rajagopal, "Modification of Jet Substructure in Heavy Ion Collisions as a Probe of the Resolution Length of Quark-Gluon Plasma", *JHEP* **2020** (2020) 044, `arXiv:1907.11248 [hep-ph]`.

[15] **ALICE** Collaboration, "Measurement of the angle between jet axes in pp collisions at $\sqrt{s} = 5.02$ TeV", `arXiv:2211.08928 [nucl-ex]`.

[16] **ALICE** Collaboration, K. Aamodt *et al.*, "The ALICE experiment at the CERN LHC", *JINST* **3** (2008) S08002.

[17] **ALICE** Collaboration, B. Abelev *et al.*, "Performance of the ALICE Experiment at the CERN LHC", *Int. J. Mod. Phys. A* **29** (2014) 1430044, `arXiv:1402.4476 [nucl-ex]`.

[18] **ALICE** Collaboration, E. Abbas *et al.*, "Performance of the ALICE VZERO system", *JINST* **8** (2013) P10016, `arXiv:1306.3130 [nucl-ex]`.

[19] **ALICE** Collaboration, B. Abelev *et al.*, "Centrality determination of Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV with ALICE", *Phys. Rev. C* **88** (2013) 044909, `arXiv:1301.4361 [nucl-ex]`.

[20] **ALICE** Collaboration, "Centrality determination in heavy ion collisions", *ALICE-PUBLIC-2018-011* (2018) . `https://cds.cern.ch/record/2636623`.

[21] **ALICE** Collaboration, S. Acharya *et al.*, "Measurements of inclusive jet spectra in pp and central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV", *Phys. Rev. C* **101** (2020) 034911, `arXiv:1909.09718 [nucl-ex]`.

[22] **ALICE** Collaboration, K. Aamodt *et al.*, "Alignment of the ALICE Inner Tracking System with cosmic-ray tracks", *JINST* **5** (2010) P03003, `arXiv:1001.0502 [physics.ins-det]`.

[23] J. Alme *et al.*, "The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events", *Nucl. Instrum. Meth. A* **622** (2010) 316–367, `arXiv:1001.1950` `[physics.ins-det]`.

[24] **ALICE** Collaboration, "Supplemental materials: Measurement of the angle between jet axes in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV",. `https://cds.cern.ch/record/2852587/files`. CERN-EP-2023-046.

[25] R. Brun, F. Bruyant, M. Maire, A. C. McPherson, and P. Zanarini, *GEANT 3: user's guide Geant 3.10, Geant 3.11; rev. version.* CERN, Geneva, Sep, 1987. `https://cds.cern.ch/record/1119728`.

[26] **ALICE** Collaboration, B. Abelev *et al.*, "Measurement of Event Background Fluctuations for Charged Particle Jet Reconstruction in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV", *JHEP* **03** (2012) 053, `arXiv:1201.2423` `[hep-ex]`.

[27] P. Berta, M. Spousta, D. W. Miller, and R. Leitner, "Particle-level pileup subtraction for jets and jet shapes", *JHEP* **06** (2014) 092, `arXiv:1403.3108` `[hep-ex]`.

[28] P. Berta, L. Masetti, D. W. Miller, and M. Spousta, "Pileup and Underlying Event Mitigation with Iterative Constituent Subtraction", *JHEP* **08** (2019) 175, `arXiv:1905.03470` `[hep-ph]`.

[29] M. Cacciari, G. P. Salam, and G. Soyez, "FastJet User Manual", *Eur. Phys. J. C* **72** (2012) 1896, `arXiv:1111.6097` `[hep-ph]`.

[30] G. D'Agostini, "A multidimensional unfolding method based on Bayes' theorem", *Nucl. Instrum. Meth. A* **362** (1994) 487 – 498.

[31] G. D'Agostini, "Improved iterative Bayesian unfolding", in *Alliance Workshop on Unfolding and Data Correction.* 10, 2010. `arXiv:1010.0632` `[physics.data-an]`.

[32] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, "An introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159–177, `arXiv:1410.3012` `[hep-ph]`.

[33] P. Skands, S. Carrazza, and J. Rojo, "Tuning PYTHIA 8.1: the Monash 2013 Tune", *Eur. Phys. J. C* **74** (2014) 3024, `arXiv:1404.5630` `[hep-ph]`.

[34] S. Gieseke, C. Rohr, and A. Siodmok, "Colour reconnections in Herwig++", *Eur. Phys. J. C* **72** (2012) 2225, `arXiv:1206.0041` `[hep-ph]`.

[35] K. C. Zapp, "JEWEL 2.0.0: directions for use", *Eur. Phys. J. C* **74** (2014) 2762, `arXiv:1311.0048` `[hep-ph]`.

[36] **ALICE** Collaboration, "Measurement of the radius dependence of charged-particle jet suppression in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV", `arXiv:2303.00592` `[nucl-ex]`.

[37] K. C. Zapp, F. Krauss, and U. A. Wiedemann, "A perturbative framework for jet quenching", *JHEP* **03** (2013) 080, `arXiv:1212.1599` `[hep-ph]`.

[38] R. Kunnawalkam Elayavalli and K. C. Zapp, "Medium response in JEWEL and its impact on jet shape observables in heavy ion collisions", *JHEP* **07** (2017) 141, `arXiv:1707.01539` `[hep-ph]`.

[39] J. H. Putschke *et al.*, "The JETSCAPE framework", `arXiv:1903.07706` `[nucl-th]`.

[40] **JETSCAPE** Collaboration, A. Kumar *et al.*, "Inclusive Jet and Hadron Suppression in a Multi-Stage Approach", `arXiv:2204.01163` `[hep-ph]`.

[41] A. Majumder, "Incorporating Space-Time Within Medium-Modified Jet Event Generators", *Phys. Rev. C* **88** (2013) 014909, `arXiv:1301.5323 [nucl-th]`.

[42] Y. He, T. Luo, X.-N. Wang, and Y. Zhu, "Linear Boltzmann Transport for Jet Propagation in the Quark-Gluon Plasma: Elastic Processes and Medium Recoil", *Phys. Rev. C* **91** (2015) 054908, `arXiv:1503.03313 [nucl-th]`. [Erratum: *Phys.Rev.C* **97** (2018), 019902].

[43] J.-W. Qiu, F. Ringer, N. Sato, and P. Zurita, "Factorization of jet cross sections in heavy-ion collisions", *Phys. Rev. Lett.* **122** (2019) 252301, `arXiv:1903.01993 [hep-ph]`.

[44] J.-W. Qiu, F. Ringer, N. Sato, and P. Zurita, "QCD factorization and universality of jet cross sections in heavy-ion collisions", *Nucl. Phys. A* **1005** (2021) 121853, `arXiv:2002.01652 [hep-ph]`.

[45] R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne, and D. Schiff, "Radiative energy loss of high-energy quarks and gluons in a finite volume quark–gluon plasma", *Nucl. Phys. B* **483** (1997) 291–320, `arXiv:hep-ph/9607355`.

[46] R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne, and D. Schiff, "Radiative energy loss and p(T) broadening of high-energy partons in nuclei", *Nucl. Phys. B* **484** (1997) 265–282, `arXiv:hep-ph/9608322`.

[47] R. Baier, Y. L. Dokshitzer, A. H. Mueller, and D. Schiff, "Medium induced radiative energy loss: Equivalence between the BDMPS and Zakharov formalisms", *Nucl. Phys. B* **531** (1998) 403–425, `arXiv:hep-ph/9804212`.

[48] J. Casalderrey-Solana, D. C. Gulhan, J. G. Milhano, D. Pablos, and K. Rajagopal, "A Hybrid Strong/Weak Coupling Approach to Jet Quenching", *JHEP* **10** (2014) 019, `arXiv:1405.3864 [hep-ph]`. [Erratum: JHEP 09, 175 (2015)].

[49] J. Casalderrey-Solana, D. C. Gulhan, J. G. Milhano, D. Pablos, and K. Rajagopal, "Angular Structure of Jet Quenching Within a Hybrid Strong/Weak Coupling Model", *JHEP* **03** (2017) 135, `arXiv:1609.05842 [hep-ph]`.

[50] J. Brewer, Q. Brodsky, and K. Rajagopal, "Disentangling jet modification in jet simulations and in Z+jet data", *JHEP* **02** (2022) 175, `arXiv:2110.13159 [hep-ph]`.

[51] M. Spousta and B. Cole, "Interpreting single jet measurements in Pb + Pb collisions at the LHC", *Eur. Phys. J. C* **76** (2016) 50, `arXiv:1504.05169 [hep-ph]`.

[52] W. Chen, S. Cao, T. Luo, L.-G. Pang, and X.-N. Wang, "Effects of jet-induced medium excitation in γ-hadron correlation in A+A collisions", *Phys. Lett. B* **777** (2018) 86–90, `arXiv:1704.03648 [nucl-th]`.

[53] W. Zhao, W. Ke, W. Chen, T. Luo, and X.-N. Wang, "From Hydrodynamics to Jet Quenching, Coalescence, and Hadron Cascade: A Coupled Approach to Solving the RAA⊗v2 Puzzle", *Phys. Rev. Lett.* **128** (2022) 022302, `arXiv:2103.14657 [hep-ph]`.

A   The ALICE Collaboration

S. Acharya [125], D. Adamová [86], A. Adler[69], G. Aglieri Rinella [32], M. Agnello [29], N. Agrawal [50],
Z. Ahammed [132], S. Ahmad [15], S.U. Ahn [70], I. Ahuja [37], A. Akindinov [140], M. Al-Turany [97],
D. Aleksandrov [140], B. Alessandro [55], H.M. Alfanda [6], R. Alfaro Molina [66], B. Ali [15], A. Alici [25],
N. Alizadehvandchali [114], A. Alkin [32], J. Alme [20], G. Alocco [51], T. Alt [63], I. Altsybeev [140],
M.N. Anaam [6], C. Andrei [45], A. Andronic [135], V. Anguelov[94], F. Antinori [53], P. Antonioli [50],
N. Apadula [74], L. Aphecetche [103], H. Appelshäuser [63], C. Arata [73], S. Arcelli [25], M. Aresti [51],
R. Arnaldi [55], J.G.M.C.A. Arneiro [110], I.C. Arsene [19], M. Arslandok [137], A. Augustinus [32],
R. Averbeck [97], M.D. Azmi [15], A. Badalà [52], J. Bae [104], Y.W. Baek [40], X. Bai [118], R. Bailhache [63],
Y. Bailung [47], A. Balbino [29], A. Baldisseri [128], B. Balis [2], D. Banerjee [4], Z. Banoo [91], R. Barbera [26],
F. Barile [31], L. Barioglio [95], M. Barlou[78], G.G. Barnaföldi [136], L.S. Barnby [85], V. Barret [125],
L. Barreto [110], C. Bartels [117], K. Barth [32], E. Bartsch [63], N. Bastid [125], S. Basu [75], G. Batigne [103],
D. Battistini [95], B. Batyunya [141], D. Bauri[46], J.L. Bazo Alba [101], I.G. Bearden [83], C. Beattie [137],
P. Becht [97], D. Behera [47], I. Belikov [127], A.D.C. Bell Hechavarria [135], F. Bellini [25], R. Bellwied [114],
S. Belokurova [140], G. Bencedi [136], S. Beole [24], A. Bercuci [45], Y. Berdnikov [140], A. Berdnikova [94],
L. Bergmann [94], M.G. Besoiu [62], L. Betev [32], P.P. Bhaduri [132], A. Bhasin [91], M.A. Bhat [4],
B. Bhattacharjee [41], L. Bianchi [24], N. Bianchi [48], J. Bielčík [35], J. Bielčíková [86], J. Biernat [107],
A.P. Bigot [127], A. Bilandzic [95], G. Biro [136], S. Biswas [4], N. Bize [103], J.T. Blair [108], D. Blau [140],
M.B. Blidaru [97], N. Bluhme[38], C. Blume [63], G. Boca [21,54], F. Bock [87], T. Bodova [20], A. Bogdanov[140],
S. Boi [22], J. Bok [57], L. Boldizsár [136], M. Bombara [37], P.M. Bond [32], G. Bonomi [131,54], H. Borel [128],
A. Borissov [140], H. Bossi [137], E. Botta [24], Y.E.M. Bouziani [63], L. Bratrud [63], P. Braun-Munzinger [97],
M. Bregant [110], M. Broz [35], G.E. Bruno [96,31], M.D. Buckland [23], D. Budnikov[140], H. Buesching [63],
S. Bufalino [29], P. Buhler [102], Z. Buthelezi [67,121], A. Bylinkin [20], S.A. Bysiak[107], M. Cai [6],
H. Caines [137], A. Caliva [28], E. Calvo Villar [101], J.M.M. Camacho [109], P. Camerini [23],
F.D.M. Canedo [110], M. Carabas [124], A.A. Carballo [32], A.G.B. Carcamo [94], F. Carnesecchi [32],
R. Caron [126], L.A.D. Carvalho [110], J. Castillo Castellanos [128], F. Catalano [32,24], C. Ceballos Sanchez [141],
I. Chakaberia [74], P. Chakraborty [46], S. Chandra [132], S. Chapeland [32], M. Chartier [117],
S. Chattopadhyay [132], S. Chattopadhyay [99], T.G. Chavez [44], T. Cheng [97,6], C. Cheshkov [126],
B. Cheynis [126], V. Chibante Barroso [32], D.D. Chinellato [111], E.S. Chizzali [95], J. Cho [57], S. Cho [57],
P. Chochula [32], P. Christakoglou [84], C.H. Christensen [83], P. Christiansen [75], T. Chujo [123],
M. Ciacco [29], C. Cicalo [51], F. Cindolo [50], M.R. Ciupek[97], G. Clai[II,50], F. Colamaria [49], J.S. Colburn[100],
D. Colella [96,31], M. Colocci [25], G. Conesa Balbastre [73], Z. Conesa del Valle [72], G. Contin [23],
J.G. Contreras [35], M.L. Coquet [128], T.M. Cormier[I,87], P. Cortese [130,55], M.R. Cosentino [112], F. Costa [32],
S. Costanza [21,54], C. Cot [72], J. Crkovská [94], P. Crochet [125], R. Cruz-Torres [74], P. Cui [6],
A. Dainese [53], M.C. Danisch [94], A. Danu [62], P. Das [80], P. Das [4], S. Das [4], A.R. Dash [135],
S. Dash [46], A. De Caro [28], G. de Cataldo [49], J. de Cuveland[38], A. De Falco [22], D. De Gruttola [28], N. De
Marco [55], C. De Martin [23], S. De Pasquale [28], R. Deb[131], S. Deb [47], K.R. Deja[133], R. Del Grande [95],
L. Dello Stritto [28], W. Deng [6], P. Dhankher [18], D. Di Bari [31], A. Di Mauro [32], B. Diab [128],
R.A. Diaz [141,7], T. Dietel [113], Y. Ding [6], R. Divià [32], D.U. Dixit [18], Ø. Djuvsland[20], U. Dmitrieva [140],
A. Dobrin [62], B. Dönigus [63], J.M. Dubinski[133], A. Dubla [97], S. Dudi [90], P. Dupieux [125], M. Durkac[106],
N. Dzalaiova[12], T.M. Eder [135], R.J. Ehlers [74], F. Eisenhut [63], D. Elia [49], B. Erazmus [103],
F. Ercolessi [25], F. Erhardt [89], M.R. Ersdal[20], B. Espagnon [72], G. Eulisse [32], D. Evans [100],
S. Evdokimov [140], L. Fabbietti [95], M. Faggin [27], J. Faivre [73], F. Fan[6], W. Fan [74], A. Fantoni [48],
M. Fasel [87], P. Fecchio[29], A. Feliciello [55], G. Feofilov [140], A. Fernández Téllez [44], L. Ferrandi [110],
M.B. Ferrer [32], A. Ferrero [128], C. Ferrero [55], A. Ferretti [24], V.J.G. Feuillard [94], V. Filova[35],
D. Finogeev [140], F.M. Fionda [51], F. Flor [114], A.N. Flores [108], S. Foertsch [67], I. Fokin [94], S. Fokin [140],
E. Fragiacomo [56], E. Frajna [136], U. Fuchs [32], N. Funicello [28], C. Furget[73], A. Furs [140], T. Fusayasu [98],
J.J. Gaardhøje [83], M. Gagliardi [24], A.M. Gago [101], C.D. Galvan [109], D.R. Gangadharan [114],
P. Ganoti [78], C. Garabatos [97], J.R.A. Garcia[44], E. Garcia-Solis [9], C. Gargiulo [32], A. Garibli[81],
K. Garner[135], P. Gasik [97], A. Gautam [116], M.B. Gay Ducati [65], M. Germain [103], A. Ghimouz[123],
C. Ghosh[132], M. Giacalone [50,25], P. Giubellino [97,55], P. Giubilato [27], A.M.C. Glaenzer [128], P. Glässel [94],
E. Glimos[120], D.J.Q. Goh[76], V. Gonzalez [134], S. Gorbunov[38], M. Gorgon [2], K. Goswami [47], S. Gotovac[33],
V. Grabski [66], L.K. Graczykowski [133], E. Grecka [86], A. Grelli [58], C. Grigoras [32], V. Grigoriev[140],
S. Grigoryan [141,1], F. Grosa [32], J.F. Grosse-Oetringhaus [32], R. Grosso [97], D. Grund [35],
G.G. Guardiano [111], R. Guernane [73], M. Guilbaud [103], K. Gulbrandsen [83], T. Gundem [63], T. Gunji [122],
W. Guo [6], A. Gupta [91], R. Gupta [91], R. Gupta [47], S.P. Guzman[44], K. Gwizdziel [133], L. Gyulai [136],

M.K. Habib[97], C. Hadjidakis [72], F.U. Haider [91], H. Hamagaki [76], A. Hamdi [74], M. Hamid[6], Y. Han [138], B.G. Hanley [134], R. Hannigan [108], J. Hansen [75], M.R. Haque [133], J.W. Harris [137], A. Harton [9], H. Hassan [87], D. Hatzifotiadou [50], P. Hauer [42], L.B. Havener [137], S.T. Heckel [95], E. Hellbär [97], H. Helstrup [34], M. Hemmer [63], T. Herman [35], G. Herrera Corral [8], F. Herrmann[135], S. Herrmann [126], K.F. Hetland [34], B. Heybeck [63], H. Hillemanns [32], B. Hippolyte [127], F.W. Hoffmann [69], B. Hofman [58], B. Hohlweger [84], G.H. Hong [138], M. Horst [95], A. Horzyk [2], Y. Hou[6], P. Hristov [32], C. Hughes [120], P. Huhn[63], L.M. Huhta [115], T.J. Humanic [88], L.A. Husova [135], A. Hutson [114], R. Ilkaev[140], H. Ilyas [13], M. Inaba [123], G.M. Innocenti [32], M. Ippolitov [140], A. Isakov [86], T. Isidori [116], M.S. Islam [99], M. Ivanov[12], M. Ivanov[97], V. Ivanov [140], K.E. Iversen [75], M. Jablonski [2], B. Jacak[74], N. Jacazio [25], P.M. Jacobs [74], S. Jadlovska[106], J. Jadlovsky[106], S. Jaelani [82], C. Jahnke[111], M.J. Jakubowska [133], M.A. Janik [133], T. Janson[69], M. Jercic[89], S. Ji [16], S. Jia[10], A.A.P. Jimenez [64], F. Jonas [87], J.M. Jowett [32,97], J. Jung [63], M. Jung [63], A. Junique [32], A. Jusko [100], M.J. Kabus [32,133], J. Kaewjai[105], P. Kalinak [59], A.S. Kalteyer [97], A. Kalweit [32], V. Kaplin [140], A. Karasu Uysal [71], D. Karatovic [89], O. Karavichev [140], T. Karavicheva [140], P. Karczmarczyk [133], E. Karpechev [140], U. Kebschull [69], R. Keidel [139], D.L.D. Keijdener[58], M. Keil [32], B. Ketzer [42], S.S. Khade [47], A.M. Khan [6], S. Khan [15], A. Khanzadeev [140], Y. Kharlov [140], A. Khatun [116], A. Khuntia [107], M.B. Kidson[113], B. Kileng [34], B. Kim [104], C. Kim [16], D.J. Kim [115], E.J. Kim [68], J. Kim [138], J.S. Kim [40], J. Kim [57], J. Kim [68], M. Kim [18], S. Kim [17], T. Kim [138], K. Kimura [92], S. Kirsch [63], I. Kisel [38], S. Kiselev [140], A. Kisiel[133], J.P. Kitowski [2], J.L. Klay [5], J. Klein [32], S. Klein [74], C. Klein-Bösing [135], M. Kleiner [63], T. Klemenz [95], A. Kluge [32], A.G. Knospe [114], C. Kobdaj [105], T. Kollegger[97], A. Kondratyev [141], N. Kondratyeva [140], E. Kondratyuk[140], J. Konig [63], S.A. Konigstorfer [95], P.J. Konopka [32], G. Kornakov [133], S.D. Koryciak [2], A. Kotliarov [86], V. Kovalenko [140], M. Kowalski [107], V. Kozhuharov [36], I. Králik [59], A. Kravčáková [37], L. Krcal [32,38], M. Krivda [100,59], F. Krizek [86], K. Krizkova Gajdosova [32], M. Kroesen [94], M. Krüger [63], D.M. Krupova [35], E. Kryshen [140], V. Kučera [57], C. Kuhn [127], P.G. Kuijer [84], T. Kumaoka[123], D. Kumar[132], L. Kumar [90], N. Kumar[90], S. Kumar [31], S. Kundu [32], P. Kurashvili [79], A. Kurepin [140], A.B. Kurepin [140], A. Kuryakin[140], S. Kushpil [86], J. Kvapil [100], M.J. Kweon [57], Y. Kwon [138], S.L. La Pointe [38], P. La Rocca [26], A. Lakrathok[105], M. Lamanna [32], R. Langoy [119], P. Larionov [32], E. Laudi [32], L. Lautner [32,95], R. Lavicka [102], R. Lea [131,54], H. Lee [104], I. Legrand [45], G. Legras [135], J. Lehrbach [38], T.M. Lelek[2], R.C. Lemmon [85], I. León Monzón [109], M.M. Lesch [95], E.D. Lesser [18], P. Lévai [136], X. Li[10], X.L. Li[6], J. Lien [119], R. Lietava [100], I. Likmeta [114], B. Lim [24], S.H. Lim [16], V. Lindenstruth [38], A. Lindner[45], C. Lippmann [97], A. Liu [18], D.H. Liu [6], J. Liu [117], G.S.S. Liveraro[111], I.M. Lofnes [20], C. Loizides [87], S. Lokos [107], J. Lomker [58], P. Loncar [33], J.A. Lopez [94], X. Lopez [125], E. López Torres [7], P. Lu [97,118], J.R. Luhder [135], M. Lunardon [27], G. Luparello [56], Y.G. Ma [39], M. Mager [32], A. Maire [127], M.V. Makariev [36], M. Malaev [140], G. Malfattore [25], N.M. Malik [91], Q.W. Malik[19], S.K. Malik [91], L. Malinina [VI,141], D. Mallick [80], N. Mallick [47], G. Mandaglio [30,52], S.K. Mandal [79], V. Manko [140], F. Manso [125], V. Manzari [49], Y. Mao [6], R.W. Marcjan [2], G.V. Margagliotti [23], A. Margotti [50], A. Marín [97], C. Markert [108], P. Martinengo [32], M.I. Martínez [44], G. Martínez García [103], M.P.P. Martins [110], S. Masciocchi [97], M. Masera [24], A. Masoni [51], L. Massacrier [72], A. Mastroserio [129,49], O. Matonoha [75], S. Mattiazzo [27], P.F.T. Matuoka[110], A. Matyja [107], C. Mayer [107], A.L. Mazuecos [32], F. Mazzaschi [24], M. Mazzilli [32], J.E. Mdhluli [121], A.F. Mechler[63], Y. Melikyan [43,140], A. Menchaca-Rocha [66], E. Meninno [102,28], A.S. Menon[114], M. Meres [12], S. Mhlanga[113,67], Y. Miake[123], L. Micheletti [32], L.C. Migliorin[126], D.L. Mihaylov [95], K. Mikhaylov [141,140], A.N. Mishra [136], D. Miśkowiec [97], A. Modak [4], A.P. Mohanty [58], B. Mohanty [80], M. Mohisin Khan [III,15], M.A. Molander [43], Z. Moravcova [83], C. Mordasini [95], D.A. Moreira De Godoy[135], I. Morozov [140], A. Morsch [32], T. Mrnjavac [32], V. Muccifora [48], S. Muhuri [132], J.D. Mulligan [74], A. Mulliri[22], M.G. Munhoz [110], R.H. Munzer [63], H. Murakami [122], S. Murray [113], L. Musa [32], J. Musinsky [59], J.W. Myrcha[133], B. Naik [121], A.I. Nambrath [18], B.K. Nandi[46], R. Nania [50], E. Nappi [49], A.F. Nassirpour [17,75], A. Nath [94], C. Nattrass [120], M.N. Naydenov [36], A. Neagu[19], A. Negru[124], L. Nellen [64], G. Neskovic [38], B.S. Nielsen [83], E.G. Nielsen [83], S. Nikolaev [140], S. Nikulin [140], V. Nikulin [140], F. Noferini [50], S. Noh [11], P. Nomokonov [141], J. Norman [117], N. Novitzky [123], P. Nowakowski [133], A. Nyanin [140], J. Nystrand [20], M. Ogino[76], A. Ohlson [75], V.A. Okorokov [140], J. Oleniacz [133], A.C. Oliveira Da Silva [120], M.H. Oliver [137], A. Onnerstad [115], C. Oppedisano [55], A. Ortiz Velasquez [64], J. Otwinowski [107], M. Oya[92], K. Oyama [76], Y. Pachmayer [94], S. Padhan[46], D. Pagano [131,54], G. Paić [64], A. Palasciano [49], S. Panebianco [128], H. Park [123], H. Park [104], J. Park [57], J.E. Parkkila [32], R.N. Patra[91], B. Paul [22], H. Pei [6], T. Peitzmann [58], X. Peng [6], M. Pennisi [24],

13

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