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Jets in Nuclear Collisions

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Abstract

These proceedings from the Quark Matter 2018 Conference provide an overview of recent experimental results of jet measurements in heavy ion collisions at the LHC and RHIC and thoughts on future measurements.

1. Introduction

Jets in heavy ion collisions are used as a short distance probe of the quark-gluon plasma (QGP) created in these collisions. Measurements of jets and high transverse momentum (p_{T}) particles from jets have shown that the rates and properties of jets are modified in Pb+Pb collisions compared to those measurements in pp collisions (for a recent review see Ref. [1]). With the wealth Pb+Pb data available at the Large Hadron Collider (LHC), many important measurements have been made in heavy ion collisions recently. The large statistics allow for systematic studies of inclusive jets as function of the jet transverse momentum, $p_{\mathrm{T}}^{\mathrm{jet}}$, and rapidity, y^{jet}, as well as improved measurements of jets azimuthally balanced with photons and other measurements in which particles are identified within jets. Together, these measurements provide a more comprehensive look at how jets are modified in heavy ion collisions. In addition, there has been continuing interest in adopting jet substructure techniques for heavy ion collisions. Finally, the 2017 Xe+Xe data recorded by the LHC experiments provides a first look at smaller symmetric collision systems at the LHC.

In this proceedings, recent measurements from the LHC and RHIC are discussed which provide new, differential access to how jets are modified in the QGP. A discussion of future areas of interest is presented.

2. Inclusive Jets

Inclusive jets dominantly originate from light quarks and gluons. The high rates of these jets allow for measurements over a very large kinematic range. Figure 1 shows recent ATLAS results of the jet nuclear modification factor, R_{AA}, measured in 0–10% central collisions from 100 GeV to 1 TeV for $R = 0.4$ jets [2]. R_{AA} remains below unity over the entire kinematic range. Figure 1 also shows the first evidence for a rapidity dependence of R_{AA} [2]. There are two reasons this could be expected. First, the gluon jet fraction

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in the inclusive jet sample decreases toward increasing rapidity at fixed jet transverse momentum, p_T^{jet}, (see, for example Ref. [3]). As gluons are expected to lose more energy than quarks in the QGP due to their larger color factor, the value of R_{AA} would be expected to increase as $|y^{jet}|$ increases. Second, the p_T^{jet} spectra become steeper with increasing $|y^{jet}|$ (see, for example Ref. [4]); this would cause a reduction in the R_{AA} value for the same energy loss. Figure 1, R_{AA} is shown to decrease with increasing $|y^{jet}|$ for jets with $p_T^{jet} > 300$ GeV, suggesting that the second effect dominates for these jets. These measurements will provide input for theoretical models which seek to incorporate all these effects into a description of jet quenching.

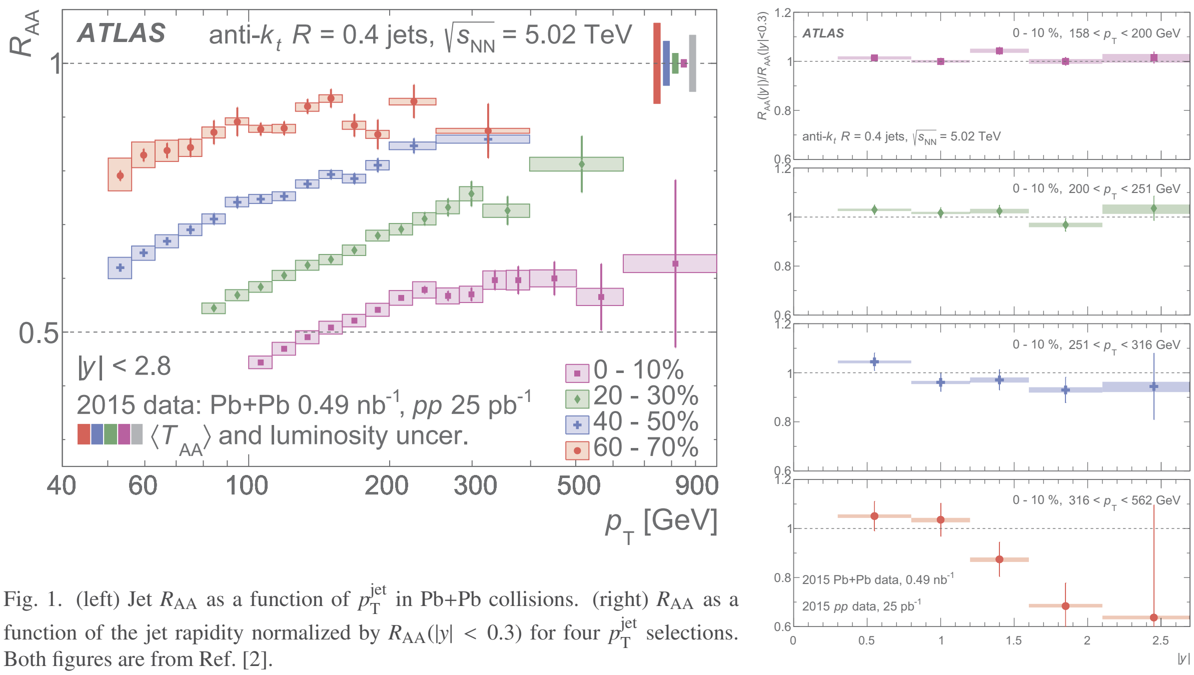


Fig. 1. (left) Jet R_{AA} as a function of p_T^{jet} in Pb+Pb collisions. (right) R_{AA} as a function of the jet rapidity normalized by $R_{AA}(|y| < 0.3)$ for four p_T^{jet} selections. Both figures are from Ref. [2].

Measurements of the fragmentation functions of jets provide information on how particles are carrying the jet momentum and extensive measurements have been done at the LHC [5, 6, 7, 8]. In these measurements, excesses of both low-p_T particles and particles carrying a large fraction of the jet momentum has been observed. Recent measurements [8] allow a more extensive study of how both of these features depend on the p_T^{jet} and y^{jet}. Figure 2 shows the fragmentation functions for three p_T^{jet} selections, plotted as a function of the charged-particle p_T and the charged-particle momentum fraction, z. It is observed that the soft-particle excess extends to approximately 4 GeV, independent of p_T^{jet}. In contrast, the hard-particle excess is found to begin at a common z value for all p_T^{jet} selections measured; this excess is described by some models [9, 10]. Ref. [10] explains the excess as being due to the combination of the larger quenching and softer fragmentation of gluon jets compared to quark jets.

An alternative method for studying the structure of jets is jet substructure. This class of observables is sensitive to the overall structure of the jet. These techniques were originally developed to look for decays of boosted objects at the LHC, but have recently become of great interest in the study of QCD jets, both in pp collisions and in heavy ion collisions; recent reviews can be found in Ref. [11, 12]. Previous substructure measurements in heavy ion collisions have included a measurement of the jet mass [13] and the jet splitting function z_g [14, 15].

Recent results presented at this conference include the measurement of the number of soft-drop splittings in charged particle jets [16] and the soft-drop mass of jets [17], both shown in Fig. 3. These results use the *soft-drop* procedure by which some of the soft radiation is removed from the jet [18], by reclustering the jet with the Cambridge-Achen [19] and checking if each step in the clustering tree satisfies a momentum balance condition known as the soft-drop condition. ALICE measured, n_{SD}, the number of splittings in charged-particle jets which satisfy the soft-drop condition. It might be expected that the interaction of the

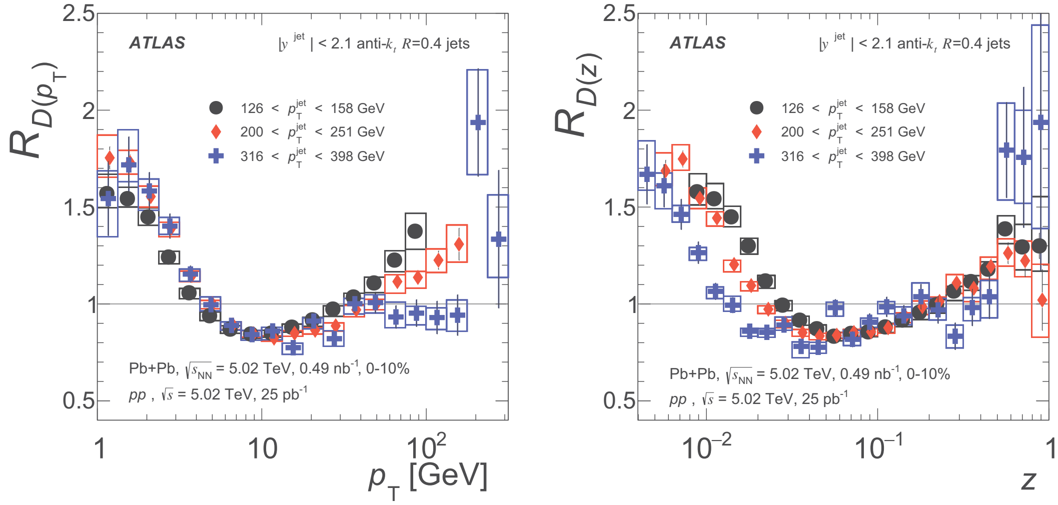


Fig. 2. Ratios of jet fragmentation functions in 0–10% central Pb+Pb collisions to those in pp collisions as a function of charged particle p_{T} (left) and z (right). Both figures are from Ref. [8].

parton shower and the QGP would increase the number of such splittings. The result, shown in Fig. 3, was found to be unchanged between Pb+Pb collisions and Pythia6 jets embedded into Pb+Pb data [16].

The jet mass is related to the angular size of the jet and thus how the mass distributions change in heavy ion collisions provide information about how the QGP interacts with the parton shower. There are a variety of mass measurements already available. The soft-drop procedure changes the mass distribution and a new quantity, the soft-drop mass, can be defined. Ref. [17] investigated two settings of the soft-drop algorithm which lead to very different soft-drop mass distributions. These settings are expected to be differently sensitive to the modification of the jets by the QGP. For the soft-drop mass distributions shown in Fig. 3, the distributions are found to be consistent with those in pp collisions (after smearing to match the underlying event effects), except for an enhancement of jets with high soft-drop mass in the most central collisions. No modification compared to smeared pp collisions was found with the other soft-drop algorithm setting. In addition, the first measurement of the jet mass (without soft-drop), m, over a wide range in $p_{\mathrm{T}}^{\mathrm{jet}}$ was reported [20]. No modification of the jet suppression as a function of the jet mass scaled by $p_{\mathrm{T}}^{\mathrm{jet}}$ was observed. This could suggest that the jets are dominantly losing energy as a single object rather than parts of the jet de-cohering and losing energy independently [21]. More studies of the mass and other quantities related to the angular distribution of particles within the jet in heavy ion collisions are necessary to understand these measurements further.

3. Photon-jet correlations

Jets opposite a photon in azimuth are of great interest in heavy ion collisions because the photon does not lose energy in the plasma as quarks and gluons do. These measurements complement inclusive jet measurements. Previous measurements have shown the p_{T} of the jet relative to that of the photon is reduced in heavy ion collisions relative to pp collisions [24]. New measurements allow the study of the photon-jet momentum balance as a function of the photon p_{T} [25, 22]. The ATLAS results are unfolded for detector resolution effects and are shown in Fig. 4 for 100-158 GeV photons in 0–10% central collisions. A peak of nearly balanced photon-jet pairs as well as a wide distribution due to jets which have much less energy than the photons is observed. Additionally, the first measurements of the fragmentation of the jets opposite a photon have been performed [26, 23]. These fragmentation functions differ from inclusive fragmentation functions in a few ways. First, the jets are possibly quenched more due to the bias from the photon selection. Second, the jets are at lower $p_{\mathrm{T}}^{\mathrm{jet}}$ than the inclusive jet fragmentation functions. Finally, these jets have a

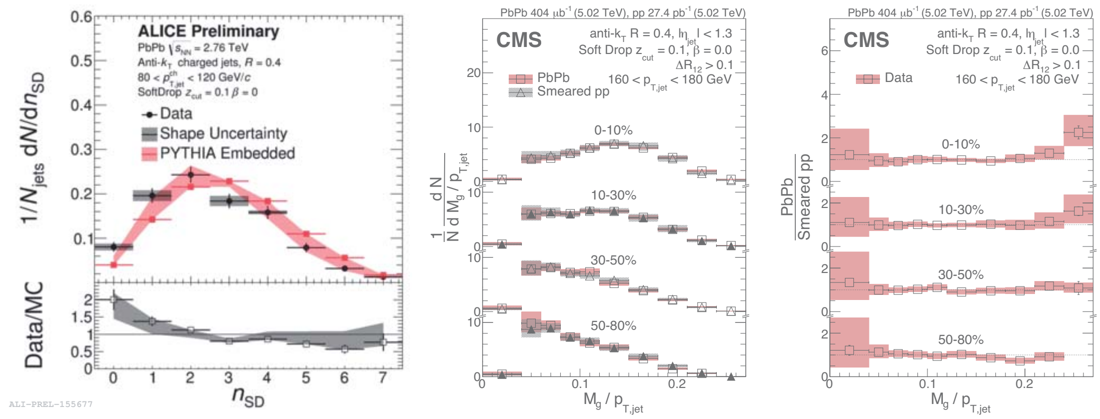


Fig. 3. (left) Distribution of the number of soft-drop splittings, n_{SD} in Pb+Pb collisions compared to those from Pythia6 events embedded into Pb+Pb data (top) and the ratio of data to the simulation (bottom) [16]. (center) Distribution of the groomed jet mass divided by $p_{\mathrm{T}}^{\mathrm{jet}}$ for four centralities in Pb+Pb collisions (squares) and the same quantity for pp collisions smeared to have the same underlying event effects as those in the Pb+Pb data. (right) Ratios of the groomed jet mass divided by $p_{\mathrm{T}}^{\mathrm{jet}}$ in Pb+Pb collisions compared to those in the smeared pp collisions [17]

much higher fraction of quark-jets than the inclusive jet sample. Measurements of photon-hadron correlations had been made at RHIC [27, 28, 29], but only recently were measurements made of the hadrons in reconstructed jets back-to-back with a photon in Pb+Pb collisions [26, 23]. In the measurements shown in Fig. 4 [23], a similar magnitude and p_{T}-range of the low-p_{T} enhancement is observed as in the fragmentation functions shown in Fig. 2. The p_{T} range of the low-p_{T} excess is also similar to that observed at RHIC [29].

4. J/ψ and D^0 in Jets

At this conference, new results were shown from reconstructing mesons carrying charm quarks within jets. In pp collisions, these measurements are important to tune MC generators and provide references for measurements in heavy ion collisions. In Pb+Pb collisions, D^0 measurements are used to tag charm-quark jets. The comparison of the properties of these jets to inclusive jets can provide information about the parton flavor dependence of the jet quenching process.

A measurement of the fragmentation function of J/ψ particles is reported in Ref. [30], Fig. 5, and shows that the momentum fraction of prompt (not from B decay) J/ψ mesons within jets differs qualitatively from what is expected from Pythia8; there is much more jet energy around these high-p_{T} J/ψ particles than is expected from Pythia8. In contrast, the non-prompt J/ψ from B-meson decays are well described by Pythia8. These findings are similar to those from LHCb [33], though the kinematics is different.

Two new results study D^0 mesons within jets. ALICE has measured the momentum distributions of D^0 mesons within jets in pp collisions and compared the results to Powheg+Pythia6 MC [31] and CMS has measured the radial distribution of D^0 mesons inside jets in pp and Pb+Pb collisions. ALICE finds that the MC describes the pp data to within the systematic uncertainties. CMS finds that in pp collisions the data favor a narrower radial profile than the MC. The result in Pb+Pb collisions is compatible with that in pp collisions with the current uncertainties. Further measurements with smaller uncertainties would allow comparison to light quark and gluon jets.

5. Xe+Xe collisions

In 2017 there was a short Xe+Xe run at the LHC. This data has provided new information about how jet quenching depends on the size of the system produced. ALICE [34], ATLAS [35], and CMS [36] have measured how the charged particle R_{AA} compares between Pb+Pb and Xe+Xe collisions as a function of variety of measures of the system size. Figure 6 shows a comparison of the R_{AA} in Pb+Pb and Xe+Xe

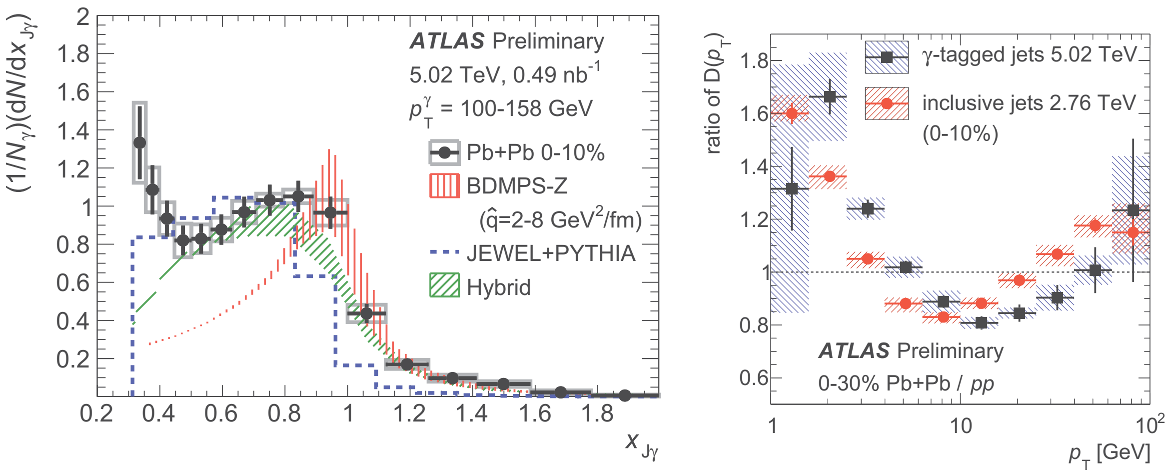


Fig. 4. (left top) Ratio of the jet transverse momentum to the photon p_T, $x_{J\gamma}$, in central Pb+Pb collisions [22]. Also shown on the figure are calculations from various theoretical models. (right) The ratio of the fragmentation function as a function of charged particle p_T in central Pb+Pb collisions to *pp* collisions for jets opposite a photon (squares) and inclusive jet fragmentation functions [7] (circles). Figure is from Ref. [23].

collisions for two centrality bins selected to have the same average charged particle multiplicity. The R_{AA} values are consistent between the two collision systems in both of these selections.

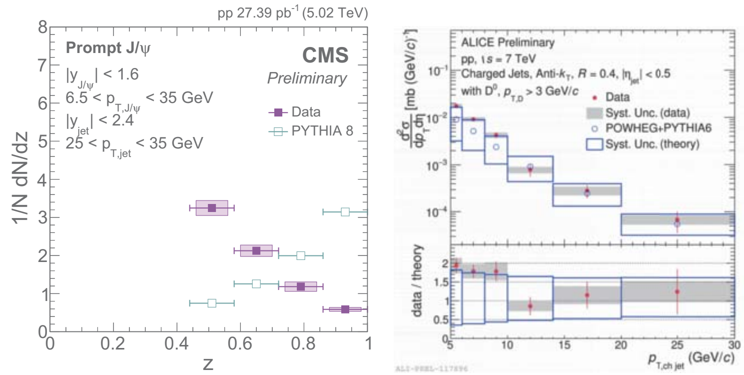
Figure 6 also shows ATLAS measurements of the dijet asymmetry in Pb+Pb and Xe+Xe collisions from Ref. [35] for four p_T^{jet} selections. The measurement is performed in a fixed forward transverse energy selection, which provides a similar comparison to that made for the charged particle R_{AA} above. The measurement is not unfolded for detector resolution and the jet energy resolution (JER) is different between the two collision systems. In this case the Xe+Xe measurement has a better JER than the Pb+Pb measurement so an additional smearing is applied to the Xe+Xe data to make it directly comparable to the Pb+Pb measurement. In this case the effect of this additional smearing is quite small and the Pb+Pb measurement is in agreement with both the Xe+Xe with and without the additional smearing.

6. Future Measurements

In these proceedings many new jet measurements from RHIC and the LHC have been discussed. There are a wealth of both precision measurements and exploratory studies which will greatly benefit from the larger datasets expected in 2018 and LHC Run 3 and Run 4. Data which has been unfolded for detector effects can be directly compared to both other data and model calculations. This has already been used to measure the jet transverse momentum dependence of the fragmentation functions and to compare the photon-jet fragmentation functions to the inclusive jet fragmentation functions. These types of comparisons are crucial to extracting the maximum information from the results.

The recent Xe+Xe run was extremely useful for jet physics; the jet related observables discussed here are found to be modified approximately according to the multiplicity or forward transverse energy. This observation helps to understand what could be gained from accumulating a large luminosity of ions smaller than lead. This could serve two purposes: to increase the available number of jets and hard probes available in heavy ion collisions [37] and to understand the role, if any, of jet quenching in *p*A collision systems.

Most of the measurements discussed here are from the LHC, however precision measurements from other collision center-of-mass energies are necessary to constrain the temperature dependence of jet quenching in the QGP. The sPHENIX experiment [38], expected to start taking data in 2023, is necessary for this. It will provide for the first time fully calorimetric jet measurements at RHIC and allow jet measurements over nearly all of the available kinematic range at $\sqrt{s_{NN}}$ = 200 GeV. The combination of sPHENIX and the LHC will provide the best opportunity to constrain how jets interact with the quark gluon plasma.



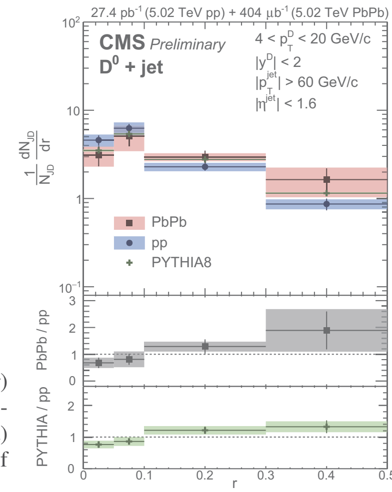


Fig. 5. (left) Fragmentation function of prompt J/ψ mesons in pp collisions [30]. (center) Transverse momentum distribution of D^0 mesons within charged particle jets in pp collisions and the ratio of of the measurement to Powheg+Pythia6 simulations [31]. (right) Radial distribution of D^0 mesons within jets in pp and Pb+Pb collisions and the ratio of Pb+Pb to pp collisions and the ratio of Pythia8 simulations compared to pp data [32].

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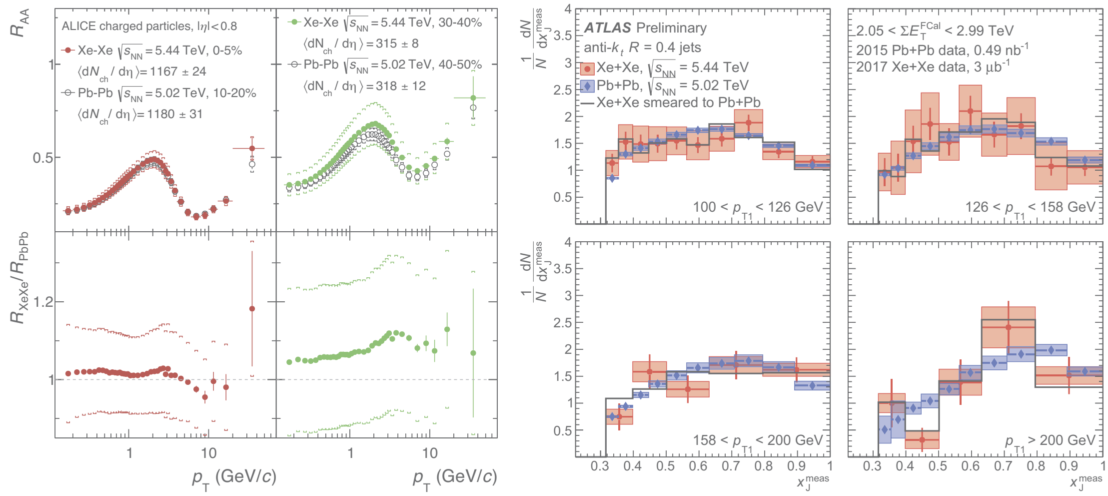

Fig. 6. (left) Charged particle R_{AA} as a function of p_{T} for central and mid-central Xe+Xe collisions compared to the same quantity in Pb+Pb collisions at the same average charged particle multiplicity as well as the ratio of the R_{AA} values [34]. (right) The ratio of the sub-leading to leading jet transverse momentum, x_J^{meas}, for four selections in leading jet p_{T}. Results are shown for Xe+Xe collisions (red), Pb+Pb collisions (blue) and Xe+Xe collisions which have had an additional smearing applied to match the JER in Pb+Pb collisions [35]

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