MEASUREMENTS OF JETS IN ALICE*

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The ALICE detector can be used for measurements of jets in pp, pPb, and Pb–Pb collisions. Measurements of jets in pp collisions are consistent with expectations from perturbative calculations and jets in pPb scale with the number of nucleon–nucleon collisions, indicating that cold nuclear matter effects are not observed for jets. Measurements in Pb–Pb collisions demonstrate suppression of jets relative to expectations from binary scaling to the equivalent number of nucleon–nucleon collisions.

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1. Introduction

Jets are the collimated sprays of particles created from a fragmenting parton. In order to compare measurements of jets to theoretical calculations, both the measurements and the theory calculations need to use the same unambiguous definition of a jet, specified by a jet finding algorithm. A jet finding algorithm groups final state particles into jet candidates. The ideal jet finding algorithm is both infrared and colinear safe [1]. The anti-$k_{\rm T}$ algorithm, a sequential recombination jet finding algorithm which results in conical jets, is both colinear and infrared safe [2], and is the primary jet finding algorithm used by the ALICE Collaboration.

ALICE has measured jets in pp, pPb, and Pb–Pb collisions. Measurements in pp collisions are consistent with calculations from pQCD. Measurements in pPb collisions test for cold nuclear matter effects, which are not observed for jets. Partons interact with the hot, dense Quark–Gluon Plasma (QGP) formed in heavy-ion collisions, leading to the suppression of jets observed in Pb–Pb collisions [3–9].

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ALICE [10] is a general purpose detector optimized for measurements in the high track density environment of heavy-ion collisions. The Inner Tracking System (ITS) [10], the Time Projection Chamber (TPC) [11], and the Electromagnetic Calorimeter (EMCal) [12, 13] are the primary detectors used for the reconstruction of jets. These detectors are in a uniform 0.5 T magnetic field. The TPC and ITS provide tracking with high efficiency above 150 MeV/c. The EMCal is a lead/scintillator sampling calorimeter covering $|\eta| < 0.7$ in pseudorapidity and 100° in azimuth in 2011. Future measurements will be aided by the Dijet Calorimeter (DCal), covering $|\eta| < 0.7$ in pseudorapidity and 60° in azimuth. ALICE measures two types of jets, charged track jets and full jets. Track jets use information from the tracking detectors only and charged track jet energies are corrected up to the energy of primary charged particles (mostly pions, kaons, and protons). Full jets combine information from the tracking detectors and the EMCal and are corrected up to the full jet energy at the particle level. Tracks above 150 MeV/c and EMCal clusters above 300 MeV are used for jet reconstruction. For full jets, the track momentum is subtracted from clusters which are matched to tracks in order to avoid double counting. The boost-invariant p_{T} recombination scheme [1] is used, meaning that jet momentum $p_{\mathrm{T,jet}}$ is the scalar sum of the constituent momenta.

2. Jets in *pp* collisions

Measurements of full jet spectra using the anti-k_{T} algorithm in pp collisions at $\sqrt{s} = 2.76$ TeV are in agreement with calculations based on Next-to-Leading Order (NLO) perturbative QCD (pQCD) for radii $R = 0.2$ and 0.4 [14]. The ratio of the cross section for $R = 0.2$ to that at $R = 0.4$, shown in Fig. 1, is particularly sensitive to the jet shape. Theoretical calculations are only able to describe this ratio well when the effects of hadronization are included. The process of hadronization leads to final state particles which are not exactly aligned with their parent partons. For large jet radii, the difference between jets identified using partons and final state hadrons as input for the jet finder is often negligible because hadronization may lead to a particle either being moved into or out of a jet. For narrower jets, however, hadronization is more significant because hadronization is likely to lead to more particles being swept out of the jet than into it. The theoretical calculations shown in Fig. 1 demonstrate the importance of hadronization in the formation of small jets.

Figure 2 shows the charged track jet cross section as a function of transverse jet momentum in pp collisions at $\sqrt{s} = 7$ TeV using the anti-k_{T} algorithm for $R = 0.2, 0.4$, and 0.6. Since charged track jet energies are corrected only to the energy of charged particles in the jet, these measurements are compared to calculations from several PYTHIA [15] tunes and to

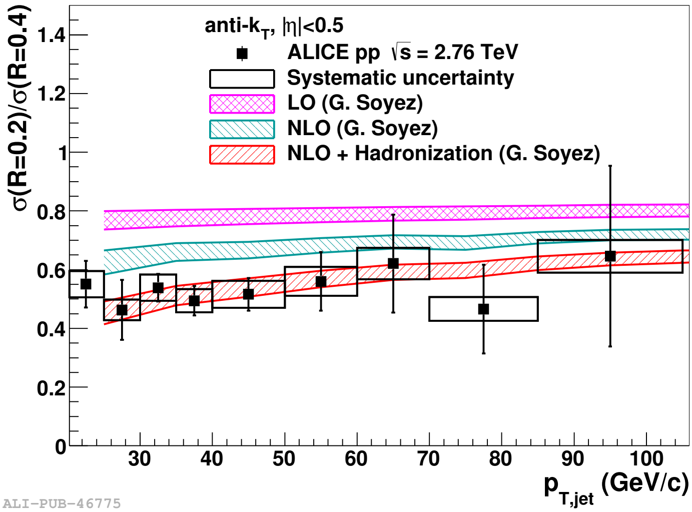

Fig. 1. Ratio of inclusive differential full jet cross sections for $R = 0.2$ to $R = 0.4$ using the anti-$k_{\rm T}$ algorithm in pp collisions at $\sqrt{s} = 2.76$ TeV [14] compared to pQCD calculations. Data points are placed at the center of each bin.

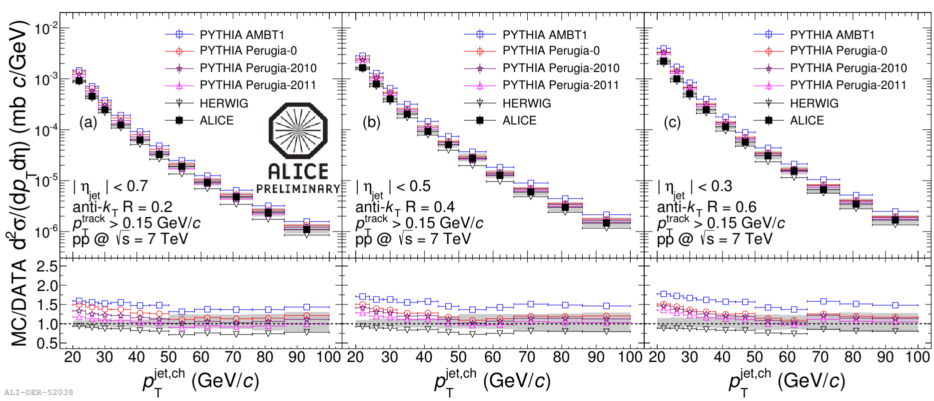

Fig. 2. Inclusive differential charged track jet cross sections using the anti-$k_{\rm T}$ algorithm in pp collisions at $\sqrt{s} = 7$ TeV for $R = 0.2, 0.4$, and 0.6 compared to calculations from PYTHIA [15] tunes and HERWIG [16].

HERWIG [16]. The Perugia tunes [17] and calculations from HERWIG [16] are within error of the measurements. This demonstrates that jet production is reasonably well-understood both experimentally and theoretically in pp collisions and, therefore, pp collisions provide a reasonable baseline for studies of potential cold nuclear matter effects in pPb collisions and jet quenching in Pb–Pb collisions.

3. Jets in pPb collisions

Cold nuclear matter effects have been observed in measurements of open heavy flavor and charmonium production [18–20] and there are some indications of collective flow in nuclei [21]. It is therefore important to investigate whether or not jet production is modified by cold nuclear matter in order to be able to properly interpret the results observed in Pb–Pb collisions. Nuclear effects are characterized using the nuclear modification factor

$$R_{p\mathrm{Pb}} = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}^2 N_{p\mathrm{Pb}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}{\mathrm{d}^2 N_{pp}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta} \,. \tag{1}$$

An $R_{p\mathrm{Pb}} < 1$ indicates suppression relative to binary scaling of pp collisions, $R_{p\mathrm{Pb}} > 1$ indicates enhancement, and $R_{p\mathrm{Pb}} = 1$ indicates no cold nuclear matter effects. Figure 3 shows $R_{p\mathrm{Pb}}$ for charged track jet cross sections using the anti-k_{T} algorithm in collisions at $\sqrt{s_{NN}} = 5.02$ TeV. $R_{p\mathrm{Pb}}$ is within error of 1 for all momenta, consistent with no cold nuclear matter effects. This indicates that any modifications observed for jets in Pb–Pb collisions are from hot nuclear matter effects.

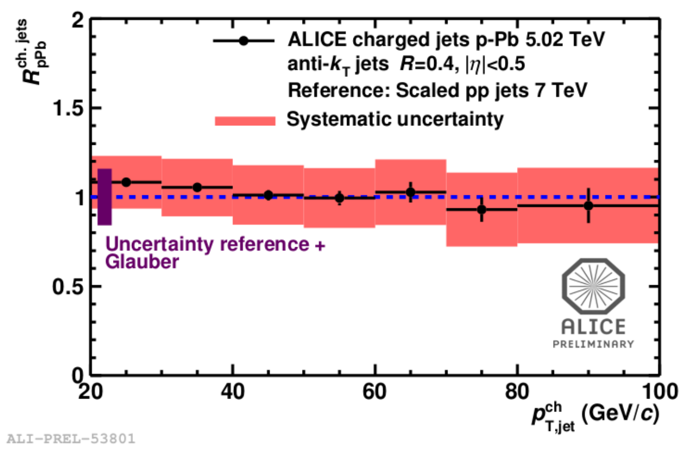

Fig. 3. Nuclear modification factor $R_{p\mathrm{Pb}}$ for charged track jets cross sections using the anti-k_{T} algorithm in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

The ratio of the cross sections for jets with different radii is also sensitive to cold nuclear matter effects. Measurements in pp demonstrated that this ratio is sensitive to hadronization effects, so this ratio would be sensitive to possible modification of hadronization in nuclei. It would also be sensitive to possible energy loss from jet formation in the nuclei. Figure 4 shows the ratio of cross sections of $R = 0.2$ to $R = 0.4$ charged track jets in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared to calculations from PYTHIA. The data are systematically lower than the calculations from PYTHIA, however, these data are approximately consistent with the results in Fig. 1. This indicates that there are no significant modifications of the jet shape or to hadronization in pPb collisions.

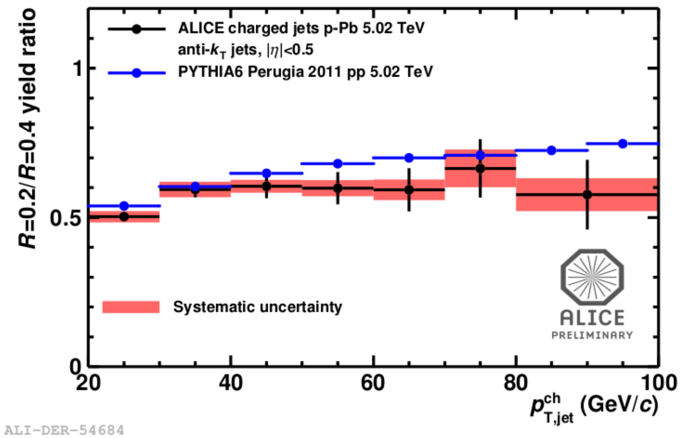

Fig. 4. Ratio of inclusive charged track jet cross sections for $R = 0.2$ to $R = 0.4$ using the anti-k_T algorithm in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [14] compared to PYTHIA calculations.

4. Jets in Pb–Pb collisions

Measurements of jets in Pb–Pb collisions are complicated by the large combinatorial background due to tracks unassociated with jet production. This background leads to both a shift in the reconstructed jet energy and combinatorial jets comprised entirely of tracks which were produced due to processes other than hard scattering. There are several methods to deal with these backgrounds. The background subtracted jet p_T is given by

$$p_{T,jet} = p^{rec}_{T,jet} - \rho A_{jet} , \qquad (2)$$

where $p^{rec}_{T,jet}$ is the p_T reconstructed from the jet finder, ρ is the average energy density per unit area and A_{jet} is the area of the jet. Due to the restricted acceptance for full jets, ρ is calculated from the background from charged track jets, ρ_{ch}. Charged jets are reconstructed using a random cone, the two jets with the highest p_T are excluded, and the median value of $p^{rec}_{T,jet}/A_{jet}$ is used to determine ρ_{ch} for each event [7]. To calculate ρ for full jets, ρ_{ch} is scaled up by a factor s: $\rho = \rho_{ch} * s$. This factor s is the ratio of the charged plus neutral energy to the charged energy in the event averaged over the event class. It is determined from data and is centrality-dependent.

The fluctuations in the background also impact the reconstructed jet energies because they lead to distortions in the jet spectra. The background fluctuations are quantified by placing cones randomly in the event and summing up the energy within them. The average energy contained in a cone of that size is then subtracted. The difference δp_{T} between the reconstructed energy and the average background energy given by

$$\delta p_{\mathrm{T}} = p_{\mathrm{T,RC}}^{\mathrm{rec}} - \rho\pi R^2\,, \tag{3}$$

where $R = \sqrt{\varDelta\phi^2 + \varDelta\eta^2}$ is the radius of the random cone. This distribution is used to create the background response matrix. Unfolding is done using the Bayesian method in the RooUnfold package [22]. The uncertainty is dominated by the uncertainty due to the tracking efficiency and the unfolding algorithm.

Even with the subtraction of the average energy due to the background and unfolding for resolution effects due to fluctuations, low momentum jet candidates are still dominantly combinatorial. These combinatorial jets are suppressed by requiring a high momentum track. Figure 5 shows the uncorrected jet spectra in 0–10% Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with and without this 5 GeV/c track bias. This shows that requiring a high momentum track suppresses combinatorial jets.

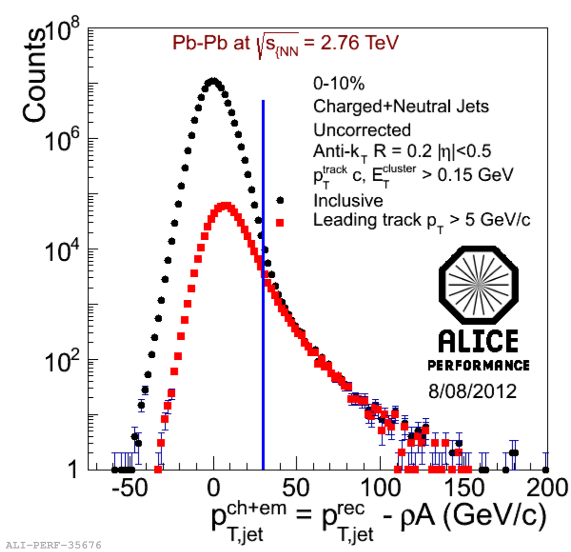

Fig. 5. Uncorrected full jet spectra in 0–10% Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with and without a 5 GeV/c track bias.

The nuclear modification factor in Pb–Pb collisions

$$R_{AA} = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}^2 N_{\mathrm{PbPb}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta}{\mathrm{d}^2 N_{pp}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}\eta} \tag{4}$$

is shown in Fig. 6 for full jets with a 5 GeV/c track bias in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV using the anti-k_{T} algorithm. It is compared to R_{AA}

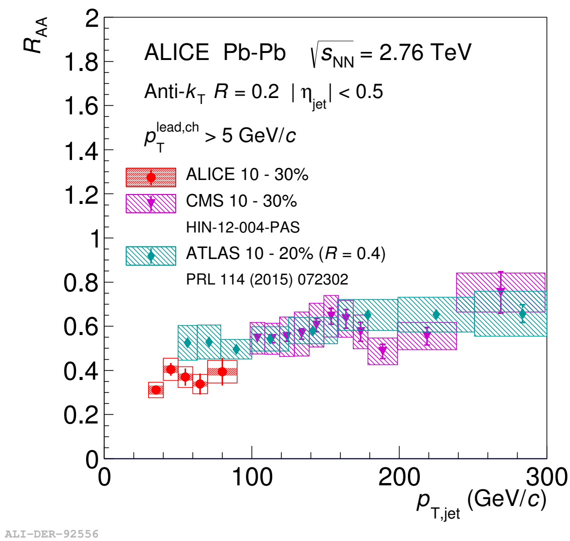

Fig. 6. R_{AA} in 0–10% Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with a 5 GeV/c track bias from ALICE [27] compared to results from ATLAS [23] and CMS [24].

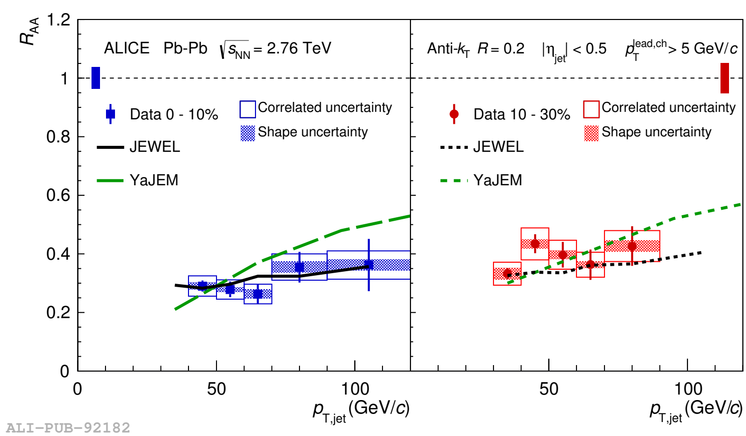

Fig. 7. R_{AA} in 0–10% Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with a 5 GeV/c track bias from ALICE [27] compared to predictions from JEWEL [25] and YaJEM [26].

measured by ATLAS [23] and CMS [24]. Results from ATLAS for jets with $R = 0.4$ are higher than the R_{AA} from ALICE with $R = 0.2$, indicating that $R = 0.2$ jets are slightly more suppressed. These results show strong suppression of jets in heavy ion collisions. Figure 7 compares the measured R_{AA} to predictions from JEWEL [25] and YaJEM [26], demonstrating that the suppression is described qualitatively by these models.

5. Conclusions

The ALICE detector can be used for measurements of both full jets and charged track jets in a range of collision systems, including *pp*, *p*Pb, and Pb–Pb collisions. Measurements in *pp* collisions demonstrate that jets are well-understood and consistent with expectations from pQCD. Measurements in *p*Pb demonstrate that there are no significant cold nuclear matter effects for midrapidity jets. Measurements in Pb–Pb collisions show strong suppression of jets in heavy-ion collisions, which can be interpreted as a hot nuclear matter effect since no suppression is observed in *p*Pb collisions.

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